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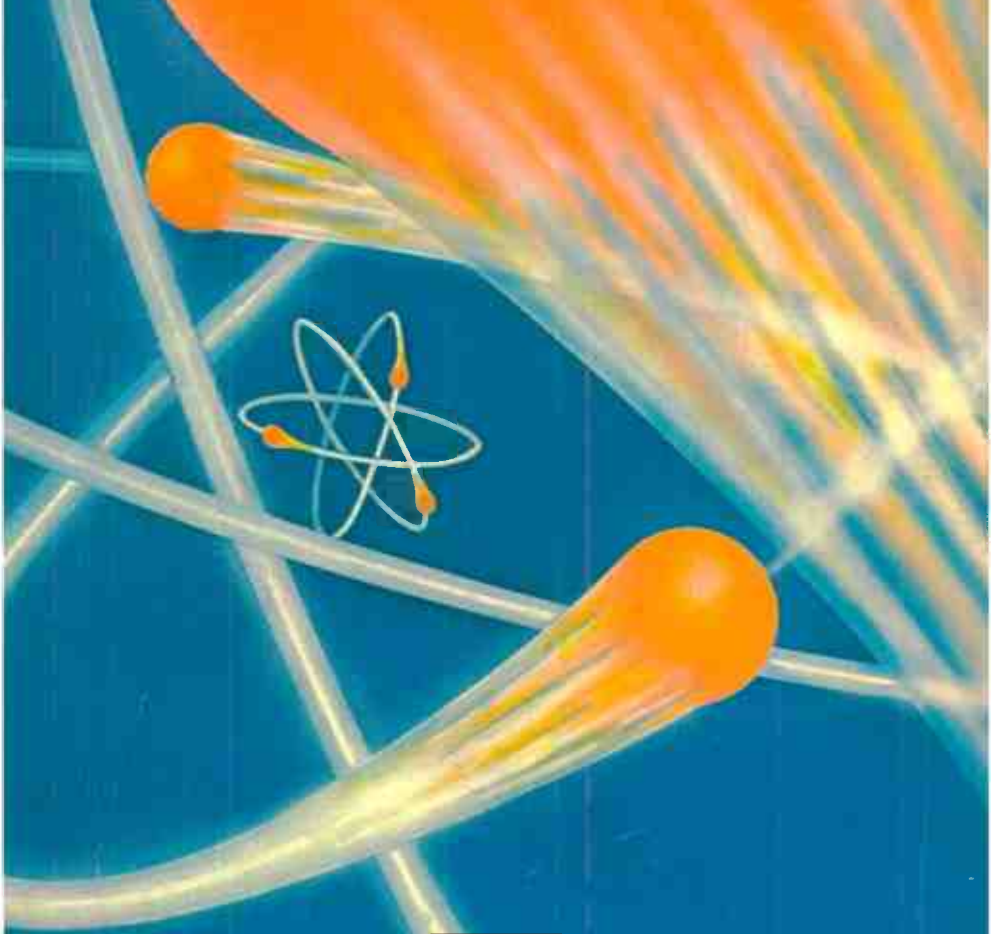
BASIC ELECTRICITY/ ELECTRONICS

VOLUME 3

UNDERSTANDING ELECTRONIC CIRCUITS

SECOND EDITION



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BASIC

ELECTRICITY/ELECTRONICS

VOLUME 3

Understanding Electronic Circuits

by

Training & Retraining, Inc.

Second Edition Revised by

Joe Risse

Howard W. Sams & Co., Inc.

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TRAINING & RETRAINING, INC.

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Introduction

This third volume in the series introduces you to vacuum tubes, transistors, and the ways in which these devices are put to work. Although all of the topics discussed provide background information for further study, many of them also have direct practical applications in circuit design and analysis. After studying this volume, you will have expanded your knowledge of electrical fundamentals to include the basic devices and circuits that make radio, television, radar, computers, and countless other areas of electronics technology possible. With this knowledge you will be better able to understand how electronic equipment works.

WHAT YOU WILL LEARN

Nearly all modern electronic equipment depends on semiconductor devices for its operation. Other equipment uses vacuum tubes. In this volume you will learn about both vacuum tubes and transistors.

Vacuum tubes depend on the behavior of electrons in an electric field for their operation. This subject is discussed along with the ways in which electrons are emitted into the electric field. You will learn about the Edison effect and how the diode (two-element) tube operates. You will see how the addition of more elements to the tube makes it useful in a variety of applications. Tube parameters (numbers that indicate the usefulness of a tube) are explained in detail. The text shows how the operation of vacuum tubes can be described and studied by means of graphs. The meaning of the term amplification is explained, and the most common types of vacuum-tube amplifiers are shown. You will learn about the classification of amplifiers according to the way the vacuum tubes in the amplifiers are operated. Several methods of coupling (connecting) more than one amplifier stage are discussed.

The coverage of semiconductor devices begins with an explanation of what a semiconductor is. You will learn about the pn junction and how the semiconductor diode and the transistor depend on the operation of this junction. As with tubes, the operation of transistors can be described in terms of parameters and graphs. You will learn about these aids and how to work with them. You will be shown how transistors amplify and how they are connected in amplifier circuits. Methods of coupling transistor amplifier stages are explained.

You will learn how power supplies work. Such terms as rectifier, filter, pulsating dc, regulated power supply, and others are explained.

Also, you will learn how pulses are generated and amplified. Some of the applications of pulse circuits are discussed. Finally you will learn about field-effect transistors, unijunction transistors, triacs, diacs, SCRs, and integrated circuits.

WHAT YOU SHOULD KNOW BEFORE YOU START

Before beginning your study of tube and transistor circuits, you should have a good understanding of the basic principles of ac and dc circuit operation. (Such knowledge can be obtained from Volume 2 of this series.) All new terms are carefully defined. Enough math is used to give precise interpretation to important principles, but if you know how to add, subtract, multiply, and divide, the mathematical expressions will give you no trouble.

WHY THE TEST FORMAT WAS CHOSEN

During the past few years, new concepts of learning have been developed under the common heading of programmed instruction. Although there are arguments for and against each of the several formats or styles of programmed textbooks, the value of programmed instruction itself has been proved to be sound. Most educators now seem to agree that the style of programming should be developed to fit the needs of teaching the particular subject. To help you progress successfully through this volume, a brief explanation of the programmed format follows.

Each chapter is divided into small bits of information presented in a sequence that has proved best for learning purposes. Some of the information bits are very short—a single sentence in some cases. Others may include several paragraphs. The length of each presentation is determined by the nature of the concept being explained and the knowledge the reader has gained up to that point.

The text is designed around two-page segments. Facing pages include information on one or more concepts, complete with illustrations designed to clarify the word descriptions used. Self-testing questions are included in most of these two-page segments. Many of these questions are in the form of statements requiring that you fill in one or more missing words; other questions are either multiple-choice or simple essay types. Answers are given on the succeeding page, so you will have the opportunity to check the accuracy of your response and verify what you have or have not learned before proceeding. When you find that your answer to a question does not agree with that given, you should restudy the information to determine why your answer was incorrect. As you can see, this method of question-answer programming insures that you will advance through the text as quickly as you are able to absorb what has been presented.

The beginning of each chapter features a preview of its contents, and a review of the important points is contained at the end of the chapter. The preview gives you an idea of the purpose of the chapter—what you can expect to learn. This helps to give practical meaning to the information as it is presented. The review at the completion of the chapter summarizes its content so that you can locate and restudy those areas which have escaped your full comprehension. And, just as important, the review is a definite aid to retention and recall of what you have learned.

HOW YOU SHOULD STUDY THE TEXT

Naturally, good study habits are important. You should set aside a specific time each day to study in an area where you can concentrate without being disturbed. Select a time when you are at your mental peak, a period when you feel most alert.

Here are a few pointers you will find helpful in getting the most out of this volume.

1. Read each sentence carefully and deliberately. There are no unnecessary words or phrases; each sentence presents or supports a thought which is important to your understanding of electricity and electronics.
2. When you are referred to or come to an illustration, stop at the end of the sentence you are reading and study the illustration. Make sure you have a mental picture of its general content. Then continue reading, returning to the illustration each time a detailed examination is required. The drawings were especially planned to reinforce your understanding of the subject.
3. At the bottom of most right-hand pages you will find one or more questions to be answered. Some of these contain "fill-in" blanks. Since more than one word might logically fill a given blank, the number of dashes indicates the number of letters in the desired word. In answering the questions, it is important that you actually do so in writing, either in the book or on a separate sheet of paper. The physical act of writing the answers provides greater retention than merely thinking the answer. Writing will not become a chore since most of the required answers are short.
4. Answer all questions in a section before turning the page to check the accuracy of your responses. Refer to any of the material you have read if you need help. If you don't know the answer even after a quick review of the related text, finish answering any remaining questions. If the answers to any questions you skipped still haven't come to you, turn the page and check the answer section.
5. When you have answered a question incorrectly, return to the appropriate paragraph or page and restudy the ma-

terial. Knowing the correct answer to a question is less important than understanding **why** it is correct. Each section of new material is based on previously presented information. If there is a weak link in this chain, the later material will be more difficult to understand.

6. In some instances, the text describes certain principles in terms of the results of simple experiments. The information is presented so that you will gain knowledge whether you perform the experiments or not. However, you will gain a greater understanding of the subject if you do perform the suggested experiments.
7. Carefully study the review, "What You Have Learned," at the end of each chapter. This review will help you gauge your knowledge of the information in the chapter and actually reinforce your knowledge. When you run across statements you don't completely understand, reread the sections relating to these statements, and recheck the questions and answers before going to the next chapter.

This volume has been carefully planned to make the learning process as easy as possible. Naturally, a certain amount of effort on your part is required if you are to obtain the maximum benefit from the book. However, if you follow the pointers just given, your efforts will be well rewarded, and you will find that your study of electricity and electronics will be a pleasant and interesting experience.

1

Vacuum Tubes

what you will learn

In this chapter you will learn how an electric field influences the motion of electrons. You will be able to name the elements of a diode tube and to explain how the diode operates. You will also learn how graphs are used to show the relationship existing between voltage and current in a diode.

ELECTRONS IN AN ELECTRIC FIELD

The electron is a negatively charged particle. Under the proper conditions, an electron can be moved by placing it under the influence of an electric field. Such a field is formed when a difference of potential, or voltage, exists between two

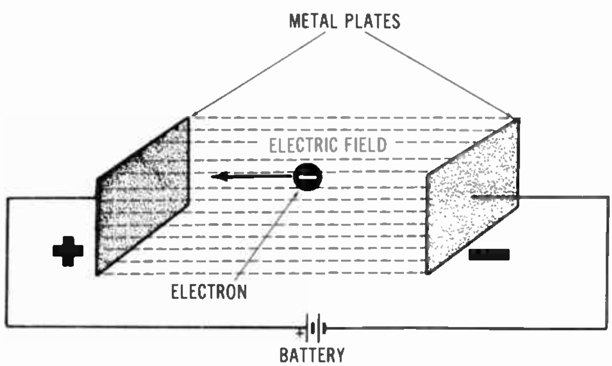


Fig. 1-1. Electron movement in an electric field.

points. If free to move in this field, the electron will move toward the more positive point.

Electron Movement in a Vacuum

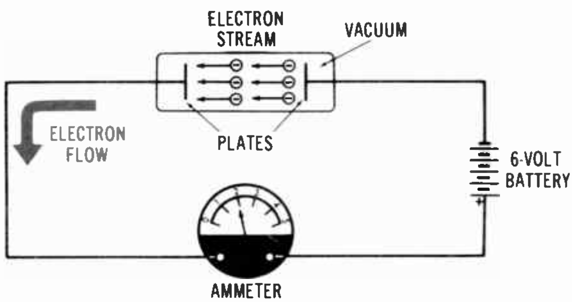
It is difficult to control the motion of electrons through a medium such as air because the electrons collide with the air molecules. For this reason electrons can move more easily in a vacuum.

Many electrons moving in the same direction in an electric field form an electron stream. The number of electrons passing a given point in a given period of time is called **current.** The unit of current is the **ampere.** When 6 quintillion, 240 quadrillion electrons pass a point in a circuit each second, a current of 1 ampere is said to be flowing. This number of electrons is called a **coulomb.** Therefore, 1 coulomb per second is 1 ampere.

Resistance Between Two Conducting Plates

Consider two plates placed a specified distance apart in a vacuum, and assume electrons are able to leave one of the plates. A difference of potential between the plates will cause a certain amount of current to flow. If the value of the voltage is known and the current can be measured, the resistance can be calculated by using Ohm's law.

One terminal of a 6-volt battery is connected to one of the plates, and the other terminal is connected to the other plate



$$E = 6 \text{ VOLTS}$$

$$I = 2 \text{ AMPERES}$$

$$R = \frac{E}{I} = \frac{6 \text{ VOLTS}}{2 \text{ AMPERES}} = 3 \text{ OHMS}$$

Fig. 1-2. Resistance measurement between two plates.

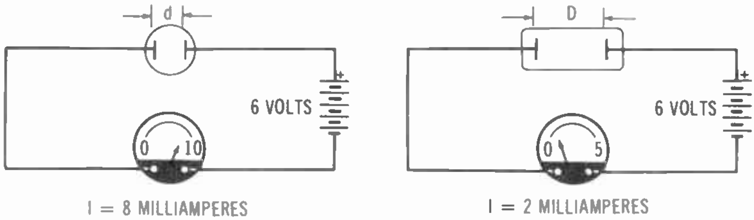


Fig. 1-3. Variation of current with plate spacing.

through an ammeter (a current-measuring meter). An electron stream flows through the vacuum between the plates, and the ammeter measures a current of 2 amperes. Using Ohm's law, 6 (volts) divided by 2 (amperes) gives 3 ohms.

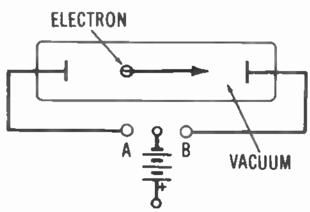
Three factors determine the resistance between a set of plates: 1. Distance between the plates. 2. Voltage difference between the plates. 3. Temperature of the plates.

Distance Between the Plates—Fig. 1-3 shows two sets of plates with the same voltage applied between the plates of each set. The plates in one are twice as far apart as the plates in the other. The plates that are **d** distance apart allow four times as much current to flow as the plates **D** distance apart.

Q1-1. What is the resistance across the d set of plates?

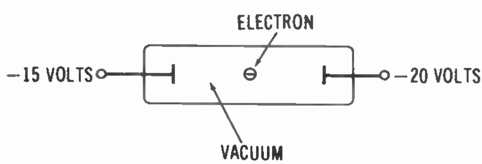
Q1-2. What is the resistance across the D set of plates?

Q1-3. Connect the battery so that the electrons move in the direction shown below.



Q1-4. An electron moves readily in a ______.

Q1-5. Which way will an electron move in the field shown below?



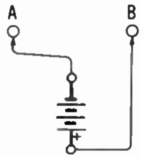
Your Answers Should Be:

A1-1. The resistance is **750 ohms.**

$$R = \frac{E}{I} = \frac{6 \text{ volts}}{8 \text{ milliamps}} = 750 \text{ ohms}$$

A1-2. The resistance is **3,000 ohms.**

$$R = \frac{E}{I} = \frac{6 \text{ volts}}{2 \text{ milliamps}} = 3{,}000 \text{ ohms}$$



A1-3. The battery should be connected as shown.

A1-4. An electron moves readily in a **vacuum.**

A1-5. The electron must **move away from the more negative 20-volt plate and move toward the less negative 15-volt plate.**

Voltage Across the Plates—Fig. 1-4 shows that as the voltage across the plates is increased, the current increases. Note, however, that although the voltage doubles (from 4 volts to 8 volts), the current more than doubles (from 2 milliamperes to 6 milliamperes).

The resistance of the 4-volt circuit is 2,000 ohms. The resistance of the 8-volt circuit is 1,333 ohms. It can be seen that as the voltage between the plates increases, the resistance between the plates decreases.

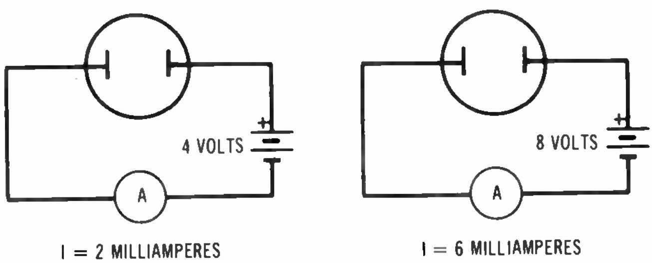


Fig. 1-4. Current depends on voltage between plates.

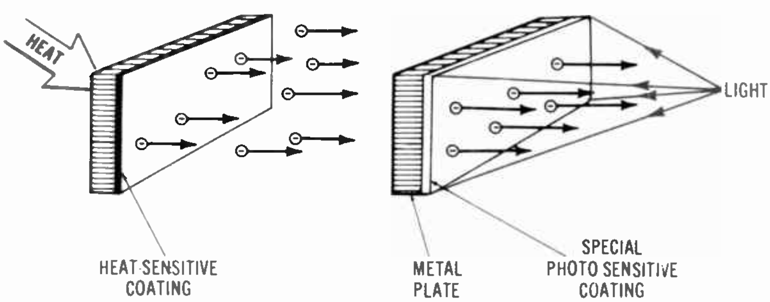
Temperature of the Plates—Electrons are agitated, or "excited," by heat. This agitation causes an increase in electron velocity (movement), and the increase in velocity makes it easier for the electrons to leave the plate. Thus, as the plate that emits the electrons is heated, more current flows.

THE CATHODE AND ELECTRON EMISSION

Since they are bound to the nucleus of an atom, electrons are difficult to move. To flow through an electric field, electrons must be freed from their atoms. Such electrons are called **free electrons.**

An electrode from which electrons are emitted is called a **cathode.** One method of generating free electrons is to expose certain materials to light. These materials are called **photosensitive.** If a metal is coated with a photosensitive material and then exposed to light, electrons will be emitted. This type of emission is called **photoelectric emission.**

Certain materials emit electrons readily when heated. This is called **thermionic emission.**



(A) Thermionic.

(B) Photoelectric.

Fig. 1-5. Electron emission.

Q1-6. As the distance between the plates decreases, the resistance between the plates (increases, decreases).

Q1-7. As the voltage between the plates decreases, the resistance between the plates (increases, decreases).

Q1-8. As the temperature of the emitting plate is decreased, the resistance between the plates (increases, decreases).

Your Answers Should Be:

A1-6. As the distance between the plates decreases, the resistance between the plates **decreases.**

A1-7. As the voltage between the plates decreases, the resistance between the plates **increases.**

A1-8. As the temperature of the emitting plate is decreased, the resistance between the plates **increases.**

The Heater

Thermionic emission is the method most commonly used to supply free electrons. The element used to supply the heat for the cathode is called the **heater.** The heater is a very thin filament of wire through which electric current is passed. If coated with a heat-sensitive material, the filament then serves as a cathode and is called **a directly heated cathode.**

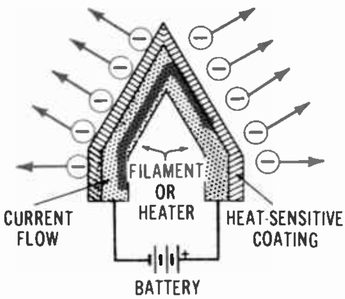


Fig. 1-6. Directly heated cathode.

The **indirectly heated** cathode is made of a good emitting material shaped like a tube or cylinder, open at both ends. A filament is placed inside, but not touching, the cathode. No heater current passes through the cathode.

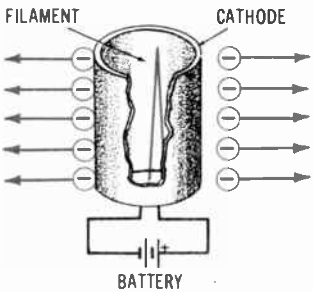


Fig. 1-7. Indirectly heated cathode.

ATTRACTING THE EMITTED ELECTRONS

The free electrons perform useful work if they are moved through an electronic circuit. An element called a **plate** is used to attract the electrons emitted from the cathode. The plate, made of metal, and the cathode are connected to a source of potential which makes the plate positive with respect to the cathode. Therefore, the negative electrons flow to the plate (often called anode).

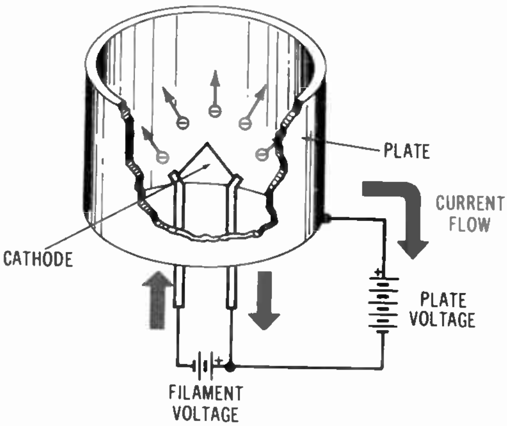


Fig. 1-8. Positive plate attracts electrons from cathode.

Q1-9. An electrode from which electrons are emitted is called a ________.

Q1-10. Electrons are emitted from a substance that has been exposed to light. This process is called ________________ emission.

Q1-11. The method most commonly used to generate free electrons is called ____________ emission.

Q1-12. A heated filament coated with a material that will emit electrons very readily is called a(an) _________ _______ cathode.

Q1-13. A heated cathode through which no heating current passes is called a(an) ____________ _______ cathode.

Q1-14. The element that attracts electrons emitted from the cathode is called the ______.

Your Answers Should Be:

A1-9. An electrode from which electrons are emitted is called a **cathode.**

A1-10. Electrons are emitted from a substance that has been exposed to light. This process is called **photo-electric** emission.

A1-11. The method most commonly used to generate free electrons is called **thermionic** emission.

A1-12. A heated filament coated with a material that will emit electrons very readily is called a **directly heated** cathode.

A1-13. A heated cathode through which no heating current passes is called an **indirectly heated** cathode.

A1-14. The element that attracts electrons emitted from the cathode is called the **plate.**

DEVELOPMENT OF THE DIODE

In one of his experiments with the electric lamp, Thomas A. Edison placed a small metal plate inside the evacuated envelope surrounding the filament. This plate was not touching the filament. By placing a galvanometer (a very sensitive ammeter) between the positive side of the filament and the plate,

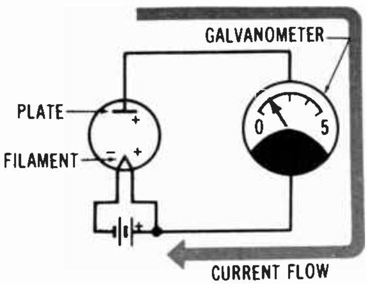
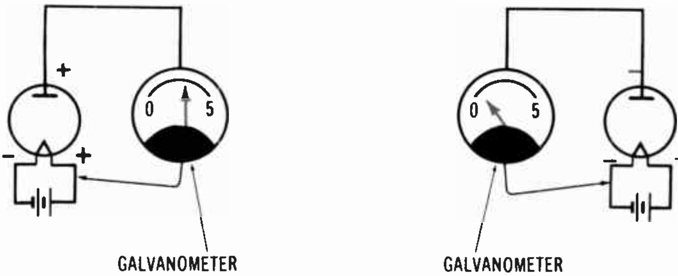


Fig. 1-9. Circuit for demonstrating Edison effect.

Edison noted a current was flowing through the seemingly open circuit between the filament and the metal plate. This action is known as the **Edison effect.**

In 1904 Ambrose Fleming improved the plate by forming it into a tubular shape and using it to completely surround the filament. This two-element tube was called a **diode.** Fleming's experiments with the diode proved that current flowed through it in only one direction—from cathode to plate. Fleming tried an experiment similar to that shown in Fig. 1-10.



(A) Current flow.

(B) No current flow.

Fig. 1-10. Circuit for demonstrating undirectional conduction of a diode.

In the figure showing Edison's experiment, notice that the sides of the filament connected to the galvanometer and to the plate are at the same positive potential (the voltage of the battery). Therefore, current cannot flow between these two points. However, the side of the filament connected to the negative terminal of the battery is negative with respect to the plate. As a result, electrons emitted from this side (negative) of the filament are attracted to the plate and cause a small current through the galvanometer.

In Fleming's experiment, a similar situation existed when the galvanometer was connected to the positive side of the filament. However, when the galvanometer is connected to the negative side of the filament, the plate and that side of the filament are at the same potential. But the plate is more negative than the positive side of the filament. Therefore, no current flows through the galvanometer.

Q1-15. A two-element tube is called a ______.

Q1-16. The apparent flow of current between a filament and a plate is called the ______ ______.

Q1-17. Diode current flows only from ________ to ______.

Your Answers Should Be:

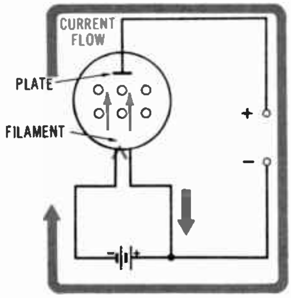
A1-15. A two-element tube is called a **diode.**

A1-16. The apparent flow of current between a filament and a plate is called the **Edison effect.**

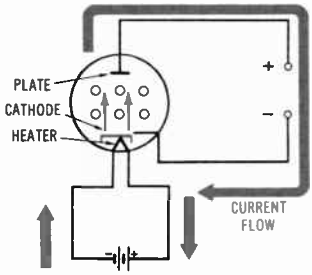
A1-17. Diode current flows only from **cathode** to **plate.**

THE CATHODE

The directly heated cathode is a "coated" filament. The filament is often made of tungsten coated with thorium (this is called thoriated tungsten). The thorium acts as a good emitter of electrons when it is heated. The electrons emitted by the thorium are replaced by the tungsten. Fig. 1-11 shows how the filament battery sends current through the filament, heating it and causing it to emit electrons.



(A) Directly heated.



(B) Indirectly heated.

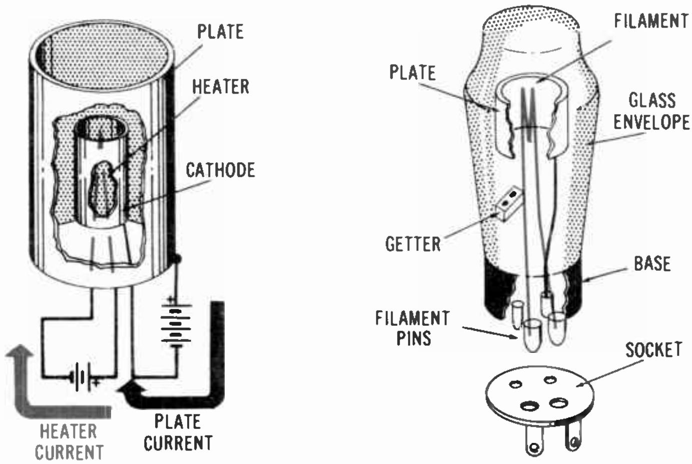
Fig. 1-11. Types of cathodes.

The indirectly heated cathode consists of a metal cylinder heated by a filament placed inside, but not touching it. This type of cathode is usually coated with barium or strontium oxide, which serves as the electron-emitting material.

THE PLATE

In the diode, the element that collects the electrons is called the plate. This element is usually constructed so that it completely surrounds the cathode.

A pictorial representation of a diode with an indirectly heated cathode is shown in Fig. 1-12. Current flowing through the heater heats the cathode. The cathode emits electrons which flow to the plate and through the battery back to the cathode. Fig. 1-12 also shows the actual construction of a diode with a directly heated cathode.



(A) Indirectly heated cathode. (B) Directly heated cathode.

Fig. 1-12. Diode construction.

Because of the gases retained in the metal parts, it is very difficult to completely evacuate a vacuum tube. For this reason, a part called the **getter** is provided. The tube elements are brought up to a red heat after the air has been pumped from the tube. This releases the trapped gases, and then the getter is caused to burn quickly by an electromagnetic field surrounding the tube. The getter absorbs the gases released by the heat and, in the process, deposits a silver coating on the inside of the glass envelope.

Q1-18. In a diode, the element that emits electrons is called a _______.

Q1-19. A separate filament circuit is used to provide heat for the ___________ heated cathode.

Q1-20. A ______ is used to remove gases retained in the metal parts of a diode.

Your Answers Should Be:

A1-18. In a diode the element that emits electrons is called a **cathode.**

A1-19. A separate filament circuit is used to provide heat for the **indirectly** heated cathode.

A1-20. A getter is used to remove gases retained in the metal parts of a diode.

TUBE CHARACTERISTICS AND EFFECTIVE RESISTANCE

Three factors affect the amount of current through a diode. They are the temperature of the cathode, the voltage between the plate and cathode, and the space charge.

Temperature of the Cathode

The hotter the cathode becomes, the more electrons it emits per unit time. There are practical limits to this, however. If the

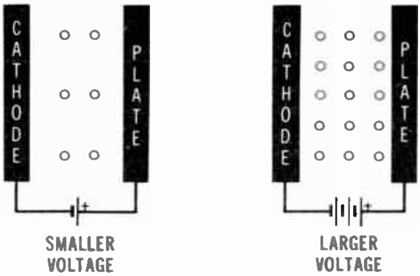


Fig. 1-13. Current flow is affected by plate voltage.

temperature of the cathode is increased too much, the filament will burn out. Also, if the voltage is too high, the diode will be destroyed. In addition, there is a limit to the maximum rate at which a cathode can emit electrons.

Plate Voltage

As the positive voltage of the plate increases with respect to the cathode, current flow through the tube increases.

There is also a limit to the tube current that can be obtained by increasing the plate voltage, because the plate cannot attract more electrons than the cathode emits.

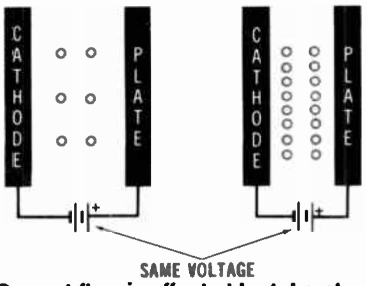
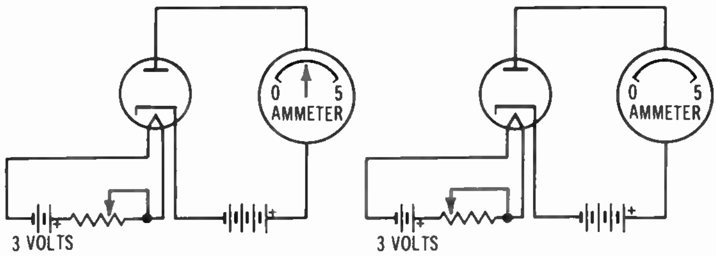


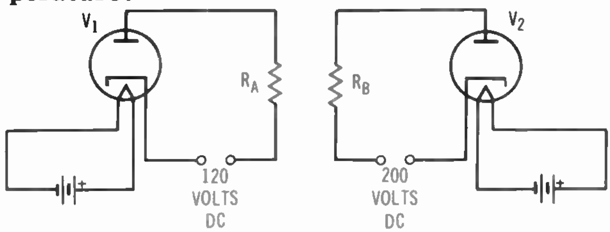
Fig. 1-14. Current flow is affected by tube-element spacing.

Suppose that the voltage on the plate remained the same but the plate was moved closer to the cathode. How would this affect the current through the diode? Under these conditions the current would increase.

Q1-21. Supply the missing meter pointer (approximate position) in the figure below.



Q1-22. If resistors R_A and R_B in the two circuits below are identical, which resistor will have the higher temperature?



Q1-23. Moving the plate away from the cathode (increases, decreases) the current flow through the diode.

Your Answers Should Be:

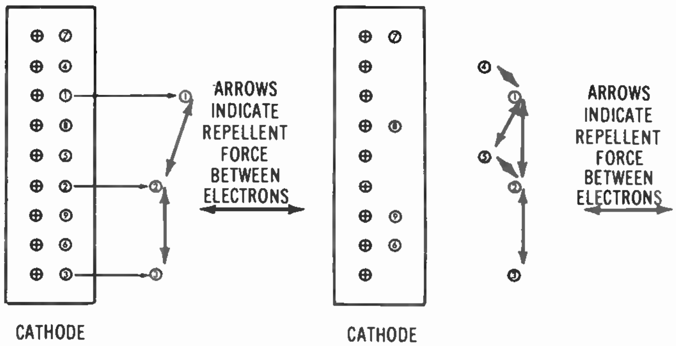
A1-21. The needle should indicate that there is **more current flow in the plate circuit of the diode.** As the arm of the potentiometer in the filament circuit is positioned farther to the left, more current flows in the filament circuit. The filament gets hotter and emits more electrons, and more current then flows in the plate circuit.

A1-22. With a higher plate voltage (200 volts), V2 conducts more current than V1, and the current through R_B is more than the current through R_A. Therefore I^2R_B is greater than I^2R_A, and **R_B is hotter than R_A.**

A1-23. Moving the plate away from the cathode **decreases the current flow through the diode.**

Space Charge

A condition called "space charge" plays an important part in the operation of a vacuum tube. In Fig. 1-15 heat acts as the driving force to push electron number 1 into the space



(A) Electrons begin leaving cathode. (B) More electrons leave cathode.

Fig. 1-15. Forming a space charge.

around the cathode. Initially, the electron has much energy. However, most of this energy is used up in breaking away from the cathode. The electron moves very slowly out into the space around the cathode and soon stops moving. Since the cathode has lost one of its electrons, it now has more positive charges (protons) than electrons.

As a result, the electron is attracted back to the now positive cathode. However, heat is still driving other electrons from the cathode. As electron number 1 heads back toward the cathode, it encounters electrons 2 and 3. Since they are also negative, they repel electron number 1, preventing it from returning to the cathode. The attempt of these electrons to return to the cathode is blocked by electrons 4, 5, and 6, and so on. As the electrons move out into space, they form a cloud of negative charges. The larger this cloud becomes, the more opposition it offers to additional electrons leaving the cathode.

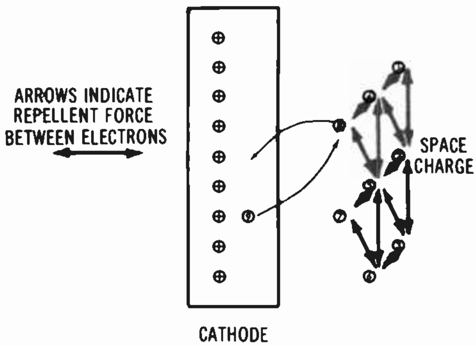


Fig. 1-16. Emission saturation.

Finally, a point is reached where, when a sufficient quantity of electrons has been emitted, the cloud has enough negative charge to force newly emitted electrons back to the cathode. From then on, for every electron emitted by the cathode, one will be returned to the cathode. This condition of equilibrium is called **emission saturation.** The cloud of electrons around the cathode is called the **space charge.**

Q1-24. The cloud of electrons that forms around the cathode is called the _____ ______.

Q1-25. The condition of equilibrium of the electron cloud around the cathode is called ________ __________.

Your Answers Should Be:

A1-24. The cloud of electrons that forms around the cathode is called the **space charge.**

A1-25. The condition of equilibrium of the electron cloud around the cathode is called **emission saturation.**

HOW THE SPACE CHARGE AFFECTS CURRENT FLOW

When a plate is placed in a vacuum tube, it does not receive electrons directly from the cathode. Instead, it takes them from the side of the space charge nearest the plate.

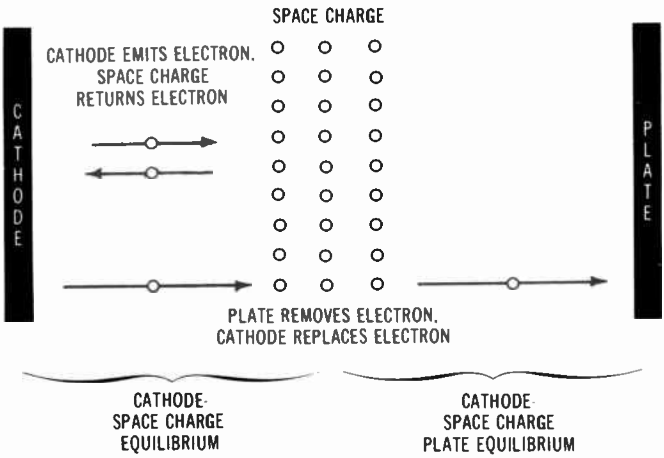


Fig. 1-17. Two equilibrium conditions in a diode.

Each time the plate removes one electron from the space charge, the overall negative charge is decreased. Another electron must then be placed in the space charge to take its place. Thus, equilibrium (state of balance) in the space charge is maintained. Note there are now two conditions of equilibrium being maintained. One is when the electrons are emitted by the cathode into the space charge and are then returned to the cathode. The other condition of equilibrium is when the plate removes an electron from the space charge and the cathode replaces this electron.

Space-Charge Equilibrium

A state of equilibrium is set up between the plate, the cathode, and the space charge. This is shown in Fig. 1-18. Electrons are emitted from the cathode into the space charge from which the plate draws some electrons (plate current). The remaining or surplus electrons not required by the plate are returned to the cathode. The quantity returned is the difference between the amount of electrons originally emitted by the cathode and the amount going to make up the plate current. The result of all this is that the space charge is maintained at a constant size. In other words, it reaches and stays in a state of equilibrium.

This cloud of electrons making up the space charge provides a steady source of electrons for the plate current. This reservoir permits short periods of greater plate current flow than could be supplied directly from the cathode.

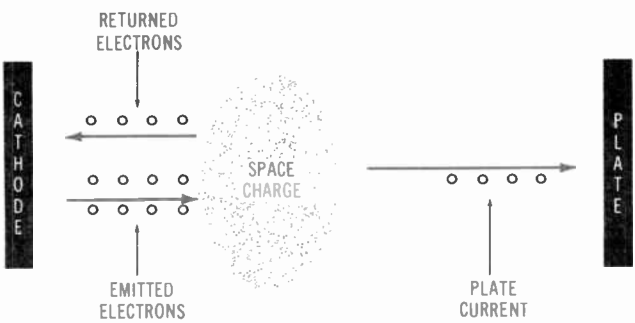


Fig. 1-18. Equilibrium in a diode.

Q1-26. The space charge is a substantial (negative, positive) charge between cathode and plate.

Q1-27. The field that repels the electrons emitted by the cathode lies between the _ _ _ _ _ _ _ and the _ _ _ _ _ _ _ _ _ _ _ _.

Q1-28. The field that removes electrons from the space charges lies between the _ _ _ _ _ _ _ _ _ _ _ and the _ _ _ _ _.

Q1-29. The plate exerts its force directly on the _ _ _ _ _ _ _ _ _ _ _.

Your Answers Should Be:

A1-26. The space charge is a **substantial negative charge** between the cathode and the plate.

A1-27. The field that repels the electrons emitted by the cathode lies between the **cathode** and the **space charge.**

A1-28. The field that removes electrons from the space charge lies between the **space charge** and the **plate.**

A1-29. The plate exerts its force directly on the **space charge.**

Current-Flow Control

In Fig. 1-19, the applied plate voltage is 100 volts. This results in a plate current of 18 mA (milliamperes). The cathode

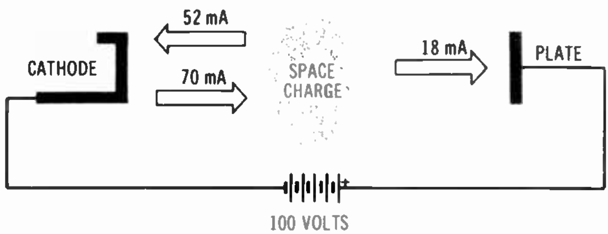


Fig. 1-19. Plate 100 volts positive.

emits enough electrons to produce a current of 70 mA, but the space charge prevents some of them from reaching the plate. The 52-mA surplus is returned to the cathode.

If the plate voltage is increased to 200 volts, the plate current becomes 50 mA, and the current returned is 20 mA.

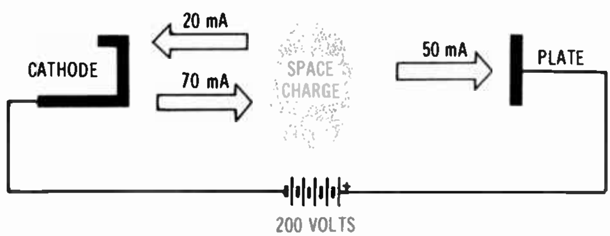


Fig. 1-20. Plate 200 volts positive.

In Fig. 1-21, the plate voltage has been increased to 400 volts, and the plate current becomes 69 mA. Note that in each of these cases the sum of the plate current and the current returned to the cathode is equal to the current emitted by the cathode.

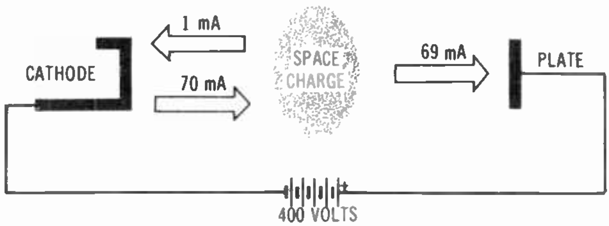


Fig. 1-21. Plate 400 volts positive.

When the plate voltage is increased to 450 volts, the plate current equals the cathode emission. This is illustrated in the figure below.

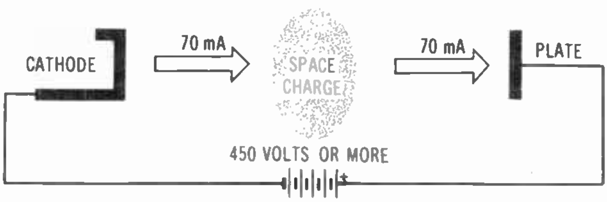


Fig. 1-22. Plate 450 volts or more positive.

Any further increase in the plate voltage will result in reducing the space charge. Then the voltage on the plate acts directly on the cathode and forces the cathode to emit more electrons than it is designed to emit. This results in rapid destruction of the emitting material and reduced life of the tube.

Q1-30. **Draw a diagram showing the conditions of equilibrium in a diode.**

Q1-31. **The number of electrons returned to the cathode plus the _____ ________ equals the number of electrons emitted by the cathode.**

Q1-32. **If the emitted electrons produce a current of 90 mA and the returned electrons produce a current of 30 mA, the plate current is ____ mA.**

Your Answers Should Be:

A1-30. Your diagram should be similar to the one on page 32.

A1-31. The number of electrons returned to the cathode plus the **plate current** equals the number of electrons emitted by the cathode.

A1-32. If the emitted electrons produce a current of 90 mA and the returned electrons produce a current of 30 mA, the plate current is 60 mA.

GRAPH OF PLATE VOLTAGE VERSUS PLATE CURRENT

The most important fact to remember about a diode is how much current it will pass with a given amount of plate voltage. This type of information is summarized by a graph of plate voltage versus plate current.

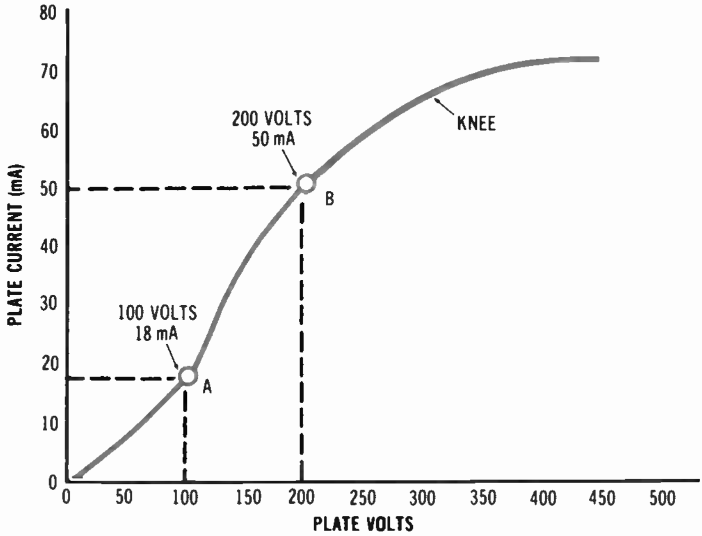


Fig. 1-23. Graph of plate voltage versus plate current.

Each point on the graph represents a plate current for a particular plate voltage. For instance, the current for a plate voltage of 100 volts is found by drawing a vertical line from the 100-volt point on the horizontal axis to the curve. This locates point A. A horizontal line through point A passes through the 18-mA point on the vertical axis. Thus the graph shows that a current of 18 mA flows through the diode when the plate voltage is 100 volts. The current corresponding to any value of plate voltage can be found in the same way.

The graph can also be used to determine the plate voltage necessary to cause a certain amount of current to flow. Assume that you wish to know the value of plate voltage required to cause a current of 50 mA. First find the 50-mA point on the vertical axis. A horizontal line through this point intersects the curve at point B. A vertical line through point B passes through the 200-volt point on the horizontal axis. Therefore, a plate voltage of 200 volts is required to produce a current flow of 50 mA.

A graph similar to the one shown here can be prepared for any type of diode tube. Of course, a graph for one type of tube usually cannot be used to find voltage and current values for another type of tube.

Notice the **knee** of the curve at around 400 volts. Increasing the voltage in this area changes the plate current very little. Therefore, this must be the point where practically all of the emitted electrons are being attracted to the plate.

You have just seen how to use a graph of plate voltage versus plate current. The illustration in Fig. 1-24 shows a circuit that can be used to obtain data for such a graph.

Q1-33. **In a graph of plate current versus plate voltage, the voltage is shown along the __________ axis.**

Q1-34. **In a graph of plate current versus plate voltage, the current is shown along the _________ axis.**

Q1-35. **The part of the curve where all of the emitted electrons are attracted to the plate is called the ____ of the curve.**

Q1-36. **A graph for one type of tube usually (can, cannot) be used for another type of tube.**

Your Answers Should Be:

A1-33. In a graph of plate current versus plate voltage, the voltage is shown along the **horizontal** axis.

A1-34. In a graph of plate current versus plate voltage, the current is shown along the **vertical** axis.

A1-35. The part of the curve where all of the emitted electrons are attracted to the plate is called the **knee** of the curve.

A1-36. A graph for one type of tube usually **cannot** be used for another type of tube.

PLOTTING A PLATE-VOLTAGE, PLATE-CURRENT CURVE

To plot a plate-voltage, plate-current curve, the arrangement in Fig. 1-24 can be used. Each time the position of the arm of the variable resistor is changed, read the voltage and the current. After recording several of these readings, plot a graph similar to the one in Fig. 1-23.

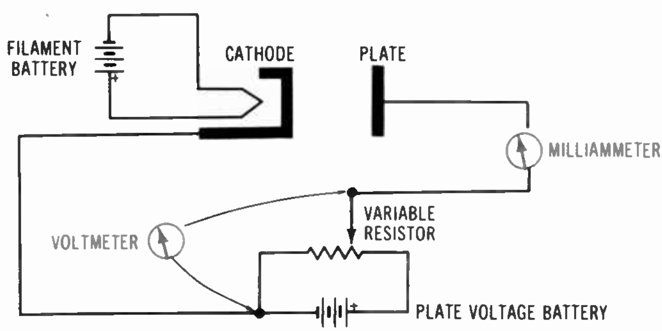


Fig. 1-24. Circuit to obtain data for graph.

EFFECT OF PLATE VOLTAGE ON EFFECTIVE RESISTANCE

Remember the effective resistance between conducting plates in a vacuum? This same opposition exists between the cathode and plate of a vacuum tube and is called **dc plate resistance, R_p.**

Calculating DC Plate Resistance

Assume that the graph in Fig. 1-25 has been obtained by taking voltage and current readings on a diode tube.

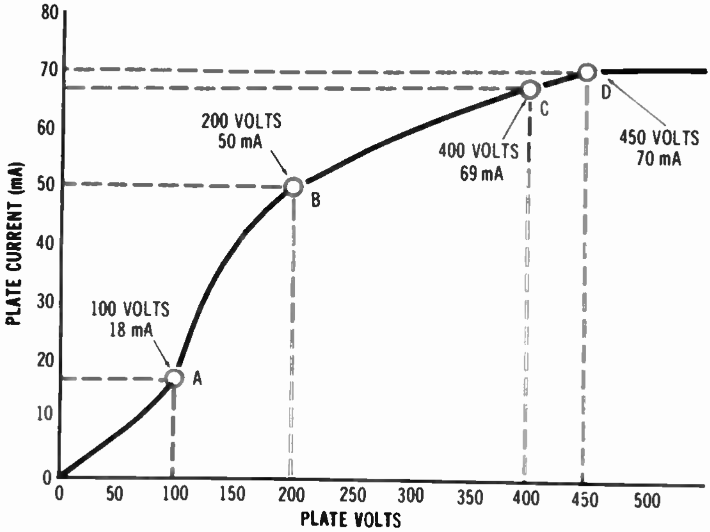


Fig. 1-25. Points for calculating dc plate resistance.

To see how the dc plate resistance varies with plate voltage, calculate R_p at each of the points marked on the graph. The calculations yield the following results:

$$\text{Point A}: \frac{100 \text{ volts}}{18 \text{ mA}} = 5{,}555 \text{ ohms}$$

$$\text{Point B}: \frac{200 \text{ volts}}{50 \text{ mA}} = 4{,}000 \text{ ohms}$$

$$\text{Point C}: \frac{400 \text{ volts}}{69 \text{ mA}} = 5{,}800 \text{ ohms}$$

$$\text{Point D}: \frac{450 \text{ volts}}{70 \text{ mA}} = 6{,}429 \text{ ohms}$$

Q1-37. To obtain data for a graph of plate current versus plate voltage, ________ readings are taken as the ________ is varied.

Your Answer Should Be:

A1-37. To obtain data for a graph of plate current versus plate voltage, current readings are taken as the voltage is varied.

Variations of DC Plate Resistance

In going from point A to point B (see Fig. 1-25), the plate voltage increases and the dc plate resistance decreases. However, in going from point B to point D, the resistance increases as the voltage increases. This happens because points C and D are on the knee of the curve. The portion of the curve between points A and B is almost (but not quite) a straight line. It is often called the **linear** part of the curve. Normally, in the linear part of the curve, R_p decreases when the plate voltage is increased.

APPLICATIONS

Because of the unidirectional current characteristic of the diode, it can perform many valuable functions. In Fig. 1-26,

Fig. 1-26. Detection.

the diode is used as a **detector**. A typical tv picture signal is shown. It is passed through a diode detector which selects only the positive half of the signal.

A diode can also eliminate undesired portions of a signal. This is called **limiting, or clipping.** In Fig. 1-27, another type of tv signal is shown; it is the composite video signal. For certain applications, only the two sync pulses are needed.

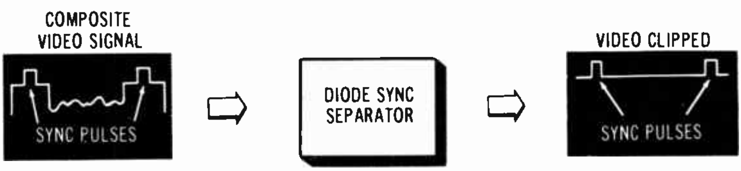


Fig. 1-27. Clipping.

The composite video signal is sent through a diode sync separator which clips the video and leaves the sync signal.

Fig. 1-28. Clamping.

Another use for a diode is to maintain a special voltage level for a signal—this is called **clamping,** or **DC restoration.** Fig. 1-28 shows a composite video signal whose pedestal is riding at positive 20 volts. The diode clamp causes this pedestal to ride at negative 50 volts.

Fig. 1-29. Rectification.

In Fig. 1-29, an ac signal is shown entering a diode rectifier and leaving as pulsating dc. This step in changing ac to dc is called **rectification.** It is the basis for all electronic power supplies.

Fig. 1-30. Gating.

In gate-circuit action, several signals must be present at the same time for an output to be obtained. In Fig. 1-30 you see one signal which opens the gate at regular intervals. However, the only time there is an output is when two signals are present at the same time.

Q1-38. A diode circuit used to pass one-half of a signal is a _________.

Q1-39. A diode circuit used as a sync separator is a ________.

Q1-40. A ___________ changes ac to pulsating dc.

Your Answers Should Be:

A1-38. A diode circuit used to pass one-half of a signal is a **detector.**

A1-39. A diode circuit used as a sync separator is a **clipper.**

A1-40. A **rectifier** changes ac to pulsating dc.

WHAT YOU HAVE LEARNED

1. Electrons move most easily in a vacuum.
2. Electrons move from negative to positive in an electric field.
3. Electrons are emitted from the cathode of a diode tube and are attracted to the plate.
4. Some cathodes emit electrons due to the action of light and others due to the action of heat.
5. Cathodes may be either directly or indirectly heated.
6. A space charge consisting of a cloud of electrons exists between the cathode and the plate.
7. Equilibrium normally exists in a diode between the cathode and the space charge and between the cathode, space charge, and plate.
8. The relationship of plate voltage and plate current in a diode can be shown by a graph.

2

Multielement Tubes

what you will learn

You will learn about triodes, tetrodes, and pentodes. You will be shown schematic symbols for these tubes and the shorthand notations used to identify the various voltages and currents associated with amplifiers. You will learn about the three tube parameters (amplification factor, ac plate resistance, and transconductance) and about bias. You will also learn how to use a tube manual to obtain information about vacuum tubes.

THE TRIODE

In 1907 Lee De Forest took out a patent on a Fleming valve containing a third element. Because of its gridiron-like construction, this element was called a grid. This three-element vacuum tube is called a **triode.**

De Forest's experiments proved that the triode could do something that had never been done before—it could make small signals larger. The process of making strong signals out of weak signals is called **amplification.** The triode is often used as an amplifier.

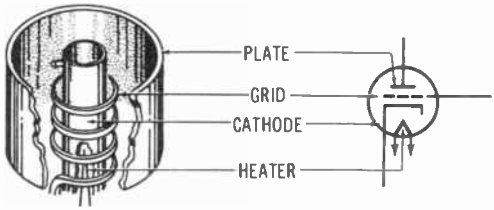


Fig. 2-1. Typical triode.

THE GRID

Through the years, grids have been constructed in many different ways. Some of these are improvements on the basic design, and others are for new applications. All of the grids have one thing in common—they are always placed between the cathode and the plate.

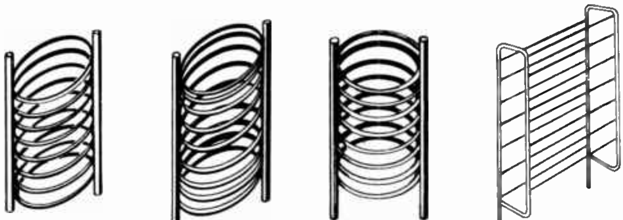


Fig. 2-2. Typical grids.

The Grid Introduces a Third Electric Field

Adding a grid between the cathode and the plate introduces another electric field in the triode. The effect of this additional electric field is shown in Fig. 2-3.

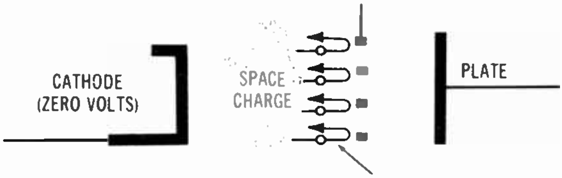


Fig. 2-3. Effect of the grid in a triode.

The direction of this field is determined by the polarity of the voltage applied to the grid. For reasons which will become evident later, the grid is operated with a small negative voltage (relative to the cathode) applied to it. The effect of this voltage is to repel electrons which would otherwise leave the space charge and flow to the plate.

Plate Voltage Accelerates Electrons

As plate voltage is applied to the triode, electrons leave the space charge and head for the plate. As they travel toward the plate, they gain momentum. As they approach the grid, the negative voltage on this element slows them down. Some, in fact, are even turned back to the space charge. However, due to the mesh-like construction of the grid, many of the electrons pass between the wires and continue on to the plate.

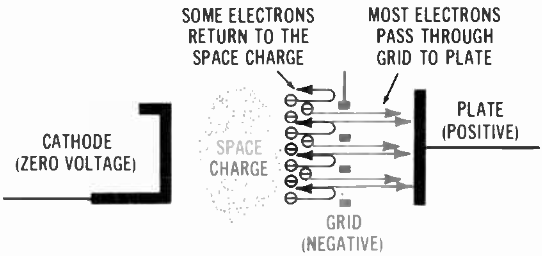


Fig. 2-4. Electron movement in a triode.

Distance Between the Grid and Cathode

This factor of triode construction affects the electron flow in the following manner. The slower the electrons move, the easier it is to stop them and return them to the space charge. Therefore, a grid placed near the space charge (before the electrons have gained much momentum) is better able to stop the electrons than one placed farther away (where the electrons have had a chance to gain momentum). In other words, the closer the grid is to the cathode, the more control it will have on electron flow to the plate.

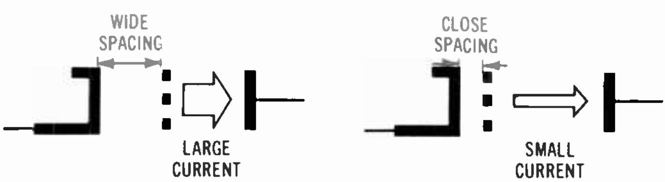


Fig. 2-5. Effect of cathode-grid distance on plate current.

Q2-1. A three-element tube is called a _______.

Q2-2. What are the names of the elements of a triode?

Q2-3. The process of making small signals larger is called _______________.

Q2-4. The negative grid tends to ________ electrons from reaching the plate.

Your Answers Should Be:

A2-1. A three-element tube is called a **triode.**

A2-2. The names of the three elements of a triode are the **plate,** the **grid,** and the **cathode.**

A2-3. The process of making small signals larger is called **amplification.**

A2-4. The negative grid tends to **prevent** electrons from reaching the plate.

Spacing Between the Grid Wires

This factor of construction affects the flow of plate current in a rather obvious manner. Closely spaced grid wires tend to concentrate the electric field. Therefore, the grid is better able to turn back the electrons when the grid wires are closely spaced. That is, the electrons have less chance of passing through the grid wires.

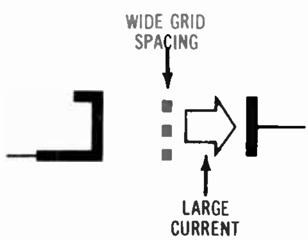


Fig. 2-6. Effect of wide grid spacing on plate current.

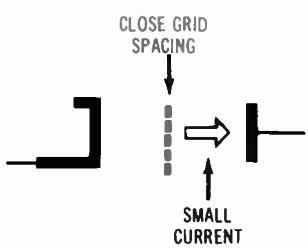


Fig. 2-7. Effect of close grid spacing on plate current.

Negative Voltage Applied to the Grid

As the grid is made more negative with respect to the cathode, its repelling effect becomes greater. Therefore, the more negative the grid, the less the plate current will be.

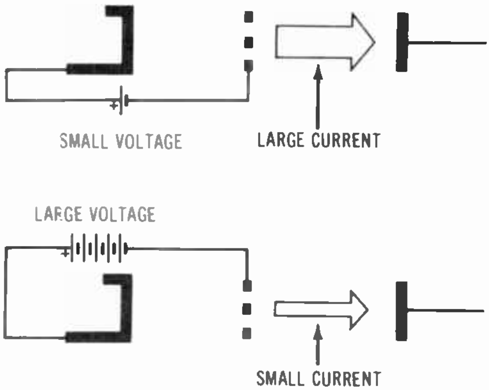


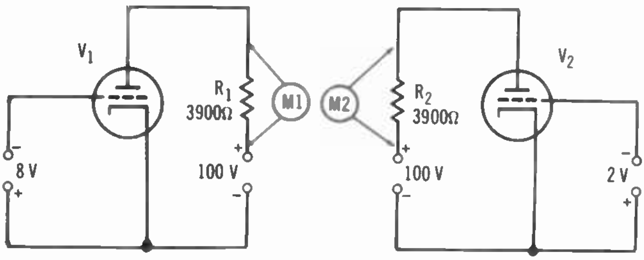
Fig. 2-8. Effect of grid voltage on plate current.

Q2-5. The grid is separated (negative, positive) with respect to the cathode.

Q2-6. The farther the grid is from the cathode, the (more, less) the plate current is.

Q2-7. The wider the spacing between the grid wires, the (more, less) the plate current is.

Q2-8. Which meter, M_1 or M_2, measures more voltage?



Q2-9. The more negative the grid, the (more, less) the plate current.

Your Answers Should Be:

A2-5. The grid is operated **negative** with respect to the cathode.

A2-6. The farther the grid is from the cathode, the **more** the plate current is.

A2-7. The wider the spacing betwen the grid wires, the **more** the plate current is.

A2-8. **M_2 measures more voltage.** The plate voltages are the same. The grid voltage of V_2 is less negative than that of V_1. Therefore, V_2 conducts more, causing a larger voltage drop across R_2 than across R_1. Meter M_2 thus measures more voltage than M_1.

A2-9. The more negative the grid, the **less** the plate current.

EFFECT OF THE GRID ON TRIODE PLATE CURRENT

The plate and cathode in a triode are essentially the same as those used in a diode. You know that increasing the voltage on the plate increases the plate current. The grid can also be used to increase plate current. However, since the voltage on the grid is a small negative voltage as opposed to the large positive voltage on the plate, the grid is made **less negative** to increase the plate current. **Making the grid less negative is the same as making it more positive.** Thus, there are two ways of varying the plate current. However, one of these ways provides more efficient control than the other. Since the grid is nearer to the cathode, its effect on the electrons is much greater than that of the plate.

Look at Fig. 2-9. In the upper left corner is a tube whose grid voltage is −10 volts and whose plate voltage is +150 volts. This results in a current flow of 20 mA. When the plate voltage is increased to +200 volts, the plate current is 30 mA, a 10-mA increase.

Now look at the tube in the upper right corner of Fig. 2-9. Again the plate voltage starts at +150 volts and the grid voltage starts at −10 volts, resulting in a plate current flow of 20 mA. But this time the plate voltage is kept at +150 volts and the grid voltage is varied from −10 to −8 volts. The plate current changes 10 mA as before, from 20 mA to 30 mA. Thus, to change the plate current 10 mA, either the plate voltage can be changed 50 volts or the grid voltage changed 2 volts (for the tube in this example). In most cases, this is done by varying the grid voltage.

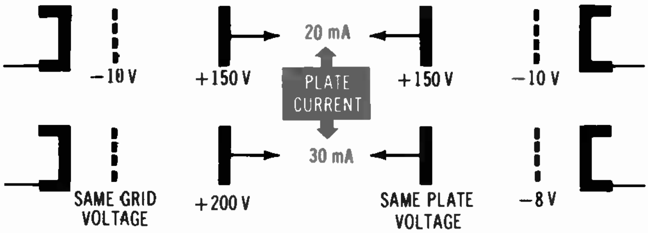


Fig. 2-9. Relative effects of changes in grid and plate voltage.

The constant use of the terms plate voltage, grid voltage, and filament voltage has led to the use of some simple shorthand notations, as shown in Fig. 2-10.

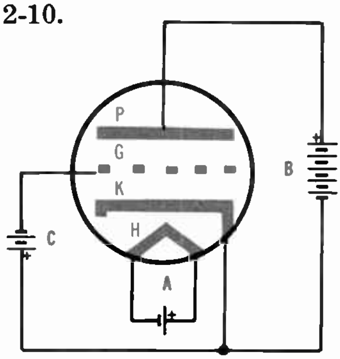
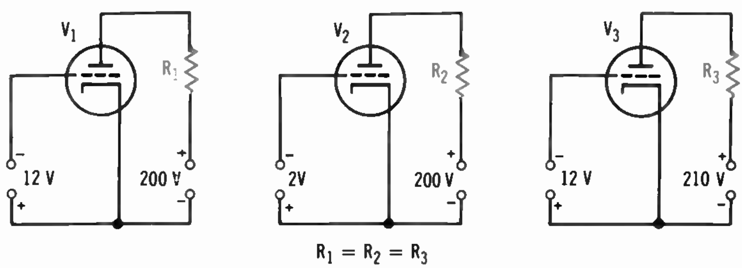


Fig. 2-10. Letter designations for triode voltage supplies.

Q2-10. List the following resistors in order of decreasing wattage rating.



Your Answer Should Be:

A2-10. R_2, R_3, R_1. Since all of the resistors have the same resistance, the one through which the most current flows requires the highest wattage rating. All that is necessary is to determine which tube has the highest plate current. V_1 and V_2 both have plate voltages of 200 volts, but V_2 has a grid voltage that is less negative than V_1 by 10 volts. Therefore V_2 conducts more heavily than V_1. The grid voltages of V_1 and V_3 are the same, but the plate voltage of V_3 is 10 volts higher than the plate voltage of V_1. For this reason, V_3 also conducts more heavily than V_1. Thus, V_1 has the least plate current; its resistor needs the lowest wattage rating. Note that both V_2 and V_3 have had a change of 10 volts (with respect to V_1)—V_2 +10 volts to the grid and V_3 +10 volts to the plate. Since the grid has more effect on the plate current and since the voltage changes were the same, V_2 must conduct more heavily than V_3. Thus R_2 requires a higher wattage rating than R_3.

TUBE CHARACTERISTICS

You have already learned that three factors affect the amount of current passing through a diode. These are the temperature of the cathode, the voltage on the plate (with respect to the cathode), and the space charge. The plate current of a triode is also affected by all of these factors and, in addition, one more—the voltage on the grid with respect to the cathode.

Remember the diode characteristic called dc plate resistance (R_p) : **Increases in plate voltage** cause **decreases in R_p** (in the linear part of the curve). Do changes in grid voltage affect the R_p of a triode in a similar fashion? To find out, plot a curve of grid voltage versus plate current. The circuit shown in the figure on the next page can be used to obtain the information for this curve. The method used to obtain this information is also explained in the paragraphs that accompany the illustration.

Grid-Voltage, Plate-Current Characteristic

Note that the filament voltage is not shown in Fig. 2-11, but it must be supplied. The plate-supply voltage (E_b) is 250

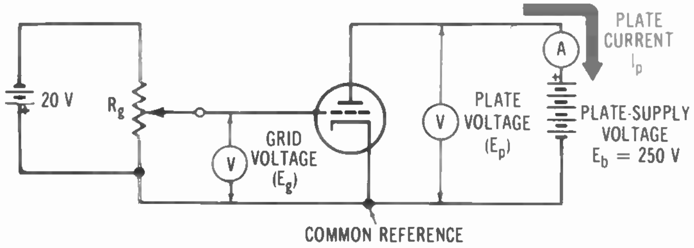


Fig. 2-11. Circuit to obtain data for triode characteristic curve.

volts, but any voltage may be used as long as it is correct for the tube you have selected (you may determine this voltage from a tube manual). The plate-supply voltage will be held constant throughout this test. Adjust R_g until some plate-current flow is indicated on ammeter A. Read the value of this current and the grid voltage and record these values. Continue to change the grid voltage and read the two meters until you have obtained about five pairs of readings. Plot the data on a graph. You should obtain a graph similar to that shown in Fig. 2-12.

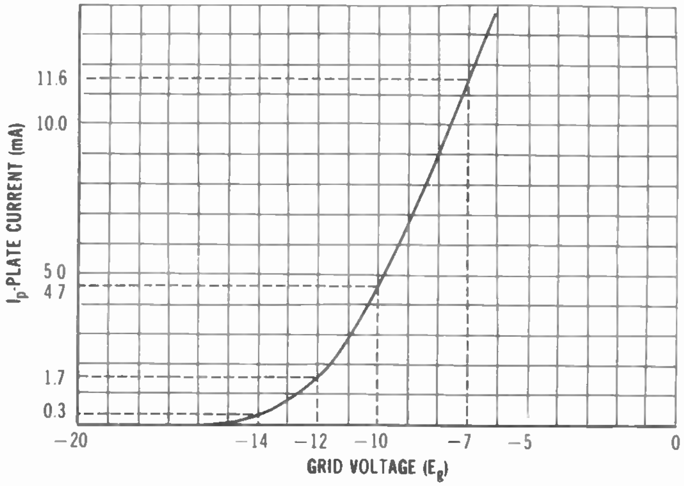


Fig. 2-12. Triode plate current versus grid voltage.

Q2-11. Determine R_p for each of the points on the graph.

Your Answers Should Be:

A2-11. For each of the selected grid voltages, R_p should be:

e_g	R_p
−7	21.4K
−10	53.2K
−12	147K
−14	833K

Sample Calculation:

$$R_p = \frac{E_b}{I_p} = \frac{250\ V}{4.7\ mA}$$

$$R_p = 53.2K$$

First find the point at which a vertical line through the desired grid voltage intersects the curve. Next, observe where a horizontal line through this point on the curve passes through the vertical axis. Read the plate current at this point. Use this value along with the value of E_b to calculate R_p.

Shorthand Notations

Below is a list of some of the shorthand notations used to represent the various voltages and currents associated with a triode.

E_b = the plate-supply voltage.
e_p = the instantaneous total plate voltage.
I_b = the average total plate current.
E_c = the control-grid supply voltage.
e_g = the instantaneous total grid voltage.

Note that capital letters are used to indicate source or average values and small letters are used to indicate instantaneous values.

FAMILIES OF CURVES

When discussing the characteristics of a diode, it was only necessary to plot one curve to completely describe the behavior of the tube. However, with the addition of a grid, another variable must be added to cover the operating conditions. In plotting the curve of grid voltage versus plate current, one of the tube voltages must be maintained constant or the result will be meaningless. In plotting the grid-voltage, plate-current curve, the plate voltage was maintained constant at 250 volts. Plot the curve again for plate voltages of 200 and 300 volts. These curves make up a **family of curves** to describe the operation of the triode almost as thoroughly as the one curve described the operation of the diode. To improve on the coverage given by these curves, just add additional curves at other plate voltages. This group of curves is called the **grid family of characteristic curves.**

Grid Family of Curves

Fig. 2-13 shows a grid family of characteristic curves. Three of the curves were determined previously—the ones for E_b equal to 300, 250, and 200 volts. Note the points at which the plate current is zero. The grid voltage that is sufficiently negative to stop the flow of plate current is called the **cutoff voltage.** Note that the higher the value of E_b, the more negative the cutoff voltage is.

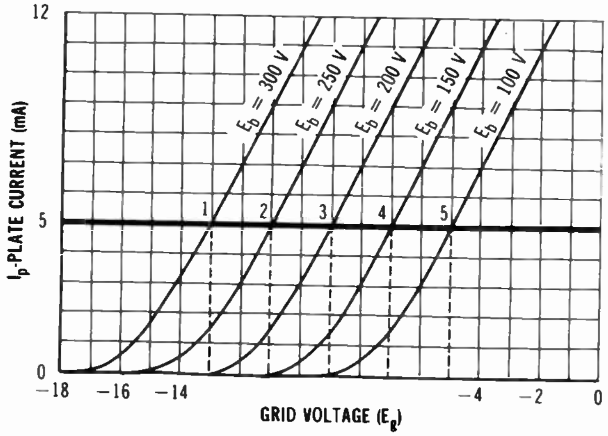


Fig. 2-13. Grid family of characteristic curves.

Q2-12. A group of curves that describes the operation of a tube is called a ______ of ________________ curves.

Q2-13. ________ letters are used to indicate source or average values; ______ letters are used to indicate instantaneous values.

Q2-14. The _____ voltage is held constant for each curve in a grid family of characteristic curves.

Your Answers Should Be:

A2-12. A group of curves that describes the operation of a a tube is called a **family** of **characteristic** curves.

A2-13. **Capital** letters are used to indicate source or average values; **small** letters are used to indicate instantaneous values.

A2-14. The **plate** voltage is held constant for each curve in a grid family of characteristic curves.

Interpreting the Curves

Suppose that R_p was calculated for the points shown in Fig. 2-13. When e_p is 300 volts, R_p is 60K; when e_p is 100 volts, R_p is 20K. These results seem to show that as the plate voltage decreases, R_p decreases. Why was this wrong conclusion reached? The plate voltage was changed at the same time the grid voltage was changed. Note, however, that the plate current remains the same. You will soon see that even though this method of collecting information does not give the correct information about how the R_p of a tube varies with plate voltage, it does offer very useful information. This information is one of three measures of the usefulness of a tube known as **tube parameters.**

TUBE PARAMETERS

In referring to vacuum tubes, the term parameter is defined as a **measure.** It is usually a combination of more than one measure (often a ratio). A parameter is normally fairly constant for the item it describes.

Suppose you wish to describe a bar of steel. You might say that it is 6 feet long, but this can change (you might cut some of it off). Its weight may be 30 pounds; this would also change if the bar were cut. Length and weight are not parameters because they do not remain constant. How about the density of the steel (its weight per cubic foot)? This does not change as you change the dimensions of the steel. Therefore, density is a parameter of the steel.

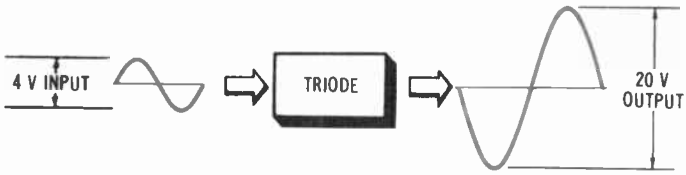
Suppose you were told that two cars made a trip of 80 miles. It is easy to see that these trips were entirely different in nature if one was made in an hour and the other was made in six days. In the same fashion, what if two cars traveled for four hours? What does this mean? Nothing until it is specified that one car traveled 80 miles and the other traveled 320 miles. The best way to compare the speeds of the two cars is to specify their speeds in miles per hour (this is a parameter).

R_p is not a parameter because it changes as the plate voltage and grid voltage change. The parameters used to describe vacuum tubes are often called **tube constants.** They are amplification factor, ac **plate resistance,** and **transconductance.**

Amplification Factor

Amplification factor is the tube parameter that indicates the maximum amplification of which the tube is capable. (In actual circuits this maximum is never reached.) The symbol for amplification factor is the Greek letter μ (also written mu).

You know that a triode is an amplifier. Just how much can it amplify a signal applied to it? The amplification is the ratio of the amplitude of the output signal to the amplitude of the input signal.



$$\text{AMPLIFICATION} = \frac{\text{OUTPUT}}{\text{INPUT}} = \frac{\text{20 VOLTS}}{\text{4 VOLTS}} = 5$$

Fig. 2-14. Amplification.

In Fig. 2-14, the amplification is 20 volts divided by 4 volts, or 5.

Q2-15. The symbol for amplification factor is __.

Q2-16. The ratio of the ______ voltage over the _____ voltage in a triode is called amplification.

Your Answers Should Be:

A2-15. The symbol for amplification factor is μ.

A2-16. The ratio of the **output** voltage over the **input** voltage in a triode is called amplification.

Calculating the Amplification Factor

Imagine that you have just designed a new triode. In order to check its characteristics you have collected a grid family of curves, such as the one that was illustrated in Fig. 2-13. Returning to the erroneous conclusion about the relationship between the plate voltage and the dc plate resistance, select

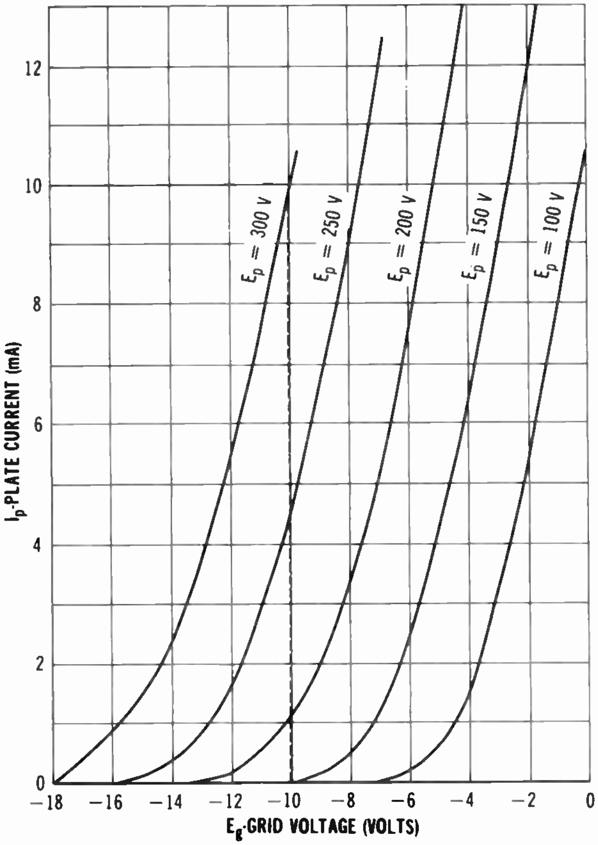


Fig. 2-15. Ac plate resistance.

points 1 and 2 on the graph. In going from point 1 to point 2 the plate voltage decreases 50 volts. But the plate current remains the same (5 mA). Picture this in steps. Lower the plate voltage 50 volts and cause a decrease in plate current. Now raise the plate current back to its original value (5 mA in this example) by making the grid voltage less negative (from −13 to −11 volts). It takes a 50-volt change of plate voltage to change the plate current a certain amount, but a grid-voltage change of only 2 volts is required to return the plate current to normal. The ratio of these two voltage changes is the amplification factor of the triode. In this case:

$$\mu = \frac{\text{Change in Plate Voltage}}{\text{Change in Grid Voltage}} = \frac{50\text{ V}}{2\text{ V}} = 25$$

AC Plate Resistance

You have seen how dc plate resistance varies for a triode. The resistance that a triode offers to changing voltages, such as sine waves, is called **ac plate resistance**, r_p. Unlike R_p, r_p remains fairly constant for a particular triode; it is a parameter.

In Fig. 2-15, the line for a grid voltage of −10 volts intersects the curve for $e_p = 300$ volts at a plate current of 10 mA. It also intersects the curve for $e_p = 250$ volts at a plate current of 4.6 mA. To simplify what is to follow, a new symbol is introduced. The symbol is Δ, the Greek letter delta. This symbol means a "change in" or the "difference between" two successive values of something. For example, the change in e_p from 300 volts to 250 volts may be written $\Delta e_p = 50$ volts. The ac plate resistance is the ratio between Δe_p and its corresponding change in plate current (Δi_p) with the grid voltage held constant. In this case,

$$r_p = \frac{\Delta e_p}{\Delta i_p} = \frac{300 - 250\text{ volts}}{10 - 4.6\text{ mA}} = \frac{50\text{ volts}}{5.4\text{ mA}} = 9{,}259\text{ ohms}$$

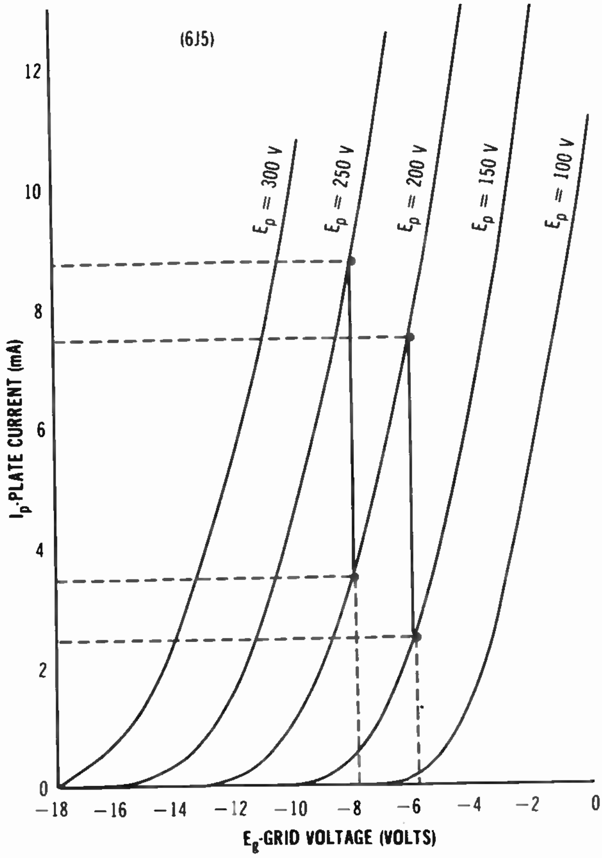
Use Fig. 2-15 to calculate r_p at −6 volts and −8 volts. Work right on the figure.

Q2-17. For $e_g = -6$ volts, $r_p =$ __________ ohms.
Q2-18. For $e_g = -8$ volts, $r_p =$ __________ ohms.

Your Answers Should Be:

A2-17. $r_p = \dfrac{200 - 150 \text{ volts}}{7.5 - 2.5 \text{ mA}} = \dfrac{50 \text{ volts}}{5 \text{ mA}} = 10{,}000 \text{ ohms}$

A2-18. $r_p = \dfrac{250 - 200 \text{ volts}}{9.0 - 3.5 \text{ mA}} = \dfrac{50 \text{ volts}}{5.5 \text{ mA}} = 9{,}090 \text{ ohms}$



Note that these values (9,259, 10,000, and 9,090 ohms) are all fairly close to each other. When compared to the changes in R_p (from thousands of ohms to hundreds of thousands of ohms), the ac plate resistance (r_p) may be considered almost a constant for a particular triode.

Linear Portion of the Curve

In considering r_p to be a constant, the points used to calculate this parameter must be selected with care. For example, suppose the −8-volt point is selected again, but this time the plate-voltage curves for 200 and 150 volts are used. The resultant calculation gives:

$$r_p = \frac{200 - 150 \text{ volts}}{3.5 - 0.5 \text{ mA}} = \frac{50 \text{ volts}}{3 \text{ mA}} = 16{,}700 \text{ ohms}$$

What makes this value so much different from the others? This is due to the selection of the point on the 150-volt curve. What's different here? Refer to the curve on the opposite page. Notice how it starts out as a gentle curve but soon straightens out. Place a straightedge against it and notice that this portion of the curve is practically a straight line. This straight-line portion is called the **linear** portion of the curve. When points are selected on the linear portion of the curve, the result is a fairly constant r_p. Those selected on the curved portion result in quite different values of r_p (see the previous page). This linear portion of the curve plays a great part in preventing distortion of signals.

Tubes Are Like Highways

It may be helpful to think of vacuum tubes as being like highways with electrons for cars. The electrons try to go from cathode to plate just as cars try to reach their destination. A highway also has a property that can be thought of as resistance. Which offers more resistance to cars, a dirt road or a paved road? Think of other factors that affect the "resistance" of a highway (curves, hills, intersections, etc.).

Many kinds of signs give the driver an idea of the "resistance" of the road. As a result they caution him to change his speed. But how slow should he go? There are signs that tell the exact "resistance" of the highway. A lot of resistance calls for a slower speed—a small resistance allows a higher speed. In other words, the speed-limit signs tell the driver the amount of opposition the highway offers.

Q2-19. The value of r_p is (nearly, not) constant when it is calculated from points on the linear parts of the curves.

Your Answer Should Be:

A2-19. The value of r_p is nearly constant when it is calculated from points on the linear parts of the curves.

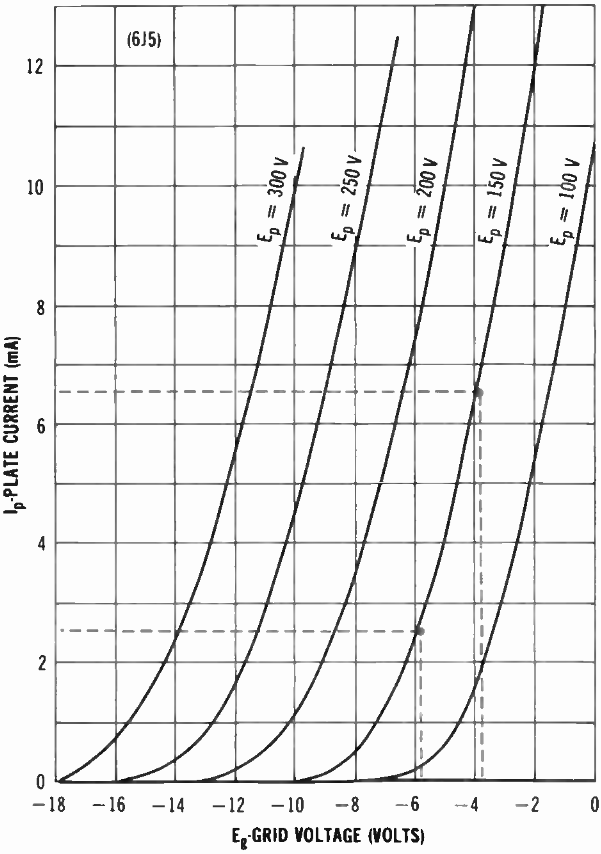


Fig. 2-16. Transconductance.

Transconductance

The speed limit is based on an estimated safe traveling speed for a particular road. In this sense, it is a parameter. Notice something about it. Instead of a number increasing as resistance increases, the number expressing speed limit of a highway decreases as the "resistance" of the highway increases.

There is a tube constant that describes a tube in much the same fashion as a speed limit describes highways. This constant is called **transconductance.** Transconductance is a measure of the effect that changes in grid voltage have on plate current. The symbol for transconductance is g_m.

You can find g_m from the grid family of curves in the following manner. Inspect the curve for a plate voltage of 150 volts. Record the current at grid voltages of −6 and −4 volts. Then divide the change in plate current by the change in grid voltage to find g_m.

$$g_m = \frac{\Delta i_p}{\Delta e_g} = \frac{6.5 - 2.5 \text{ mA}}{(-4) - (-6) \text{ volts}} = \frac{4 \text{ mA}}{2 \text{ volts}} = 2$$

The result is in milliamps over volts. Volts over milliamps results in resistance in thousands of ohms (kilohms). The inverse of the ohm is called the **mho** (ohm spelled backward). Just as most of the currents in vacuum tubes are in the order of thousandths of an ampere (milliamps), so the units of transconductance are usually in the order of millionths of a mho (micromhos) or thousands of a mho (millimhos). Micromho is often written as μmho. Returning to the answer in the previous calculation, it should be 2 millimhos, or 2,000 μmhos. Transconductance is usually measured in micromhos.

Q2-20. The transconductance at $e_p = 200$ volts is ______ ______. (Use the graph in Fig. 3-16.)

Q2-21. The transconductance at $e_p = 300$ volts is ______ ______.

Q2-22. Write the equations for each of the three tube constants.

Q2-23. Transconductance is usually measured in units called __________.

Your Answers Should Be:

A2-20. At $e_p = 200$ volts:

$$g_m = \frac{\Delta i_p}{\Delta e_g} = \frac{7.5 - 3.4 \text{ mA}}{(-6) - (-8) \text{ V}}$$

$$= \frac{4.1 \text{ mA}}{2 \text{ volts}} = \mathbf{2{,}050\ \mu mhos}$$

A2-21. At $e_p = 300$ volts:

$$g_m = \frac{\Delta i_p}{\Delta e_g} = \frac{10 - 5.5 \text{ mA}}{(-10) - (-12) \text{ V}}$$

$$= \frac{4.5 \text{ mA}}{2 \text{ volts}} = \mathbf{2{,}250\ \mu mhos}$$

A2-22. $\mu = \frac{\Delta e_p}{\Delta e_g}$ (i_p constant)

$r_p = \frac{\Delta e_p}{\Delta i_p}$ (e_g constant)

$g_m = \frac{\Delta i_p}{\Delta e_g}$ (e_p constant)

A2-23. Transconductance is usually measured in units called **micromhos.**

Significance of Transconductance

Transconductance is the parameter most used to describe the characteristics of a vacuum tube. For example, a tube with a transconductance of 2,000 μmhos would give more amplification (at the same plate voltage) than a tube with a transconductance of 1,500 μmhos. Note from answers A19 and A-20 above that the g_m for a particular triode remains fairly constant over the entire grid family of curves, except in the nonlinear portions.

Tube-Constant Relationships

All of the parameters (μ, g_m, and r_p) are obtained from the same family of curves. It would appear there must be a relationship existing between the parameters. That relationship is:

$$\mu = g_m \times r_p = \frac{\text{mA}}{\text{volts}} \times \frac{\text{volts}}{\text{mA}}$$

Note how the volts and milliamps cancel. As a result, the amplification factor has no units.

To show this relationship, take the values of r_p found around the 200- and 150-volt curves (10,000 ohms) and the g_m found on the 150-volt curve (2,000 μmhos). These values of transconductance and ac plate resistance can be substituted in the equation, and the value of the amplification factor can be calculated.

$$\mu = 10{,}000 \text{ ohms} \times 2{,}000\ \mu\text{mhos} = 20$$

Note how the ohms cancel out the mhos. This is the same value calculated earlier for the μ of the tube.

The equations for μ, g_m, and r_p can be used to prove the equation for the relationship of the parameters. Start with the equation for μ:

$$\mu = \frac{\Delta e_p}{\Delta e_g} \qquad (1)$$

Take the equation $r_p = \dfrac{\Delta e_p}{\Delta i_p}$, and solve for Δe_p:

$$e_p = \Delta i_p r_p \qquad (2)$$

Take the equation $g_m = \dfrac{\Delta i_p}{\Delta e_g}$, and solve for Δe_g:

$$e_g = \frac{\Delta i_p}{g_m} \qquad (3)$$

Substitute equations (2) and (3) in equation (1).

$$\mu = \frac{\Delta e_p}{\Delta e_g} = \frac{\Delta i_p r_p}{\dfrac{\Delta i_g}{g_m}} = g_m r_p.$$

TUBE MANUALS

Up until now you have been supplied with data on how tubes behave under various conditions. You have also seen how to generate this information experimentally. However, where can you obtain this information on a particular tube? Nearly all manufacturers of vacuum tubes publish manuals containing tube data.

Q2-24. $r_p = 7.5K$; $\mu = 15$; $g_m = ?$

Q2-25. $\mu = 45$; $g_m = 9$ millimhos; $r_p = ?$

Your Answers Should Be:

A2-24. $g_m = \frac{\mu}{r_p} = \frac{15}{7{,}500 \text{ ohms}} = 2{,}000\ \mu\text{mhos}$

A2-25. $r_p = \frac{\mu}{g_m} = \frac{45}{0.009 \text{ mho}} = 5{,}000 \text{ ohms}$

General Contents of a Tube Manual

Most tube manufacturers publish a new manual each year, but there are those who publish only one manual every three or four years and keep it up to date by mailing data sheets to subscribers. The manual published by one leading tube manufacturer contains the following sections.

Electrons, Electrodes, and Electron Tubes—This section contains the basic theory of vacuum tubes from the electron to the cathode-ray tube. It is a very condensed version and is intended as a refresher rather than as a textbook presentation.

Electron-Tube Characteristics — This section contains a brief review of the tube characteristics, parameters, and curves already covered in this chapter.

Electron-Tube Applications—In this section you will find brief descriptions of many vacuum-tube applications. In this particular manual these are divided into the following nine categories: amplification, rectification, detection, automatic volume or gain control, tuning indication with electron-ray tubes, oscillation, deflection circuits, frequency conversion, and automatic frequency control.

Electron-Tube Installation—Under this heading you will find various suggestions and precautions to be followed when installing electron tubes.

Interpretation of Tube Data—This section lists the information necessary to interpret the data provided in the Tube Types section of the tube manual.

Receiving-Tube Classification Chart—This section provides a chart summarizing all of the tubes in the manual. It groups them according to tube types and characteristics, as well as to physical configuration.

Tube Types–Technical Data—This section comprises the bulk of the manual. It lists all of the tubes in alphanumeric order. A tube is identified by a combination of numbers and letters. The first grouping in the identification code is usually numeric and may contain as many as three digits. This grouping is usually an indication of the filament voltage necessary to operate the tube. For example, a 1A3 uses a heater voltage of 1.4 volts, a 5U4 uses a heater voltage of 5.0 volts, and a 117Z3 uses a heater voltage of 117 volts. (For picture tubes, the initial digits do not give the heater voltage.) This section of the manual is discussed in more detail later.

Picture-Tube Characteristics Chart—This chart summarizes the physical and electrical characteristics of television picture tubes in much the same fashion as the receiving-tube classification chart.

Electron-Tube Testing—This section gives information and circuits that describe and illustrate practical tube-tester considerations.

Resistance-Coupled Amplifiers—This section describes the use of the resistance-coupled amplifier and provides charts showing the voltages and components necessary to operate over 50 different type tubes as resistance-coupled amplifiers.

Circuits—Here you will find a number of representative circuits complete with component values. Some of the circuits included are am, fm, and auto receivers; microphone and phonograph amplifiers; a code practice oscillator; and an electronic volt-ohmmeter.

Outlines—This section gives the physical dimensions of every tube in the manual. There are only a few pages because many of the tubes have the same external physical construction.

Index—The index for this manual is in a standard alphabetical form as used in most publications.

Q2-26. The first digits in a tube-type number usually represent the ______ _______ of the tube.

Q2-27. Tube manuals usually list tubes in _____ _______ order in the technical-data section.

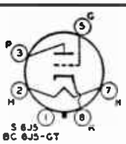
Q2-28. (A few, nearly all) tube manufacturers publish manuals giving data on the tubes they manufacture.

Your Answers Should Be:

A2-26. The first digits in a tube type number usually represent the **heater voltage** of the tube.

A2-27. Tube manuals usually list tubes in **alphanumeric** order in the technical-data section.

A2-28. **Nearly all** tube manufacturers publish manuals giving data on the tubes they manufacture.



MEDIUM-MU TRIODE

6J5
6J5GT
Related type: 12J5GT

Metal type 6J5 and glass octal type 6J5-GT used as detectors, amplifiers, or oscillators in radio equipment. These types feature high transconductance together with comparatively high amplification factor. Outlines 2 and 14C, respectively, OUTLINES SECTION. Tubes require octal socket and may be mounted in any position. For typical operation as resistance-coupled amplifiers, refer to RESISTANCE-COUPLED AMPLIFIER SECTION. Type 6J5-GT is used principally for renewal purposes.

HEATER VOLTAGE (AC/DC)		6.3	volts
HEATER CURRENT		0.3	ampere
DIRECT INTERELECTRODE CAPACITANCES (Approx.):	*6J5**	*6J5-GT***	
Grid to Plate	3.4	38	pf
Grid to Cathode and Heater	3.4	4.2	pf
Plate to Cathode and Heater	3.6	5.0	pf

* Shell connected to cathode. ** Base sleeve and external shield connected to cathode.

CLASS A₁ AMPLIFIER

Maximum Ratings, (Design-Center Values):

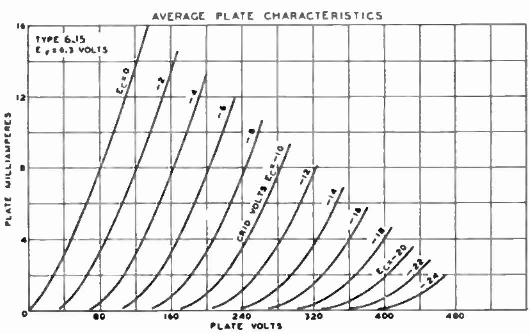
PLATE VOLTAGE	300 *max*	volts
GRID VOLTAGE, Positive-bias value	0 *max*	volts
PLATE DISSIPATION	2.5 *max*	watts
CATHODE CURRENT	20 *max*	ma
PEAK HEATER-CATHODE VOLTAGE:		
Heater negative with respect to cathode	90 *max*	volts
Heater positive with respect to cathode	90 *max*	volts

Characteristics:

Plate Voltage	90	250	volts
Grid Voltage	0	−8	volts
Amplification Factor	20	20	
Plate Resistance (Approx.)	6700	7700	ohms
Transconductance	3000	2600	μmhos
Grid Voltage (Approx.) for plate current of 10 μa	−7	−18	volts
Plate Current	10	9	ma

Maximum Circuit Value:

Grid-Circuit Resistance	1.0 *max*	megohm



Courtesy RCA Corp.

Fig. 2-17. Page from a typical tube manual.

Technical Data

A typical technical-data page is shown in Fig. 2-17. These data are for a type 6J5 vacuum tube, the type that has been used for all the examples concerning tube characteristics and parameters. On the left side of the data sheet is a diagram showing how each of the elements is connected to the tube pins. These connections (pins) are numbered in a clockwise direction as you look at the bottom of the tube. In addition, there are letters next to these pins that identify the elements to which they are connected. These letters are identified in the diagram below.

Key to socket connection diagrams.

Bottom Views

• = Gas-Type Tube	F_M = Filament Mid-Tap	IS = Internal Shield
BC = Base Sleeve	G = Grid	K = Cathode
BS = Base Shell	H = Heater	NC = No Connection
C = External Conductive Coating	H_L = Heater Tap for Panel Lamp	P = Plate or Anode
CL = Collector	H_M = Heater Mid-Tap	RC = Ray-Control Electrode
DJ = Deflecting Electrode	IC = Internal Connection— Do Not Use	S = Shell
ES = External Shield		TA = Target
F = Filament		*Courtesy Radio Corporation of America*

Alphabetical subscripts B, D, HP, HX, P, and T indicate, respectively, beam unit, diode unit, heptode unit, hexode unit, pentode unit, and triode unit in multi-unit types.

At the top of the sample page is a short paragraph describing the important features of and suggested uses for the tube. References are made to other portions of the manual where additional information about this tube can be found. Below this paragraph is a tabular presentation of significant tube characteristics.

Use the sample page to obtain the following information:

Q2-29. The amplification factor of the 6J5 is ____.

Q2-30. The 6J5 may be used as a __________, __________, or ____________.

Q2-31. With a plate voltage of 90 and a grid voltage of 0, the g_m is ______ ______.

Q2-32. With a grid voltage of −8 and a plate voltage of 250, the r_p is ______ _____.

Your Answers Should Be:

A2-29. The amplification factor of the 6J5 is 20.

A2-30. The 6J5 may be used as a **detector, amplifier,** or **oscillator.**

A2-31. With a plate voltage of 90 and a grid voltage of 0, the g_m is **3,000 μmhos.**

A2-32. With a grid voltage of −8 and a plate voltage of 250, the r_p is **7,700 ohms.**

Characteristic Curves

At the bottom of the sample page is a family of curves. This is not the grid family that you have been using up until now. The grid family of curves (also referred to as the **transfer-characteristic curves**) was obtained by varying e_g while observing i_p with several fixed values of e_p. The curve in the tube manual is called the **plate characteristic curve** (also called the **plate family of curves**) and is obtained by observing i_p as e_p is varied with e_g held constant.

BIASING

Grid bias is the difference in dc potential between the grid and the cathode. Bias determines the operating point of the tube. Consider the tube in Fig. 2-18.

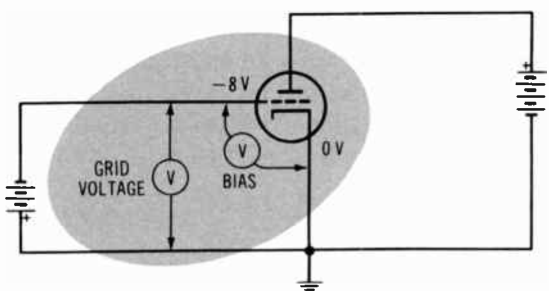


Fig. 2-18. Grid voltage and bias.

The bias on the tube in Fig. 2-18 is equal to the difference between the grid voltage (−8 volts in the figure) and the cathode voltage (0 volts in the figure). Therefore, the bias in this case is equal to −8 volts.

One way to measure the bias on a tube is to measure the voltage on the grid and then the voltage on the cathode (always with respect to the same common point, or ground). Add these voltages as if you were going from the grid to the cathode, and observe the polarities of the voltages. For example, in Fig. 2-19 you will measure −8 volts from grid to ground. The cathode voltage measured will be +4 volts (4 mA × 1K). However, in going from grid to cathode, you pass through the battery from negative to positive and then through the cathode resistor from negative to positive. Thus, you pass through a total of −12 volts of bias.

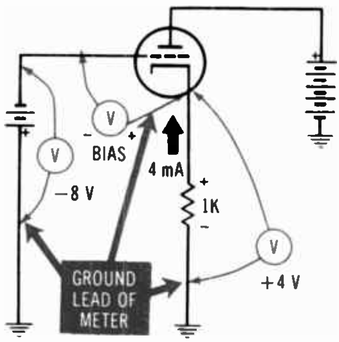
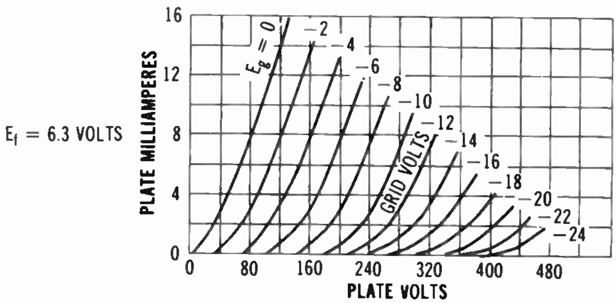


Fig. 2-19. Measuring bias voltage.

Q2-33. Use the graph below to find μ at a plate current of 8 mA.

Q2-34. Use the graph to find g_m at an E_p of 120 volts.



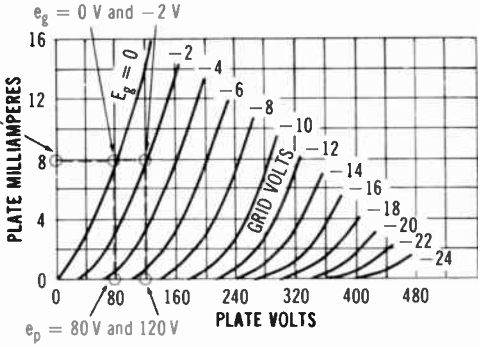
Q2-35. Grid bias is the difference in dc potential between the ____ and the ________.

Q2-36. Bias voltage equals grid voltage if the ________ voltage is zero.

Your Answers Should Be:

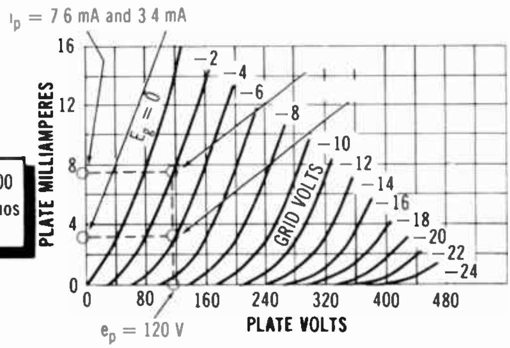
A2-33.

$$\mu = \frac{\Delta e_p}{\Delta e_g} = \frac{40\ V}{2\ V} = 20$$



A2-34.

$$g_m = \frac{\Delta i_p}{\Delta e_g} = \frac{4.2\ mA}{2\ V} = 2{,}100\ \mu mhos$$



A2-35. Grid bias is the difference in potential between the grid and the **cathode** (not cathode to grid).

A2-36. Bias voltage equals grid voltage if the **cathode** voltage is zero.

Biasing Methods

There are several methods of supplying bias. The fundamental method is the application of a steady dc voltage to the grid of the tube. Other methods will be discussed in the chapter on vacuum-tube amplifiers.

The bias determines the operating point of the tube. That is, with no signal applied to the tube a certain plate current will flow. This current is the static plate current and is controlled by the bias. The bias is nearly always negative. Fig. 2-20 shows what happens when the bias is positive.

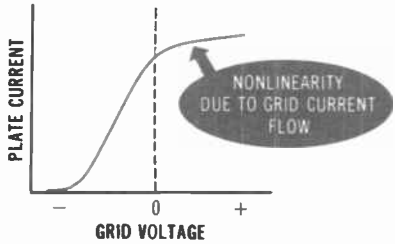


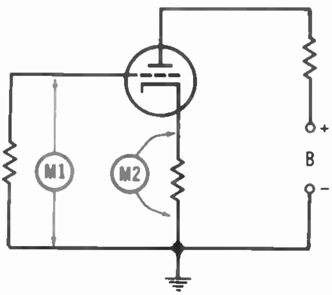
Fig. 2-20. Effect of positive grid voltage.

When the grid voltage is positive, it can remove electrons from the electron stream. These are electrons that would normally be part of the plate current. Thus, increasing the grid voltage in the positive region would increase the number of electrons taken from the space charge and would also draw more and more electrons from the plate current. This would result in a nonlinearity at the top of the e_g-i_p curve, as shown in Fig. 2-20. This is just as objectionable as the nonlinearity at the bottom of the curve.

Q2-37. Bias determines the __________ ______ of the tube.

Q2-38. When the meters measure the voltages shown below, what is the bias?

M1	M2	BIAS
0	+6	
−3	+3	
−6	0	



> **Your Answers Should Be:**
>
> A2-37. Bias determines the **operating point** of the tube.
>
> A2-38. **All of your answers should have been −6 volts.** In each case, as you look from the grid to the cathode, you are looking through 6 volts of potential. Thus, the grid must be 6 volts negative with respect to the cathode.

MULTIGRID TUBES

As electronics advanced and became more complex, the design of the electron tube also progressed. Many of these advancements have resulted in a need for new kinds of diodes and triodes. Others have made it necessary to add other elements to the triode.

Feedback in the Triode

The elements of a triode act like capacitors. This effect is called **interelectrode capacitance.** The capacitances are very small, but at high frequencies they become quite objectionable. This is especially true of the capacitance between the grid and plate (C_{gp}).

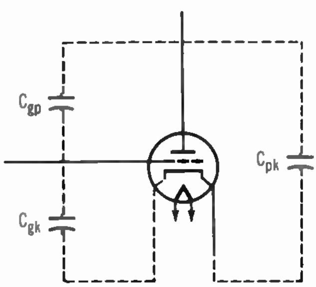


Fig. 2-21. Triode interelectrode capacitances.

In the circuit in Fig. 2-22, some of the output signal from the triode plate is returned (fed back) to the input grid circuit through C_{gp}. The nature of this **feedback voltage** is such that it tends to reduce the input signal on the grid (this is called **negative feedback**). The reasons for this negative feedback are demonstrated in the chapter on vacuum-tube amplifiers. At present it is enough to say that as the signal goes

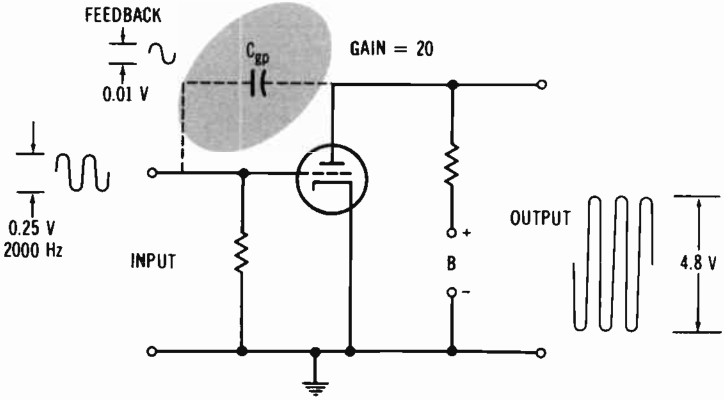


Fig. 2-22. Effects of grid-plate capacitance.

from grid to plate, it undergoes a phase shift of 180°. Thus, the signal fed back from the plate will be going negative when the grid signal is going positive. The effect of this is to decrease the signal on the grid.

Fig. 2-22 shows a typical triode amplifier circuit. Later you will learn exactly how it operates, but for now observe the following. The input signal (0.25 volt peak-to-peak) is applied to the grid. Since the gain of the amplifier is 20, the output should be multiplied by that amount (0.25×20), resulting in an output of 5.0 volts at the plate. However, at a frequency of 2,000 Hz the capacitive reactance of C_{gp} is such that there is a feedback voltage of 0.01 volt. Since this is a negative feedback, it results in a reduction of the input signal ($0.25 - 0.01 = 0.24$). This signal is then multiplied by the amplification (0.24×20), resulting in an output voltage of 4.8. Thus, the gain of the amplifier is 4.8 volts ÷ 0.25, or 19.2 instead of 20. (Of course, reducing the output voltage also reduces the feedback voltage slightly.) If the frequency of the input signal is increased to 20,000 Hz, would the gain of the triode increase or decrease?

Q2-39. The capacitance between elements of a tube is called ______________ _____________.

Q2-40. The most objectionable capacitance in a triode is the ____ __ _____ capacitance.

Q2-41. Negative feedback ________ the gain of an amplifier.

Your Answers Should Be:

A2-39. The capacitance between elements of a tube is called **interelectrode capacitance.**

A2-40. The most objectionable capacitance in a triode is the **grid-to-plate** capacitance.

A2-41. Negative feedback **reduces** the gain of an amplifier.

eedback at Higher Frequencies

Fig. 2-23 shows the same circuit as before, but the input ignal is at a higher frequency. Since the capacitive reactance f C_{gp} decreases with the change in frequency, there is a reater feedback voltage. In this case it is 0.10 volt. Subtracting 0.10 from 0.25 leaves an input signal of 0.15 volt. Multiplying 0.15 volt by 20 gives an output signal of 3.0 volts. The ain is thus 3.0 ÷ 0.25, or 12.

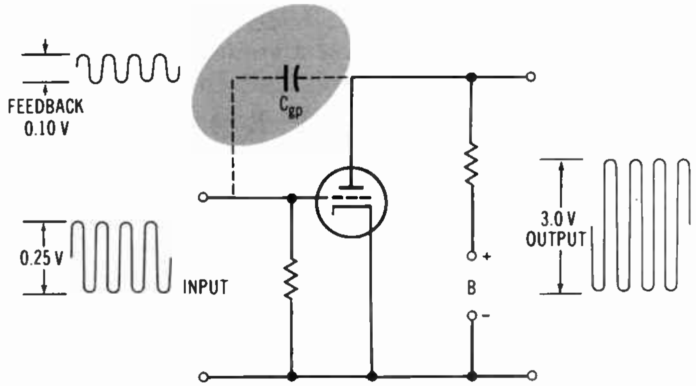


Fig. 2-23. Effects of grid-plate capacitance at a higher frequency.

etrodes

To prevent or reduce feedback, the grid-to-plate capacitance must be decreased. To do this, another element is added between the grid and the plate.

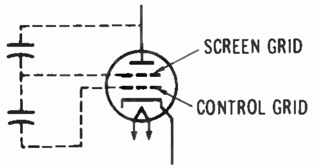


Fig. 2-24. Grid-plate capacitances in a tetrode.

This element, called a **screen grid**, is similar in construction to the control grid. The screen grid introduces two capacitances in series—a capacitance between the plate and the screen grid and the capacitance between the screen grid and the control grid. As a result, the capacitance between the plate and the control grid is considerably reduced. The screen grid of the **tetrode** (so-called because of the addition of the fourth element) is wound with a very thin wire. The screen grid usually operates with a high positive voltage on it. This voltage is never higher than that on the plate.

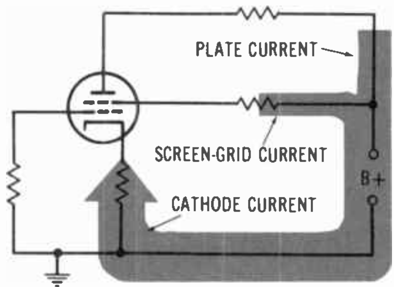


Fig. 2-25. Current flow in a tetrode circuit.

The voltage on the screen grid helps to pull electrons out of the space charge. Because of the thin, widely spaced wires, most of the electrons are not collected by the screen grid but pass through to the plate. Some of the electrons will be attracted to the screen grid, but its current is usually small compared to the plate current. The result of this new construction is a tube with high ac plate resistance. A high r_p means that changes in plate voltage have little effect on the plate current. As a result, the tetrode has a high μ (in the order of 200 or 300 as opposed to 20 to 50 for a triode). In addition, the interelectrode capacitance is very low, and the tube is more suitable for high-frequency applications than a triode.

Q2-42. The effects of grid-to-plate capacitance (increase, decrease) as frequency increases.

Q2-43. When capacitors are connected in series, the total capacitance is (greater, less) than that of the smaller capacitor.

Q2-44. The element added to the triode to make a tetrode is the ______ ____.

Your Answers Should Be:

A2-42. The effects of grid-to-plate capacitance **increase** as frequency increases.

A2-43. When capacitors are connected in series, the total capacitance is **less** than that of the smaller capacitor.

A2-44. The element added to the triode to make the tetrode is the **screen grid.**

Pentodes

The tetrode is a high-mu tube that can operate at high frequencies. But this type of tube presents another problem. Due to the extra grid operating at a high positive voltage, electron speed is increased. Some move so fast that they dislodge other electrons when they strike the plate. This is called **secondary emission.** Some of these extra electrons are attracted to the screen grid.

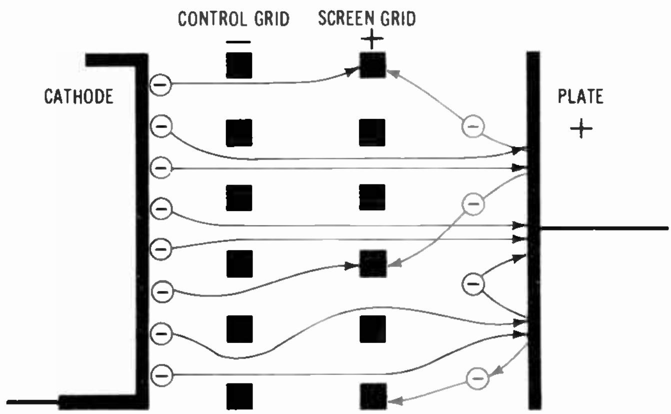


Fig. 2-26. Secondary emission.

When the screen-grid voltage is equal to or greater than the plate voltage, the amount of current drawn by the screen grid is enough to disturb the operation of the tube. This problem was solved by the development of the **pentode.**

To prevent the screen grid from drawing too much current due to secondary emission, another element, also grid-like in construction, was added to the tetrode. Physically, this extra element is placed between the screen grid and the plate; electrically, it is connected to either the cathode or to ground. As far as the plate is concerned, this element is negative. Electrons leaving the plate due to secondary emission are forced back to the plate by this negative element. Since this element helps suppress secondary emission, it is called the **suppressor grid.**

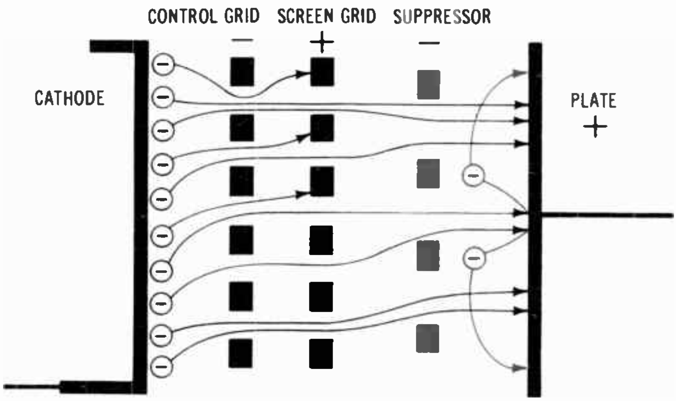


Fig. 2-27. Action of a suppressor grid.

The addition of the suppressor grid between the plate and screen grid also serves to reduce the interelectrode capacitance between the plate and control grid still further. This results in a tube with even better high-frequency performance than the tetrode. Pentode amplification factors are in the order of 1200 to 1500 (as opposed to 200 or 300 for a tetrode).

Q2-45. The release of electrons from the plate when it is struck by electrons from the cathode is called ________ ________.

Q2-46. A ________ tube results when a third grid is added to a tetrode.

Q2-47. The third grid in a pentode is called a ___________ grid.

Q2-48. The amplification factor of a pentode is (higher, lower) than that of a triode or a tetrode.

Q2-49. The suppressor grid of the pentode reduces ________ ________.

Your Answers Should Be:

A2-45. The release of electrons from the plate when it is struck by electrons from the cathode is called **secondary emission.**

A2-46. A **pentode** tube results when a third grid is added to a tetrode.

A2-47. The third grid in a pentode is called a **suppressor** grid.

A2-48. The amplification factor of a pentode is **higher** than that of a triode or a tetrode.

A2-49. The suppressor grid of the pentode reduces **secondary emission.**

WHAT YOU HAVE LEARNED

1. A tube containing a cathode, control grid, and plate is a triode.
2. The voltage on the control grid of a triode has a greater effect on plate current than does the plate voltage.
3. A triode can be used to amplify signals.
4. The control grid is usually operated negative with respect to the cathode.
5. There are three tube constants—amplification factor (μ), ac plate resistance (r_p), and transconductance (g_m).
6. Tube-constant values can be determined from graphs called tube characteristics.
7. Tube manuals contain information about tubes.
8. Bias is the difference of potential between the grid and cathode. It determines the operating point of the tube.
9. The screen grid in a tetrode tube reduces undesirable grid-to-plate capacitance.
10. μ and r_p are higher for a tetrode than for a triode.
11. The suppressor grid in a pentode reduces the effects of secondary emission.
12. The amplification factor for a pentode is very high.

3

Basic Semiconductor Devices

what you will learn

In this chapter the difference between n- and p-type semiconductor material is discussed. A semiconductor diode will be compared with a vacuum-tube diode. You will learn the difference between forward and reverse bias. You will also learn about the elements of a transistor, and how transistors are used as amplifiers. Transistor characteristic curves are also introduced.

WHAT IS A SEMICONDUCTOR?

Materials can be classed in three groups, according to their electrical properties—conductors, semiconductors, and insulators. Metals such as silver, copper, and aluminum have many free electrons. This makes it easy for current to flow through them. For this reason these metals are called **conductors.**

Materials such as glass, rubber, and many plastics have practically no free electrons. This makes it very difficult for current to flow through them. These materials are known as **insulators** and are used in a variety of applications ranging from the covering on conductors to the dielectric in capacitors.

Materials such as selenium, silicon, and germanium have some free electrons—more than an insulator but fewer than a conductor. These materials are generally referred to as **semiconductors.**

WHY SEMICONDUCTOR MATERIALS ARE IMPORTANT

A diode made of semiconductor material is called a **solid-state** diode. Semiconductor materials are also the basic ingredients of transistors. Solid-state diodes can replace vacuum-tube diodes, and transistors can replace vacuum-tube triodes. Why is this important? Solid-state diodes and transistors are smaller, weigh less, and use less power than their vacuum-tube counterparts. They are also more rugged and last longer than vacuum tubes. In addition, they do not require a filament-supply voltage.

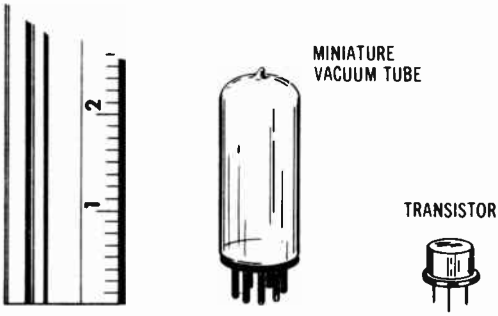


Fig. 3-1. Transistors are smaller than vacuum tubes.

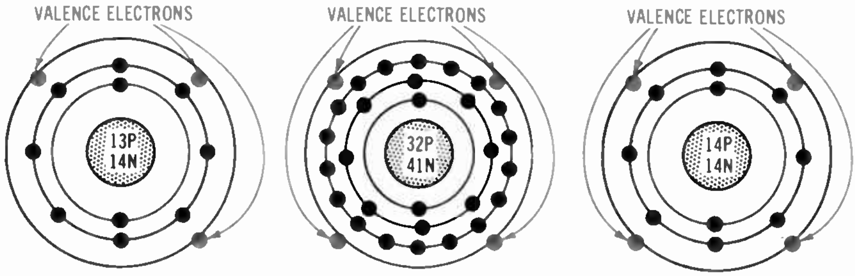
How do solid-state diodes and transistors work? How can a solid substance maintain unidirectional current flow in the same manner as a vacuum-tube diode? How can a solid substance amplify like the triode? To answer these questions we must first go back and examine the basic building blocks of matter—atoms.

MATTER, ELEMENTS, AND ATOMS

Matter is defined as anything that has mass and occupies space. Air, water, books, and people are examples. Matter consists of one or more materials called **elements.** Elements are substances that cannot be divided into other substances. Copper, aluminum, silicon, and germanium are examples of elements. The smallest particle of an element is an atom, which has all the properties of the element and can take part in chemical reactions.

The Aluminum Atom

The aluminum atom has 13 electrons circling in orbits around a nucleus of 13 protons and 14 neutrons. The negative charges on the 13 electrons are exactly balanced by the positive charges on the 13 protons. The three **valence** electrons in the outer shell, or ring, are loosely bound to the atom and are easily dislodged. These three loosely bound electrons are the reason why aluminum is a conductor. Aluminum has a valence of minus three. This means that aluminum easily gives up the three electrons in its outer ring.



(A) Aluminum. (B) Germanium. (C) Silicon.

Fig. 3-2. Diagrams of atoms.

The Germanium and Silicon Atoms

The nucleus of the germanium atom is larger than the aluminum nucleus. It has 32 protons and 41 neutrons. There are 32 orbiting electrons. Silicon has 14 orbiting electrons. Germanium and silicon each have four electrons in the outer ring. These four electrons make germanium and silicon semiconductors. Germanium and silicon atoms can either give up these electrons or take on four more to complete its outer ring.

Q3-1. Copper is a(n) __________.

Q3-2. Glass is a(n) __________.

Q3-3. A conductor has many ____ __________.

Q3-4. Silicon is a(n) ______________.

Q3-5. A substance that cannot be subdivided into other substances is called a(n) ________.

Q3-6. The electrons in the outer shell of an atom are known as ________ electrons.

Your Answers Should Be:

A3-1. Copper is a **conductor.**

A3-2. Glass is an **insulator.**

A3-3. A conductor has many **free electrons.**

A3-4. Silicon is a **semiconductor.**

A3-5. A substance that cannot be subdivided into other substances is called an **element.**

A3-6. The electrons in the outer shell of an atom are known as **valence** electrons.

SEMICONDUCTOR CRYSTALS

The illustration in Fig. 3-3 shows a typical arrangement of germanium (or silicon) atoms. Each germanium atom shares its four outer electrons with four neighbor atoms. This sharing of electrons causes a bond which tends to keep the atoms

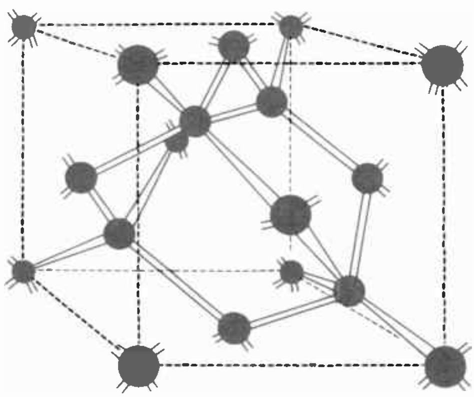


Fig. 3-3. Semiconductor crystal lattice.

together. This electron-pair bond, called a **covalent bond,** is formed because each atom of germanium attempts to complete a full count of eight electrons in its outer ring. Whenever several cubic structures combine, the lattice-like effect becomes evident. A visible crystal of germanium is composed of many millions of these basic crystal lattices. This crystalline semiconductor is electrically neutral.

INTRINSIC SEMICONDUCTORS

The crystal just examined is an ideal crystal. It probably never exists in nature as such. Because of its purity, this crystal is called **intrinsic**—intrinsic semiconductors are free from impurities. Manufacturing intrinsic germanium and silicon is the first step in the production of solid-state diodes and transistors.

Conduction in Intrinsic Germanium

How do electrons flow in germanium and other semiconductors? The outer shells of the germanium atoms form covalent bonds, so these shared electrons are not easily dislodged to provide electric current. This is true of all semiconductors. The reason for current flow in semiconductors is the addition of energy to the material. This energy may be in the form of heat, light, or the application of an electric field, such as that due to a voltage. Notice that these properties differ for different semiconductors. When crystals of germanium are heated, for example, the energy level of one of the electrons in a covalent bond is raised. The electron frees itself from the bond and can wander through the crystal lattice. Such free electrons are then available for conduction when an electric field is applied.

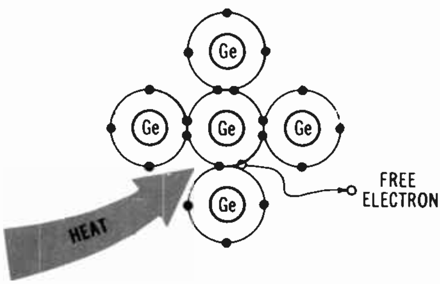


Fig. 3-4. Covalent bond broken by heat.

Q3-7. Germanium that is free from impurities is called __________ germanium.

Q3-8. Germanium atoms are held together in a crystal by ________ ______.

Q3-9. Conduction is produced in intrinsic semiconductors by the addition of ______.

Your Answers Should Be:

A3-7. Germanium that is free from impurities is called **intrinsic** germanium.

A3-8. Germanium atoms are held together in a crystal by **covalent bonds.**

A3-9. Conduction is produced in intrinsic semiconductors by the addition of **energy.**

Electron Flow Through Intrinsic Semiconductors

In Fig. 3-5 you see a few covalent bonds of intrinsic germanium after the material has been heated. Electrons have been liberated from each of the bonds shown. A positive voltage is applied to the germanium. Since an electron is missing from each of the bonds, there is, in effect, a positive charge at each covalent bond. This positive charge is called a **hole.** A free electron drifting in the direction of the applied positive voltage drifts from hole to hole until it finally reaches the positive voltage.

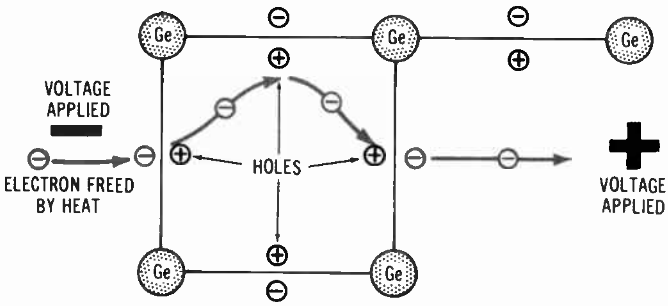


Fig. 3-5. Electron flow through intrinsic germanium.

Hole Flow Through Intrinsic Semiconductors

Examine Fig. 3-6. For each of the four electrons in the outer ring of each atom, there is a corresponding proton in the nucleus. When heat is applied (1), an electron is liberated and starts drifting toward the positive voltage. The electron leaves a hole which may be considered to be positive. This hole attracts an electron from the next covalent bond (2), thus leaving a hole at that point. The effect of this is that the hole has moved from point 1 to point 2. In a similar fashion the hole will move to points 3, 4, and 5, and will eventually be filled by an electron from the applied-voltage source. As long as heat continues to liberate electrons at point 1, this action will continue.

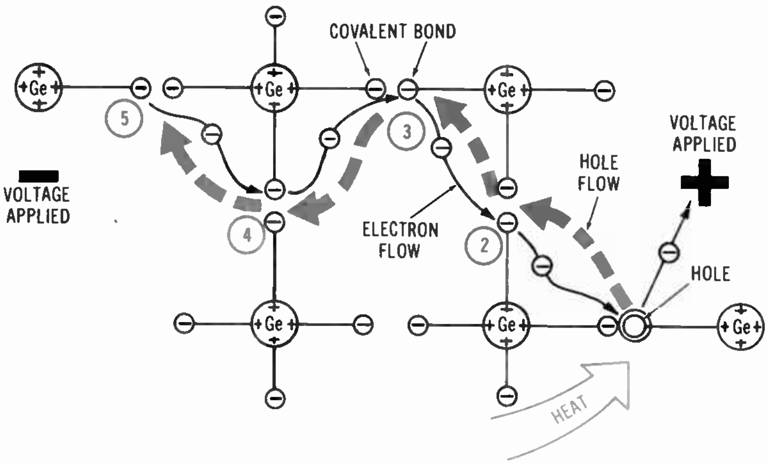


Fig. 3-6. Hole flow in intrinsic germanium.

Doping Intrinsic Germanium

You have seen how electrons and holes flow through germanium and other semiconductors. This was done by adding heat to liberate electrons and create holes. An electric field was set up to control the direction of hole and electron flow (also called drift). However, for transistors and solid-state diodes, intrinsic semiconductors are of little value. There is a more efficient way of causing conduction in germanium (or any semiconductor)—by adding impurities to the intrinsic material. This process is called **doping**. The type of impurity must be carefully selected and the amount accurately controlled. Accuracies up to one part in ten million are often required.

Q3-10. The addition of controlled amounts of impurities to a semiconductor is called ______.

Q3-11. Current flow in a semiconductor consists of the movement of __________ and ______.

Your Answers Should Be:

A3-10. The addition of controlled amounts of impurities to a semiconductor is called **doping.**

A3-11. Current flow in a semiconductor consists of the movement of **electrons** and **holes.**

Types of Impurities

Two types of impurities can be added to semiconductors. One type produces free electrons, and the other type produces holes. The electron-producing type of impurity is known as **n-type** (negative type) and the hole-producing type is known as **p-type** (positive type).

N-TYPE GERMANIUM

Examine the germanium in Fig. 3-7. Notice that the crystal is no longer intrinsic. An n-type impurity atom (arsenic) has replaced a germanium atom. Arsenic has five electrons in its

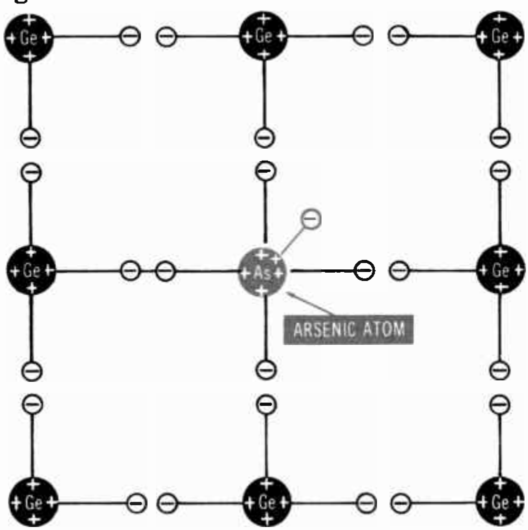


Fig. 3-7. Germanium doped with arsenic.

outer ring. Therefore, it can combine with four electrons from an adjacent germanium atom. When this covalent bond is established, an extra electron is left unpaired. This electron is loosely attached to the arsenic nucleus because the arsenic atom now has eight electrons in its outer ring. In order for this electron to free itself, it requires only one-seventieth of the energy needed to free an electron from a covalent bond. Because the arsenic has donated an electron to the crystal, it is called a **donor** atom. The crystal is called n-type germanium because of the presence of loosely bound negative electrons. To form n-type silicon, phosphorous is used as the donor. The extra electrons or current carriers control the resistance of a semiconductor material. Obviously, more heavily doped materials contain more donor atoms and more extra electrons for conduction, and thus have less electrical resistance.

When an electric field is applied to an n-type crystal, most of the electron flow is due to donor atoms. Some minor amount of additional current flows due to the breaking of covalent bonds. The amount of electron flow and hole flow due to break-

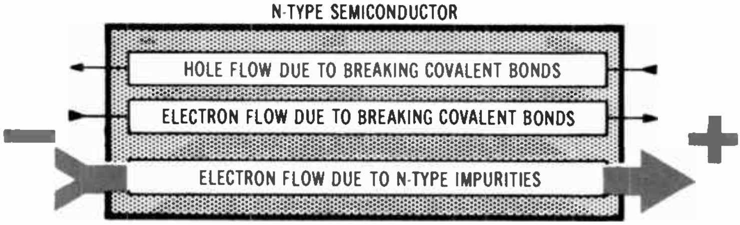


Fig. 3-8. Electrons as majority carriers.

ing of covalent bonds will be equal. Since most of the flow is due to donor electrons, they are called the **majority carriers.** The holes are called the **minority carriers.**

Q3-12. The type of germanium containing an impurity that produces free electrons is called _____ germanium.

Q3-13. The free electrons in n-type germanium are called ________ carriers.

Q3-14. Does hole flow equal electron flow in n-type germanium? Why?

Your Answers Should Be:

A3-12. The type of germanium containing an impurity that produces free electrons is called **n-type** germanium.

A3-13. The free electrons in n-type germanium are called **majority carriers.**

A3-14. **No.** n-type germanium is made by adding an n-type donor atom, such as arsenic (some others are antimony and boron), to the crystal. Most of the current flow in a crystal is due to loosely bound electrons from the donor atoms.

P-TYPE GERMANIUM

Suppose an aluminum atom replaced a germanium atom in a germanium crystal. Aluminum has three electrons in its outer ring. In the crystal, the aluminum atom combines with four germanium atoms. The aluminum atom establishes a cova-

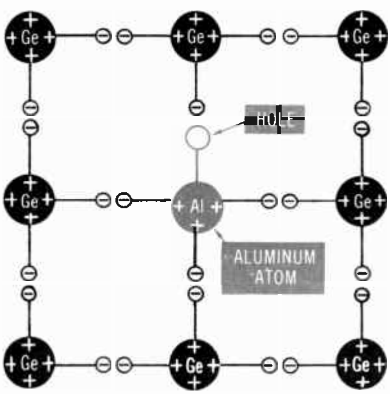


Fig. 3-9. Germanium doped with aluminum.

lent bond with three of its neighbors. In place of the fourth covalent bond there is a combination of an electron and a hole. This hole acts as a strong positive charge and tends to attract electrons from nearby covalent bonds. When an electron leaves a neighboring bond, it leaves a hole which is then filled by an electron from another covalent bond. Thus, holes wander through p-type germanium just as electrons wander through n-type germanium.

Because the aluminum atom is capable of accepting an electron, it is called an acceptor atom. The crystal is known as p-type germanium because of the presence of positive holes. When an electric field is applied to the crystal, aluminum acceptor atoms accept more electrons to fill holes than are allowed to flow freely. Therefore, the majority current carriers are holes, and the minority carriers are electrons. To form p-type silicon, boron may be used as the donor.

To sum up, n-type semiconductor material has extra electrons donated by the impurity (donor) atom, while p-type semiconductor material has excess holes contributed by acceptor impurities. The more heavily the material is doped, the lower its electrical resistance will be.

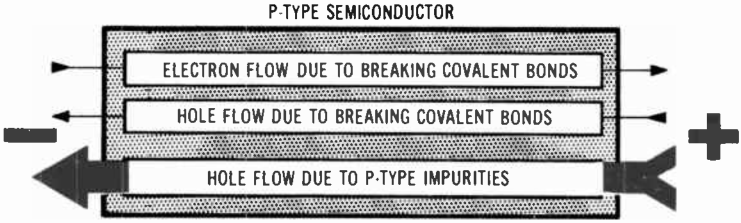


Fig. 3-10. Holes as majority carriers.

THE TRANSISTOR

The transistor controls the flow of majority carriers through the semiconductor crystal of which it is made. The transistor can be compared to a triode. In fact, it is convenient to think of the transistor as a solid-state triode.

Q3-15. The hole left by an electron has a _________ charge.

Q3-16. An electric field causes electrons to flow to the _________ terminal while holes flow to the _________ terminal.

Q3-17. The majority carriers in p-type germanium are the _____.

Q3-18. P-type atoms are also called _________ atoms.

Q3-19. The transistor can be compared to a ______ vacuum tube.

Your Answers Should Be:

A3-15. The hole left by an electron has a positive charge.

A3-16. An electric field causes electrons to flow to the positive terminal while holes flow to the negative terminal.

A3-17. The majority carriers in p-type germanium are the holes.

A3-18. P-type atoms are also called acceptor atoms.

A3-19. The transistor can be compared to a triode vacuum tube.

The symbols for the triode and the transistor can be compared in Fig. 3-11. Each has three elements, one of which acts as a source of current. In the triode, this element is called the cathode; in the transistor, this element is called an emitter. (The arrow in the symbol points in the direction of hole movement.) Both the transistor and triode vacuum tube have a control element. In the triode, it is called the grid, and in the transistor it is called the base. The tube and transistor each have a current collector, called the plate in the triode and the collector in the transistor.

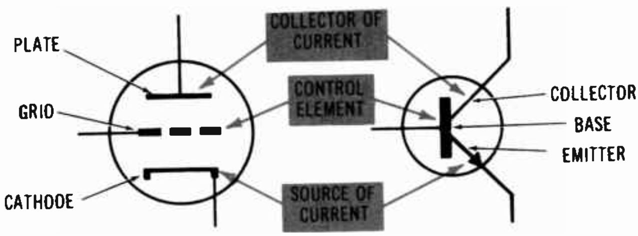


Fig. 3-11. Comparison of transistor and triode tube.

In a similar fashion, a solid-state diode may be compared to a vacuum-tube diode. Here there are only two elements.

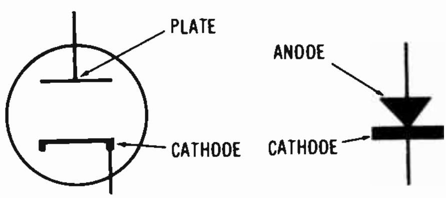


Fig. 3-12. Comparison of diodes.

SEMICONDUCTOR DIODES

Early radios used crystal diodes to detect radio signals. These diodes allowed current to flow in one direction but not in the other. This **unidirectional** current capability is the distinguishing feature of the diode.

A solid-state diode consists of a section of p-type semiconductor material joined to an n-type section. The activity occurring at the junction of the materials is responsible for the unidirectional property of the diode. The contacting surface is called the **pn junction.**

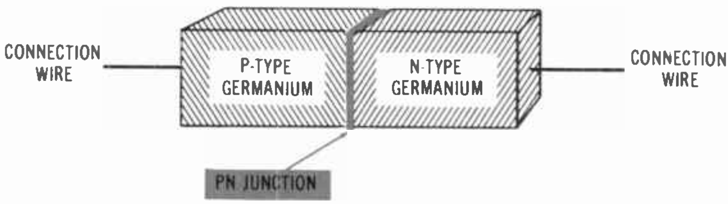


Fig. 3-13. Diagram of a solid-state diode.

PN JUNCTION

Although an n-type semiconductor has an excess of free electrons, it is electrically neutral. This is because each donor atom becomes positively charged when it gives up an electron. Thus, for every freed electron in the crystal there is a positively charged donor atom. Therefore, the crystal is only negative in the sense that the freed electrons are the most mobile particles.

Q3-20. The ability of a diode to conduct current in only one direction is called a _______________ capability.

Q3-21. N-type semiconductor crystals are electrically ________.

Q3-22. When p- and n-type germanium are joined together, the contacting surface is called the ___________.

Your Answers Should Be:

A3-20. The ability of a diode to conduct current in only one direction is called a **unidirectional** capability.

A3-21. N-type semiconductor crystals are electrically **neutral.**

A3-22. When p- and n-type germanium are joined together the contacting surface is called the **pn junction.**

Joining P- and N-Type Germanium

Like n-type germanium, p-type germanium is also electrically neutral.

(A) N-type germanium.

(B) P-type germanium.

Fig. 3-14. Doped germanium is electrically neutral.

When n-type germanium and p-type germanium are joined, some electrons and holes combine at the junction. In the region of the junction, n-type germanium loses some of its electrons. Thus, it is no longer neutral in this area; it now has a positive charge. The electrons it loses combine with holes from the p-type germanium at the junction. Thus, the p-type germanium becomes negative. The majority carriers have combined at the junction, leaving charged atoms (ions) in the area near the junction. A potential difference (in the order of several tenths of a volt) exists between the n- and p-type germanium ions. If more electrons try to move from the n-type to the p-type, they are stopped by the negatively charged ions in the p-type germanium near the junction. In a similar fashion, holes from the p-type are prevented from crossing the junction by the buildup of positively charged ions in the n-type germanium near the junction. The net effect of this action is to set up a **barrier voltage** that prevents further combination of electrons and holes. The area in which this voltage exists is called the **barrier region.**

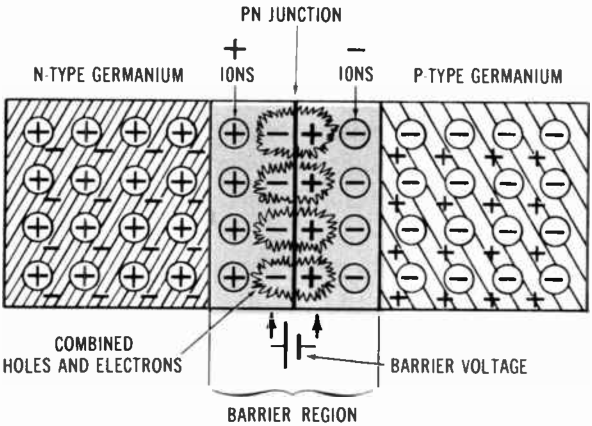


Fig. 3-15. Action in a pn junction.

Reverse Bias

You know that a diode passes current more readily in one direction than in the other. Let's consider the effect of the barrier region on current flow through a semiconductor diode. Suppose that the positive terminal of a battery is connected to the n-type germanium of a diode and the negative terminal to the p-type germanium.

The positive terminal of the battery attracts electrons from the pn junction, and the negative terminal of the battery attracts holes from the pn junction. This results in more positive ions (donor atoms that have lost their free electrons) in the n-type germanium in the vicinity of the pn junction and more negative ions (acceptor atoms that have lost their holes)

Q3-23. The area at the junction is called the _______ _______.

Q3-24. At the junction, n-type germanium is ___________ charged.

Q3-25. The _______ _______ prevents complete combination of all of the holes and electrons.

Q3-26. The barrier voltage is in the order of ______ __ _ ____.

Your Answers Should Be:

A3-23. The area at the junction is called the barrier region.

A3-24. At the junction, n-type germanium is positively charged.

A3-25. The barrier voltage prevents complete combination of all the holes and electrons.

A3-26. The barrier voltage is in the order of tenths of a volt.

in the p-type germanium in the same area. This action creates a wider barrier region and results in a larger barrier voltage.

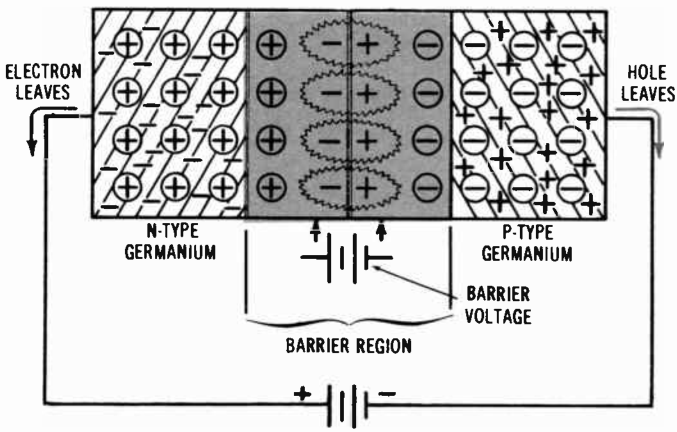


Fig. 3-16. Reverse-biased diode.

The action continues until the barrier voltage equals the reverse bias (battery voltage). No current flows because these voltages are equal and opposite. This condition is called equilibrium.

Forward Bias

Now suppose the battery leads are reversed. Instantly, electrons are attracted to the positive terminal of the battery. An electron flow is set up in the N-type germanium and moves toward the pn junction. When an electron reaches the junction, it combines with a hole. The n-type germanium is now

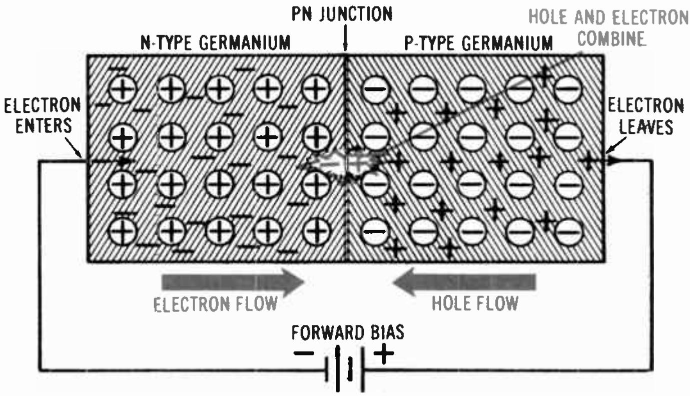


Fig. 3-17. Forward-biased diode.

positive and may accept an electron from the negative battery terminal. Similarly, the p-type becomes negative when a hole combines with an electron at the barrier. Thus, it gives up an electron to the positive battery terminal. A solid-state diode symbol is shown in Fig. 3-18.

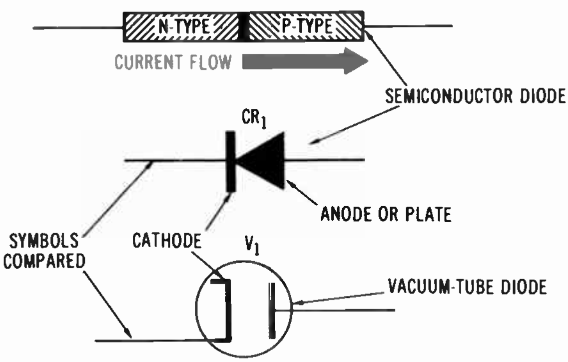


Fig. 3-18. Diode symbols.

Q3-27. Equilibrium due to reverse bias occurs when the ________ voltage equals ________ voltage.

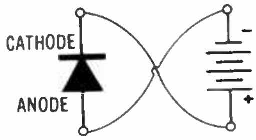
Q3-28. Connect the diode to the battery so the diode is reverse biased.

Q3-29. Conduction is due to ____ flow in p-type germanium and __________ flow in n-type germanium.

Your Answers Should Be:

A3-27. Equilibrium due to reverse bias occurs when the **barrier voltage** equals **battery** voltage.

A3-28. For the diode to be reverse-biased, the **positive terminal** of the battery must be connected to the **cathode**, and the **negative terminal** of the battery must be connected to the **anode.**



A3-29. Conduction is due to **hole** flow in p-type germanium and **electron** flow in n-type germanium.

DIODE CHARACTERISTICS

You have learned how a solid-state diode operates. Now some of its important characteristics will be examined. These are the current-voltage, resistance, temperature, and capacitance characteristics.

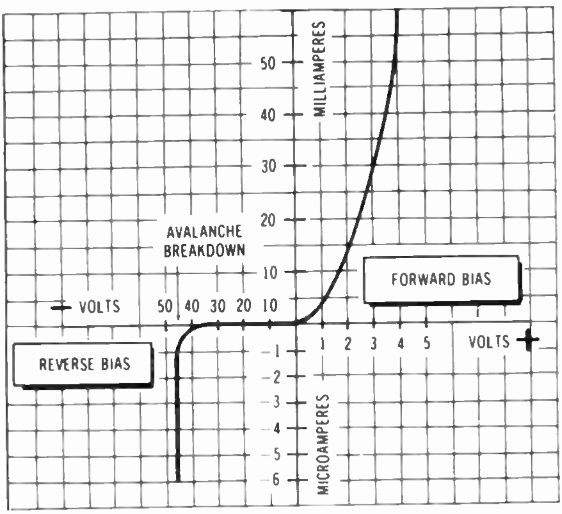


Fig. 3-19. Current-voltage characteristic curve.

Current-Voltage Relationships

The graph in Fig. 3-19 shows the amount of current that will flow through a typical diode when various voltages are applied. The positive-voltage region is the area in which the diode is forward-biased. The reverse-bias region is to the left of the origin. Remember that the diode will not conduct in the reverse direction. This is true on the graph up to almost 40 volts of reverse bias. Above this value, small currents in the order of a few microamps start to flow. This current flow is due to the minority carriers. When the reverse bias reaches about 45 volts there is a sharp increase in reverse current. This is called **avalanche breakdown.**

Resistance

The resistance of solid-state diodes varies with the applied voltage. Resistance is high for low forward-bias voltages and is low for high forward-bias voltages. For reverse biases, the resistance is very high until avalanche breakdown occurs.

Temperature

Solid-state diodes have a negative temperature coefficient. This means that as the temperature increases, the resistance of the diode decreases. Within certain limits the effects of resistance changes due to temperature change are not detrimental to the operation of the diode. However, when a very high temperature is reached, the resistance of the diode decreases so much that the current through the diode may be high enough to permanently damage the crystalline structure. This action is called **thermal runaway** and presents a serious problem in circuit design.

Q3-30. The condition in which the current through a reverse-biased, solid-state diode sharply increases is called _________ _________.

Q3-31. The resistance of a solid-state diode varies with the _______ _______.

Q3-32. Solid-state diodes have a ________ temperature coefficient.

Your Answers Should Be:

A3-30. The condition in which the current through a reverse-biased, solid-state diode sharply increases is called **avalanche breakdown.**

A3-31. The resistance of a solid-state diode varies with the **applied voltage.**

A3-32. Solid-state diodes have a **negative** temperature coefficient.

Capacitance

Two conductors separated by a dielectric constitute a capacitor. Thus, a solid-state diode is a capacitor in which the barrier region serves as the dielectric. At low frequencies the effects of this capacitance need not be considered. At high frequencies, however, this capacitance of about 3 to 5 picofarads becomes an important factor.

SEMICONDUCTOR-DIODE DATA

Most electronic parts catalogs have several pages devoted to semiconductor diodes. An example of some of the data you will see in such a catalog is shown in Table 3-1. Notice that diodes are designated 1N34, 1N58, etc. Just as with vacuum tubes, manufacturers have agreed to call diodes having the same characteristics by the same type number.

The table shows some of the characteristics for the 1N34A, 1N58A, and 1N914A. Peak inverse voltage (piv) is the reverse bias at which avalanche breakdown occurs. The ambient temperature range is that range of temperatures over which the diode will operate and still maintain its basic characteristics. Forward current values are given for both the average current

Table 3-1. Semiconductor Diode Characteristics

Type	Peak Inverse Volts	Ambient Temperature Range—°C	Forward Peak mA	Current Average mA	Capacitance pF
1N34A	60	−50 to +75	150	50	1.0
1N58A	100	−50 to +75	150	50	1.0
1N914A	75	−65 to +200	100	150	1.0

(current at which the diode is usually operated) and the peak current (current which, if exceeded, will damage the diode). The only difference between the first two diodes (which are germanium types) is in the peak inverse voltage. Therefore, the 1N34A could be substituted for the 1N58A in applications involving signals of less than 60 volts peak-to-peak.

TRANSISTORS

Understanding how the semiconductor pn junction operates was the first step in understanding how a transistor operates. As you will see, a transistor is a semiconductor device with two pn junctions. The two junctions are in the form of a sandwich made up of two types of material (n and p). This sandwich can form either an npn or pnp transistor.

NPN Transistors

By sandwiching a very thin piece of p-type germanium between two slices of n-type germanium, an npn transistor is formed. A transistor made in this way is called a **junction transistor.** The symbol for this type of transistor showing the three elements (emitter, base, and collector) is given below. The three elements correspond to the cathode, grid, and plate, respectively, of a vacuum-tube triode.

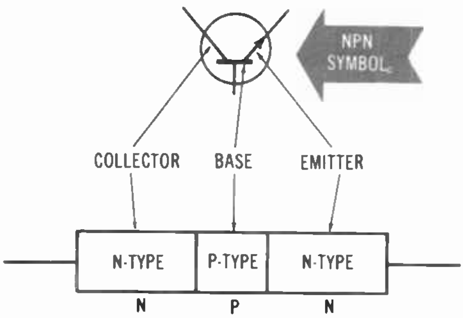


Fig. 3-20. Npn transistor symbol.

Q3-33. The capacitance of a solid-state diode must be considered at _ _ _ _ frequencies.

Q3-34. The three elements of a transistor are the _ _ _ _ _ _ _ _, _ _ _ _ _, and _ _ _ _ _ _ _ _ _ _ _.

Your Answers Should Be:

A3-33. The capacitance of a solid-state diode must be considered at **high** frequencies.

A3-34. The three elements of a transistor are the **emitter**, **base**, and **collector**.

PNP Transistors

By placing n-type semiconductor between two slices of p-type semiconductor, a pnp junction transistor is formed. A pnp **point-contact** transistor can be made by fusing two "cat-whiskers" to a large n-type base.

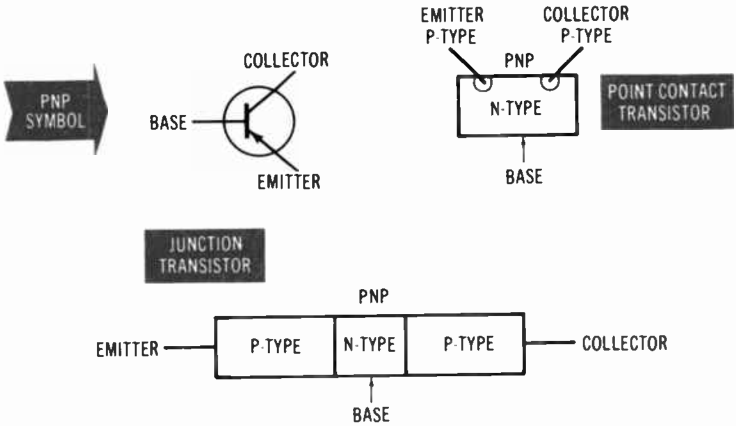


Fig. 3-21. Pnp transistor symbol.

The symbol for the pnp transistor is almost identical to that of the npn transistor. The only difference is the direction of the emitter arrow. In the npn transistor it points away from the base, and in the pnp it points toward the base. **Electrons always flow against the direction of the arrow.** Electron flow is from n-type to p-type semiconductor. If the arrow points toward the base, the electron flow is in the opposite direction —from base to emitter. Thus, the emitter must be p-type semiconductor and the transistor is pnp. The reverse is true for npn transistors.

TRANSISTOR OPERATION

Several questions have probably come to mind by now. How can a solid-state material amplify? Is there a difference between a junction and point-contact transistor or between a pnp and an npn transistor? One of these questions can be answered immediately. Junction and point-contact transistors are almost identical in operation. Therefore, all discussion will be directed to junction transistors, but it is understood that it applies to both types.

Biasing

The pn junction establishes a barrier voltage in solid-state diodes. In the junction transistor, two such pn junctions are established, each with its own barrier voltage. If these pn junctions are properly biased, the transistor can be made to operate as an amplifier. The proper method for biasing an npn transistor is discussed next.

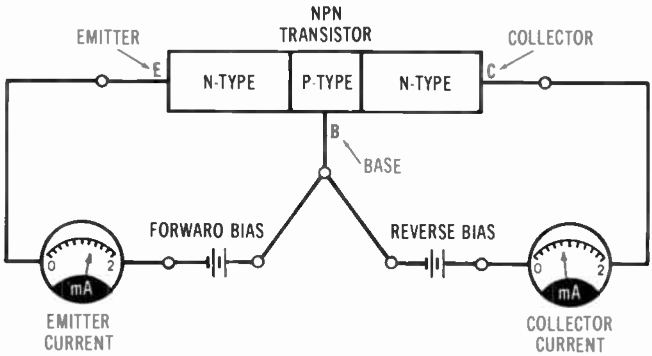


Fig. 3-22. Bias for npn transistor amplifier.

Fig. 3-22 shows an npn transistor biased properly to operate as an amplifier. Addition of certain resistors (which you will see later) would complete the picture.

Q3-35. A transistor is a single semiconductor crystal with ___ pn junctions.

Q3-36. A transistor can perform the same function as a ______ ____ ______.

Q3-37. P-type semiconductor material sandwiched between two pieces of n-type material forms an ___ transistor.

Your Answers Should Be:

A3-35. A transistor is a single semiconductor crystal with two pn junctions.

A3-36. A transistor may perform the same function as a vacuum-tube triode.

A3-37. P-type semiconductor material sandwiched between two pieces of n-type material forms an npn transistor.

In the arrangement in Fig. 3-22, a forward bias is applied between the base and the emitter. This results in emitter current. A reverse bias is applied between the collector and the base. This results in a flow of collector current that is nearly equal to the emitter current. The reason for this seeming contradiction is that the base is very thin—less than one-thousandth of an inch.

Before continuing, it is time to learn a few more shorthand notations used when referring to transistors:

B—Base
E—Emitter
C—Collector
I_b—Base current
I_e—Emitter current
I_c—Collector current
V_{eb}—Voltage from emitter to base
V_{cb}—Voltage from collector to base

Note: these are all average values

Current Flow in a Biased Transistor

Fig. 3-23 shows the electron and hole flow in a biased npn transistor. With the emitter-base junction forward-biased, electrons in the emitter drift into the base to combine with the holes in the base. For each combination an electron enters the emitter from V_{eb}. At the same time, an electron leaves the base (creating another hole) and returns to V_{eb}. Thus, there is electron flow in the emitter and hole flow in the base.

Since the base-collector junction is reverse-biased, very little current will flow through it. This current is produced by minority carriers—hole flow in the n-type collector and electron flow in the p-type base—due to V_{cb}.

Why is I_c almost equal to I_e? Since the base is very thin, there is not a sufficient number of holes in the base region to combine with the large number of electrons coming from the emitter. These excess electrons pass through the base and on to the collector due to the presence of V_{cb}. The reason why these electrons are not stopped by the collector-base barrier voltage is that there is a strong positive voltage attracting them. This voltage is due to the series combination of V_{eb} and V_{cb}. The major portion of I_c is due to the electron flow from

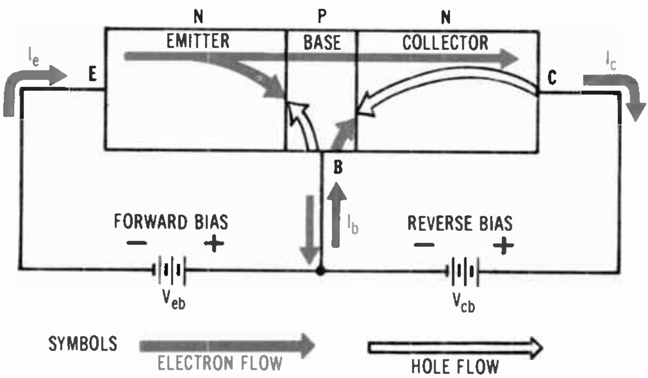


Fig. 3-23. Current in a biased npn transistor.

emitter to collector. Notice that current flow in the base is due to both electron and hole flow. Thus, there are current flows indicated in both directions. Base current I_b is the difference between these two currents.

Q3-38. The emitter-base junction of a transistor amplifier must be ________ biased and the collector-base junction must be ________ biased.

Q3-39. Under these conditions collector current is (equal to, slightly less than, more than) emitter current.

Q3-40. This is explained by the fact that not enough ______ exist in the base to combine with all the __________ coming from the ________.

Q3-41. Identify the following shorthand notations: I_b, I_c, I_e, V_{eb}, and V_{cb}.

Your Answers Should Be:

A3-38. The emitter-base junction must be **forward-biased** and the collector-base junction **reverse-biased.**

A3-39. Under these conditions collector current is **slightly less than** emitter current.

A3-40. This is explained by the fact that not enough **holes** exist in the base to combine with all the **electrons** coming from the **emitter.**

A3-41.

I_b—**Base current** I_c—**Collector current** I_e—**Emitter current** V_{eb}—**Voltage from emitter to base** V_{cb}—**Voltage from collector to base**	All average values

Biasing PNP Transistors

The difference in operation between pnp and npn transistors is that holes are the majority carriers in the pnp transistor. Proper bias for a pnp unit is achieved by using "negative" voltage polarities—just the opposite of those used for an npn transistor. However, the bias between emitter and base is still forward bias and the bias between collector and base is still reverse bias. Since the emitter is p-type and the base is n-type semiconductor, a battery with its positive terminal connected to the emitter will forward-bias the emitter-base junction. In a similar fashion, a battery whose negative terminal is connected to the p-type collector will reverse-bias the collector-base junction.

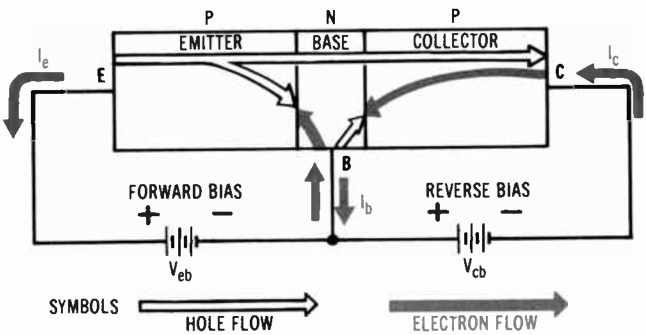


Fig. 3-24. Current in a biased pnp transistor.

When so biased, the transistor conducts. The emitter, being a p-type semiconductor, releases holes to combine with electrons in the base. For each combination an electron in the emitter enters the positive terminal of the bias battery. This leaves a hole to migrate toward the base. At the same time, an electron from the negative terminal of the battery enters the base. Notice that electrons, and not holes, flow in the external circuit.

Because the base is thin, many more emitter holes exist than base electrons. The excess holes are drawn to the negative battery terminal connected to the collector.

HOW A TRANSISTOR AMPLIFIES

Recall how the control grid in a vacuum-tube triode has a much greater control of plate current than the plate. A transistor is capable of amplification because of a similar arrangement. The base in the transistor acts to control current through the transistor in much the same fashion as the grid controls current in the triode.

Consider another arrangement of the transistor. This arrangement is similar to the one showing a properly biased npn transistor. The only difference is that the reverse bias between collector and base is provided by V_{ce} in series with but opposing V_{be}, and V_{ce} is large compared to V_{be}. Thus, V_{ce} replaces V_{cb} in series with V_{be}. This is called a **grounded-emitter circuit.**

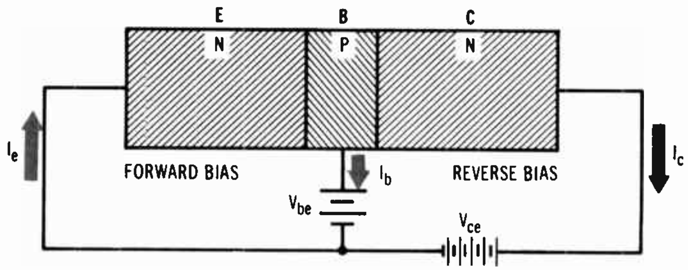


Fig. 3-25. Grounded-emitter circuit.

Q3-42. Bias polarities for a pnp transistor are the _________ of those for an npn transistor.

Q3-43. The base in a transistor has an action similar to the ____ in a triode.

Your Answers Should Be:

A3-42. Bias polarities for a pnp transistor are the **opposite** of those for an npn transistor.

A3-43. The base in a transistor has an action similar to the **grid** in a triode.

Triode Amplifier Versus Transistor Amplifier

The grounded-emitter circuit shown in Fig. 3-25 is the most common arrangement for a transistor amplifier. Let's compare it with the most common triode circuit, the grounded-cathode amplifier. You can see from Fig. 3-26 where this amplifier gets its name.

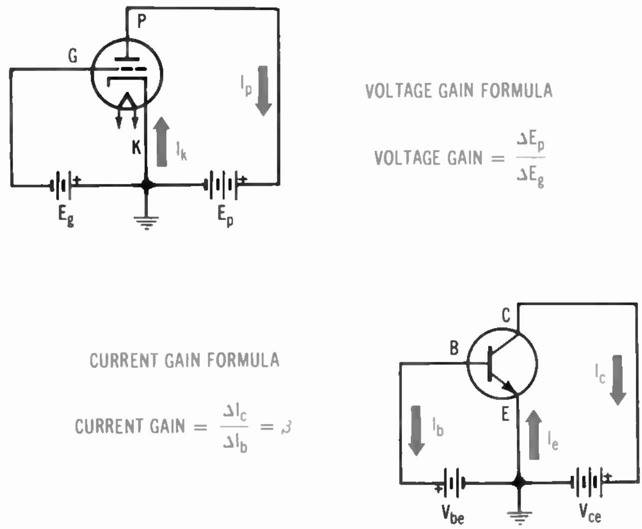


Fig. 3-26. Basic amplifiers.

Compare the two circuits shown in Fig. 3-26. The triode is composed of a cathode (K) that emits electrons; a plate, or anode (P) that collects the electrons; and a grid (G) that controls the flow of electrons to the plate. The transistor is composed of an emitter (E) that supplies electrons, a collector (C) that collects the electrons, and a base (B) that controls the flow of electrons. The transistor base is very thin, and the vacuum-tube grid has a fine-wire construction. Each of these elements, therefore, allows accelerated electrons to pass through. However, each has great control over the number of electrons that actually reach the collector of electrons (the plate or collector).

The gain of a triode is determined as follows. The change in plate voltage necessary to produce a change in plate current is compared with the change in grid voltage that produces the same change in plate current. In the transistor the forward bias (V_{be}) serves the same function as the negative bias in the triode. Instead of a voltage gain, however, a current gain will be measured. The symbol for current gain is the Greek letter β (beta). To obtain this current gain, I_c and I_b recorded for a particular V_{be}. Voltage V_{be} is changed and the new I_c and I_b recorded (V_{ce} is held constant). Current gain is then calculated by dividing the change in I_c by the change in I_b. Beta is often called h_{fe}.

Another parameter of the transistor (beta is a parameter like mu in the triode tube) is alpha (α). Alpha is the ratio of the change in collector current to the corresponding change in emitter current, when the collector voltage is constant (common base circuit). Another symbol for α is h_{fb}. It has been shown that under most biasing methods the collector current is slightly less than the emitter current (due to the base drawing some of the current from the emitter). Therefore the ratio of ΔI_c and ΔI_e must be less than one. For example, if the collector current changes 4.8 mA and the emitter current changes 5 mA, then the base current must change 0.2 mA. Calculate alpha as follows:

$$\alpha = \frac{\Delta I_c}{\Delta I_e} = \frac{4.8\,\text{mA}}{5.0\,\text{mA}} = 0.96$$

Q3-44. A _________ ________ transistor configuration corresponds to a grounded-cathode triode amplifier.

Q3-45. The numerical value of alpha is ____ ____ ___.

Q3-46. If I_b is 100 μA when I_c is 1.0 mA, and I_b is 50 μA when I_c is 0.5 mA, what is β?

Your Answers Should Be:

A3-44. A **grounded-emitter** transistor configuration corresponds to a grounded-cathode triode amplifier.

A3-45. The numerical value of alpha is **less than one.**

A3-46.

$$\beta = \frac{\Delta I_c}{\Delta I_b} = \frac{1.0\,\text{mA} - 0.5\,\text{mA}}{100\,\mu\text{A} - 50\,\mu\text{A}} = \frac{0.5\,\text{mA}}{50\,\mu\text{A}} = 10$$

Transistor Amplification

How can a current gain (α) of less than one result in amplification? The answer is that a power gain is realized. The reason for this can be found in the values of the input and output impedances (resistances) of the transistor. The input resistance of the forward-biased, emitter-base junction is low. The output impedance of the reverse-biased, collector-base junction is very high. Consider the formula for power:

$$P = I^2R$$

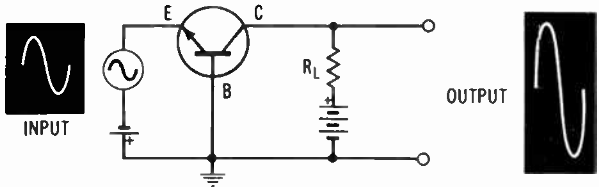
If you compare the input and output circuits of the transistor in terms of their power consumption, you will see that there is a power gain. Consider a transistor with an emitter-base resistance of 100 ohms and a collector-base resistance of about 1 megohm. Since the collector and emitter currents are very nearly the same, the difference in the power produced by each will depend largely on the resistance. Thus, the power in the collector circuit will be much larger than that in the emitter circuit. The transistor is capable of matching low-resistance circuits to high-resistance circuits and providing a power gain. It is this transfer of resistance that gives the transistor its name. Contracting **transfer** and **resistor** gives **transistor.**

BASIC TRANSISTOR AMPLIFIERS

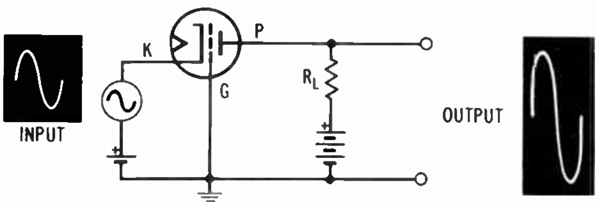
Npn or pnp transistors can also be used as grounded-collector and grounded-base amplifiers. The three basic transistor amplifiers can be compared with the three basic vacuum-tube amplifiers—the grounded-cathode, grounded-grid, and grounded-plate.

Common-, or Grounded-, Base Amplifier

Shown in Fig. 3-27 are an npn, **common-base amplifier** and its vacuum-tube equivalent, the **grounded-grid amplifier.** The base and grid are grounded. The input signal is applied to



(A) Grounded base.



(B) Grounded grid.

Fig. 3-27. Comparison of amplifiers.

the emitter in the common-base circuit, and to the cathode in the grounded-grid circuit. The output signal is taken from the collector and the plate. The input and output signals of these amplifiers have the same polarity; that is, they are in phase. The common-base circuit is used mostly as a voltage amplifier. It has these characteristics:

1. The input impedance is low, about 60 to 100 ohms.
2. The output impedance is high, about 0.5 to 1.0 megohm.
3. Current gain (α) is less than one.
4. Voltage gain is medium, about 150.
5. Power gain is medium, about 450.
6. No phase reversal occurs.

Q3-47. Phase shift in a grounded-base amplifier is _____.

Q3-48. The voltage gain in a grounded-base amplifier is _______.

Q3-49. In a grounded-base amplifier, the input impedance is ___, and the output impedance is ____.

Your Answers Should Be:

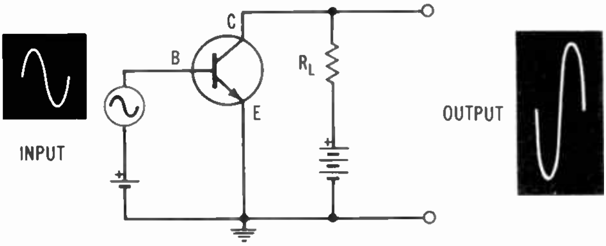
A3-47. Phase shift in a grounded-base amplifier is **zero.**

A3-48. The voltage gain in a grounded-base amplifier is **medium.**

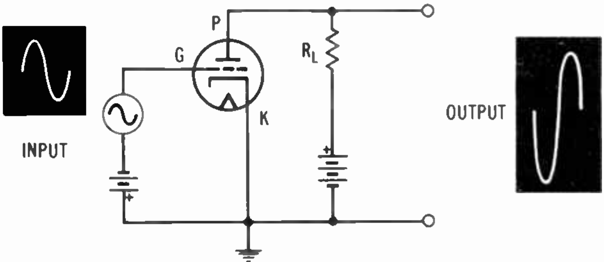
A3-49. In a grounded-base amplifier, the input impedance is low, and the output impedance is **high.**

Common-, or Grounded-, Emitter Amplifier

Fig. 3-28 shows a **common-emitter amplifier** and its vacuum-tube equivalent, **the grounded-cathode amplifier.** The emitter and cathode are grounded. The input signal is applied to the base and the grid, respectively, and the amplifier output is taken from the collector and the plate, respectively. A phase



(A) Grounded emitter.



(B) Grounded cathode.

Fig. 3-28. Comparison of amplifiers.

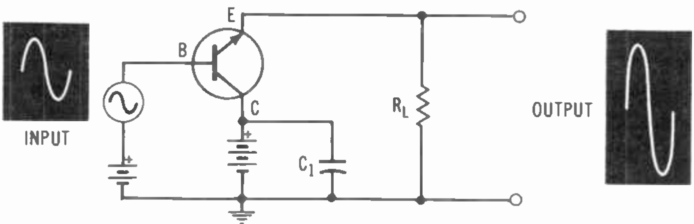
reversal of 180° occurs between the input and the output. This phase reversal will be explained in the chapter on triode amplifiers. The common-emitter amplifier has these characteristics:

1. Input impedance is low, about 700 to 1000 ohms.
2. Output impedance is high, about 50,000 ohms.

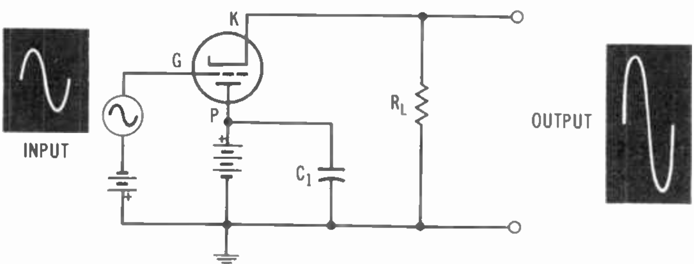
3. Current gain (β) is about 50.
4. Voltage gain is high, about 500.
5. Power gain is very high, about 800.
6. Phase reversal occurs.

Common-, or Grounded-, Collector Amplifier

The figure shows a **common-collector amplifier** and its vacuum-tube equivalent, the **grounded-plate amplifier.** Notice that the collector and plate are not at dc ground, but at ac ground, due to the large capacitor bypassing the battery. The input signal is applied to the base and grid, respectively. The



(A) Grounded collector.



(B) Grounded plate.

Fig. 3-29. Comparison of amplifiers.

output signal is taken from the emitter and cathode, respectively. This circuit is also called an **emitter follower,** and its equivalent is called a **cathode follower.** The characteristics of the emitter-follower amplifier are summarized on the next page.

Q3-50. A common-emitter amplifier produces a phase shift of _____ .

Q3-51. The voltage gain of a common-emitter amplifier is _____ .

Your Answers Should Be:

A3-50. A common-emitter amplifier produces a phase shift of 180°.

A3-51. The voltage gain of a common-emitter amplifier is high.

Emitter-Follower Characteristics

The gain of an emitter-follower and a cathode-follower circuit is always less than one. These circuits are usually used to match impedances between two circuits. The common-collector amplifier has these characteristics:

1. Input impedance is very high, about 300K to 600K.
2. Output impedance is low, about 100 ohms.
3. Current gain is about 50.
4. Voltage gain is less than 1.
5. Power gain is low, about −250. (The negative sign means that power is consumed by R_L.)
6. No phase reversal occurs.

TRANSISTOR CHARACTERISTICS

The performance of transistors, like solid-state diodes, is affected by temperature. A change in temperature varies the junction resistance. From the study of diodes you learned that the pn junction has a negative temperature coefficient. This changes the junction bias and the current flow across the junction and therefore affects transistor performance. For this reason, manufacturers list operating temperatures for their transistors.

TRANSISTOR CHARACTERISTIC CURVES

Do you remember how to obtain information from the family of curves associated with the vacuum-tube amplifier? Transistors have similar curves. Fig. 3-30 shows the family of curves for both a pentode amplifier and an npn-type transistor connected as a common-emitter amplifier. Notice the correspondence between I_p and I_c, E_p and V_c, and E_g and I_b.

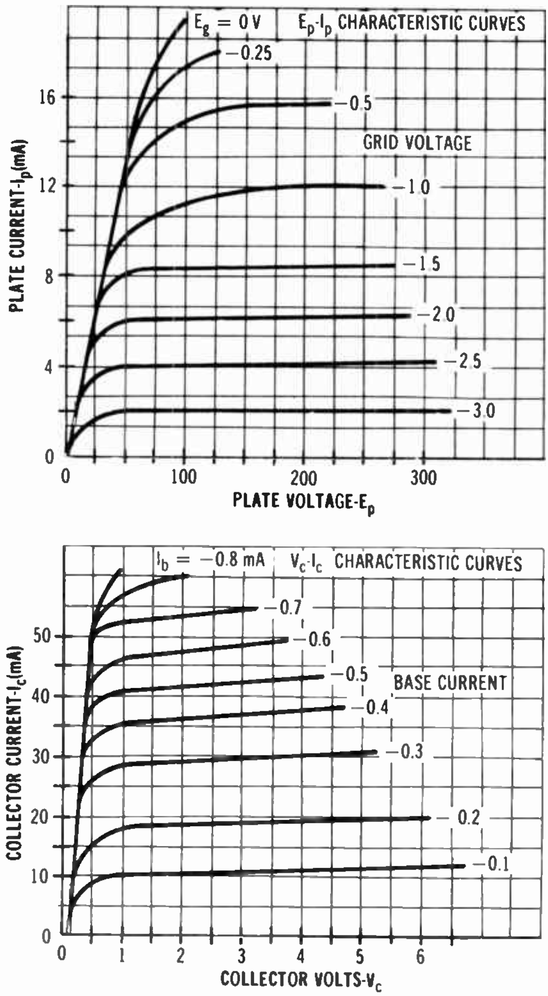


Fig. 3-30. Characteristic curves.

Q3-52. The emitter follower is best used for what purpose?

Q3-53. The common-base circuit is most used as a

________ ___________.

Q3-54. The _______ ________ circuit may best be used as a power amplifier.

Q3-55. Use the V_c-I_c curves to obtain beta.

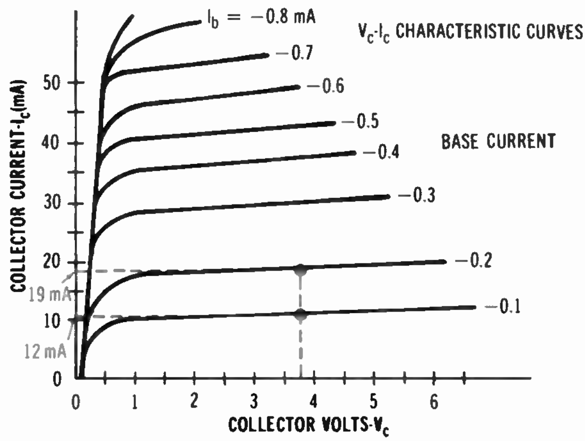
Your Answers Should Be:

A3-52. The emitter follower is best used to **match high-impedance circuits to low-impedance circuits.**

A3-53. The common-base circuit is most used as a **voltage amplifier.**

A3-54. The **common-emitter** circuit may be used as a power amplifier.

A3-55.



$$\beta = \frac{\Delta I_c}{\Delta I_b} = \frac{19 - 12\ \text{mA}}{0.2 - 0.1\ \text{mA}} = \frac{7\ \text{mA}}{0.1\ \text{mA}} = 70$$

Notice that this method is almost identical to the method used to obtain parameters from vacuum-tube curves.

TRANSISTOR SPECIFICATION SHEETS

Most transistor manufacturers present transistor information on specification sheets. These sheets are the equivalent of a tube manual. Fig. 3-31 shows some of the typical data.

Each manufacturer selects some of his own special electrical specifications for presentation on these data sheets. Notice that the temperature at which these specifications were obtained is mentioned. Many specifications differ at other temperatures. The maximum values listed are limiting values. Above these values transistor life and performance are impaired.

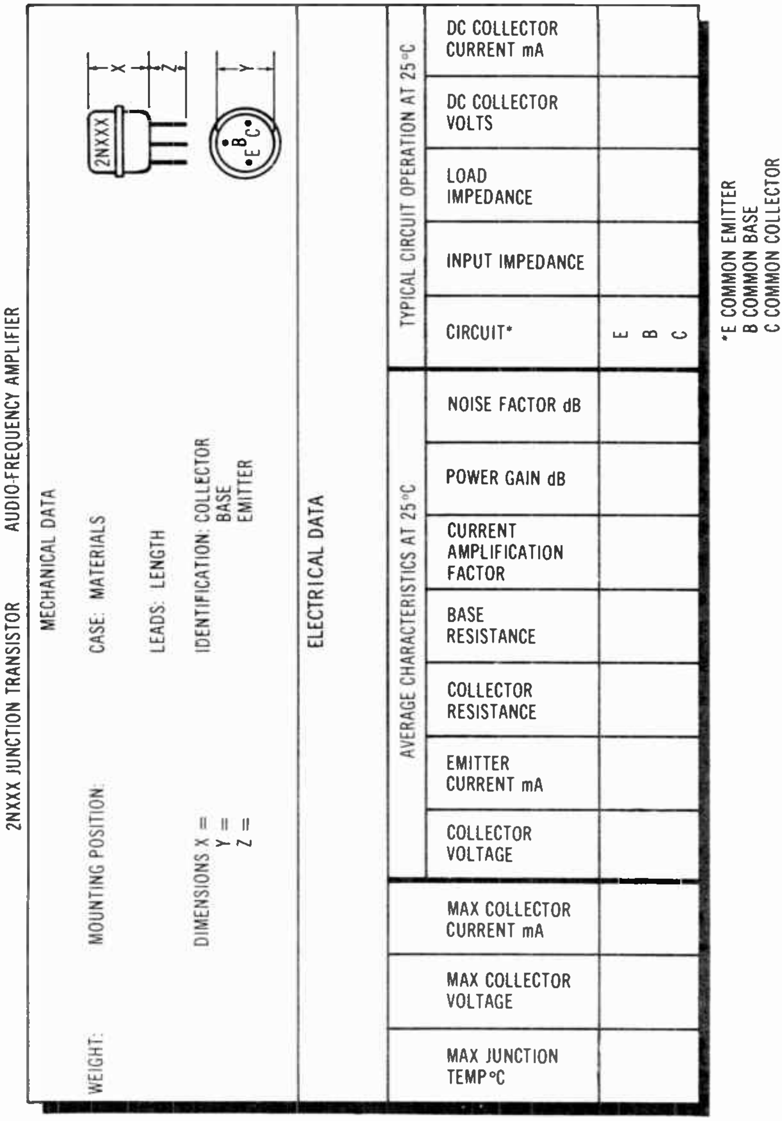


Fig. 3-31. Typical transistor data sheet.

Q3-56. Transistor data sheets give ____________ and ____________ specifications.

Your Answer Should Be:

A3-56. Transistor data sheets give **electrical** and **mechanical** specifications.

WHAT YOU HAVE LEARNED

1. Semiconductors are materials that are neither good conductors nor acceptable insulators.
2. Transistors and solid-state diodes replace vacuum tubes because they are smaller, weigh less, are more rugged, use less power, and have a longer useful life.
3. Intrinsic germanium has no impurities.
4. When an electron leaves a covalent bond, the space it leaves is called a hole.
5. Holes behave as though they were positively charged particles.
6. Adding impurities to intrinsic semiconductors is known as doping. In a semiconductor doped with n-type impurities, the electrons serve as majority current carriers. In a semiconductor doped with p-type impurities, the holes serve as the majority current carriers.
7. The pn junction establishes a barrier region that prevents recombination of holes and electrons.
8. Current flows through a forward-biased pn junction but not through a reverse-biased pn junction.
9. Transistors function like valves to amplify signals.
10. The emitter, base, and collector of a transistor correspond to the cathode, grid, and plate of a triode tube.
11. The collector-base junction must be reverse-biased. The base of the transistor is very thin, so there aren't enough majority carriers in the base to combine with the majority carriers in the emitter. The excess majority carriers are drawn to the collector by the voltage connected to the collector terminal.
12. Transistor current gain (measured from collector to base) is called beta (β) and may be quite large. Another current gain (measured from emitter to collector) is called alpha (α) and is usually less than one.

4

Power Supplies

what you will learn

In this chapter you will learn how diodes are used to change ac to pulsating dc. You will learn how filters are used to provide dc that is free from the variations of the original ac. You will also learn how regulated power supplies provide nearly constant dc output.

PURPOSE OF A POWER SUPPLY

Some source of electrical power is required for the operation of all electronic equipment. This can be a **prime power source**, such as a battery or a generator. Most electronic equipment, however, cannot make direct use of prime power sources. For such equipment it is necessary to convert the output of a prime power source into an electrical form suitable for the particular piece of equipment. The devices used to do this are known as **power supplies.**

COMPONENTS OF A DC POWER SUPPLY

The components of a dc power supply are the voltage control, the rectifier, and the filter. The voltage control serves to adjust the output of the power supply so that it is correct for the circuits that the power supply feeds. The rectifier serves to change the ac voltage into a pulsating dc voltage. (A rectifier may be a vacuum-tube diode, a semiconductor diode, or a metallic-oxide rectifier.) The filter changes the pulsating dc into a smooth dc.

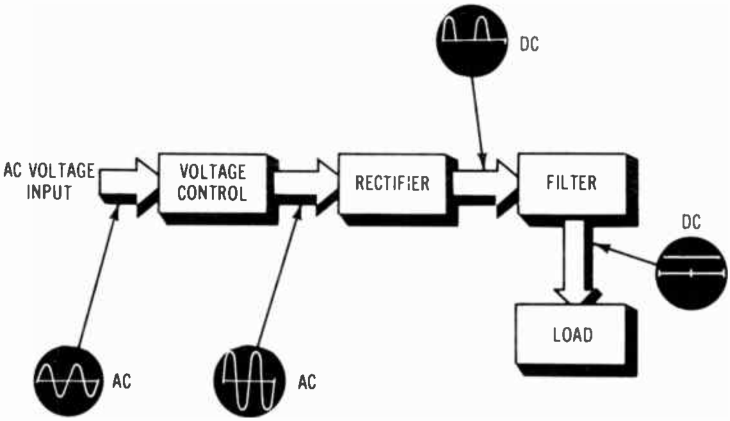


Fig. 4-1. Components of a dc power supply.

The basic functions of a power supply are to **rectify** and **filter.** The voltage-control function is actually identical to the operation of the power supply. Once you learn to separate the rectifier and filter circuits from the power supply, you will see that the leftover components are in the voltage-control portion.

THE RECTIFICATION PRINCIPLE

The rectification principle is very simple. If it is desired to change an ac voltage to a pulsating dc voltage, a unidirectional current-control device must be used. The diode is such a device. Any device that accomplishes this result is called a **rectifier.**

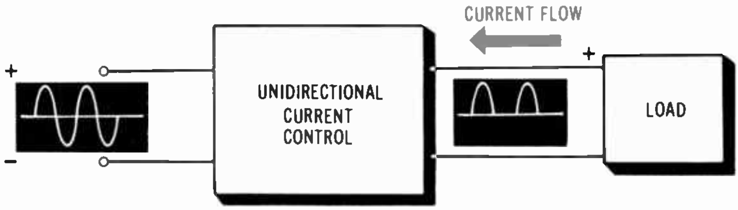


Fig. 4-2. Rectification principle.

This simple principle is shown in Fig. 4-2. An ac voltage is applied to a unidirectional current-control device. Current flows only during the positive portions of the input signal.

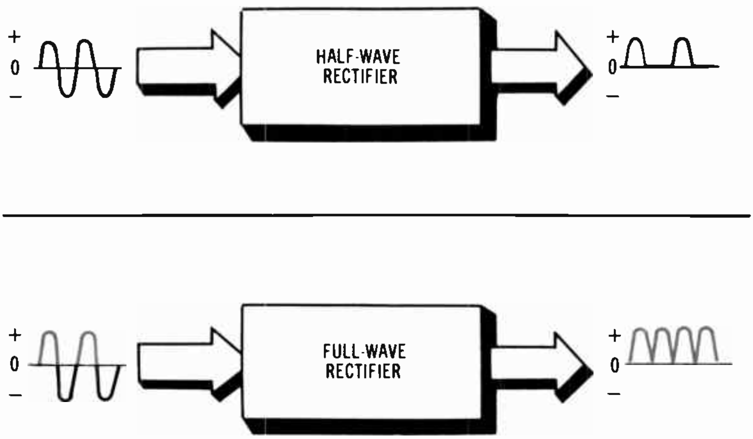


Fig. 4-3. Types of rectifiers.

The output voltage is therefore composed of only the positive portion of the input. This output is called **pulsating dc.**

The two most common rectifiers in use are the **full-wave** and **half-wave.** The differences between the two are obvious from Fig. 4-3. When an ac voltage is applied to a half-wave rectifier, only half of each cycle is made available to the load. You will see later that not only is this type of rectification inefficient, but it also makes it more difficult to obtain the pure dc voltages required by some electronic circuits.

When ac voltage is applied to a full-wave rectifier, the load receives current during both half cycles. Notice that the negative half cycles have been inverted so that all the half cycles are positive at the output of the rectifier. This type of pulsating dc is much easier to smooth (filter) than the output of the half-wave rectifier. Thus, smaller and less expensive components can be used in the filter section.

Q4-1. An ac voltage is converted into a dc voltage by a __________.

Q4-2. The two major functions of a power supply are to ________ and _______.

Q4-3. The component of a power supply that changes ac voltage to a pulsating dc voltage is the __________.

Q4-4. The component of a power supply that smooths out pulsating dc into almost pure dc is the ______.

Your Answers Should Be:

A4-1. An ac voltage is converted into a dc voltage by a rectifier.

A4-2. The two major functions of a power supply are to rectify and filter.

A4-3. The component of a power supply that changes ac voltage to pulsating dc voltage is the rectifier.

A4-4. The component of a power supply that smooths out pulsating dc to become almost pure dc is the filter.

FILTERING ACTION

After rectifying the ac voltage, the power supply must then filter it. The function of the filter is to smooth out the pulsating dc and provide an almost pure dc. You can see in Fig. 4-4 that the actual output is not quite pure dc. The amplitude of the ripple is the factor that determines how close the output

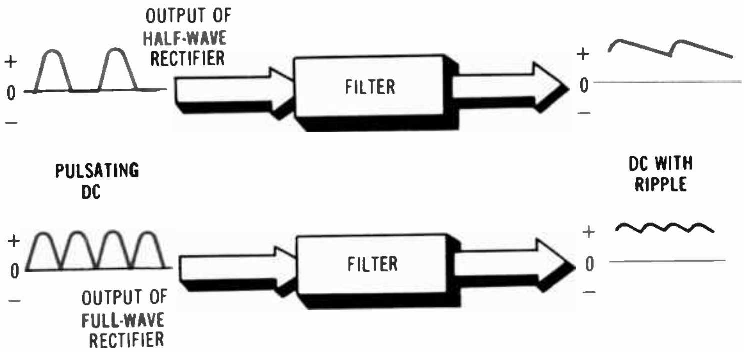


Fig. 4-4. Filter action.

is to dc. The higher the amplitude of the ripple voltage, the less perfect is the dc output.

VOLTAGE CONTROLS

Several types of voltage controls are used in power supplies. Fig. 4-5 shows the locations they may have in a power supply. The types of voltage control can be roughly divided into two classes—automatic and manual. Either type serves the same function, to supply the correct voltage to the load.

The voltage control used at point 1 is the power transformer. It may be some sort of variable transformer that can be manually controlled to provide the desired output voltage. Or it may be a power transformer with several windings, each of which provides a different voltage.

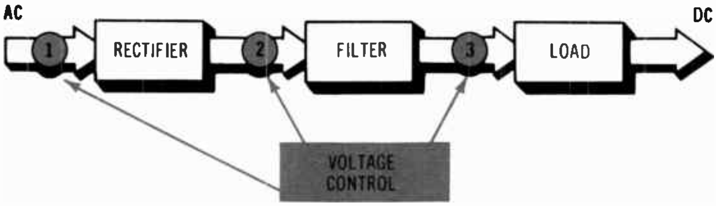


Fig. 4-5. Control circuit locations.

The power transformer in Fig. 4-6 has an input winding (1 and 2), a 5-volt filament winding (5 and 6) for the rectifier, a 6.3-volt filament winding (7 and 8) for the vacuum tubes in the equipment, and two step-up voltage windings to supply voltage to the rest of the load. One of these windings

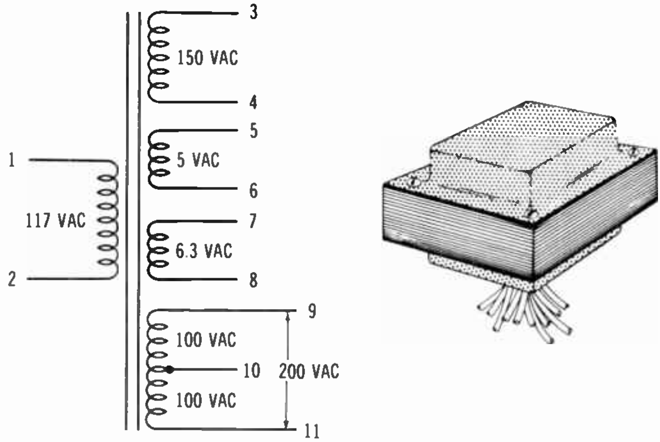


Fig. 4-6. A power transformer.

(3 and 4) provides 150 volts ac, and the other (9, 10, and 11) provides 200 volts ac with a center tap. The use of this center tap will be explained later.

Q4-5. The function of a filter is to ______ pulsating dc.

Q4-6. Voltage controls can be either __________ or ______.

Your Answers Should Be:

A4-5. The function of a filter is to **smooth** pulsating dc.

A4-6. Voltage controls can be either **automatic** or **manual.**

The type of voltage control used at point 2 (see Fig. 4-5) is capable of making automatic voltage changes. This is accomplished by using various types of rectifier circuits that may double, triple, or even quadruple the input voltage.

The type of voltage control used at point 3 can vary the output voltage either automatically or manually, and is called **a regulator circuit.** Its main function is to maintain a steady output voltage from the power supply. A power supply using a regulator is called **a regulated power supply.**

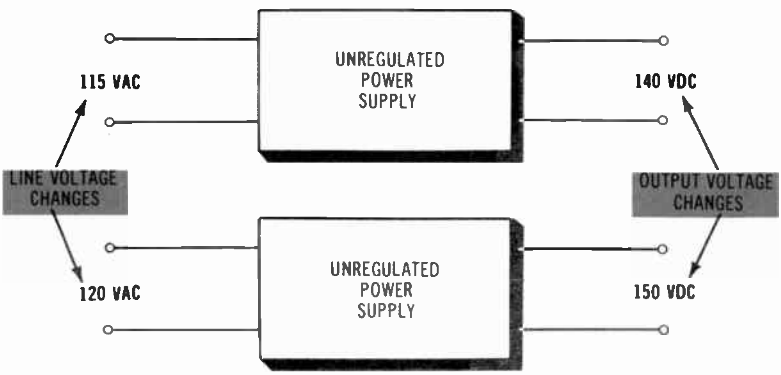


Fig. 4-7. Unregulated power-supply action.

Fig. 4-7 shows an unregulated power supply fed by a line voltage of 115 volts ac. It provides an output voltage of 140 volts dc to its load. Now suppose the line voltage changes to 120 volts ac.

When there is an increase in the line voltage, there is an increase in the output voltage. In Fig. 4-7 it happens to be an increase of 10 volts dc. Many electronic circuits are not affected by this much change. Others are affected only slightly. However, many circuits are disturbed considerably by this type of change, and a voltage regulator must be used to correct it.

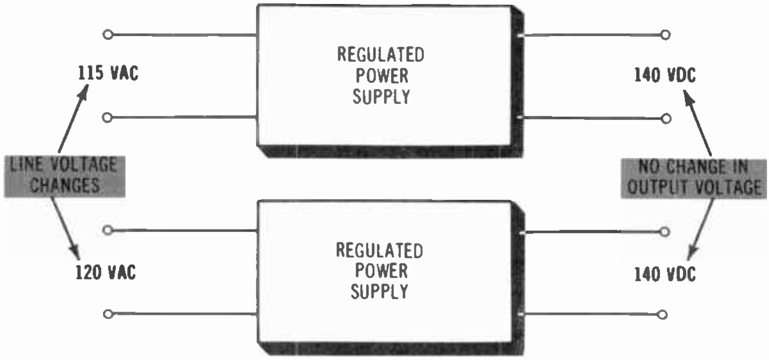


Fig. 4-8. Regulated power-supply action.

The power supply above has a voltage regulator. When the line voltage increases 5 volts, the output voltage remains at 140 volts dc. Changes in the load current will also change the output of a power supply. Voltage regulators are designed to prevent changes under these conditions as well. Notice that many voltage regulators can be manually controlled, incorporating an adjustment used for selecting a particular voltage output.

VACUUM-TUBE AND SEMICONDUCTOR RECTIFIERS

A diode is sensitive to the polarity of an applied voltage. A positive voltage applied to the plate, or anode, causes a diode to conduct readily, while a negative voltage applied to the same point results in no conduction (in the case of the vacuum diode) or very slight conduction (in the case of a semiconductor). It is this unidirectional property that makes a diode useful as a rectifier.

Q4-7. In an unregulated power supply, the output voltage ________ when the input voltage changes.

Q4-8. The output voltage of an unregulated power supply (changes, does not change) when the load current changes.

Q4-9. A ________ __________ is used to keep the output voltage of a power supply constant.

Q4-10. A diode conducts only when its plate, or anode, is _________.

Your Answers Should Be:

A4-7. In an unregulated power supply, the output voltage changes when the input voltage changes.

A4-8. The output voltage of an unregulated power supply changes when the load current changes.

A4-9. A **voltage regulator** is used to keep the output voltage of a power supply constant.

A4-10. A diode conducts only when its plate, or anode, is positive.

Half-Wave Rectifier Circuits

A half-wave rectifier converts an ac voltage into a pulsating dc voltage. It does this by removing either the positive or negative half cycles from the input voltage. In other words, only half of each sine-wave cycle is used to provide power to the load. It can readily be seen that this type of supply is relatively inefficient.

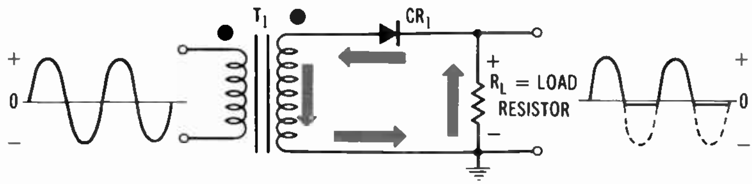


Fig. 4-9. Half-wave rectifier.

A typical half-wave rectifier with a power transformer in the input is shown in Fig. 4-9. Notice the dots at the top of each winding of T_1. These dots indicate that the transformer is wound in such a fashion that the voltage at the ends of the windings marked with the dots are in phase with each other; when the top of the primary is positive, the top of the secondary is also positive.

When the positive half cycle of the input voltage is applied to the primary winding of T_1, there is a positive voltage applied to the anode of semiconductor CR_1, causing it to be forward-biased. Diode CR_1 then conducts, causing a current flow and a voltage drop across the load resistor (R_L). During the negative half cycle, CR_1 is reverse-biased and very little current flows. There is very little voltage dropped across R_L during this half cycle.

A half-wave rectifier can also be made using a vacuum-tube diode. Such a circuit is shown in Fig. 4-10. The small secondary winding is a filament winding to supply heating current to the filament of V_1. (Notice that this winding was not needed for the semiconductor diode in Fig. 4-9.) Observe the negative voltage output shown at the top of R_L. This is obtained by connecting the diode so that it permits control to flow down through the load resistor (R_1). Therefore, the diode plate is connected to the top of R_L. The bottom of R_L is connected to the bottom of T_1, and the cathode of V_1 is connected to the top of T_1. The diode could just as easily be connected in the reverse direction to give the opposite polarity at the top of R_L.

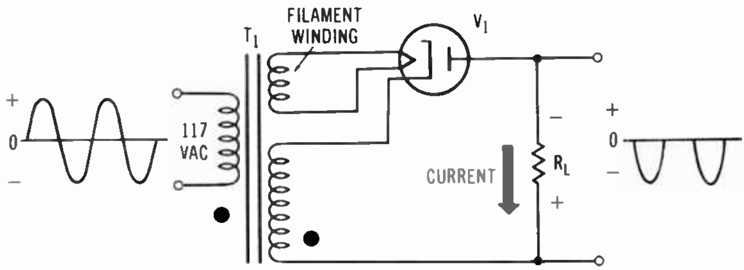


Fig. 4-10. Half-wave vacuum-tube rectifier.

In its operation, this circuit is very similar to the semiconductor half-wave rectifier. On the positive half cycles, a positive voltage is applied to the cathode of the diode, and the diode will not conduct. On the negative half cycles a negative voltage is applied to the cathode, and the diode does conduct. Current flows down through R_L, producing an output of the polarity shown. Thus, only negative half cycles appear at the output.

Q4-11. **A half-wave rectifier passes current to the load during (one half, both halves) of each cycle of applied voltage.**

Q4-12. **A half-wave rectifier can be made using a ______________ or ______ ____ diode.**

Q4-13. **Output-voltage polarity depends on the connections to the ______.**

Your Answers Should Be:

A4-11. A half-wave rectifier passes current to the load during **one-half** of each cycle of applied voltage.

A4-12. A half-wave rectifier can be made using a **semiconductor** or **vacuum-tube** diode.

A4-13. Output-voltage polarity depends on the connections to the **diode.**

Full-Wave Rectifier Circuits

A full-wave rectifier differs from a half-wave rectifier in that it utilizes both halves of the input-voltage cycles for its pulsating dc output voltage. Such a rectifier is shown in Fig. 4-11.

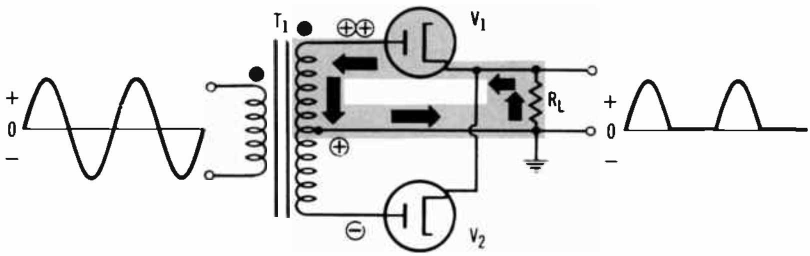


Fig. 4-11. Full-wave rectifier (positive half cycle).

Two diodes are employed in this circuit. A special transformer is used with its center tap connected to one side of R_L and to ground. When the dot side of T_1 is positive with respect to the center tap, V_1 will not conduct. The plate of V_2 is connected to the other end of T_1, which is negative with respect to the center tap. Thus V_2 will not conduct. The output of the circuit is as shown in Fig. 4-11. Compare this output with that of the half-wave rectifier.

On the negative half cycle, the top of T_1 is negative with respect to the center tap, so V_1 will not conduct. The bottom of T_1 is positive with respect to the center tap, and V_2 will now conduct. Notice the direction of current flow—through V_2, to the bottom of T_1, out of the center tap, **up through R_L,** and back to the cathode of V_2. Current flows through R_L in the same direction as it did for the positive half cycle. This results in the output half cycles all being positive. The effect is just like passing the positive half cycles and inverting the negative half cycles. The result is the waveform shown in Fig. 4-12.

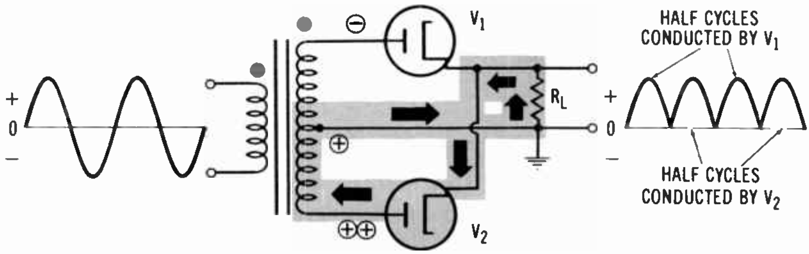


Fig. 4-12. Full-wave rectifier (negative half cycle).

Notice the difference between the pulsating dc from a half-wave rectifier and from a full-wave rectifier. The variation in the output from the half-wave rectifier has half the frequency of the variation from the full-wave rectifier.

Full-wave rectifiers are now more often made using semiconductor diodes. The circuit in Fig. 4-13 shows this. Although the position of R_L on the diagram has been changed, the circuit is still the same.

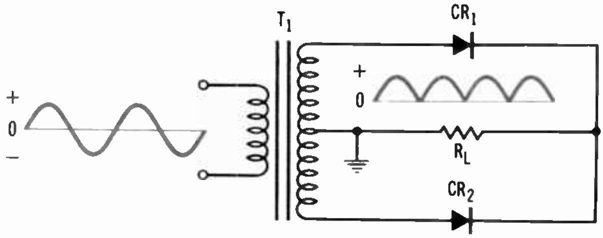


Fig. 4-13 Full-wave semiconductor rectifier.

Q4-14. A full-wave rectifier uses a transformer with a ______ ______ secondary.

Q4-15. A full-wave rectifier conducts during (one half, both halves) of the applied-voltage cycle.

Your Answers Should Be:

A4-14. A full-wave rectifier uses a transformer with a **center-tapped** secondary.

A4-15. A full-wave rectifier conducts during **both halves** of the applied-voltage cycle.

Bridge Rectifier Circuit

There is a type of full-wave rectifier circuit that does not require a transformer with a center tap. Instead, it uses four diodes. This circuit is called a **bridge rectifier circuit.**

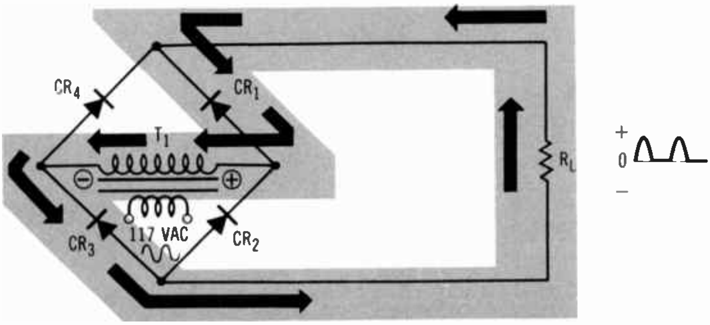


Fig. 4-14. Bridge rectifier (positive half cycle).

On the positive half cycle, current flows through CR_3, up through the load resistor, and back through CR_1. CR_2 and CR_4 are reverse-biased and act like open switches.

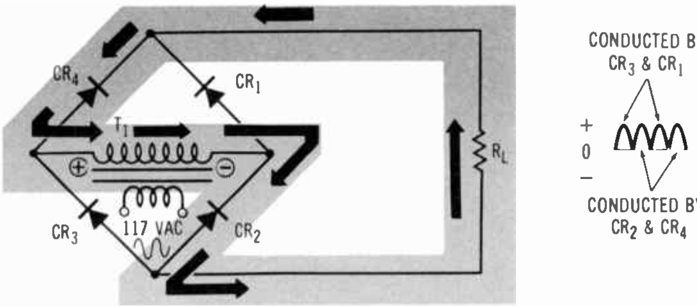


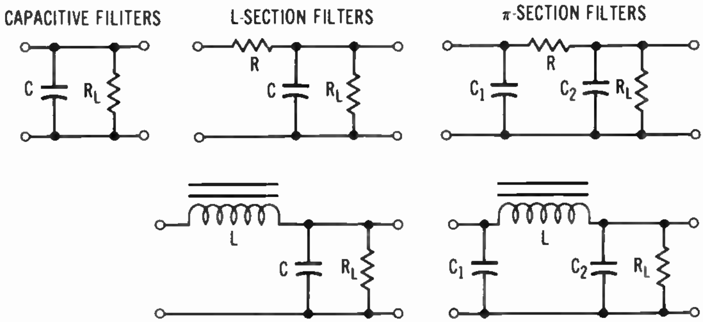
Fig. 4-15. Bridge rectifier (negative half cycle).

Fig. 4-15 shows the current direction for the negative half cycle.

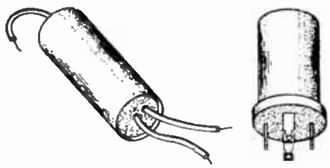
The bridge rectifier is usually used in power supplies that must deliver a large amount of current. Semiconductor diodes for large currents were special selenium or copper-oxide metallic rectifiers in the past, but now silicon rectifiers are usually used.

FILTERS

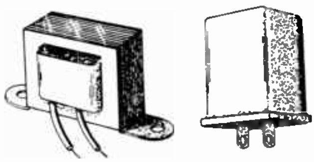
The filter is the section of a power supply that smooths the pulsating dc to make it almost pure dc. The types of filters most commonly used are shown below. As you see, filters are simply circuits made up of resistors, capacitors, and inductors in various combinations. The operation of filters depends on the ways that L, C, and R affect changing voltages and currents.



(A) Schematic diagrams.



(B) Capacitance.



(C) Chokes.

Fig. 4-16. Filter circuits and components.

Q4-16. A bridge rectifier is a type of (full-wave, half-wave) rectifier.

Q4-17. What are the three types of filters most commonly used?

Your Answers Should Be:
A4-16. A bridge rectifier is a type of **full-wave** rectifier.
A4-17. The three types of filters most commonly used are the: 1. **capacitive filter,** 2. **L-section filter,** and 3. **π (pi)-section filter.**

The Capacitive Filter

Basically, the capacitive filter is simply a capacitor connected in parallel with the load resistance. As the pulsating dc voltage from a half-wave or full-wave rectifier is applied across the capacitor, it charges to the peak applied voltage. If there were no load resistance connected across the output, the capacitor would remain charged to the peak voltage.

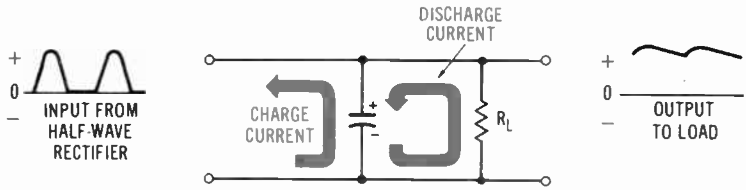


Fig. 4-17. Capacitive filter action.

In practice, there is always a load resistance connected across the capacitor. Between peaks, the capacitor discharges through the load resistance, and the voltage gradually decreases. The amount the voltage decreases before the capacitor is charged again by a peak in the pulsating dc is called **ripple voltage.**

The amount of capacitor discharge between voltage peaks is controlled by the RC time constant of the filter capacitor and the load resistance. If the load resistance is large and the capacitance is large, the ripple voltage is small; the pulsating dc has been smoothed out until it is almost a pure, constant dc voltage.

Variations in the output voltage are not desirable because they affect the operation of vacuum-tube or transistor circuits receiving the dc. The increased ripple voltage caused by reduced load resistance is one undesirable feature of the capacitive filter.

A second undesirable feature of a capacitive filter is the large charging current. This excessive current flows into the capacitor to charge it when the power supply is first turned on. This initial current is often called a surge current. Over a

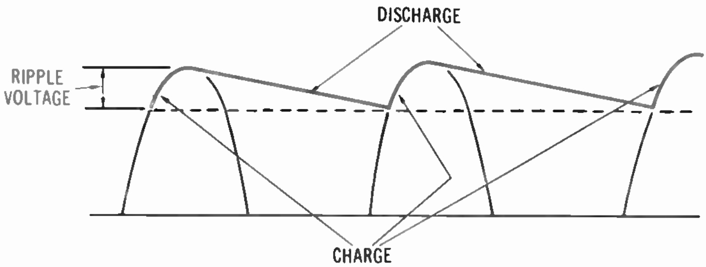


Fig. 4-18. Capacitive filter charge and discharge.

period of time, surge currents can cause injury to fuses and rectifiers, resulting in eventual burnout. Each surge current can cause part of a fuse to melt slightly, for example, until it finally burns out. The same thing can happen to the rectifier. A small surge of current flows through the rectifier during each cycle to recharge the partially discharged capacitor. Under certain conditions these charging surges can become large enough to damage a diode. The remaining two types of filters have components to reduce the effect of ripple-voltage variations and surge currents.

Q4-18. What will happen to the RC time constant of the capacitor and load resistance if the load resistance is decreased?

Q4-19. If the load resistance is decreased, the filter capacitor will discharge (more, less) rapidly.

Q4-20. What will happen to the amount of ripple voltage if the load resistance is decreased?

Q4-21. The large current that flows for a short time to charge the capacitor is called a(n) _____ ________.

Q4-22. If a load resistance is not connected across the filter capacitor, what will happen to the output voltage?

Your Answers Should Be:

A4-18. If R_L is decreased, the RC time constant will be **shorter.**

A4-19. If the load resistance is decreased, the filter capacitor will discharge **more** rapidly.

A4-20. The amount of the ripple voltage **increases** as the load resistance of a capacitive filter is decreased.

A4-21. The large current that flows for a short time to charge the capacitor is called a **surge current.**

A4-22. If a load resistance is not connected across the filter capacitor, the capacitor will charge to the **peak value of the filter input voltage and the output voltage will remain at this value.**

L-Section Filters

An L-section filter, so-called because its schematic, see Fig. 4-19, looks like the letter L on its side, reduces surge currents by using a current-limiting resistor or inductor. This limiting

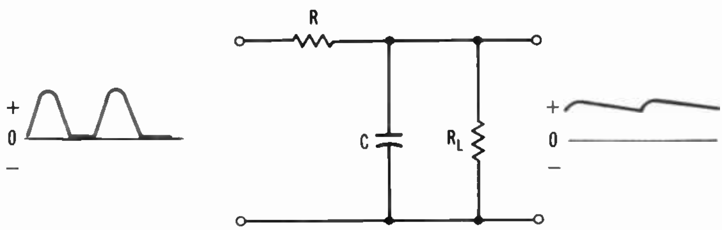


Fig. 4-19. L-section filter with series resistor.

resistor or inductor is connected in series with the capacitor. A limiting resistor controls surge currents by introducing an RC time constant to slow the charging of the capacitor.

When an inductor is used as the series element, the surge currents are reduced in a different manner. The inductor opposes a change in current by creating a counter emf. As a result, the surge current is greatly reduced and the capacitor charges more slowly.

An inductor used in an L-section filter also adds to the filtering action of the capacitor. The inductor reacts to changes in current caused by the ripple voltage the same way it reacts to the surge current. The counter emf tends to cancel out the effects of the ripple voltage.

The operation of the L-section filter can also be explained in terms of reactance. In a simple capacitive filter, and in an L-section filter with a limiting resistor, the filtering action is the result only of the reactance of the capacitor (X_c). The capacitor presents a low reactance to ac and a very high reactance to dc. The ac part of the input is therefore bypassed through the capacitor, but the dc part goes directly to the load.

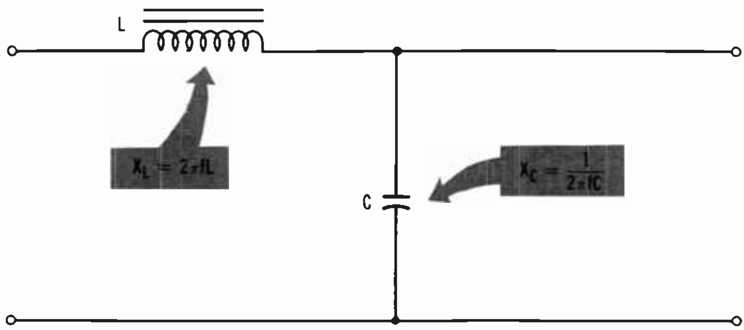


Fig. 4-20. L-section filter with series inductor.

To understand the L-section filter with an inductor, the reactance of the inductor must also be considered. The reactance is high for ac, but it is nonexistent for dc. The inductor presents a high reactance to the ac current produced by the ripple voltage. The inductor therefore tends to block this current. It presents zero reactance to the dc and allows it to pass readily. The ac that is not blocked by the inductor is mostly bypassed by the capacitor.

Q4-23. In an L-section filter, ac ripple can be blocked by a(n) _________.

Q4-24. In an L-section filter, ac ripple can be bypassed by a(n) __________.

Q4-25. An L-section filter with a limiting resistor is (more, less) effective than one with an inductor.

Q4-26. An inductor has a ______ reactance for ac than for dc.

Your Answers Should Be:

A4-23. In an L-section filter, ac ripple voltages can be blocked by an **inductor.**

A4-24. In an L-section filter, ac ripple voltages can be bypased by a **capacitor.**

A4-25. An L-section filter with a limiting resistor is **less** effective than one with an inductor.

A4-26. An inductor has **higher** reactance for ac than for dc.

Pi-Section Filters

A pi-section (or π-section) filter has three elements—a shunt input capacitor, a series **choke** (inductor), and a shunt output capacitor. As the input voltage reaches the first capacitor, the capacitor bypasses most of the ac ripple current to ground. This presents a smoother waveshape to the choke. The choke presents a high inductive reactance to the ac ripple

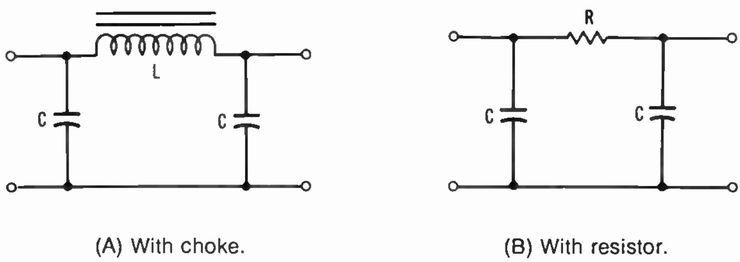


Fig. 4-21. Pi-section filters.

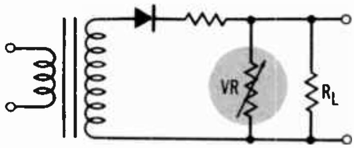
current and tends to block it. To put it another way, the choke opposes a change in current, and so it acts to smooth the current passing through it. Finally, the second capacitor is designed to bypass to ground any remaining ac components. The resulting output is a smooth dc voltage.

To save money, the choke is sometimes replaced with a resistor. This results in less smoothing action. A pi-section filter using a resistor depends for some of its effectiveness on the long time constant of the series resistor and the output capacitor. If this time constant is much longer than the period of the ac ripple, the output capacitor will charge and discharge very little during any one pulse of the ripple voltage. The waveshape will then be smoothed out. However, the resistor also consumes power. This is an important consideration in a power-supply circuit.

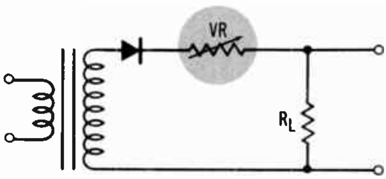
REGULATED POWER SUPPLIES

Regulated power supplies are those that keep the voltage (or current) supplied to the load constant, even if the power-source voltage fluctuates or the load changes.

Basically, the voltage-regulator part of a regulated power supply is a variable resistance that automatically changes as the output voltage changes. (For simplicity, no filter is shown in Fig. 4-22.)



(A) In shunt with power supply.



(B) In series with power supply.

Fig. 4-22. Voltage regulators represented as variable resistors.

A shunt voltage regulator combines with the resistance of the power supply itself, or with an additional resistor, to form a voltage divider. As the shunt resistance increases, more voltage appears across it as an output to the load. As the shunt resistance decreases, less voltage appears across it.

The series voltage regulator forms a voltage divider in series with the load resistance. As the series resistance increases, less voltage appears across the load resistance. As the series resistance decreases, more voltage appears across the load.

Q4-27. What are the three elements of a pi-section filter?

Q4-28. A pi-section filter with a resistor gives (better, poorer) filtering action than one with a choke.

Q4-29. A voltage regulator may be compared to a _________ resistor.

Your Answers Should Be:

A4-27. The three elements of a pi-section filter are a **shunt input capacitor, a series choke or resistor, and a shunt output capacitor.**

A4-28. A pi-section filter with a resistor gives **poorer** filtering action than one with a choke.

A4-29. A voltage regulator may be compared to a **variable resistor.**

The resistance of a shunt voltage regulator increases when the output voltage decreases. It decreases when the output voltage increases. Thus, it automatically returns the output voltage to normal. Similarly, the resistance of a series voltage regulator increases as the output voltage increases and decreases as the output voltage decreases.

There are several ways of achieving resistance that varies with output voltage. One of these is the gaseous voltage-regulator (vr) tube. This is a diode filled with a current-conducting gas. As the voltage applied across this tube increases, the gas becomes more ionized, and the resistance of the tube decreases. This type of tube can be used as a shunt voltage regulator.

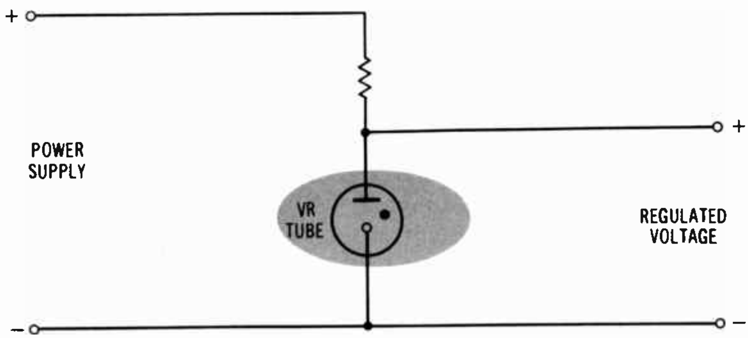


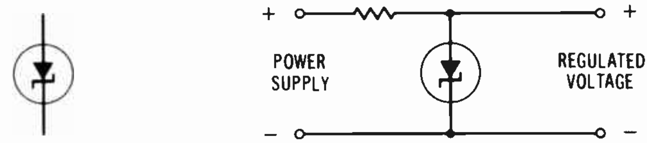
Fig. 4-23. Simple vr-tube voltage regulator.

The limiting resistor in series with the vr tube is selected to limit the current through the tube to a safe value. Gaseous voltage regulators keep the output voltage constant to within about 1%. They come in a number of specific voltage ratings.

To change the constant output voltage, it is necessary to change the tube. To obtain higher voltage ratings, vr tubes can be connected in series so that only part of the output voltage appears across each one.

The regulated voltage from a vr-tube regulator is fixed in value.

Power-supply voltages can also be regulated by use of zener diodes. The zener diode consists of two layers of doped semiconductor, usually silicon, one n-layer and one p-layer, with the doping a little heavier than for ordinary diodes. The symbol for the zener diode is shown in Fig. 4-24, along with a circuit showing its use as a shunt regulator. The cathode (n-layer) connects to the positive of the power supply and the anode (p-layer) connects to the negative side. This is the reverse of the usual connections for a diode to conduct. The zener diode is specifically manufactured to operate in the "breakdown region." When the reverse voltage across it exceeds the zener breakdown voltage, large currents can flow in the junction and the voltage across the diode will remain constant for all normal values of diode current.



(A) Symbol. (B) Schematic diagram.

Fig. 4-24. Zener-diode voltage regulator.

The zener diode used as a regulator operates much the same as the vr tube—a limiting resistor is used in series with the diode to limit the current through the zener diode to safe values. Zener diodes are available in different voltage ratings.

Q4-30. The resistance of a shunt voltage regulator decreases as the output voltage __________.

Q4-31. The resistance of a series voltage regulator __________ as the output voltage decreases.

Your Answers Should Be:

A4-30. The resistance of a shunt voltage regulator decreases as the output voltage **increases.**

A4-31. The resistance of a series voltage regulator **decreases** as the output voltage decreases.

Where it is desired to vary the value of a regulated voltage or to set the voltage at a certain value, a vacuum-tube or a transistor can be used.

A vacuum-tube circuit can be used as a series voltage regulator. The current passing through the tube from cathode to plate depends on the grid bias. Another way to say this is that the resistance of the tube depends on the grid bias. Therefore, by varying the voltage on the grid, the tube resistance can be changed as necessary.

A source for the grid bias is needed. This may be a battery or it can be a vr regulator connected to the power source. A potentiometer in the grid circuit makes it possible to adjust the bias.

If the voltage of the unregulated power source rises, the voltage at the cathode of the triode also increases. This causes

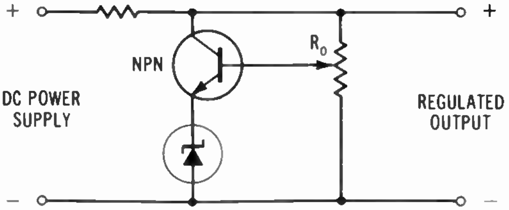


Fig. 4-25. Shunt-type voltage regulator.

an increase in the negative grid bias and reduces the current through the tube, effectively increasing the plate resistance. The output voltage is thus reduced. If the power source voltage drops, the opposite action takes place. This circuit will also compensate for changes in load resistance.

A transistor instead of a tube can be used as a shunt-type voltage regulator (Fig. 4-25). The zener diode establishes a reference for the emitter. If the input voltage increases or load current decreases, current through the transistor will increase and so will current through R_s. The increased current through R_s causes the output voltage to decrease. This reduces

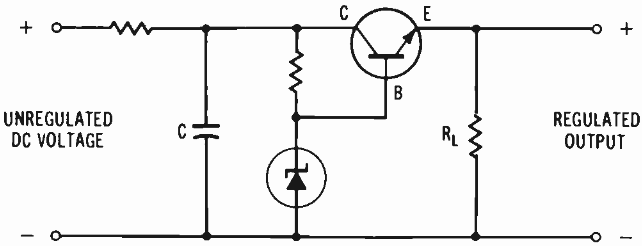


Fig. 4-26. Simple series regulator.

the base-emitter voltage and thus collector current. The output voltage decreases to its normal value. However, if the output voltage decreases, the base-emitter voltage will decrease, the collector current will decrease, and the output voltage will increase to its normal value. The setting of R_o determines the output voltage.

The series regulator transistor circuit is used more often than the shunt regulator transistor type of circuit. An example of a series regulator circuit is shown in Fig. 4-26. Capacitor C is a filter capacitor. Operation is as follows: If there is no load, no collector current flows through the transistor and the base is held at a fixed voltage by the zener diode. When load R_L is connected, collector current flows through the transistor. There will be a drop of approximately 0.6 volt between emitter and base if the transistor is a silicon type and if the load current is moderate. The regulated output voltage will be equal to the unregulated output voltage minus the 0.6 volt emitter-base voltage. If the load current increases, tending to decrease the regulated output voltage, the collector current increases and the emitter-base voltage increases slightly representing an increased forward bias for the transistor. The transistor then passes more current to the load and the output voltage tends to rise.

Q4-32. In the vacuum-tube series regulator, the current passing through the tube from cathode to plate depends on the ____ ____.

Q4-33. In the shunt-regulator circuit using a transistor, the reference for the emitter is established by the _____ _____.

Your Answers Should Be:

A4-32. In the vacuum-tube series regulator, the current passing through the tube from cathode to plate depends on the **grid bias.**

A4-33. In the shunt-regulator circuit using a transistor, the reference for the emitter is established by the **zener diode.**

WHAT YOU HAVE LEARNED

1. Power supplies are most often used to convert ac voltages into dc voltages.
2. The components of a dc power supply are a voltage control, rectifier, and filter.
3. A power transformer provides ac at desired voltage values as an input to a power supply.
4. A diode (or combination of diodes) is used to convert ac into pulsating dc.
5. There are basically two types of rectifiers—half-wave and full-wave.
6. A bridge rectifier is one type of full-wave rectifier; another type uses two diodes.
7. The filter smooths out the pulsating dc and provides almost pure dc.
8. Three of the most commonly used filters are capacitive, L-section, and pi-section.
9. The ac component of the filtered dc is called ripple voltage.
10. Voltage regulators are used to provide fairly constant dc.
11. Voltage regulators make adjustments in the power-supply output voltage by varying the resistance of vacuum tubes and/or transistors.
12. Voltage regulators are connected in series or in parallel with the load resistance.
13. Gas tubes, triodes, and transistors are three common devices used to provide a variable resistance in regulator circuits.

5

Vacuum-Tube Amplifiers and Oscillators

what you will learn

You will now learn how vacuum tubes are used in practical amplifier circuits, and receive more practice in using tube-characteristic curves. You will find out how to develop equivalent circuits for tubes and learn something about biasing circuits. You will discover the difference between voltage and power amplifiers. The common methods of coupling a series of single-tube amplifiers to produce a multistage, or cascaded, amplifier will be discussed. You will become familiar with the way in which oscillators generate ac voltages by the use of positive feedback.

WHAT IS AN AMPLIFIER?

Amplifiers are probably the most common circuits in electronics. They are used everywhere, from radio receivers and television transmitters to radar sets and complex computers.

Everyone knows what a high-fidelity audio amplifier does. It takes a very weak signal from a phonograph pickup or tape head and increases the amplitude of this signal until it has enough strength to drive several large speakers.

All amplifiers increase the amplitude of an input signal until it is large enough for the intended application. One of the main functions of a television receiver is to amplify the extremely weak signal voltage induced in the antenna enough to produce an image on a picture tube.

There are many different kinds of amplifiers. Some have the main function of amplifying a signal voltage; these are voltage amplifiers. Others are power amplifiers for driving final loads. Some are designed for low frequencies; these are dc and operational amplifiers. Others work best in the audio-frequency (af) range. There are radio-frequency (rf) amplifiers designed for higher frequency ranges. Some have a very narrow passband; they amplify only a narrow range of frequencies. The amplifiers in a radio receiver are an example of this type. They are concerned with amplifying sine waves. Others, like the video signal amplifiers in television sets, must have a fairly wide passband so that complex waveforms are not distorted.

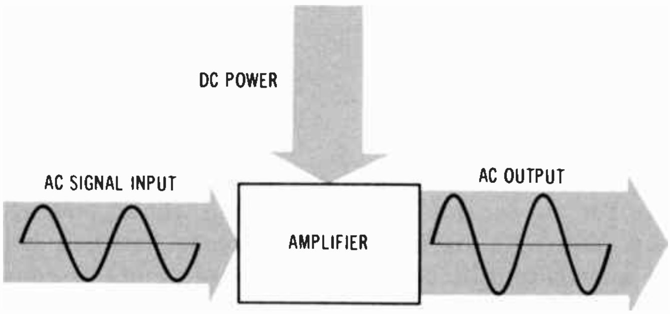


Fig. 5-1. Basic amplifier principle.

You can see from Fig. 5-1 that the amplifier does not magically transform a low-power or low-voltage signal into a larger one. You can't get more power out than you put in. Instead, an amplifier controls the dc power from the power supply according to the variations in the ac input signal.

It is often desirable to have an output that is a reasonably good duplication of the input. But due to the limitations of tubes and circuits, this is not always possible. When the output does not follow the input exactly, there is distortion. The amount of permissible distortion depends on the purpose of the output signal. Distortion-free amplifiers are usually complex and costly.

Plate-Current Flow in an Amplifier

Now look at a simple vacuum-tube amplifier (Fig. 5-2). This one uses a triode, a tube with three elements—cathode, grid, and plate. There is also a heater to keep the cathode at emission temperature, but normally it is not considered as an active circuit element.

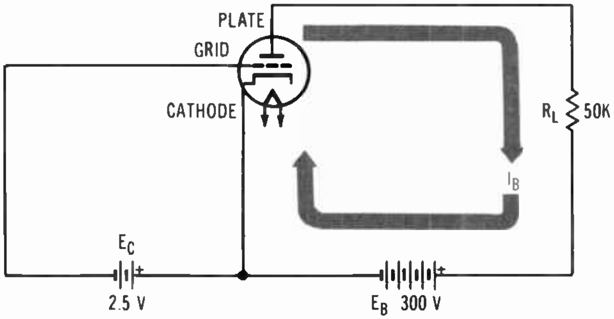


Fig. 5-2. Basic triode amplifier circuit.

As the cathode is heated to emission temperature, it begins to emit electrons into the space around it. A positive voltage (E_B) applied to the plate of the tube attracts the negative electrons. Electrons leave the 300-volt battery from its negative terminal, flow into the cathode, are emitted, and pass into the electron cloud. Then the electrons are attracted to the plate and flow through the load resistor back to the positive terminal of the battery. This is the steady-state dc plate current (I_B).

The tube current flows in a loop, as shown, and encounters several resistances on its way. These include the small internal resistances of the battery, the resistance of the cathode-plate path through the tube (plate resistance R_p), and the load resistance (R_L). The sum of these three resistances and the amount of the battery voltage determine the magnitude of the plate current (I_B). Current I_B and the battery voltage determine the dc-power input to the amplifier.

Q5-1. An amplifier has two inputs: a large __ _____ input and a small __ ______ input.

Q5-2. The output of an amplifier is the __ _____ input altered so that it resembles the ______ input.

Your Answers Should Be:
A5-1. An amplifier has two inputs: a large **dc-power** input and a small **ac-signal** input.
A5-2. The output of an amplifier is the **dc-power** input altered so that it resembles the **signal** input.

Plate-Current Control

The amplifier circuit diagram shows a small negative voltage (E_c) on the grid. The grid therefore has the effect of repelling the negative electrons in the electron cloud surrounding the cathode. Since the grid is closer than the plate to the cathode, a small change in grid voltage affects plate current as much as a large change in plate voltage. To put it another way, a small grid voltage controls a large plate current, making amplification possible.

Voltage Gain

The grid bias (E_c) is adjusted in such a way that it allows a small amount of plate current to flow when no input signal is present. Now an ac input-signal voltage (e_g) is introduced. Suppose the dc grid bias voltage is −2.5 volts and an ac signal that swings 2 volts in each direction (4 volts peak-to-peak) is superimposed on it. The graph in Fig. 5-4 shows how the plate current and voltage change with the grid voltage for a

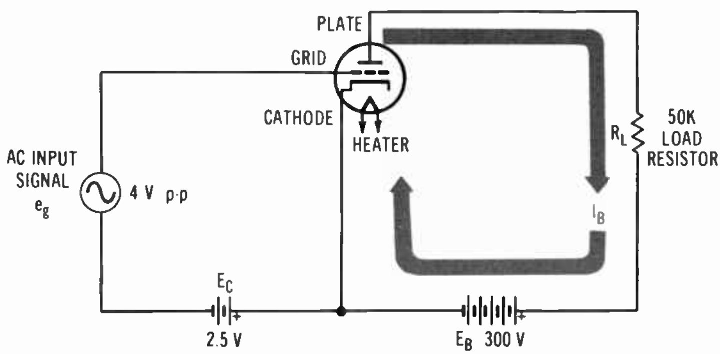


Fig. 5-3. Amplifier with input signal.

particular type of tube used in the circuit shown in Fig. 5-3. The plate current changes from 1.2 to 1.8 milliamperes. This current, flowing through load resistor R_L, produces a change in voltage drop from $50{,}000 \times 0.0012 = 60$ volts to $50{,}000 \times 0.0018 = 90$ volts. The voltage drop with just the dc bias applied (no signal input) is 75 volts.

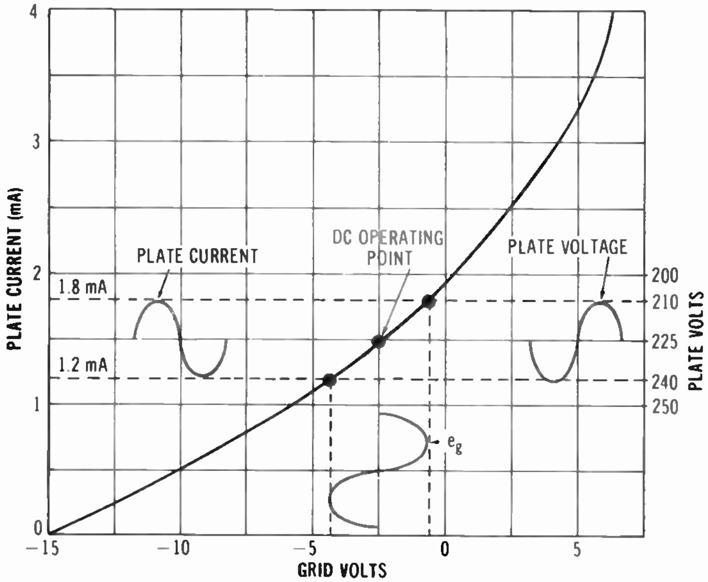


Fig. 5-4. Graph of amplifier operation.

Since the plate-battery voltage is 300 volts, the voltage between plate and cathode will be 300 minus the load-resistor voltage drop (neglecting the small battery resistance). Thus, the plate voltage has a quiescent (no-signal) value of 225 volts, and with the 4-volt (peak-to-peak) input signal it swings between 210 and 240 volts.

An ac signal with a peak of 2 volts was put into the amplifier, and an ac output with a peak amplitude of 15 volts (½ of 240 − 210 volts) was produced. This ac output voltage has 7.5 times the amplitude of the ac input voltage. This is a net voltage gain of 7.5.

Q5-3. In Fig. 5-4, the ac input signal is applied to the ____ of the tube.

Q5-4. The output voltage is produced by changes in the ______ _______ flow through the ____ resistor.

Your Answers Should Be:

A5-3. In Fig. 5-4, the ac input signal is applied to the **grid** of the tube.

A5-4. The output voltage is produced by changes in the **plate-current** flow through the **load** resistor.

Phase Reversal

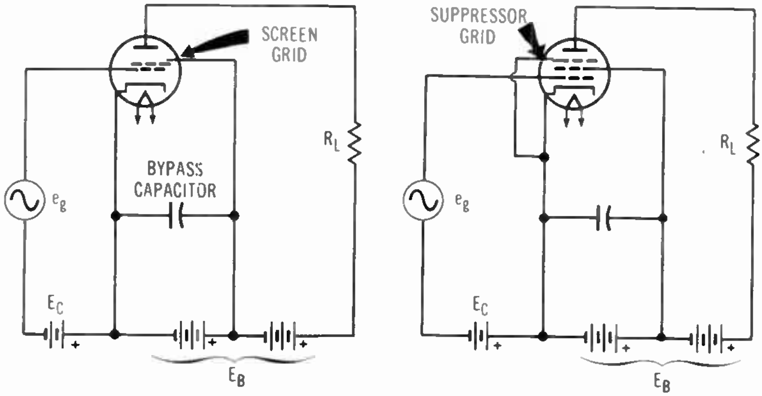
In the amplifier described on the previous pages, the plate voltage is the difference between the plate-supply voltage and the load-resistor voltage drop. Thus, when the load-resistor drop is greatest, the remaining plate voltage is at the lowest value. The load-resistor drop is greatest (the plate voltage is the lowest) when the grid-signal voltage is at its positive peak. When the grid voltage is at its negative peak, the plate voltage is at its highest value. This means then that a phase difference of 180° exists between the input and output voltages.

TETRODES AND PENTODES

As you know, many tubes have more electrodes than the three of the triode described so far in this chapter. The **tetrode** (four-electrode) tube has a fourth element, called the **screen grid,** between the control grid and the plate. This tube was developed to overcome a particular shortcoming of triodes.

One of the practical limitations of triode amplifiers is that at higher frequencies the **interelectrode capacitance** becomes important. This capacitance exists between cathode and grid, between grid and plate, and between cathode and plate, and is normally very small. As the input frequency increases, the reactances of these capacitances decrease, causing undesirable effects. The capacitive coupling from plate (output) to grid (input) is especially undesirable. This capacitance can result in undesirable feedback, gain reduction, and distortion. The screen grid of a tetrode acts as an electrostatic shield between the grid and plate. In this way it reduces the undesirable plate-to-grid capacitance to a much lower value.

The **pentode** has a third grid placed between the screen grid and the plate. This fifth electrode is called the **suppressor grid.** The purpose of the suppressor grid is to prevent a form of reverse conduction which occurs in tetrodes. When electrons strike the plate with enough velocity, the force dislodges other electrons which bounce back toward the screen grid. This **secondary emission** is, in effect, a reverse current flow from plate to screen grid.



(A) Tetrode.

(B) Pentode.

Fig. 5-5. Amplifiers with multigrid tubes.

The suppressor grid prevents this current from flowing. It is electrically connected to the cathode, making it negative with respect to the plate, and thus repels any electrons that try to travel from the plate to the screen grid. The suppressor grid is actually a fairly coarse screen so that it does not interfere with the main current flow between cathode and plate.

Although tetrode and pentode characteristic curves differ from those of the triode, the basic amplifier action is no different. Throughout this chapter amplifiers will be explained in terms of triodes. It should be understood that, according to the need, tetrodes and pentodes may also be used as amplifiers.

Q5-5. The phase difference between input and output signals in the voltage amplifier just described is ____.

Q5-6. The basic amplifier action of tetrodes and pentodes (is, is not) the same as that of triodes.

Your Answers Should Be:

A5-5. The phase difference between input and output signals in the voltage amplifier just described is 180°.

A5-6. The basic amplifier action of tetrodes and pentodes is the same as that of triodes.

BIASING

The graph in Fig. 5-4 shows the plate current and voltage for any given grid voltage for one particular amplifier circuit. A point on the curve indicates the dc bias voltage applied to the grid. This is called the **dc operating point,** or the **quiescent point.** With every amplifier circuit, this point must be chosen correctly in order to have proper operation. For an accurate reproduction of the input signal, the grid bias is usually chosen so that:

1. It is greater than the peak value of the signal; thus, the signal-voltage swing never drives the grid positive with respect to the cathode.
2. The entire signal-voltage swing operates over a linear (straight) portion of the characteristic curve.

Both of the above rules are ignored in special types of circuits. Normally, however, the grid is not driven positive during any part of the input cycle. If this happens, the positive grid attracts electrons, and a current flows from cathode to grid. This causes distortion because, during the part of the

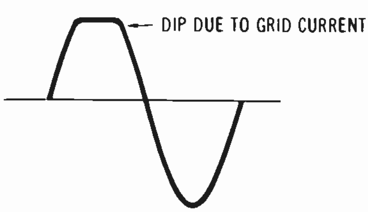


Fig. 5-6. Distorted plate-current waveform.

cycle when grid current flows, the amount of current flowing to the plate is diminished by the amount of the grid current. Therefore, as far as the plate is concerned, there is a dip in the waveform, and the waveshape is distorted. Also, the total power developed at the plate is made smaller, resulting in an overall power loss. If rule 2 is violated and the tube is operated on a curved portion of its characteristic curve, the output wave will be distorted, as shown in Fig. 5-7. The positive and negative halves of the input signal are equal, but because of the shape of the curve, the positive and negative halves of the output are quite unequal.

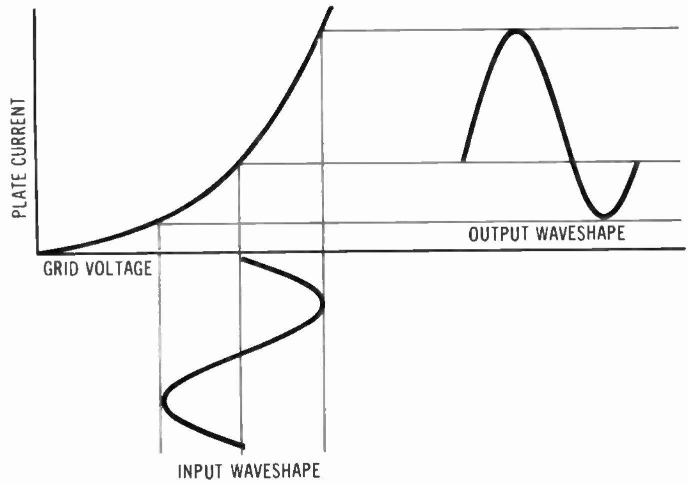
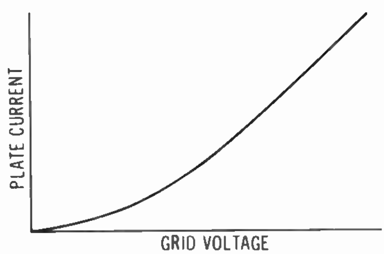


Fig. 5-7. Distortion due to nonlinear operation.

Q5-7. What are the two rules for determining a suitable dc grid-bias voltage?

Q5-8. The dc voltage applied to the grid is called ________.

Q5-9. Indicate on the curve shown below where a suitable dc operating point might be located.

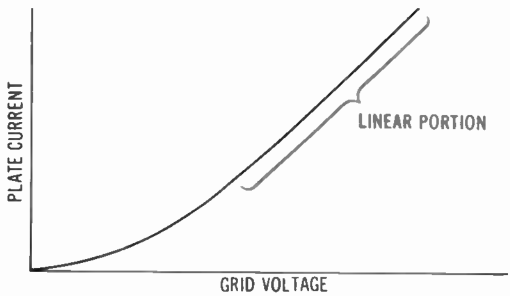


Your Answers Should Be:

A5-7. The dc grid voltage should be **greater than the highest voltage of the ac signal.** The dc voltage plus the signal voltage **should be on a straight-line portion of the plate-current–grid-voltage curve.**

A5-8. The dc voltage applied to the grid is called **grid bias.**

A5-9. The dc operating point should be located on the **linear portion** of the curve.



LOAD LINE

A convenient way to analyze an amplifier is with a load line drawn on the plate-characteristic curves of the tube (Fig. 5-8). These curves relate plate current (I_p) to plate voltage (E_p) for different values of grid voltage (E_g).

The load line is drawn as follows: A point corresponding to the value of the plate-supply voltage (E_B) is selected on the horizontal axis. Another point is marked on the vertical axis at a value of I_p equal to the plate-supply voltage divided by the effective value of the load resistance. The load line joins these two points.

These points represent the theoretical extremes the tube could reach. If the grid voltage is such that no current can flow, I_p is zero, and all of voltage E_B appears across the tube. This is the point on the X axis. If the grid voltage is such that the tube conducts so heavily as to have zero resistance, the plate current is limited only by the load resistance, and there is no voltage drop between plate and cathode. This is the point on the Y axis. This point, of course, is only theoretical. The tube is never a perfect conductor, so it can never reach that point on its load line.

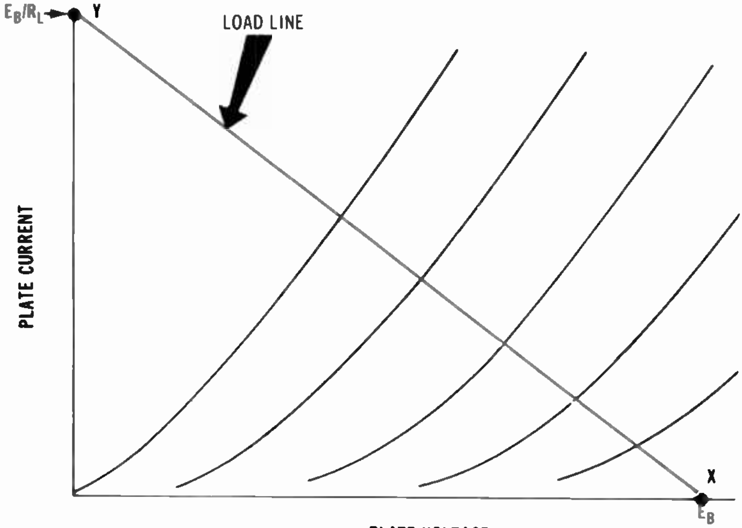


Fig. 5-8. A load line.

Changing the plate-supply voltage changes the position of the load line. Changing the load resistance changes the slope of the load line.

Q5-10. One end of a load line passes through the point on the horizontal axis corresponding to the ______ ______ voltage.

Q5-11. The other end of the load line passes through a point on the vertical axis corresponding to what value of plate current?

Q5-12. How does changing R_p and E_B affect the load line?

Your Answers Should Be:

A5-10. One end of a load line passes through the point on the horizontal axis corresponding to the **plate-supply** voltage.

A5-11. The other end of the load line passes through a point on the vertical axis corresponding to a value of plate current equal to the **plate-supply voltage divided by the load resistance.**

A5-12. Changing R_p changes the **slope** of the load line. Changing E_B changes the **position** of the load line.

Operating Point

By marking the load line with the point corresponding to the negative bias applied to the grid, the operating point of the tube is found. This point gives the values of E_p, I_p, and E_g with no input signal applied.

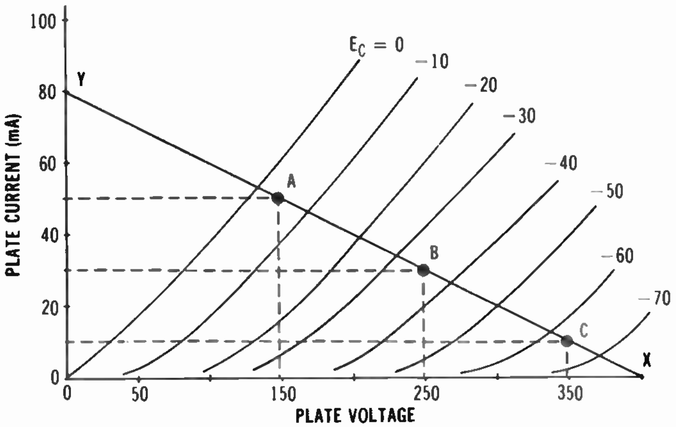


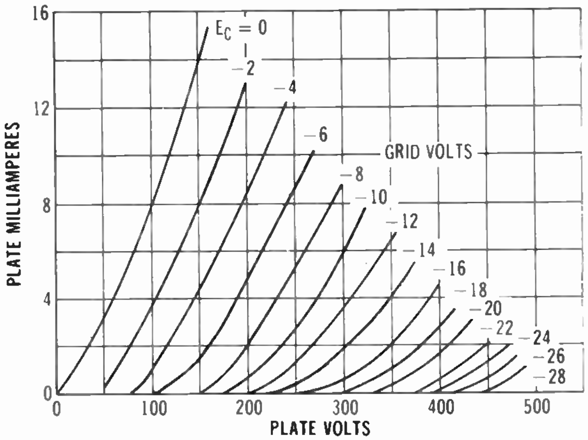
Fig. 5-9. Points on a load line.

If the amplitude of the ac input signal is known, it can be marked off along the load line, as shown in Fig. 5-9. By running vertical and horizontal lines from the two peak E_g points (points A and C in Fig. 5-9), the corresponding plate current and voltage can be determined.

In the diagram shown, the plate-supply voltage is 400 volts (point X). The quiescent operating point (B) shows that the dc grid bias is −35 volts. A signal having a peak value of 30 volts produces swings of grid voltage from −5 to −65 volts, causing variations of plate current from 10 to 50 milliamperes. The plate voltage swings from 150 to 350 volts.

The slope of the load line depends only on the value of the effective load resistance (R_L). This resistance may be a parallel combination of a load resistor and a grid-leak resistor. Or it may be an equivalent value from the primary of a coupling transformer. In any case, the points for the load line are always calculated as if the load resistance were a single resistor in the plate circuit.

The figure below shows a set of characteristic curves for a tube. Suppose the B voltage is 400 volts and the load resistance is 40K.



Q5-13. Draw the load line.

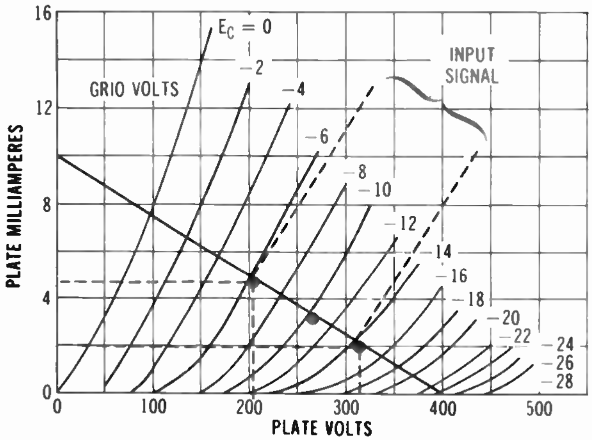
Q5-14. If the grid bias is −10 volts and the ac signal voltage has a peak value of 4 volts, draw lines to show the limits of plate current and plate voltage.

Your Answers Should Be:

A5-13. The load line should connect these two points:

$$I_p = 0,\ E_B = 400\ \text{V};\ I_p = 10\ \text{mA},\ E_B = 0$$

A5-14. Plate current varies between 2 mA and 5 mA, approximately. Plate voltage varies between 200 V and 310 V, approximately.



AMPLIFIER CLASS

The class of an amplifier depends on the grid-voltage range. A **class-A amplifier** is one in which the grid is never driven positive or to cutoff by the signal voltage. This means that grid current does not flow during any portion of the cycle, and no power is consumed in the grid circuit.

A **class-B amplifier** is one in which the grid is biased at or very near cutoff. The tube conducts during approximately half of the cycle (usually a little less than half). Grid current may flow during a part of the conduction period.

A **class-C amplifier** is one in which the grid voltage is beyond cutoff for most of the cycle but goes positive on positive signal peaks. Grid current flows on these positive signal peaks.

Class-B and class-C amplifiers, as you see, violate the usual rules for establishing a dc operating point. These amplifiers are used when it is unnecessary to obtain accurate reproduction of the entire input signal.

EQUIVALENT CIRCUITS

It is difficult to analyze an amplifier circuit because vacuum tubes are complex circuit elements. A convenient way of analyzing vacuum-tube circuits is by substituting an **equivalent circuit** made up of conventional elements for the tube. For the purpose of the analysis, the equivalent circuit accurately represents the behavior of the tube as far as the ac signal is concerned.

There are two basic equivalent circuits for a vacuum tube. Either one can be used, depending on which is more convenient. These equivalent circuits make use of the concepts of the constant-voltage generator and the constant-current generator.

In Chapter 2 you learned about tube parameters. These are the amplification factor, μ (mu); the transconductance (g_m) in micromhos; and the plate resistance (r_p) in ohms. You also learned the relationship between these three quantities: $\mu = g_m \times r_p$.

Constant-Voltage Generator

The equivalent circuit with a constant-voltage generator represents a vacuum tube as a voltage source of $-\mu e_g$ volts in series with a resistance r_p. The symbol e_g represents the signal voltage applied to the grid. The voltage at the output terminals of this circuit depends on the load resistance (R_L). The output voltage e_o is developed across R_L.

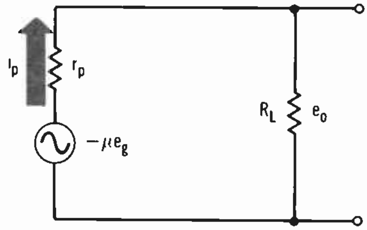


Fig. 5-10. Equivalent circuit using constant-voltage generator.

Q5-15. What class of amplifier must be used when minimum signal distortion is desired?

Q5-16. What is an equivalent circuit?

Your Answers Should Be:

A5-15. A **class- A amplifier** must be used when minimum signal distortion is desired.

A5-16. An equivalent circuit is a circuit **made up of conventional elements and used to represent a vacuum-tube circuit.**

Constant-Current Generator

The constant-current generator representation uses a constant-current source. This source generates a current of $g_m e_g$ amperes. (Remember that $I = E/R$, and conductance $= 1/R$.) The total current is i_p, the plate current. This current source is always in parallel with r_p, and the entire circuit is connected to a load (R_L).

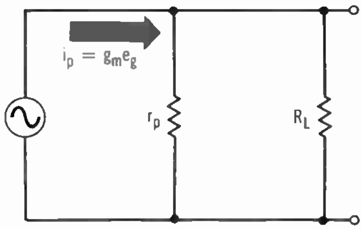


Fig. 5-11. Equivalent circuit using constant-current generator.

The two equivalent circuits produce the same results. Usually, when dealing with currents you will want to use the constant-current circuit. When dealing with voltages, the constant-voltage circuit is usually most convenient.

One word of caution—the two equivalent circuits can be used safely only for small values of signal voltage. This is because they are based on linear tube-characteristic curves. Actual tubes do not have straight-line characteristics. When the circuit is operating over a wide range of voltages, the straight-line approximation is no longer correct.

GAIN AND LOAD RESISTANCE

The **voltage gain,** or **amplification,** of an amplifier circuit is given by the formula:

$$\text{amplification} = \mu \frac{R_L}{R_L + r_p}$$

With a given tube, the only variable in this formula is the load resistance (R_L). If the plate resistance is increased, the gain will be increased; but it can never become greater than the ideal amplification factor (μ) of the tube. It will approach this value as R_L becomes appreciably larger than the plate resistance (r_p).

VOLTAGE AND POWER AMPLIFIERS

To obtain high amplification of **voltage,** a load resistor that is large compared to r_p must be used. However, as the value of the load resistor is increased, the output voltage across it rises more and more slowly. Finally, any further increase of R_L produces only a negligible increase in output voltage. This is because the tube begins to operate on a nonlinear portion of the grid characteristic curve as the load resistance is increased. This, as you have seen, results in a low output and produces distortion. The best value of load resistance is normally one that will give a reasonable amount of gain. A load with a resistance about four times that of the plate resistance of the tube is usually a satisfactory value.

Maximum **power** is obtained from the output of a vacuum-tube amplifier when the value of the load resistance is equal to r_p. However, distortion of the output signal occurs when this value of load resistance is used. For triodes, the best balance between power output and distortion exists when R_L is two to four times r_p. For pentodes, the best value for R_L is about one-tenth of r_p.

Q5-17. If a triode tube being used as an amplifier has a plate resistance of 32,000 ohms and a load resistance of 68,000 ohms, it is probably being used to produce an output of maximum _____, with minimum ___________.

Q5-18. What is the amplification of a circuit if the tube has a μ of 100, a plate resistance of 32,000 ohms, and a load resistance of 50,000 ohms?

Q5-19. What is the gain if R_L is increased to 100,000 ohms?

Q5-20. What is the gain if R_L is increased to 1 megohm?

Your Answers Should Be:

A5-17. If a triode tube being used as an amplifier has a plate resistance of 32,000 ohms and a load resistance of 68,000 ohms, it is probably being used to produce an output of maximum **power** with minimum **distortion.**

A5-18. $\text{Gain} = \dfrac{\mu R_L}{R_L + r_p} = \dfrac{100 \times 50{,}000}{50{,}000 + 32{,}000} = \mathbf{61}$

A5-19. Gain = **76**

A5-20. Gain = **97**

AUTOMATIC GRID BIAS

In the amplifier circuits shown so far, a battery (E_C) has been used to provide the small negative voltage for grid biasing. This is not always a practical arrangement, however. It is also possible to get the bias voltage from a resistance voltage divider in the power supply. The voltage-divider method and the battery method provide what is known as **fixed bias.**

In practical circuits, another common method of supplying grid voltage is by **automatic bias.** One type of automatic bias

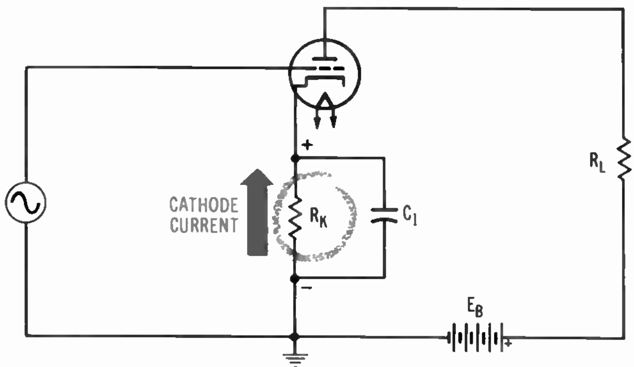


Fig. 5-12. Circuit using cathode-bias resistor.

is provided by the use of a cathode-bias resistor. The circuit for this is shown in Fig. 5-12. There are other types of automatic bias that work on similar principles.

In the circuit shown, the full cathode current flows through resistor R_K. The cathode current in a triode circuit equals the plate current. In a tetrode or pentode circuit the cathode current is the sum of the plate and screen-grid currents.

Current through R_K results in a voltage drop which makes the cathode more positive than the negative end of the plate-supply voltage to which the grid is connected. This is the same thing as making the grid negative with respect to the cathode.

If the desired grid-bias voltage and the total cathode current are known, the required value of resistor R_K can be calculated. For example, if E_c is to be −5 volts and the cathode current for this grid bias is 0.25 milliampere, the value of R_K is:

$$R_K = \frac{E_c}{I_K} = \frac{5\ \text{V}}{0.25\ \text{mA}} = 20\text{K}$$

In this arrangement the bias voltage depends on the amount of the cathode current. The current, in turn, depends on the plate voltage of the tube. As the plate voltage increases, the bias automatically increases (becomes more negative). As the plate voltage is reduced, the bias becomes less negative. This is why this circuit is called an automatic biasing circuit.

However, it is not desirable to have the bias affected by a continuously varying signal voltage. Therefore, biasing resistor R_K is bypassed with capacitor C_1 so that the ac component of the cathode current has no effect on the bias voltage. Capacitor C_1 is chosen so that its reactance at the signal-voltage frequency is small compared to R_K, usually about one-tenth. The dc current must pass through R_K because the capacitor appears as an open circuit to dc. However, the ac signal component can pass through C_1 10 times more easily than through the resistor. The ac voltage across the resistor is therefore very small. The cathode is then at ground potential as far as ac is concerned.

Q5-21. How does a cathode-bias resistor produce grid bias?

Q5-22. Why is a capacitor placed across a cathode-bias resistor?

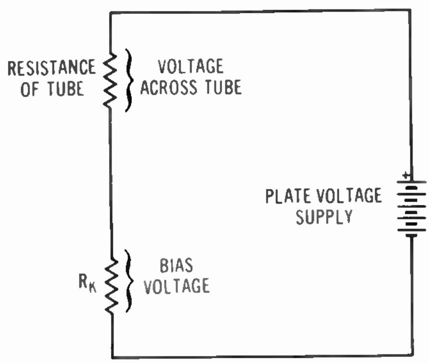
Your Answers Should Be:

A5-21. The flow of cathode current through the cathode-bias resistor causes a voltage drop which makes the **cathode positive with respect to the grid.** This is the same as **making the grid negative with respect to the cathode.**

A5-22. The capacitor across the cathode-bias resistor **prevents a signal-frequency voltage from appearing across the resistor.**

Effect of Cathode Bias

When using a cathode-bias resistor, it is necessary to have a plate-supply voltage higher than needed with fixed bias. The grid-bias voltage is, so to speak, taken from the plate-voltage supply by a voltage divider consisting of the biasing resistor



and the dc plate resistance of the tube. The plate voltage as seen by the tube is only that part of the supply voltage appearing across the plate resistance. Therefore, the plate-voltage supply must provide the bias voltage in addition to the plate voltage.

MULTISTAGE AMPLIFIERS

In many applications a single-tube amplifier cannot provide all the amplification that is required. It is then necessary to connect two or more amplifier circuits (called stages) one after the other. Each stage then amplifies the output of the preceding stage, until the desired amount of amplification is reached. This happens, for example, in television receivers that have several if amplifiers connected in sequence. This arrangement is sometimes called a **cascaded amplifier.**

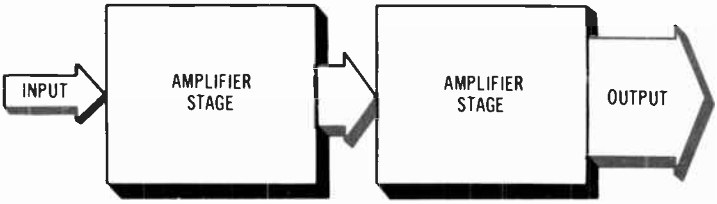


Fig. 5-13. Cascaded amplifier.

In a multistage amplifier chain, voltage amplifiers are generally used for all but the output stage. In this way only very small currents are handled. The signal is gradually developed to a higher voltage but with very little power. Only in the last stage is the signal converted into the necessary power output.

When several amplifier stages are coupled together, it is necessary to have some means of connecting them for maximum signal transfer without affecting the biasing of the individual tubes.

There are four main ways of coupling vacuum-tube amplifier stages. These are **resistance-capacitance, impedance-capacitance, transformer,** and **direct coupling.** The first two use a coupling capacitor to block the dc; the third accomplishes the same thing with a transformer.

Some special amplifiers are designed to amplify very low frequencies, even down to zero Hz (dc). The stages of these amplifiers are coupled directly, because a coupling capacitor or transformer would block dc and very low-frequency signals.

Q5-23. **In an amplifier having a cathode-bias resistor the plate voltage is less than the plate-supply voltage by the amount of the ____ ________.**

Q5-24. **What are the four ways of coupling vacuum-tube amplifier stages?**

Your Answers Should Be:

A5-23. In an amplifier having a cathode-bias resistor the plate voltage is less than the plate-supply voltage by the amount of the **bias voltage.**

A5-24. The four ways of coupling vacuum-tube amplifier stages are **resistance-capacitance, impedance-capacitance, transformer,** and **direct coupling.**

Impedance Matching

When coupling two amplifier stages together, or an amplifier stage and an output device such as a speaker, it is important to consider the output and input impedances involved.

Consider, for example, the coupling of an amplifier to a speaker. A vacuum-tube amplifier is a device that operates best at a rather low current level and a rather high voltage level (in the plate circuit). On the other hand, a speaker is a device that operates with high current and low voltage. Another way of saying this is that the amplifier has a high output impedance but the speaker has a low input impedance.

For maximum transfer of energy between two stages (or other electrical circuits), it is necessary that the output and input impedances be matched (made equal). If they are not equal, they can be matched by an **impedance-matching network.**

Remember that this applies only to energy transfer and not to voltage transfer. When coupling a voltage amplifier to the following stage, it is desirable to make the load resistor as high as practical, even though this does not result in maximum power transfer.

Resistance-Capacitance Coupling

Resistance-capacitance coupling is the most common and simplest manner of cascading amplifier stages. **RC-coupled** amplifiers are used in audio systems, video systems, oscilloscopes, radar systems, etc.

Coupling between stages of an RC-coupled amplifier is accomplished by taking the changing voltage across the load resistance of one stage and connecting it through a coupling capacitor (C_c) to the grid of the tube in the next stage. The high dc plate voltage of the first stage is blocked by C_c. The proper value of C_c is determined by the lower limit of the range of frequencies to be amplified. If C_c is too small, it will block the lower frequencies in the desired signal range.

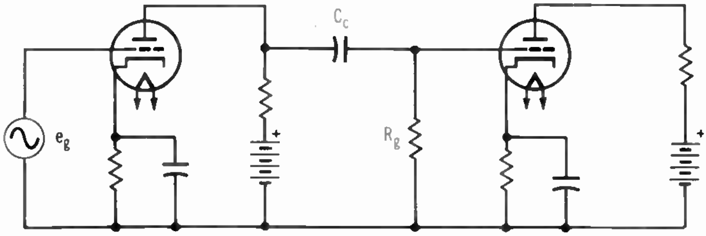


Fig. 5-14. Resistance-capacitance coupled amplifier.

Resistor R_g is called the **grid-leak resistor.** The resistor serves to keep the grid at ground potential, thus preserving the voltage difference between the grid and cathode. This resistor actually serves a dual purpose, also being used as the component across which the signal voltage from the preceding stage is developed.

Resistor R_L is called the load resistor, as before. However, notice that R_L is **not** the entire load seen by the first tube. It has the combination of C_c and R_g in parallel with it. The true load impedance is, therefore, always smaller than R_L.

An RC-coupled amplifier is sensitive to frequency. One reason is that the reactance of C_c varies with frequency. Another reason is that every circuit has several stray (unintentional) but unavoidable capacitances. At high frequencies these capacitances have low reactance values and begin to play a part in the circuit performance.

Q5-25. If two impedances are not the same, they can be matched by using a(n) __________ ________ ________.

Q5-26. Impedance matching is usually not employed when coupling a ________ __________ stage to the following stage.

Q5-27. In an RC-coupling amplifier, the true load is (equal to, less than, greater than) R_L.

Your Answers Should Be:

A5-25. If two impedances are not the same, they can be matched by using an **impedance-matching network.**

A5-26. Impedance matching is usually not employed when coupling a **voltage-amplifier** stage to the following stage.

A5-27. In an RC-coupled amplifier, the load seen by the tube is **less than R_L.**

Effect of Frequency in RC Coupling

In order to analyze a circuit accurately, the changing reactances previously mentioned must be taken into account. Since these reactances vary with frequency, a separate analysis must be made for the low, intermediate, and high frequencies. For each frequency range an equivalent circuit is chosen that will be a fairly accurate representation of the behavior of the amplifier. Remember that equivalent-circuit analysis is valid only for reasonably small signals. The three equivalent circuits for an RC-coupled triode amplifier designed to operate in the audio range are shown in Figs. 5-15, 5-16, and 5-17.

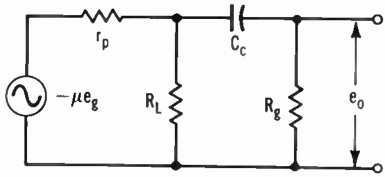


Fig. 5-15. Low-frequency equivalent circuit.

In the low-frequency range (up to 1000 Hz) no stray capacitances need be considered, but the coupling capacitor C_c has a sizable reactance. The circuit in Fig. 5-15 applies. Simple circuit techniques can be used to determine the voltage e_o, which appears at the grid of the next stage.

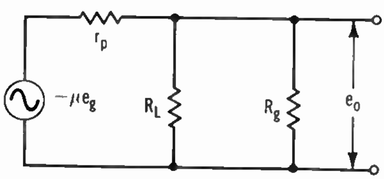


Fig. 5-16. Medium-frequency equivalent circuit.

The middle-frequency range is one in which coupling capacitor C_c can be neglected because it has a very small reactance compared to R_g. The stray capacitances likewise do not show any appreciable effect in this range.

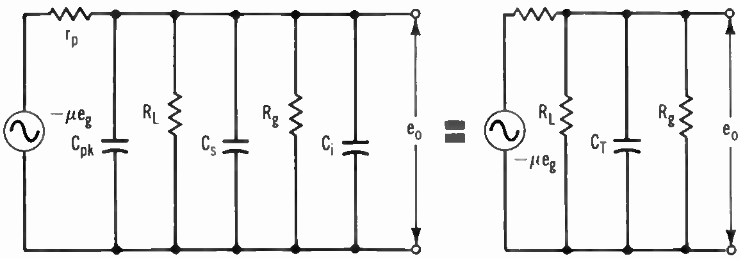


Fig. 5-17. High-frequency equivalent circuit.

In the high-frequency range, three unwanted capacitances become important. They are the plate-cathode capacitance (C_{pk}), the stray capacitance of the wiring (C_s) and the capacitance of the input circuit of the second stage (C_i). Since the equivalent circuit is a parallel one, all three capacitances may be combined into a total stray capacitance (C_T).

Fig. 5-18 shows how the gain of a typical RC-coupled amplifier varies as the signal frequency changes.

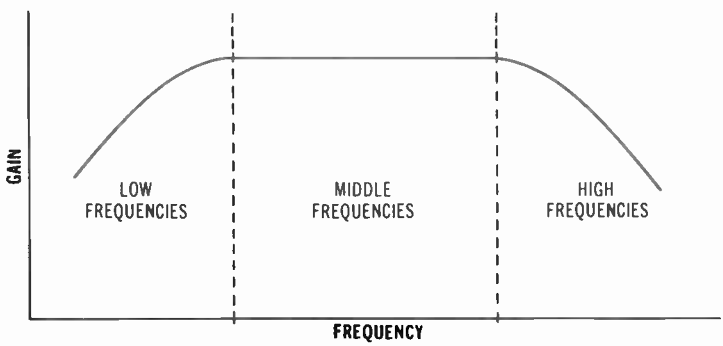


Fig. 5-18. Graph showing relationship of gain to frequency.

Q5-28. What factors affect the gain of an RC-coupled amplifier at different frequencies?

Q5-29. To fully analyze the performance of an RC-coupled amplifier, _ _ _ _ _ frequency ranges must be considered.

Your Answers Should Be:

A5-28. At low frequencies the gain of an RC-coupled amplifier depends on μ, r_p, R_L, R_g, and the reactance of C_c. At middle frequencies the factors are μ, r_p, R_L, and R_g. At high frequencies the factors are μ, r_p, R_L, R_g, C_{pk}, stray capacitance, and the input capacitance of the following stage.

A5-29. To fully analyze the performance of an RC-coupled amplifier, three frequency ranges must be considered.

Impedance Coupling

In the resistance-coupled amplifier there is a sizable dc voltage drop across the load resistor. This voltage drop is sometimes undesirable because it requires a power supply with a high voltage. The voltage drop can be minimized by using an inductor in place of the load resistor. The inductor, or choke, has low dc resistance but high reactance to ac. This makes possible a plate-supply voltage only a little higher than the plate voltage needed. The winding of the inductor develops only a small voltage drop due to the resistance of the wire.

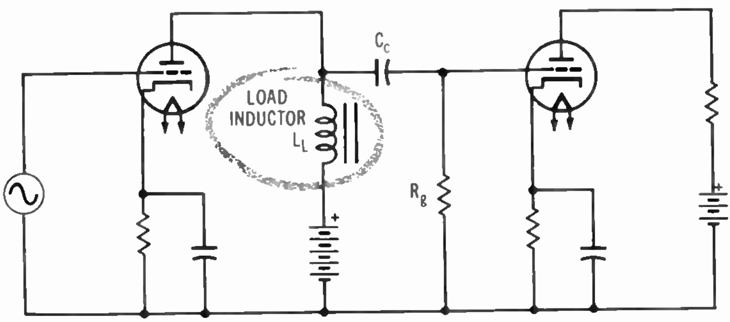


Fig. 5-19. Impedance-coupled amplifier.

In practice, **impedance-coupled amplifiers** are not often used. They are most likely to be encountered in power-amplifier circuits.

The distributed stray capacitance between the turns of the coil reduces the gain of the amplifier at the higher frequencies. At low frequencies, the choke (inductor) has a low reactance, thus causing a relatively small voltage drop to be developed across it. At the same time, the coupling capacitor has a very high reactance, preventing a good transfer of signal to the next stage. These two factors combine to reduce the low-frequency gain.

The choke is usually chosen to have a high reactance at the frequencies to be amplified so that a high signal-frequency voltage may be developed across it.

Circuit analysis and calculation of voltage gain for impedance-coupled amplifiers are very similar to those for the RC-coupled amplifier. The voltage-gain values obtained are of the same general magnitude.

Transformer Coupling

Transformer coupling is a very popular method of cascading amplifiers. It has the same advantage as impedance coupling in that no large dc drop appears across the primary winding of the transformer in the plate circuit. Direct current isolation is achieved by the natural isolation provided between the transformer windings (a transformer can transfer only alternating voltages).

Transformer coupling also has the advantage of good impedance matching between stages. This makes maximum power transfer possible. Transformer coupling is suitable for use in power stages, such as in the output circuits of audio amplifiers. The frequency response of a transformer-coupled amplifier can be excellent using modern transformer-design techniques. The major disadvantage of transformer coupling is its relatively high cost as compared to other coupling means.

Q5-30. The gain of an impedance-coupled amplifier at low frequencies is (good, fair, poor).

Q5-31. A load inductor is also called a _____.

Q5-32. The reactance of the load inductor _________ as the signal frequency decreases.

Q5-33. Transformer coupling (is, is not) suitable for use in power amplifiers.

Your Answers Should Be:

A5-30. The gain of an impedance-coupled amplifier at low frequencies is **poor.**

A5-31. A load inductor is also called a **choke.**

A5-32. The reactance of the load inductor **decreases** as the signal frequency decreases.

A5-33. Transformer coupling is suitable for use in power amplifiers.

Now you will see how a coupling transformer is used in an amplifier. The dc component of plate current flows through the primary winding without inducing any voltage in the secondary. But any fluctuations, such as ac currents, flowing through the primary induce corresponding ac voltages in the secondary winding connected directly to the grid of the next tube.

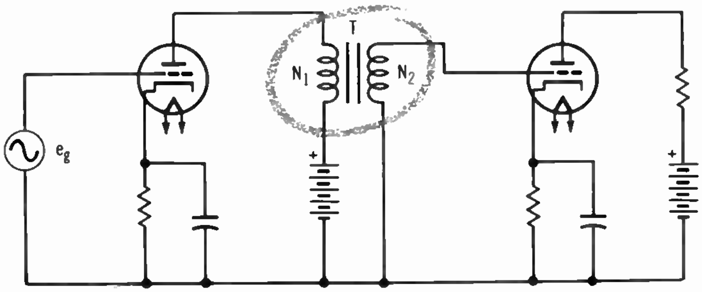


Fig. 5-20. Transformer coupling.

Since the tube is operated so that the grid is never driven positive, no grid current flows and no power is taken from the secondary winding. This means that no interaction takes place between the secondary and the primary and, therefore, the primary does not have to deliver any power to the secondary. The primary circuit sees only the impedance of the primary winding, as if it were a single coil, and its value can be chosen for the right value of reactance for maximum gain in the first stage. The voltage developed across the secondary winding depends on the turns ratio of the transformer. This voltage is equal to n_2/n_1 times the primary voltage.

The secondary voltage, and therefore, the gain, can be made quite high if the transformer winding ratio is high enough. In the early days of radio, when available tubes had very low amplification, transformers with high winding ratios were used extensively to achieve more gain.

However, there is a practical limit to the winding ratio. In order to achieve a high ratio, the secondary winding must have a large number of turns. As the frequency of the signal goes up, such a winding has enough stray capacitance to limit its high-frequency response. For a more uniform (flatter) frequency response in high-quality amplifiers, the turns ratio rarely exceeds 5 to 1.

It is important to connect the transformer correctly in a transformer-coupled amplifier. One reason, of course, is that the turns ratio must not be reversed. A more important reason is that the secondary winding is not made to carry any appreciable amount of current. But the primary does have to carry considerable plate current. Connecting the transformer into the circuit backwards may cause the secondary to burn out.

It is also important not to reverse the two leads of either winding, especially where a wide range of frequencies is concerned. The windings are wound in such a way that one end has less capacitance to ground than the other. Color coding is used to indicate the correct connections and should always be followed.

The methods used to couple amplifier stages discussed so far block all dc voltages and are for ac-signal use only. It is sometimes necessary to amplify dc signals, however.

Q5-34. Only __ flowing in the primary of a coupling transformer induces signals in the secondary.

Q5-35. The primary circuit sees the impedance of the _______ ________.

Q5-36. The voltage developed across the secondary winding is equal to the primary voltage times the _____ _____.

Q5-37. A winding with a large number of turns has a large _____ ___________.

Q5-38. Transformer leads in a transformer-coupled amplifier (may, should not) be interchanged.

Your Answers Should Be:

A5-34. Only ac flowing in the primary of a coupling transformer induces signals in the secondary.

A5-35. The primary circuit sees the impedance of the **primary winding.**

A5-36. The voltage developed across the secondary winding is equal to the primary voltage times the **turns ratio.**

A5-37. A winding with a large number of turns has a large stray **capacitance.**

A5-38. Transformer leads in a transformer-coupled amplifier **should not** be interchanged.

DIRECT-CURRENT VACUUM-TUBE AMPLIFIERS

Direct-current vacuum-tube amplifiers are known interchangeably as **direct-current amplifiers** or **direct-coupled** amplifiers (dc amplifiers for short). They are called direct-coupled amplifiers because there is no capacitor or transformer between the output of one stage and the input of the next, allowing dc signals to pass from stage to stage. Special means must be used to prevent the high dc plate potential of one stage from affecting the operation of the grid circuit of the next stage.

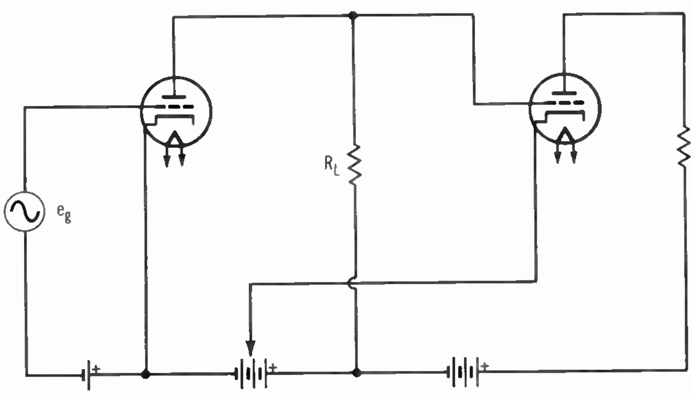


Fig. 5-21. Loftin-White circuit.

One of the main difficulties encountered with dc amplifiers is **drift**, the gradual change in output voltage without a change in the input. It is, of course, desirable to have no output voltage at all when the input is zero. Drift can be caused by a gradual change in the values of circuit components or even by replacement of a tube.

Fig. 5-21 shows one of the most common dc-amplifier circuits, the Loftin-White. Notice how the grid bias is obtained by dividing the plate-supply voltage of the previous stage. In a practical circuit the batteries are replaced by a resistor voltage divider in the main dc power supply. Because of the complexity of the required power supply, the tendency of the amplifier to drift, and the necessity for compensating networks, dc amplifiers are not used as widely as RC- or transformer-coupled units.

WHAT IS AN OSCILLATOR?

Oscillators are circuits that produce ac signals which have various applications in electronic equipment. Oscillators generate the radio-frequency carriers for radio and television transmissions. The audio or video signal is then superimposed on the carrier. Every superheterodyne radio receiver employs a local oscillator, and some electronic organs have a series of oscillators that produce different tone frequencies. All these are **sinusoidal** oscillators; that is, their output resembles a sine wave.

A second important class of oscillator circuits includes the nonsinusoidal types—circuits that produce ac other than sine waves. These types of oscillators are often called **pulse** or **square-wave generators.** They include pulse generators for radar, square-wave generators for television testing, sawtooth-wave generators in television display, marker oscillators, computer clock generators, and a host of others.

Q5-39. One of the most common direct-coupled amplifiers is the ______ _____ circuit.

Q5-40. In a dc amplifier the gradual change in output voltage without a corresponding change in the input is called _____.

Q5-41. Why is a direct-coupled amplifier so named?

Your Answers Should Be:

A5-39. One of the most common direct-coupled amplifiers is the **Loftin-White** circuit.

A5-40. In a dc amplifier the gradual change in output without a corresponding change in the input is called **drift.**

A5-41. A direct-coupled amplifier is so named because **the output signal of one stage is fed directly to the grid of the next stage** without going through a coupling capacitor or transformer.

OSCILLATOR OPERATION

How does an oscillator work? Suppose an amplifier capable of amplifying a desired frequency is turned on. Without any input there will, of course, be no output. Now connect the output back to the input, in a sort of loop, making sure that the phase relationship is such that this **feedback** will reinforce, not reduce, any input to the amplifier.

Any small signal at the input terminals will be amplified, fed back to the input, amplified again, and so on. The signal keeps going around the loop. Since all electronic circuits are frequency sensitive to some degree, this will happen only in a certain range of frequencies. The circuit oscillates; that is, it generates an ac signal without any external ac input. The oscillations may even be started by a very small amount of random noise in the tube.

There are two conditions for oscillation in a circuit. First, a feedback from output to input in the correct phase is required. This is known as **positive feedback** and may be accomplished by various kinds of coupling networks. Second, the amount of feedback must be enough to overcome any internal losses in the circuit so that the oscillations do not gradually die away.

It is important to keep in mind that the tube itself does not oscillate; it merely amplifies. The actual oscillation takes place in the **resonant circuit** that is part of the complete oscillator circuit. That is to say, the circuit constants determine the frequency of oscillation. The resonant circuit, also called a tank, functions like a flywheel rotating at its natural speed. There are some losses caused by resistance in the circuit. The power supply furnishes small amounts of energy every cycle to replace these losses and keep the oscillations going.

Thus, a basic oscillator has three necessary parts—the oscillating system, which usually is a resonant tank circuit; an amplifying device, such as a tube or transistor, to control the small amounts of energy furnished during each cycle; and a feedback system which may be either a circuit network or the interelectrode capacitance of a tube.

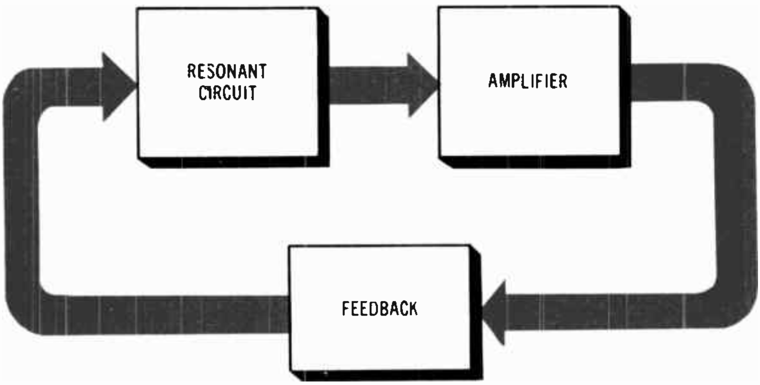


Fig. 5-22. Feedback oscillator.

The type of oscillator discussed in this chapter produces an output waveform that is considered to be a sine wave. An oscillator producing such an output is sometimes called a sinusoidal oscillator. You will learn about nonsinusoidal oscillators later in this volume.

Q5-42. An oscillator can be made by adding ________ ________ to an amplifier.

Q5-43. Another name for the resonant circuit in an oscillator is the ____ ________.

Q5-44. In what part of the oscillator do the actual oscillations take place?

Q5-45. What usually starts the oscillations in an oscillator circuit?

Your Answers Should Be:

A5-42. An oscillator can be made by adding **positive feedback** to an amplifier.

A5-43. Another name for the resonant circuit in an oscillator is the **tank circuit.**

A5-44. The actual oscillations take place **in the tank circuit.**

A5-45. **Random noise** usually starts the oscillations in an oscillator circuit.

Hartley Oscillator

One of the most common oscillator circuits is the **Hartley** The circuit shown in Fig. 5-23 is a **shunt-fed Hartley oscilla**-**tor**, which has the advantage that all dc is blocked from the oscillating tank circuit by capacitors.

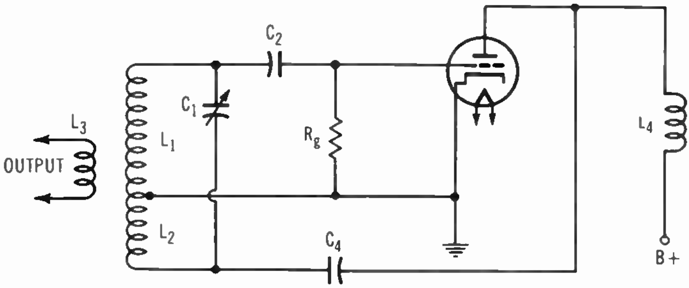


Fig. 5-23. Shunt-fed Hartley oscillator.

Random noise will produce small inputs to the parallel-resonant circuit composed of L_1, L_2, and C_1. This is the tank circuit. The noise input causes a circulating current to build up in this loop at the resonant frequency. A large current flows back and forth between the inductive and capacitive components at this frequency with only a small voltage applied. Notice that L_2, the lower half of the tapped tank coil (coil with a center connection), is also in the ac plate circuit Thus, L_2 serves to couple the ac energy in the plate circuit to the tank circuit by means of the mutual inductance (transformer action) between the two coil halves (L_1 and L_2). This produces an oscillating tank circuit (made up of L_1, L_2, and

C_1) and an amplifier. The dc in the plate circuit is blocked from the tank circuit by C_4.

The oscillating voltage in the tank circuit is coupled to the grid of the amplifier tube by RC coupling like that used between amplifier stages. The coupling network is composed of C_2 and R_g. Notice that the grid signal is taken from one end of the coil. The amplifier reverses the phase of this signal and returns it to the opposite end of the coil, where it is of the proper phase to increase the oscillations rather than cancel them. Varying the capacitance of C_1 changes the resonant frequency of the tank circuit and thus the output frequency of the oscillator.

Colpitts Oscillator

The Colpitts is another common oscillator circuit. This type of oscillator resembles the shunt-fed Hartley except that a split capacitor is used instead of a tapped coil.

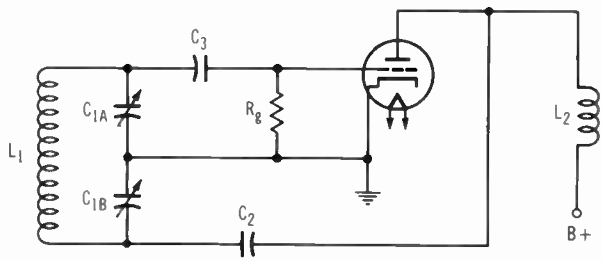


Fig. 5-24. Colpitts oscillator.

Capacitors C_{1A}, C_{1B}, and coil L_1 make up the tank circuit. The resonant frequency of the tank is changed by varying C_{1A} and C_{1B}. (These capacitors are usually on a common shaft so that both of them can be adjusted at the same time.) The output of the amplifier is introduced into the tank circuit through capacitors C_2 and C_{1B}. The tank-circuit voltage is introduced into the grid of the amplifier by the coupling network consisting of C_3 and R_g.

Q5-46. How is feedback obtained in a Hartley oscillator?

Q5-47. How does a Colpitts oscillator differ from a Hartley oscillator?

Q5-48. How is feedback obtained in a Colpitts oscillator?

Your Answers Should Be:

A5-46. Feedback is obtained in a Hartley oscillator by **returning the amplifier output to part of the coil** in the resonant circuit.

A5-47. A **Colpitts oscillator** uses a **split capacitor** in the tank circuit. A **Hartley oscillator** uses a **split coil** in the tank circuit.

A5-48. Feedback is obtained in a Colpitts oscillator by **returning the amplifier output to part of the split capacitor** in the resonant circuit.

WHAT YOU HAVE LEARNED

1. An amplifier is a circuit that acts like a valve, controlling a large amount of dc power to reproduce a small ac signal input.
2. Tetrode and pentode amplifiers operate on the same basic principle as triode amplifiers.
3. A dc operating point can be selected for a tube by examining the grid-characteristic curves of the tube.
4. By drawing a load line on a set of plate characteristic curves, values of plate current and plate voltage for a given signal voltage can be obtained.
5. The grid never goes positive in a class-A amplifier.
6. For class-A amplifiers, grid bias should be such that the signal voltage is always on a linear portion of the grid characteristic curve.
7. Class-B amplifiers are amplifiers in which the tubes conduct for about half the input cycle.
8. Class-C amplifiers are amplifiers in which the tubes conduct for less than half an input cycle.
9. The greater the load resistance of a tube amplifier, the greater is the voltage amplification.
10. The greatest power amplification is obtained when the load resistance is equal to the plate resistance of the tube.
11. An automatic grid-bias circuit varies grid bias as the

dc cathode current varies and thus compensates for variations in plate voltage.

12. Multistage amplifiers provide more amplification than can be obtained from a single stage. This is done by amplifying the output of each amplifier, one after the other.
13. Amplifiers can be resistance-capacitance, impedance, transformer, or direct coupled.
14. The first three coupling methods above are designed to pass only ac signals from stage to stage, while the last can also pass dc signals.
15. Equivalent circuits for vacuum tubes can be drawn to simplify the analysis of amplifier circuits.
16. Sinusoidal oscillators are used to produce sine-wave outputs.
17. Nonsinusoidal oscillators are used to produce pulse-type waveforms.
18. A sinusoidal oscillator is basically a combination of a resonant circuit, an amplifier, and positive feedback connections.
19. A Hartley oscillator obtains feedback from a tap in the inductive part of the resonant circuit.
20. A Colpitts oscillator obtains feedback from a tap in the capacitive part of the resonant circuit.

6

Transistor Circuits

what you will learn

When you have finished this chapter, you will know how to calculate the voltage and power gain of a transistor amplifier. You will understand several biasing arrangements and will know how the appropriate biasing voltages and currents are selected. You will learn about RC coupling, transformer coupling, direct coupling, and tuned coupling of transistor amplifiers.

TRANSISTOR AMPLIFIERS

Like a triode vacuum tube, a transistor can amplify. This means that it can control the flow of a large current by using a small signal. An amplifier provides an output signal having a greater **amplitude** than the input signal. Ideally, that is all it does; it leaves the shape of the signal waveform unchanged. If the output and input signals differ in any way other than amplitude, the amplifier is said to introduce **distortion**.

Amplification, or **gain**, is measured by comparing the output to the input. Care must be taken to compare the same quantities. The current gain is the output current divided by (compared with) the input current. The voltage gain is the output voltage divided by the input voltage. In order to have amplification, gain must be more than one.

Any individual amplifier has quite different figures for current gain, voltage gain, and power gain. In transistor circuits, gain also depends on how the transistor is connected. It can be used in a common-emitter, common-base, or common-collector circuit.

Current Gain

In the chapter on transistors you learned that in a common-emitter amplifier circuit, such as shown in Fig. 6-1, the current gain is $\beta = \frac{\Delta I_c}{\Delta I_b}$. This is also called the **common-emitter, forward-current transfer ratio** because, in a simple common-emitter circuit, it represents the current gain of the transistor (if the collector voltage is held constant).

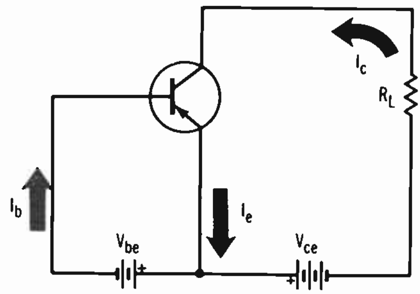


Fig. 6-1. Common-emitter circuit.

As you know, α is the ratio of collector-current change to emitter-current change and is equal to $\frac{\Delta I_c}{\Delta I_e}$. It is also called the **common-base, forward-current transfer ratio.** If the transistor were connected in a common-base circuit, α would represent its current gain (with the collector voltage held at a constant value).

A transistor, when connected in a common-emitter circuit, has a current gain of β. This means that every change in the input (base-circuit) current is magnified β times in the collector circuit. Typical values of β range from 20 to 50. The expressions α (also called h_{fb}) and β (also called h_{fe}) are related to each other as follows:

$$\beta = \frac{\alpha}{1-\alpha} \text{ and } \alpha = \frac{\beta}{1+\beta}.$$

Voltage Gain

In order to convert current amplification into voltage gain, it is necessary to know the resistances in the input and the output circuits.

In Fig. 6-2, the load resistance is R_L, and R_g is the internal resistance of the ac signal source (e_g). The signal current in the base circuit is ΔI_b. Using Kirchhoff's law in the base circuit, the ac voltage between base and emitter is equal to the source voltage (e_g) less the voltage drop across R_g, or $e_g - \Delta I_b R_g$. The base-emitter voltage is also $\Delta I_b R_i$, where R_i is the input resistance of the transistor. Remember that R_i is a property of the transistor and not a separate resistance in the circuit.

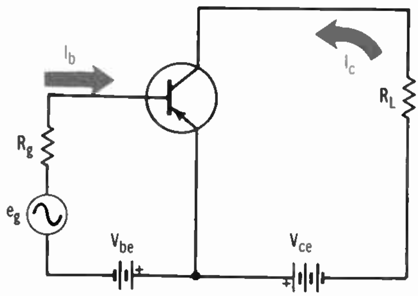


Fig. 6-2. Common-emitter circuit with ac signal source.

The voltage across load resistance R_L (which is a separate property of the circuit) is $\Delta I_c R_L$, where ΔI_c is the signal current in the collector circuit. The term R_c (collector resistance) is often used interchangeably with R_L.

The voltage gain can now be determined as the ratio of the voltage across the load resistance to the voltage between emitter and base, or $\frac{\Delta I_c R_L}{\Delta I_b R_i}$. Note that $\frac{\Delta I_c}{\Delta I_b}$ is not β because the collector voltage must be constant when β is measured.

Q6-1. When an amplifier changes the characteristics of a signal other than the amplitude, this is called ____________.

Q6-2. When measuring the gain of an amplifier, output voltage must be compared with _____ ________ or output current must be compared with _____ ________.

Q6-3. To what is the voltage gain of a common-emitter amplifier equal?

Your Answers Should Be:

A6-1. When an amplifier changes the characteristics of a signal other than the amplitude, this is called **distortion.**

A6-2. When measuring the gain of an amplifier, output voltage must be compared with **input voltage,** or output current must be compared with **input current.**

A6-3. The voltage gain of a common-emitter amplifier is equal to $\frac{\Delta I_c R_L}{\Delta I_b R_i}$

Signal Amplification

Now try to determine the voltage gain of a common-base amplifier circuit. Again, the voltage from emitter to base is e_g minus the voltage across R_g; that is, $e_g - I_e R_g$. This is also

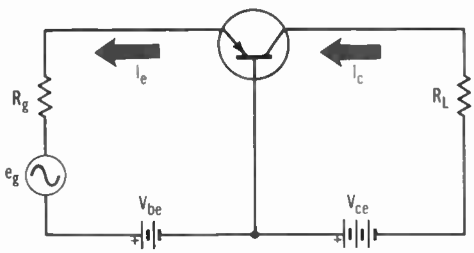


Fig. 6-3. Common-base circuit with ac signal source.

equal to $\Delta I_e R_i$. The voltage across the load resistor is $\Delta I_c R_L$. The voltage gain in this case is $\frac{\Delta I_c R_L}{\Delta I_e R_i}$. Note that $\frac{\Delta I_c}{\Delta I_e}$ in this case is not α because the collector voltage does not remain constant.

Input Resistance

The preceding gain formulas make use of transistor input impedance R_i. This is the ac base-to-emitter resistance. It can be written as $R_i = \frac{\Delta V_{be}}{\Delta I_b}$ for the common-emitter circuit and $R_i = \frac{\Delta V_{be}}{\Delta I_e}$ for the common-base circuit. Since Kirchhoff's law holds true in the input-loop circuit, the source voltage (e_g) must be equal to the voltage drops across resistance R_g and across the transistor-input resistance. From this, resistance R_i can be figured as $\frac{\Delta e_g}{\Delta I_b} - R_g$ for the common-emitter circuit and the common-base circuit. The input resistance of a transistor is not a simple, fixed value that can be measured with an ohmmeter.

Power Gain

The power gain of a transistor amplifier can be calculated by multiplying the voltage gain by the current gain. The power gain of the common-emitter amplifier is therefore:

$$\left(\frac{\Delta I_c}{\Delta I_b}\right)\left(\frac{\Delta I_c R_L}{\Delta I_b R_i}\right) = \left(\frac{\Delta I_c}{\Delta I_b}\right)^2 \frac{R_L}{R_i}$$

The power gain of the common-base amplifier is:

$$\left(\frac{\Delta I_c}{\Delta I_e}\right)^2 \frac{R_L}{R_i}$$

The various gain formulas for the different types of transistor amplifiers are shown in the following table.

	Common Emitter	Common Base
Current Gain	$\frac{\Delta I_c}{\Delta I_b}$	$\frac{\Delta I_c}{\Delta I_e}$
Voltage Gain	$\frac{\Delta I_c}{\Delta I_b} \frac{R_L}{R_i}$	$\frac{\Delta I_c}{\Delta I_e} \frac{R_L}{R_i}$
Power Gain	$\left(\frac{\Delta I_c}{\Delta I_b}\right)^2 \frac{R_L}{R_i}$	$\left(\frac{\Delta I_c}{\Delta I_e}\right)^2 \frac{R_L}{R_i}$

Q6-4. What happens to the voltage gain of a common-base amplifier as the load resistance increases?

Q6-5. What effect would an increase in input resistance have on the voltage gain of a transistor amplifier?

Q6-6. If you knew the current gain and the voltage gain of an amplifier, how would you determine the power gain?

Your Answers Should Be:

A6-4. An increase in load resistance causes an increase in voltage gain, provided other factors do not change.

A6-5. An increase in input resistance causes a decrease in voltage gain, provided other factors do not change.

A6-6. Power gain of an amplifier may be obtained by multiplying the current gain times the voltage gain.

OPERATING POINT

So far only the ac operation of transistor amplifiers has been considered. In the chapter on semiconductor devices you learned about transistor-characteristic curves of collector current (I_c) plotted against collector-emitter voltage (V_{ce}) for different constant values of base current (I_b).

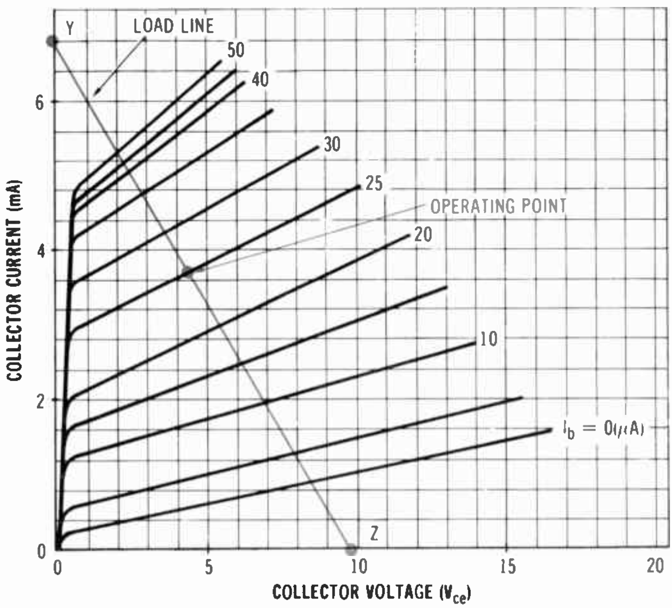


Fig. 6-4. Load line for transistor amplifier.

When designing a transistor amplifier, it is often important to make certain that the transistor will operate on a linear (straight-line) portion of the curve; otherwise, the output will be distorted.

As with vacuum tubes, a set of transistor-characteristic curves can be used to determine the points on the curves between which it is desired for the transistor to operate. The point at which the load line intersects a suitable base-current line is chosen as the operating point of the transistor. This means that with no signal input (the quiescent state of the amplifier), the collector current, collector-to-emitter voltage, and base current will be at the values which determine the point on the curves. When a signal input is applied, the conditions change along a straight line passing through the operating point. The greater the input, the farther the operating conditions will swing from the operating point. The line along which the conditions move is the load line. Its slope is determined by the value of the load resistance. An example of an operating point and load line is shown in Fig. 6-4.

Notice how similar the determination of the operating points for a transistor amplifier is to finding the operating points for a triode vacuum-tube amplifier.

Fixed Bias

Having determined from the curves where the operating point should be, the correct voltages and currents must be provided for operation at this quiescent point. This method is similar to the one used with vacuum tubes. In that case, the correct plate and grid-bias voltages were provided. In a transistor, the biasing consists of supplying a forward-bias voltage across the emitter-base junction and a reverse-bias voltage across the base-collector junction. These junction biases are essential for proper transistor operation.

Q6-7. What is a load line?

Q6-8. The point on the load line which shows the operating conditions of the transistor with no signal is the __________ point.

Q6-9. The slope of the load line is determined by the ___________ of the ____ __________.

Your Answers Should Be:

A6-7. A load line is a **line drawn on a set of characteristic curves. It shows the path followed by the operating point when a signal is applied.**

A6-8. The point on the load line which shows the operating conditions of the transistor with no signal is the **quiescent** point.

A6-9. The slope of the load line is determined by the **resistance** of the **load resistor.**

To establish the operating point on the characteristic curve, the correct values of collector voltage and emitter current must be supplied. This can be done using only one battery (Fig. 6-5) resulting in a **fixed-bias** circuit.

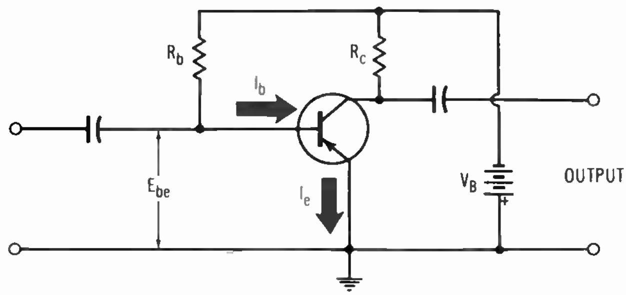


Fig. 6-5. Circuit for applying fixed bias.

The base-bias voltage is obtained from resistor R_b. The resistance of R_b is $\frac{V_B - E_{be}}{I_b}$. Since E_{be} is usually small compared to V_B, it can be disregarded when determining biasing voltages. So $R_b = \frac{V_B}{I_b}$. I_b is the chosen quiescent base-current value. Resistor R_b is usually between 100K and 1 meg.

A disadvantage of the fixed-bias circuit is that the collector current varies with temperature changes. In addition, the current may not be the same for all transistors of the same type. Generally, it is necessary to provide compensation for the temperature effects on I_c, which is a highly temperature-sensitive quantity. As the temperature increases, the collector current also increases. This tends to heat the transistor, thus causing a further current increase. If this chain reaction is allowed to continue, a condition called **thermal runaway** may occur, and the transistor will be destroyed by excessive heat.

A temperature-compensating circuit is shown in Fig. 6-6. Although its gain is not as great as that of the previous circuit, it is more stable.

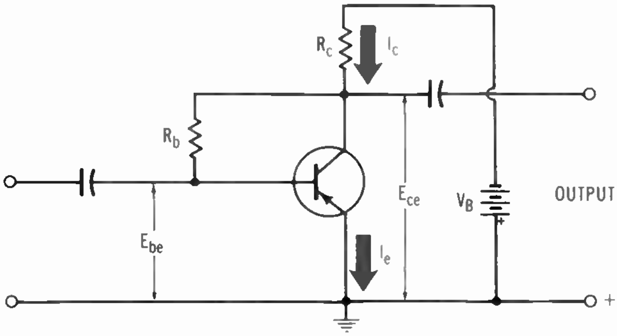


Fig. 6-6. Bias-stabilizing circuit.

If I_c increases in the above circuit, the voltage drop across R_c increases. Since the supply voltage (V_B) is relatively constant, E_{ce} must decrease as the voltage across R_c increases. The base-emitter junction and R_b are connected in series across E_{ce}. Therefore, the base current depends on E_{ce}. This means that as E_{ce} decreases, base current and I_c decrease, and the original increase in I_c is opposed.

Q6-10. If the operating temperature of a transistor rises, the collector current __________.

Q6-11. On the diagram in Fig. 6-6, trace the circuit that provides the base current.

Q6-12. If I_c increases, the voltage drop across R_c __________.

Q6-13. If I_c increases, the voltage between emitter and base __________.

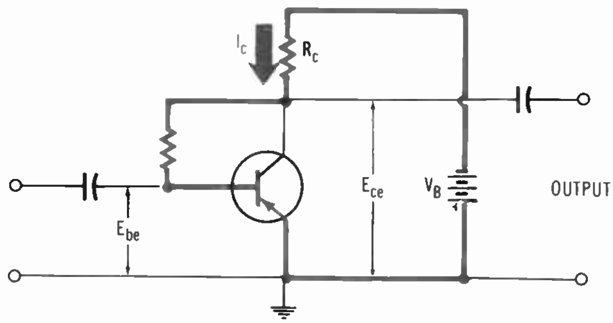
Q6-14. If the emitter-base voltage decreases, what effect will this have on the base current?

Q6-15. What effect will a decrease in the base current have on I_c?

Your Answers Should Be:

A6-10. If the operating temperature of a transistor rises, the collector current **increases.**

A6-11. The heavy line shows the base-current path.



A6-12. If I_c increases, the voltage drop across R_c **increases.**

A6-13. If I_c increases, the voltage between emitter and base **decreases.**

A6-14. If the emitter-base voltage decreases, this causes the base current to **decrease.**

A6-15. The decrease in base current will tend to **decrease** I_c.

Emitter Stabilizing Resistor

Another very common stabilizing circuit uses a resistor in series with the emitter. Such a circuit is shown in Fig. 6-7. Resistors R_1 and R_2 form a voltage divider across voltage supply V_b, providing the base with a voltage $V_A = \frac{R_2}{R_1 + R_2} V_B$. (Current I_b is assumed to be so small that it can be neglected.) In order to have good compensation, V_A must remain unaffected by variations in I_b. This is done by choosing the resistance values so that the current through R_1 and R_2 is much larger than I_b.

Resistor R_e in the emitter circuit causes E_{be} to be reduced if I_c increases due to temperature changes. It does this because when I_c increases, the voltage across R_e also increases. When this happens, E_{be} is reduced because voltage V_A is very nearly constant. A drop in E_{be} then causes a decrease in I_b and in I_c.

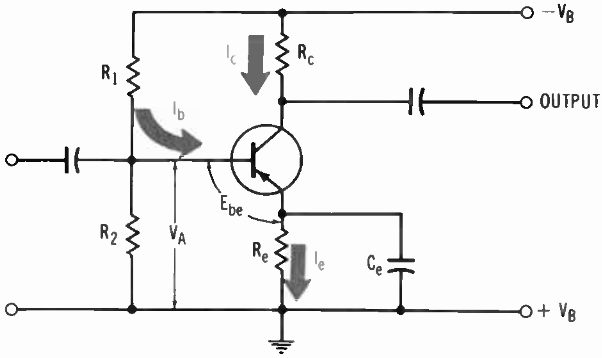


Fig. 6-7. Circuit using emitter-stabilizing resistor.

Capacitor C_e is connected across R_e to bypass the ac signal current. If this capacitor were not used, signal voltage would be present across R_e. If this happened, the action just described would tend to reduce the gain of the amplifier. This is one type of negative feedback and is the same action that takes place in a triode amplifier in which the cathode resistor is not bypassed.

Although the input resistance of a common-emitter amplifier is usually about 1000 ohms, the voltage divider reduces this to about 750 ohms.

Q6-16. Because of the voltage divider formed by resistors R_1 and R_2, the voltage between base and ground (V_A) will always equal __________ .

Q6-17. The voltage between base and emitter equals V_A minus the voltage drop across resistor ______ .

Q6-18. In the circuit in Fig. 6-7, what effect will an increase in collector current have on the voltage between the emitter and base?

Q6-19. In the circuit in Fig. 6-7, what effect will an increase in collector current have on base current?

Your Answers Should Be:

A6-16. Because of the voltage divider formed by resistors R_1 and R_2, the voltage between base and ground (V_A) will always equal

$$\frac{R_2}{R_1 + R_2} V_B$$

A6-17. The voltage between base and emitter will equal V_A minus the voltage drop across resistor R_e.

A6-18. If the collector current increases, the voltage between the emitter and base will then **decrease.**

A6-19. If the collector current increases, the base current will then **decrease.**

TWO-STAGE AMPLIFIERS

Often a single-transistor amplifier will not give the necessary amount of amplification. In this case, two or more amplifiers can be connected together to form a two-stage, three-stage, or longer chain. Each stage adds a share of amplification to the total. For the purpose of explanation, only two stages will be considered.

To have a two-stage amplifier, some method for feeding the output of the first stage to the input of the second stage is needed. In choosing an interstage coupling network, the following factors must be considered.

Frequency response—The network must have an equal effect on each of the desired frequencies. It is also sometimes necessary to filter out, or remove, all other frequencies. The range of desired frequencies is called the **passband.**

Impedance matching—The network should present the correct output impedance to the first stage for maximum gain. It should also present the correct impedance to the second-stage input so that maximum energy transfer can take place.

Operating points—The two stages may require different voltages, currents, and polarities to establish their best operating points. The interstage coupling network should be such that the dc conditions in the separate stages are not affected by each other.

RC-Coupled Amplifiers

The simple, small-signal, audio-frequency amplifier shown in Fig. 6-8 has two stages with resistor-capacitor coupling. Each of the two stages is stabilized by the familiar voltage-divider method.

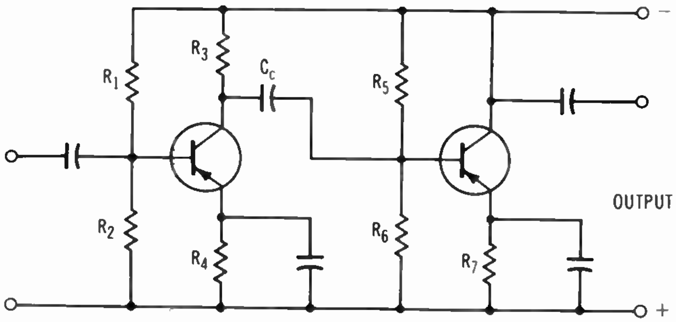


Fig. 6-8. RC-coupled transistor amplifier.

The output of the first stage is developed as a voltage across the load resistor (R_3) and is fed to the base circuit of the second stage through coupling capacitor C_c. This capacitor represents an open circuit to all dc voltages. Thus, the biasing circuits of the two stages are not influenced by the dc voltages on the other elements.

The value of coupling capacitor C_c determines the lower limit of the passband of the complete amplifier. There is no abrupt cutoff point. The response of the unit decreases gradually as the frequency decreases. For practical purposes this lower frequency limit is usually taken as the frequency at which the capacitive reactance of C_c equals the total resistance in series with C_c. This total resistance is the sum of the output resistance of the first stage and the input resistance of the second stage.

Q6-20. Which resistors stabilize the transistors in Fig. 6-8?

Q6-21. Can dc signals pass from stage to stage? Why?

Q6-22. The capacitor does not pass _ _ _ frequencies readily.

Your Answers Should Be:

A6-20. **Resistors R_4 and R_7** provide stabilization.

A6-21. Dc signals cannot pass from stage to stage **because the coupling capacitor blocks them.**

A6-22. The capacitor does not pass **low** frequencies readily.

The gain of a two-stage amplifier is the product of the gains of the individual stages. If something is increased 25 times and then the result of that increase is, in turn, increased 25 times, the final result will be an increase of 625 times the original quantity. If each stage of a two-stage transistor amplifier has a gain of 25, the total gain is $25 \times 25 = 625$.

The gain of each stage depends on its load resistance. When a second stage is connected to the output, the effective load resistance of the first stage is lowered. This is because the load resistance is in parallel with the input resistance of the next stage.

Suppose the load resistor of the first stage is 3000 ohms and the input resistance of the second stage is 1000 ohms. The **effective** load resistance of the first stage is the parallel combination of these two resistances, or $\frac{3000 \times 1000}{3000 + 1000} = 750$ ohms. The first-stage gain is then reduced to $\frac{750}{3000}$, or 0.25 times original gain. If the first-stage gain was 25 before the second stage was added, then its actual gain is only $0.25 \times 25 = 6.25$ after the second stage is added.

Transformer-Coupled Amplifier

RC-coupled amplifiers are suitable for providing voltage amplification when the gain does not need to be very high. For somewhat higher gain, a **transformer-coupled** amplifier can be used, such as the circuit shown in Fig. 6-9. Notice that the transformer does not pass dc. As with the RC-coupled amplifier, the gain of a transformer-coupled amplifier decreases at both the low- and high-frequency ends of the frequency range.

In order to get maximum energy transfer from the first stage to the second, it is desirable to choose a coupling transformer with a turns ratio that matches the output resistance of the first-stage transistor (usually about 25K) to the lower input resistance of the second-stage transistor (about 1000 ohms).

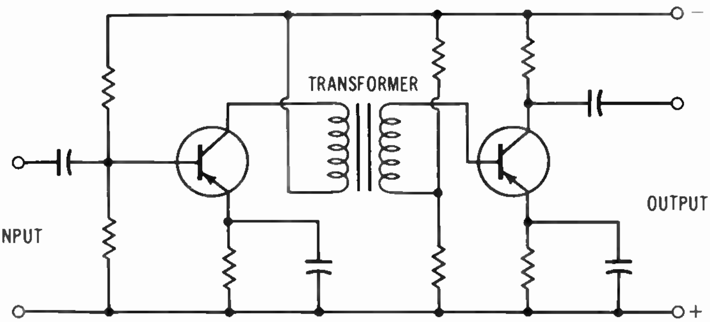


Fig. 6-9. Transformer-coupled transistor amplifier.

Suppose the output impedance of the first stage is 25K and the input impedance of the second stage is 1000 ohms. What turns ratio would the coupling transformer need? In a transformer, the impedance ratio is equal to the square of the turns ratio. The required turns ratio may be calculated as follows:

$$\frac{N_1^2}{N_2^2} = \frac{Z_1}{Z_2} = \frac{25{,}000}{1000}$$

$$\frac{N_1}{N_2} = \sqrt{\frac{25}{1}} = \frac{5}{1}$$

The turns ratio should therefore be 5 to 1.

Q6-23. If the gain of each stage of an amplifier is known how would the gain of the amplifier be calculated?

Q6-24. When RC coupling is used between two stages, what effect does adding the second stage have on the gain of the first stage?

Q6-25. Transformer coupling permits ________ gain than RC coupling.

Q6-26. How can impedance matching between amplifier stages be obtained?

Your Answers Should Be:

A6-23. The gain of an amplifier is calculated by **multiplying the gain values of the individual stages** in the amplifier.

A6-24. When RC coupling is used between stages, **the input impedance of the second stage is in parallel with the load resistance of the first stage.** This reduces the load seen by the first stage and therefore **reduces the gain of the first stage.**

A6-25. Transformer coupling permits **greater** gain than RC coupling.

A6-26. **A coupling transformer** can be used to match the output impedance of the first stage to the input impedance of the second stage.

Direct-Coupled Amplifiers

It is sometimes necessary to amplify signals that include very low frequencies, even dc. Low frequencies and dc cannot

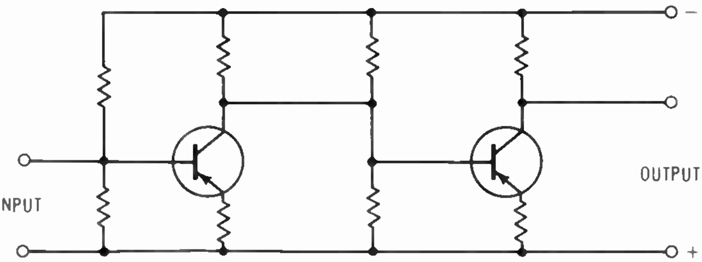


Fig. 6-10. Direct-coupled transistor amplifier.

be amplified when capacitors or transformers are used for interstage coupling. But amplifiers can be coupled without using capacitors or transformers. Connecting the collector of the first stage directly to the base of the next stage, as shown in Fig. 6-10, is known as **direct coupling.** Such amplifiers are called **direct-coupled amplifiers, direct-current amplifiers,** or simply **dc amplifiers.**

Coupling the collector of the first stage directly to the base of the second stage presents several special problems. The base of the second stage is placed at the same potential as the collector of the first stage. Such an arrangement is acceptable only if the emitter and collector voltages of the second stage can be adjusted to provide the required operating bias.

The fact that the biasing voltages of the two stages are not isolated from each other makes for a more complicated power-supply circuit. This is because the operating point for each stage must be adjusted without causing any interaction with the other stages. The power supplies must also be very accurate and stable. A dc amplifier will amplify dc voltages, so any power-supply variations will be transmitted from stage to stage and thus affect the final output of the amplifier.

The dc amplifier is usually intended to deliver an output that is proportional to the input signal. The amplification should be constant. It is very important that when the input is zero, the output is also zero. This is made difficult by the fact that there are no blocking capacitors or transformers between the stages. Any change in the operating point of one stage, therefore, affects all the other stages. Such a change may be brought about by temperature variations, which always affect the collector leakage current (I_{co}) of a transistor.

As a result, it is very important to use good temperature-compensating and stabilizing circuits in a dc amplifier. Otherwise drift results, and the output is no longer strictly proportional to the input.

The resistors shown in the emitter leads are used for stabilization. There are no bypass capacitors because this circuit is used for low frequencies where the capacitors would have a very high reactance and therefore would not pass a signal.

Q6-27. Why are RC- and transformer-coupled amplifiers not suitable for amplifying very low-frequency signals?

Q6-28. When is it acceptable to connect the collector of one stage of a transistor amplifier directly to the base of the next stage?

Q6-29. When the input to a dc amplifier is zero, the output should be ____.

Your Answers Should Be:

A6-27. RC- and transformer-coupled amplifiers are not suitable for amplifying very low-frequency signals because the **coupling capacitors or transformers block these signals.**

A6-28. The collector of one stage may be connected to the base of a second stage **if the emitter and collector voltages of the second stage can be adjusted to maintain the proper bias.**

A6-29. When the input of a dc amplifier is zero, the output should be **zero.**

Complementary Circuits

One way of coupling the stages of a dc amplifier takes advantage of the fact that there are two types of transistors—pnp and npn. This type of circuit alternates the two kinds and is known as a **complementary** circuit.

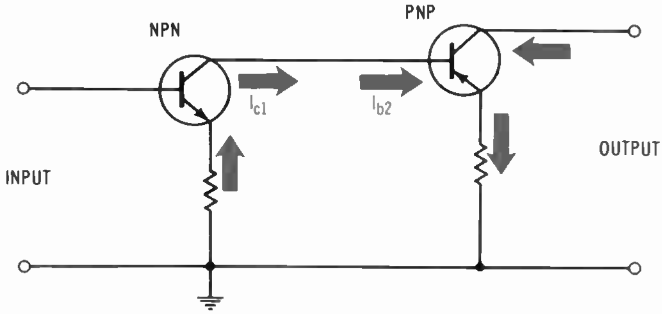


Fig. 6-11. Complementary dc-amplifier circuit.

In the npn transistor of the first stage, the collector current flows out of the transistor. In the base circuit of the second-stage pnp transistor, the base circuit flows into the transistor. If the npn collector is coupled directly to the pnp base, the current between them flows in the same direction. (For simplicity the power supplies are not shown on the diagram.)

It is sometimes necessary to have a first-stage collector current that is considerably larger than the base current of the second stage. This can be taken care of by bypassing some of the current with a resistor (Fig. 6-12).

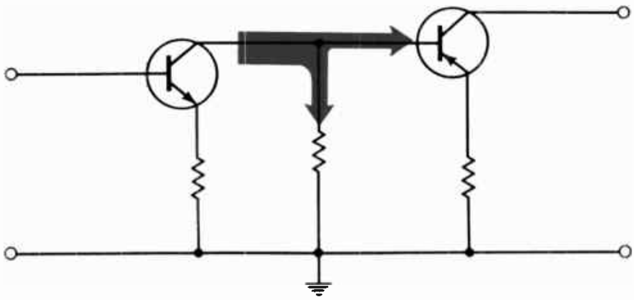


Fig. 6-12. Complementary amplifier with collector current greater than base current.

Tuned Amplifiers

Tuned amplifiers amplify only a narrow band of frequencies (i.e., a small frequency range as compared to the center frequency). Thus, tuned amplifiers are **selective.**

Tuned amplifiers are used widely in communications applications, such as radio and television receivers, to amplify rf and if frequencies. Tuned amplifiers make it possible to select one desired station from among a group of many stations whose signals may reach the receiver. Tuned circuits make possible the separation of sound and picture signals in a tv receiver. In transmitters, tuned amplifiers are used to generate large amounts of power at the assigned frequency of the station.

Q6-30. In the circuit in Fig. 6-11, what is the relationship between the base current of the second stage and the collector current of the first stage?

Q6-31. What would be the purpose of a resistor between the base of the second stage and ground?

Q6-32. Tuned amplifiers are designed to amplify only a _ _ _ _ _ _ _ _ _ _ of frequencies.

Your Answers Should Be:

A6-30. The base current of the second stage and the collector current of the first stage **are identical.**

A6-31. A resistor between the base of the second stage and ground would bypass some of the current so that the **base current of the second stage would be less than the collector current of the first stage.**

A6-32. Tuned amplifiers are designed to amplify only a **narrow band** of frequencies.

Selectivity, or tuning, is achieved in tuned amplifiers by using coupling networks that are essentially filters. That is, they pass energy between stages only in a narrow frequency band and reject signals at all frequencies outside this band. These coupling networks are almost always **parallel-resonant** (tuned) circuits. A parallel-resonant circuit has a high impedance at and near its resonant frequency. The current output of the first stage develops a voltage across the tuned circuit only in a very narrow tuned band. Therefore the following stage receives an input current only for signals in this frequency band.

The same principle is used in vacuum-tube tuned amplifiers. These are easier to build because tube amplifiers have high input and output resistances. The problem is more difficult with transistors because they have a relatively low resistance at both input and output. When a transistor amplifier stage is coupled to a parallel-resonant circuit, the low resistance of the transistor reduces the Q of the resonant circuit. This reduces the selectivity.

This makes it necessary to design a circuit that will somehow match the resistances of the stages and still leave the effective Q of the coupling as high as possible for adequate selectivity. Such a circuit is shown in Fig. 6-13. This is a single-tuned amplifier using a resonant circuit having a tertiary (third) winding. The tuned circuit (L_2C_2) is transformer-coupled to the collector circuit of the first transistor through windings L_1 and L_2. It is coupled to the base circuit of the second transistor through windings L_2 and L_3. To secure the maximum energy transfer between stages, the winding ratios must match the first-transistor output resistance to the second-transistor input resistance.

Selectivity is provided in this circuit by tuned circuit L_2C_2. When a signal at the resonant frequency is applied, a large current circulates between the capacitor and inductor of the tuned circuit. Energy is easily transferred to L_3 by transformer action. At all other frequencies the circulating current is much less, and the energy transfer is very low.

In actual practice, it is also necessary to use other components in transistor circuits. One of the component networks often used is for counteracting signal feedback from output to input. Such components form what are known as **unilateralization** networks.

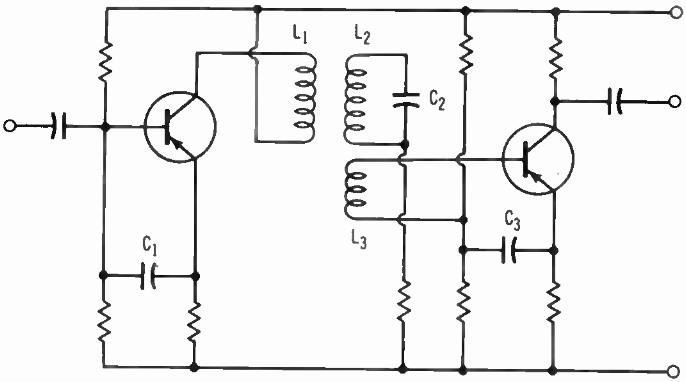


Fig. 6-13. Tuned transistor amplifier.

Q6-33. A parallel-resonant circuit has a ____ impedance at resonance.

Q6-34. What effect does connecting a transistor-amplifier stage to a tuned circuit have on the Q of the tuned circuit?

Q6-35. Another name for a third winding is ________ winding.

Q6-36. What determines the selectivity of a tuned amplifier?

Q6-37. Unilateralization networks are used to prevent _________.

Your Answers Should Be:

A6-33. A parallel-resonant circuit has a **high** impedance at resonance.

A6-34. Connecting a transistor amplifier stage across a tuned circuit **lowers the Q of the circuit.**

A6-35. Another name for a third winding is **tertiary** winding.

A6-36. The selectivity of a tuned amplifier is determined by the **Q of the resonant circuit.**

A6-37. Unilateralization networks are used to prevent **feedback.**

WHAT YOU HAVE LEARNED

1. The voltage gain of a transistor amplifier depends on its current gain and on the ratio of its load resistance to its input resistance.
2. The input resistance of a transistor amplifier is a property of a particular circuit.
3. An operating point for a transistor is selected by drawing a load line through a set of characteristic curves.
4. To maintain the desired operating point, the appropriate base current, collector-emitter voltage, and collector current must be provided.
5. A fixed-bias circuit uses a single power source and voltage-dropping resistors.
6. Voltage-divider stabilizing circuits can compensate for the effects of temperature changes.
7. The low-frequency response of an RC-coupled amplifier is limited by the coupling capacitor.
8. RC coupling passes only ac signals.
9. Transformer coupling affects the frequency response of the amplifier and passes only ac.
10. Dc coupling will pass low-frequency or dc signals but complicates the biasing arrangements in doing so.
11. Npn and pnp transistors can be combined in a dc-coupled amplifier to simplify the biasing problems.
12. Parallel-resonant circuits are used in tuned amplifiers.

7

Pulse Circuits

what you will learn

In this chapter you will learn how pulse circuits differ from sine-wave circuits. The importance of transient response in pulse circuits will be discussed. You will discover how pulse circuits can count, add numbers, shape waveforms, and act as switches. You will learn to recognize these circuits and how to diagram some of them. You will also learn some of the applications for pulse circuits.

WHAT ARE PULSE CIRCUITS?

You have already learned about power-supply circuits, in which ac is converted to specific dc voltages. You have also studied amplifier and oscillator circuits that are designed to generate and amplify sine-wave signals. These circuits are used extensively in electronics, especially in radiocommunications, television, and the reproduction of sound.

By contrast, pulse circuits are designed to handle **nonsinusoidal** signals. Typical signals found in pulse circuits are square waves, sawtooth waves, spike voltages, and wide rectangular pulses. Pulse circuits are used to count and perform mathematical operations; for switching, for example in dial-telephone systems; and to synchronize the operation of other circuits. In television and radar, for example, many different circuits must be turned on and off at exactly the same moment for the system to operate properly.

All pulse waveforms are actually complex combinations of sine-wave frequencies. This means that the frequency response of a circuit is important to proper pulse waveform reproduction. Pulse circuits must often respond well to a very wide band of frequencies. Pulse signals are often large compared to sine-wave signals, and signal levels often change from cut-off to saturation (from one end of the load line to the other) almost instantaneously.

TRANSIENT OPERATION

Transient operation describes the way circuits and components react to rapid changes in signal level. In radio circuits, tubes and transistors usually operate along the linear portion of their characteristic curves, and the transient operation of the tube or transistor is not very important.

On the other hand, pulse-circuit operations normally involve large signals. This means that amplifier operation may change very rapidly from a nonconducting state to the saturated stage, or vice versa. The transient response of tube and transistor circuits in either of these extreme states is most important in pulse-circuit operation.

The time required to turn a tube or transistor on may be as short as 0.08 to 0.10 microsecond. Turn-off time may be as short as 0.10 to 0.12 microsecond. But pulses often rise and fall sharply. Their entire duration may be measured in microseconds. Therefore, the time it takes for electrons to travel

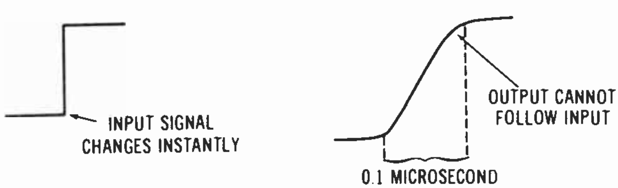


Fig. 7-1. Limited transient response of a transistor.

from cathode to plate in a vacuum tube is no longer negligible. For the same reason, the time for holes or electrons to diffuse from emitter to collector in a transistor must be considered.

Other factors affecting transient performance are the load impedance, the transistor- or tube-element capacitances, and the operating conditions before the arrival of the pulse.

TRANSISTOR TRANSIENT OPERATION

Fig. 7-2 shows an npn transistor connected as a common-emitter amplifier. With switch S_1 as shown, the emitter-base junction is reverse-biased, and no collector current flows. When S_1 is switched to the other position, the voltage of battery B_1 forward-biases the emitter-base junction. The base current quickly reaches maximum. The collector current also increases. The time required for it to increase from 10% to 90% of maximum is the **rise time.**

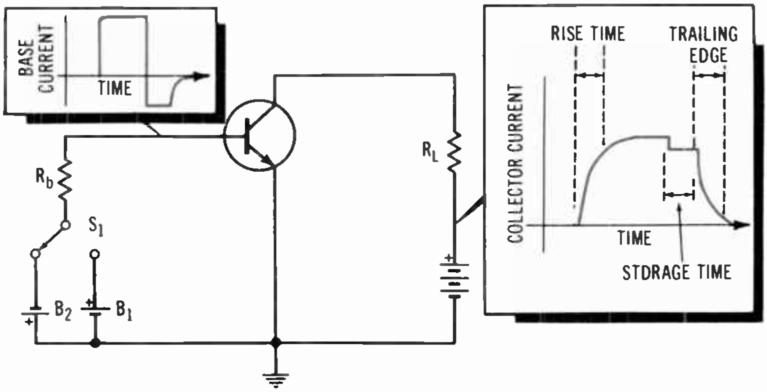


Fig. 7-2. Transient response of a circuit.

When S_1 is returned to its original position, the base current drops quickly and overshoots. This reversal is due to the minority carriers stored in the base during the forward-bias period. The reverse polarity of battery B_2 causes a reverse-current flow. The collector current does not change immediately during base-voltage cutoff. This delay is called **storage time.** It is the time required to collect the minority carriers remaining in the base.

As the current in the base decays, so does the current in the collector. This portion of the waveform is referred to as the **trailing edge.** The time it takes the trailing edge to decrease from 90% to 10% of the maximum collector current is the **decay time.**

Q7-1. What period might also be called "fall time"?

Q7-2. Pulse signals usually have _____ amplitudes.

Q7-3. A pulse amplifier must have a ____ bandwidth.

Your Answers Should Be:

A7-1. The **decay** time may also be called fall time.

A7-2. Pulse signals usually have **large** amplitudes.

A7-3. A pulse amplifier must have a **wide** bandwidth.

TRANSISTOR STATES

A transistor can be operated in the cutoff, active, or saturated state. Consider the circuit in Fig. 7-3. In the **cutoff** state, no collector current flows. This condition exists when there is no current through the base-emitter junction. The **active** state is the operating condition of the transistor in which it can be used as an amplifier. This is the state you studied in an earlier chapter. In the **saturated** state the transistor has reached a point where an increase in the input can produce no further increase in the output.

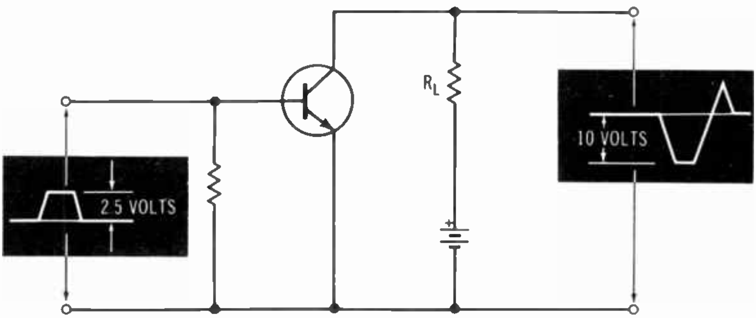


Fig. 7-3. A pulse-amplifier circuit.

With no signal applied to the base in the circuit in Fig. 7-3, no collector current flows (neglecting leakage). The transistor is in the cutoff state. With a large signal applied to the base, the transistor rapidly passes through the active state into the saturated state, and maximum current flows. The collector current rises at a rate that depends on capacitance, electron-hole diffusion time, and load impedance. The collector voltage decreases due to the voltage drop across R_L. Now collector current is at maximum. The collector voltage is lower than the 2.5-volt base voltage. Both junctions are now forward-biased.

Cutoff occurs at the maximum-voltage end of the transistor load line (see Fig. 7-4). Saturation occurs near the maximum-current end, although the current at saturation never reaches the theoretical maximum. The cutoff and saturation regions

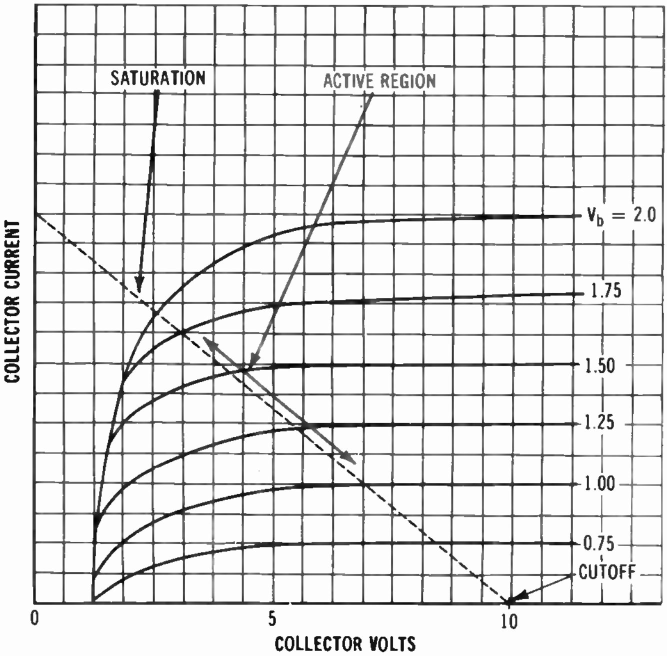


Fig. 7-4. Transistor characteristic curves.

are called the **quiescent** and **stable** states, respectively. When the emitter-base and collector-base junctions are reverse-biased, the transistor is in the quiescent state. When both junctions are forward-biased, the transistor is in the saturated state.

Q7-4. A transistor can be operated in the ______, ______, or __________ state.

Q7-5. In the circuit just discussed, the collector voltage __________ when the collector current increases.

Q7-6. When both junctions are forward-biased, the transsistor is in the __________ state.

Your Answers Should Be:

A7-4. A transistor can be operated in the **cutoff, active,** or **saturated** state.

A7-5. In the circuit just discussed, the collector voltage **decreases** when the collector current increases.

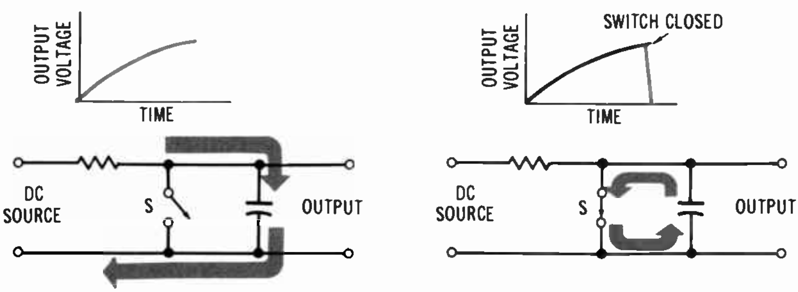
A7-6. When both junctions are forward-biased, the transistor is in the **saturated** state.

PULSE GENERATION

There are many ways of generating pulse signals. The telegraph key and the telephone dial are two common mechanical devices that are used in the generation of pulses. Both are simple switches that open and close circuits, thus generating rectangular pulses.

Sawtooth Generator

Accurately timed and shaped pulses are generated in electronic circuits. One good example is the sawtooth **generator.** Its operating frequency and output waveshape are controlled by the charging and discharging of an RC, RL, or RCL circuit.



(A) Charge. (B) Discharge.

Fig. 7-5. Sawtooth-generator action.

Most sawtooth generators use RC circuits. You have learned that a capacitor takes a certain amount of time to charge through a resistor. This time is determined by the RC time constant of the particular combination. If a capacitor is charged until the voltage across it reaches a given level and then allowed to discharge quickly, a sawtooth voltage results. The voltage gradually builds up until it reaches the discharge voltage—then it suddenly decreases to zero. The three requirements of a sawtooth generator are a power source, an RC circuit, and a voltage-controlled switch.

A gas-filled tube called a **thyratron** can act as a voltage-controlled switch. The thyratron conducts only when its plate voltage reaches a certain level. The more negative the grid is with respect to the cathode, the higher the plate potential must be to start conduction. After firing, the thyratron continues to conduct until its plate voltage has dropped to a specific lower value, called the **extinction potential.** The extinction potential depends mainly on the type of tube used.

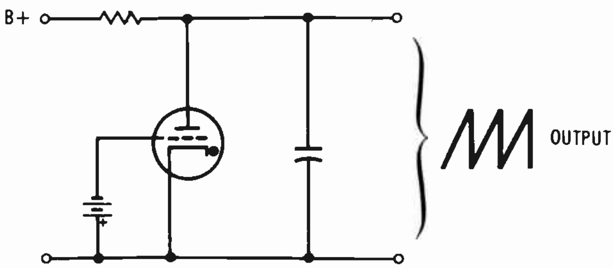


Fig. 7-6. A thyratron sawtooth generator.

During conduction, the thyratron has practically zero impedance. When not conducting, the thyratron presents a very high impedance. With power applied to the RC circuit, the capacitor charges exponentially. When the capacitor voltage reaches the necessary potential, the thyratron conducts. This discharges the capacitor quickly. When the plate voltage drops to the extinction potential, the thyratron stops conducting. This starts the charging cycle over again. The output voltage varies between the conduction and extinction voltages at a frequency determined by the time constant of the RC circuit, the supply voltage, and the grid voltage.

Q7-7. What factors affect the frequency of a sawtooth generator?

Your Answer Should Be:

A7-7. The frequency of a sawooth generator is determined by the **charging voltage applied to the RC circuit,** by the **R and C** values (which determine the RC time constant), and by the **grid voltage of the thyratron.**

The multivibrator is a circuit used to generate square or rectangular pulses. Like the sawtooth generator, its frequency is determined by RC time-constant circuits. And, just as with the conventional sine-wave oscillator, it makes use of positive feedback. Multivibrators may be either of the solid-state (transistor) type, or of the vacuum tube type.

A basic multivibrator is simply a two-stage RC-coupled amplifier in which the output of the second stage is coupled back to the input of the first stage providing the positive feedback. This forms a closed loop. In the transistor multivibrator circuit in Fig. 7-7, the output signal of the first amplifier stage, Q_1, is RC-coupled to the base of the first amplifier stage, Q_1, is RC-coupled to the base of the second stage, Q_2. Similarly, the output signal of the second stage is RC-coupled back to the grid of the first stage.

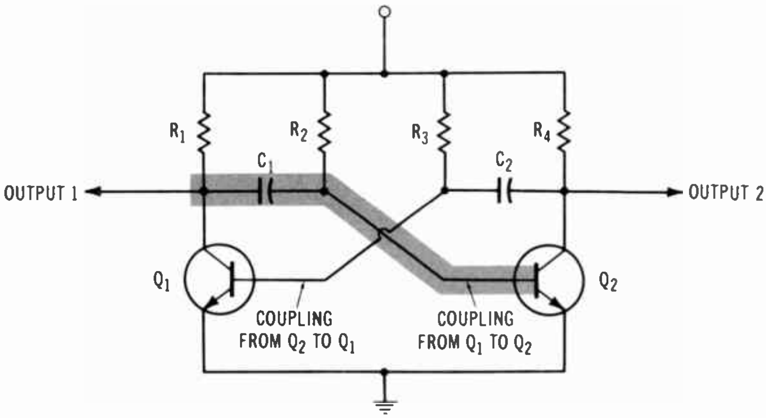
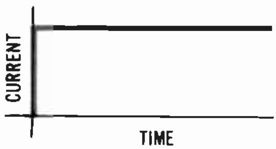


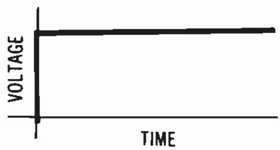
Fig. 7-7. A multivibrator circuit with the output of Q_1 applied to the base of Q_2.

How does this circuit work? When power to the circuit is applied, both transistors begin to conduct, as in a normal amplifier. If it so happened that current in both Q_1 and Q_2 were the same, that is all that would happen. However, since no pair of transistors or other parts are ever exactly alike, one transistor will draw a little more current than the other.

Let's say that Q_1 begins to conduct slightly more than Q_2. This increased current becomes the input signal to Q_2 causing Q_2 to conduct less. This decrease in conduction of Q_2 then becomes an input signal back to Q_1, causing Q_1 to conduct even more heavily. This action continues until Q_2 is very quickly cut off.



(A) Q_1 collector current.



(B) Q_2 collector voltage.

Fig. 7-8. Ideal switching in a multivibrator.

The entire initial action—one transistor reaching maximum conduction and the other being cut off—occurs almost instantly. If the voltage across Q_2 (output 2) is used as the output of the circuit, it will have changed from minimum to maximum value very quickly.

Q7-8. **If Q_1 begins to conduct slightly more than Q_2 what happens to the voltage drop across R_1?**

Q7-9. **The collector of Q_1 becomes (more, less) negative with respect to B+.**

Q7-10. **When this signal is coupled through C_1 to the base of Q_2, the base of Q_2 becomes more (positive, negative).**

Q7-11. **This causes the collector current in Q_2 to _________.**

Q7-12. **This causes the voltage drop across R_2 to _________.**

Q7-13. **The collector of Q_2 becomes (more, less) negative with respect to B+.**

Q7-14. **When this signal is coupled through C_2 to the base of Q_2 the base of Q_1 becomes ____ __________.**

Q7-15. **What effect does this have on current through Q_1?**

Your Answers Should Be:

A7-8. If Q_1 begins to conduct slightly more than Q_2, the voltage drop across R_1 **increases.**

A7-9. The collector of Q_1 becomes **more** negative with respect to B+.

A7-10. When this signal is coupled through C_1 to the base of Q_2, the base of Q_2 becomes more **negative.**

A7-11. This causes the collector current in Q_2 to **decrease.**

A7-12. This causes the voltage drop across R_2 to **decrease.**

A7-13. The collector of Q_2 becomes **less** negative with respect to B+.

A7-14. When the signal is coupled through C_2 to the base of Q_1, the base of Q_1 becomes **less negative.**

A7-15. This **increases** the current through Q_1.

In the first step of the circuit action, Q_2 goes to cutoff and Q_1 conducts heavily. When the transistors reach this steady state and the signals are no longer changing, the RC coupling is no longer effective. The voltage holding Q_2 in its cutoff state will gradually diminish.

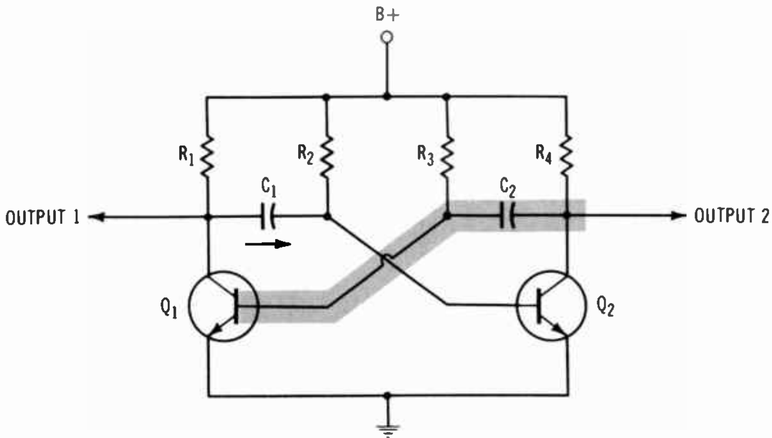


Fig. 7-9. A multivibrator circuit.

It is easy to see what happens if you look at the coupling between Q_1 and Q_2. The base of Q_2 was driven negative by the changing collector voltage of Q_1, coupled through C_1. When the collector voltage of Q_2 stops changing, the base of Q_2 is held negative by the charge of coupling capacitor C_1. But C_1 discharges gradually through Q_1, which is conducting heavily. When Q_2 begins to conduct, a process exactly like the first step begins. Transistor Q_1 is driven to cutoff, and Q_2 begins to conduct heavily. Then coupling capacitor C_2 between Q_2 and Q_1 will discharge, and the cycle will repeat itself.

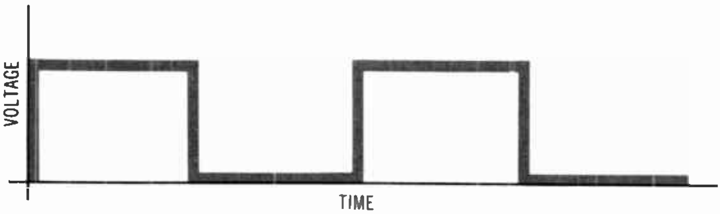


Fig. 7-10. Theoretical output of a multivibrator.

To review, a basic multivibrator is two amplifiers RC-coupled to each other. When they begin to operate, one is immediately driven to cutoff and the other conducts heavily. They continue in this state until the RC coupling network discharges enough to permit the cutoff amplifier to again conduct. When this happens, the second amplifier is driven to cutoff and the first conducts heavily. The two amplifiers continue to alternate conducting states at a rate determined by the time constant of the RC coupling networks.

Q7-16. The rate at which C_1 discharges is determined by the ____ _________ of the RC-coupled network.

Q7-17. What happens to the current in Q_2 as C_1 discharges?

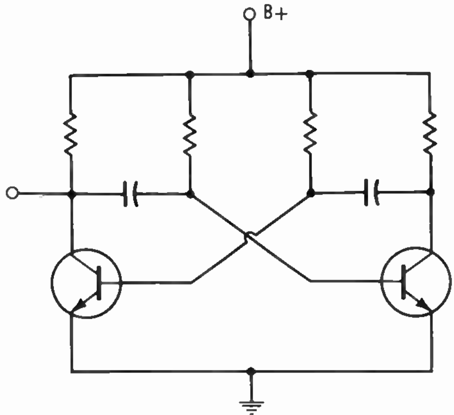
Q7-18. Draw a schematic of a basic multivibrator. Begin by drawing a two-stage, RC-coupled amplifier, and then add the extra coupling circuit.

Your Answers Should Be:

A7-16. The rate at which C_1 discharges is determined by the **time constant** of the RC-coupled network.

A7-17. As C_1 discharges, the base voltage of Q_2 **decreases.** When the base voltage passes the cutoff level, Q_2 **begins to conduct.**

A7-18. Your schematic should look like this.



Bistable Multivibrators

A **bistable multivibrator,** or **flip-flop,** is a very useful variation of the basic multivibrator. As you will see later in this chapter, it is one of the basic circuits of digital computers.

Like the basic multivibrator, the bistable multivibrator consists of a two-stage amplifier with its output coupled to its input. The difference between the two circuits is that the stages are direct-coupled instead of RC-coupled. Thus, there are no coupling capacitors to charge and discharge and control conduction. Once the circuit has assumed one state, it stays that way until an outside signal is applied to start the changeover process. Then the multivibrator "flips" or "flops" into the opposite state.

In the bistable circuit in Fig. 7-11, assume that Q_1 is saturated and Q_2 is cut off. A positive pulse applied to the trigger input and to the base of Q_1 will cut off Q_1 and cause its collector to go negative. Since the Q_1 collector connects to the Q_2 base, the Q_2 base also goes negative. This turns on Q_2 causing its collector to go positive and drive the base of Q_1 even more positive. Now Q_2 is in a saturated state where it will remain until a positive pulse comes along at the trigger input causing its base to go positive. A bistable multivibrator is also referred to as a flip-flop.

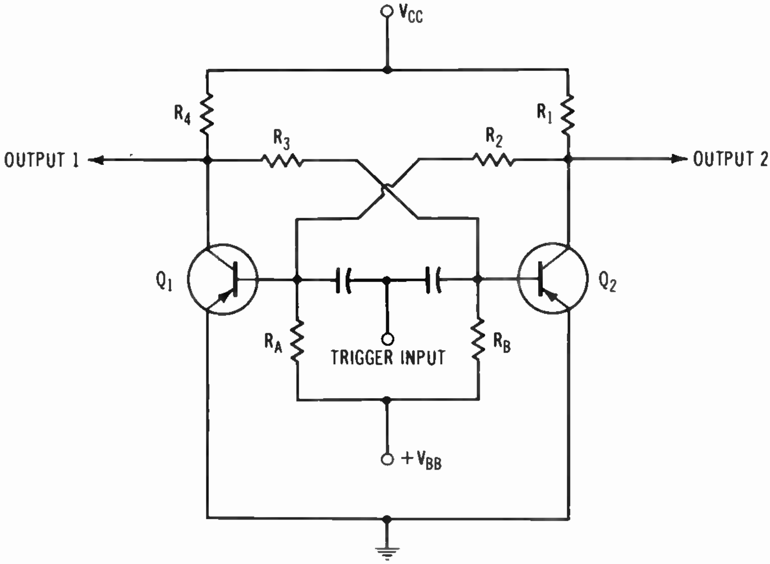


Fig. 7-11. Bistable-multivibrator circuit.

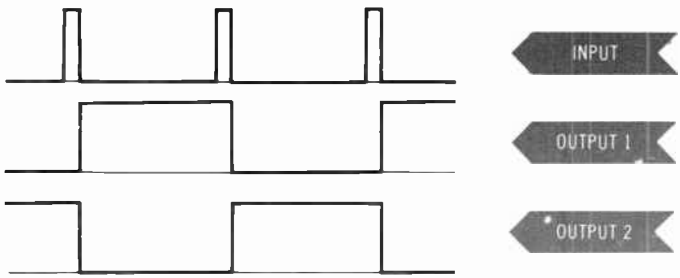


Fig. 7-12. Bistable-multivibrator pulses.

Q7-19. Which transistor in a bistable multivibrator will be affected by a negative pulse? How will it be affected?

Q7-20. How many input pulses are required to produce a single output pulse from a bistable multivibrator?

Your Answers Should Be:

A7-19. A negative pulse will **cause the conducting transistor to conduct less.** This will, in turn, allow the other transistor to start conducting a little, and the **changeover process will take place.**

A7-20. **One input pulse** is required to turn the cutoff transistor of a bistable multivibrator **on** and a **second input pulse** is required to turn it **off.** Thus, **two input pulses are required to produce one output pulse** from a bistable multivibrator.

PULSE-CIRCUIT APPLICATIONS

One of the most important uses of pulse circuits is for various kinds of switching. In these applications, pulse circuits simply turn each other or other circuits on and off. Other pulse circuits are used for counting or to change the shape of waveforms.

Electronic Switches

An ideal switch has infinite resistance when open and zero resistance when closed. Also, it has a means of being opened and closed. Vacuum tubes and transistors can act as switches that are opened and closed electronically. Instead of increasing and decreasing an output signal according to the variations of an input signal, the output is turned on or off. The tube or transistor is made to go from cutoff to saturation and vice versa instead of operating in its linear amplification region.

Electronic switches operate much faster than mechanical switches. Using mechanical and relay switches in a device such as a computer would make it too slow to be useful. Electronic switches operate rapidly and silently, are more sensitive than mechanical ones, and have no moving parts or contacts to wear out.

Transistor Switch

The illustration in Fig. 7-13 shows an electronic switch that can be turned on or off by a single pulse. The input signal will be amplified only when the electronic switch is closed.

The transistor is connected to one of the outputs of the bistable multivibrator. When the multivibrator is in one state, the transistor amplifies in the usual way. This is because of the voltage applied to the emitter. The amplifier can be turned off by applying a pulse to the multivibrator, causing it to change states. Now the multivibrator output applies a large

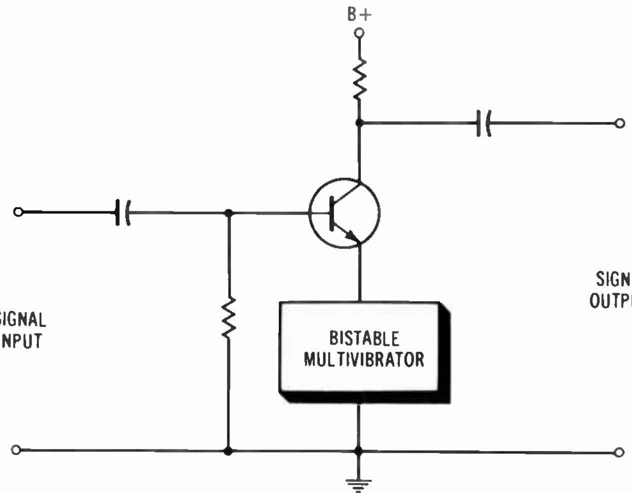


Fig. 7-13. A simple switching circuit.

positive voltage to the emitter. This has the same effect as making the base negative, and the transistor is cut off. Another pulse to the multivibrator causes it to change states again, the emitter of the transistor is returned to its operating voltage and the transistor is able to amplify.

Q7-21. **In switching circuits, tubes and transistors operate from ______ to ___________.**

Q7-22. **In Fig. 7-13, switching action depends on changing the voltage of the ________.**

Your Answers Should Be:

A7-21. In switching circuits, tubes and transistors operate from **cutoff** to **saturation.**

A7-22. In Fig. 7-13, switching action depends on changing the voltage of the **emitter.**

Turning Circuits On and Off Automatically

You have seen how an electronic switch can turn a device on or off. One practical example of automatic switching is in television. The picture-tube beam must be turned off and on 15,750 times a second. To do this, **blanking pulses** are sent out by the broadcasting station at this frequency. The receiver uses these pulses to operate an electronic switch. Each time a blanking pulse is received, the picture signal is interrupted to allow the electron beam to return across the picture tube in order to start a new line. If this arrangement were not used, the returning beam would tend to fill in the dark areas in the picture with bright retrace lines.

Gating Signals to Different Destinations

More complicated switching actions are often performed by **gate circuits.** A gate circuit allows signals to go through only when certain conditions are satisfied, but no signals can pass when these conditions are not satisfied.

Transistor gate circuits are used frequently in computer applications. They function as gates to direct signal flow to various points in the overall circuitry. Because they are able to determine computer operation from their input conditions, these circuits are referred to as **logic circuits.** AND gates and OR gates are two kinds used for logic operations. AND gates can use tubes, transistors, or semiconductor diodes, the latter being the most common.

The AND gate shown in Fig. 7-14 requires that both inputs be present before an output is generated. Without signals, current flows from the negative battery terminal through the large resistor (R) and both diodes to ground.

As a result, the output is a constant, small negative voltage. A negative pulse at point 1 reverse-biases diode CR_1. But current still flows through diode CR_2. Since R is very large compared to the other two resistors, the output remains almost unchanged. To see why this is true, notice that the total current flow is determined mainly by the resistance of R. Therefore, the voltage drop across R changes only a small amount when CR_2 stops conducting.

When negative pulses appear at points 1 and 2 at the same time, both diodes become reverse-biased. Current flow stops, and the output voltage becomes the same as the voltage of

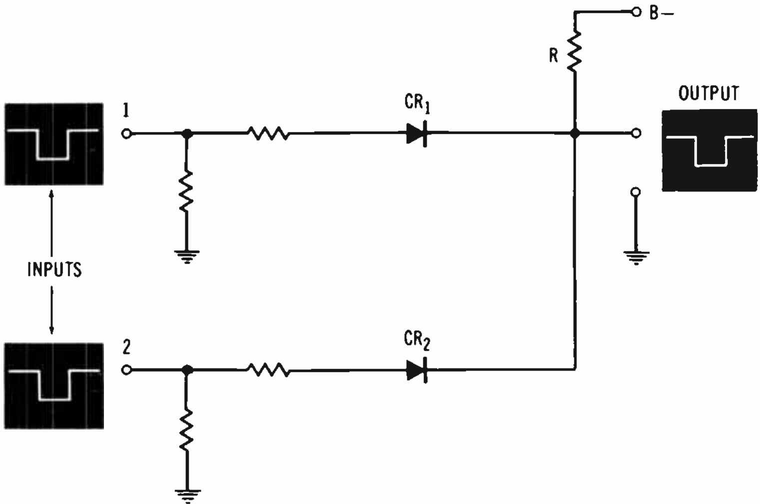


Fig. 7-14. AND gate.

the negative battery terminal for the duration of the input pulses. Therefore, to produce an output, pulse 1 *and* pulse 2 must be present. The condition necessary to produce an output from this AND gate is that two negative input pulses must occur at the same time.

Q7-23. What is a gate circuit?

Q7-24. In an AND circuit with two inputs, there is an output only if two input pulses occur at (the same time, different times).

Q7-25. The most common type of AND gate is the ______________ ______ type.

Q7-26. Gate circuits (are, are not) used in computers.

Your Answers Should Be:

A7-23. A gate circuit is one which **allows signals to go through only when certain conditions are satisfied.**

A7-24. In an AND circuit with two inputs, there is an output only if two input pulses occur at the same **time.**

A7-25. The most common type of AND gate is the **semiconductor-diode** type.

A7-26. Gate circuits are used in computers.

The OR gate in Fig. 7-15 requires either input 1 *or* input 2 to produce an output. This circuit is used when many inputs are to be gated into a single circuit.

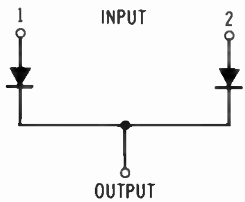


Fig. 7-15. OR gate.

Frequency-Divider Circuits

One of the most common functions of pulse circuits is counting. A step-counter or a frequency-divider circuit does this. Such a circuit may be used to count a given number of input pulses or to divide the frequency of input pulses into a lower frequency. A step counter is shown in Fig. 7-16.

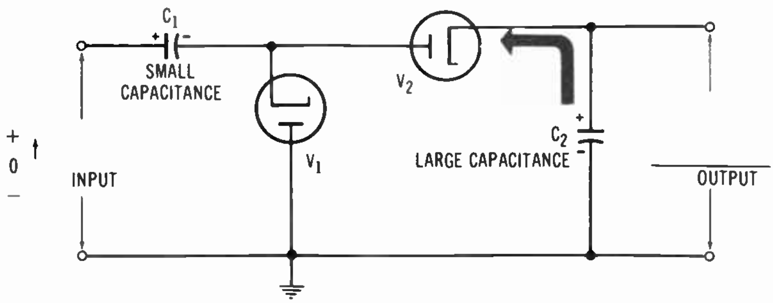
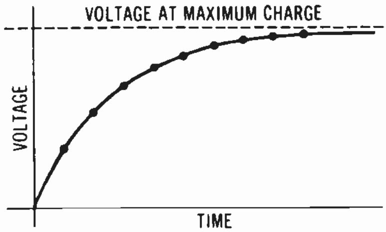


Fig. 7-16. A pulse-counter circuit.

Fig. 7-17. Capacitor charging characteristic.



When the first positive pulse is applied, electrons are removed from the left-hand plate of C_1. This causes electrons to move from the top plate of C_2, through diode V_2, to the right-hand plate of C_1. As a result, C_1 and C_2 become charged with the polarities shown. No electrons flow through V_1 because its plate is negative with respect to its cathode. At the end of the pulse, the input voltage returns to zero. Capacitor C_1 can now discharge through V_1 and the pulse source. The charge on C_2 makes the cathode of V_2 positive with respect to its plate. Therefore, V_2 cannot conduct, and capacitor C_2 cannot discharge.

Each additional pulse causes an additional charge to be added to C_2. As this cycle is repeated, the voltage across C_2 builds up in steps.

Now suppose a thyratron or another voltage-sensitive switching device is connected across the output. When the voltage across C_2 reaches the desired value, the switching device closes and C_2 is discharged. The switching device then opens, and the entire process starts over. In this example, the switching device produces an output pulse for every five input pulses; the input frequency is divided by five.

Fig. 7-17 shows the way a capacitor charges. The dots show the voltage increase for each input pulse. The actual amount of voltage depends on the nature of the pulses and the circuit. It is not desirable to design the counter so that C_2 discharges near its maximum-charge value. This is because each additional pulse causes a smaller increase in voltage, and it is difficult to be sure that the capacitor will discharge after the desired number of pulses.

Q7-27. A counter circuit counts pulses by using them to

_ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ .

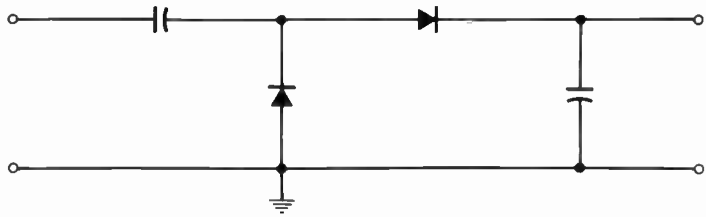
Q7-28. Draw a counter circuit that uses solid-state diodes.

Q7-29. What is an OR circuit?

Your Answers Should Be:

A7-27. A counter circuit counts pulses by using them to **charge a capacitor.**

A7-28.



A7-29. An OR circuit is a gating circuit that **produces an output when a signal is applied to any of its inputs.**

Limiters

The simplest **limiting** circuit is the positive crystal limiter. The input is a sine wave. The circuit allows only the negative half of the sine wave to pass. It blocks, or limits, the positive half—hence its name, positive limiter. Obviously, negative limiting is obtained by reversing the diode connections. This type of limiter uses zero voltage as its reference. However, other reference potentials can be used.

(A) Positive. (B) Negative.

Fig. 7-18. Sine waves limited at zero volts.

The semiconductor diode can be used to obtain a positive-limited waveform at a positive potential. In other words, less than half of the input sine wave is removed. This is accomplished by keeping the cathode at the limiting value. The battery in the illustration maintains the cathode at 25 volts positive with respect to ground. When the sine-wave input rises to 25 volts, the anode voltage rises to this amount. The diode then begins to conduct. As the input voltage increases, the diode current also increases. The voltage drop across R also increases, but the anode voltage cannot fall below 25 volts. Therefore, the anode voltage remains at 25 volts. When the sine-wave voltage goes below 25 volts positive, the anode voltage follows the input voltage.

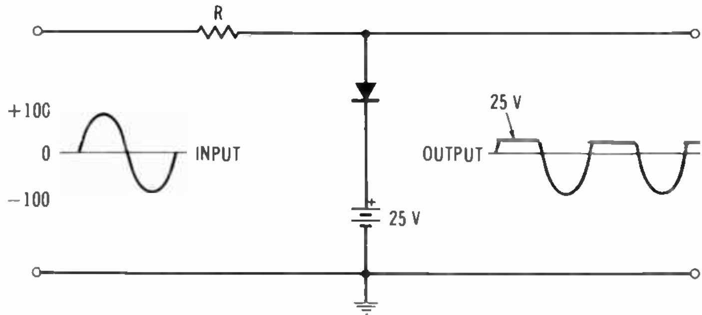


Fig. 7-19. A limiter circuit.

When a pair of diodes is biased so that one is negative and the other positive, both positive and negative limiting are obtained. The output waveform is referred to as a trapezoidal waveform.

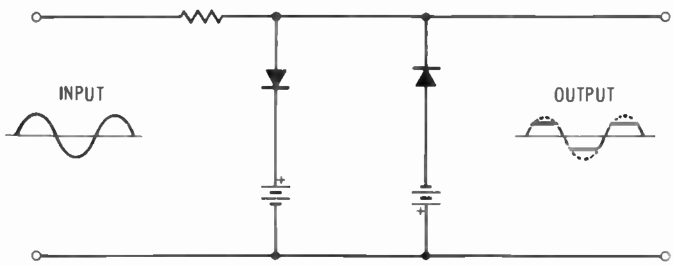


Fig. 7-20. A positive and negative limiting circuit.

Q7-30. How could the limiter circuit in Fig. 7-19 be used for negative limiting?

Q7-31. Positive and negative limiting of a waveform can be obtained by using ___ _______.

Your Answers Should Be:

A7-30. If the **battery and diode connections** were **reversed,** negative limiting would occur. In this case the reference voltage is −25 volts. The output voltage varies from −25 volts to 100 volts. The negative portion of the input sine wave is limited to −25 volts.

A7-31. Positive and negative limiting of a waveform can be obtained by using **two diodes.**

Squaring Circuit

A typical squaring circuit is the **Schmitt trigger,** shown in Fig. 7-21. This circuit can convert many input waveforms to a square-wave output. Note how it resembles a multivibrator circuit in its action.

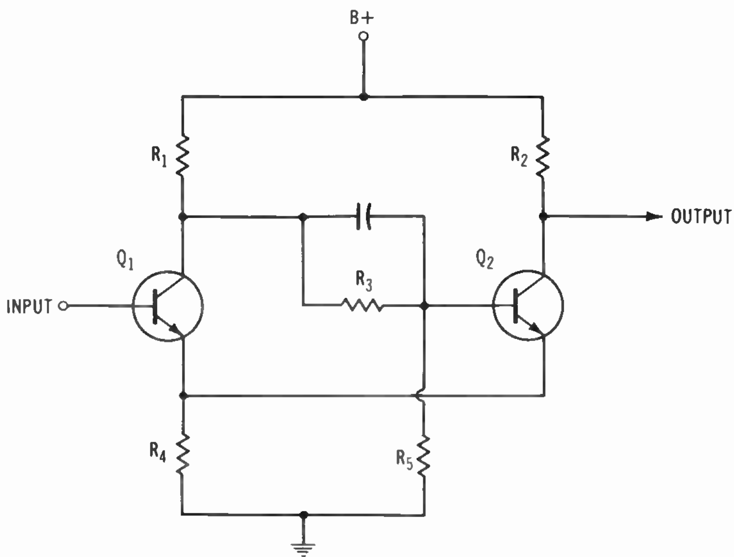
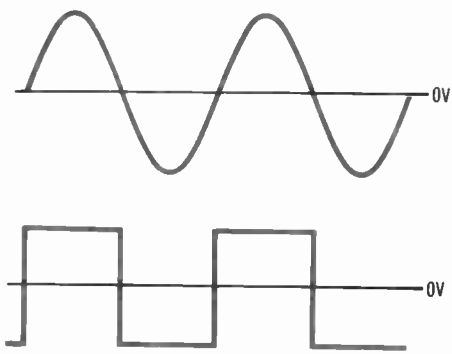


Fig. 7-21. A Schmitt-trigger circuit.

With no input, transistor Q_1 is cut off, and its collector voltage equals the battery voltage. This voltage is coupled to the base of Q_2 through R_3. Transistor Q_2 is therefore saturated. Due to the emitter current of Q_2, the top of resistor R_4 is positive.

Now a sine-wave input is placed on the base of Q_1. The positive-going signal voltage soon exceeds the emitter voltage. This causes Q_1 to conduct. The Q_1-collector voltage drops slightly, and this change is coupled to the base of Q_2. This reduces the Q_2-emitter current slightly, and the top of resistor R_4 becomes less positive. This causes Q_1 to conduct more. The current in transistor Q_1 increases regeneratively until Q_1 saturates. This immediately cuts off transistor Q_2, and its collector voltage instantly rises to its maximum positive value.

(A) Input signal.



(B) Output signal.

Fig. 7-22. Schmitt-trigger waveforms.

This state continues until the input sine wave goes negative. This reduces the Q_1-base forward bias to decrease the collector current. The Q_1-collector voltage rises. This change is coupled to the base of Q_2, causing this transistor to conduct. This condition is aided by the rising potential at the top of resistor R_4. Transistor Q_1 suddenly cuts off, and transistor Q_2 suddenly saturates. The Q_2-collector voltage drops to its lowest value. Hence a square wave has been generated from the sine-wave input.

Q7-32. The Schmitt trigger circuit produces a ______ ____ output from a sine-wave input.

Q7-33. The transistors in a Schmitt trigger circuit switch between ______ and ___________.

Your Answers Should Be:

A7-32. The Schmitt trigger circuit produces a square-wave output from a sine-wave input.

A7-33. The transistors in a Schmitt trigger circuit switch between **cutoff** and **saturation.**

DC Restorer

A **dc restorer** shifts a waveform to a level above or below a certain voltage. This is accomplished essentially by charging a capacitor to the desired level. This is also referred to as **clamping** the waveform to this level.

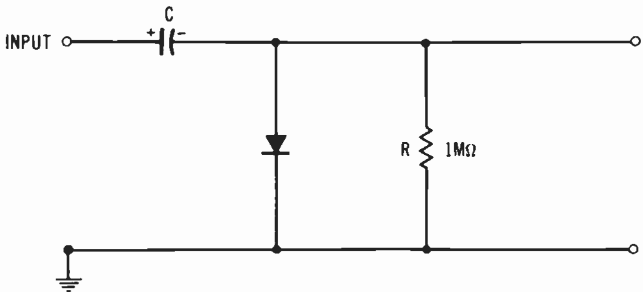


Fig. 7-23. A negative dc restorer.

Because of the presence of the diode, electrons can flow easily into the capacitor when the input voltage is positive. However, the diode does not conduct in the opposite direction, so the discharge path is through the high resistance of R. Capacitor C therefore discharges only slightly between positive half cycles. This small amount of discharge is replaced during the next positive half cycle. After a few cycles of the input voltage, capacitor C becomes charged to the peak voltage of the input sine wave.

With the capacitor charged as shown on the circuit diagram, the capacitor voltage subtracts from the input voltage when the input is positive. The voltages add when the input is negative. The result is that the output voltage is always negative, reaching zero only when the input voltage is at its positive peak.

(A) Input.

(B) Output.

Fig. 7-24. Waveforms in a negative dc restorer.

In this way the entire waveform has been shifted below the zero level to clamp the top of the waveform to zero volts. This circuit is known as a negative dc restorer. A positive dc restorer can be obtained by reversing the diode. In this case the

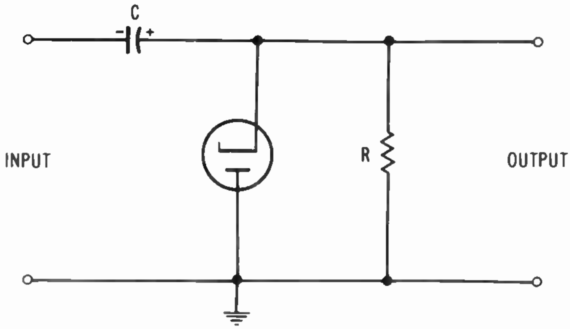


Fig. 7-25. A positive dc restorer.

entire waveform is shifted above the zero level to clamp the bottom of the waveform to zero.

Q7-34. Another name for shifting a waveform to a level above or below a certain voltage is _________.

Q7-35. Clamping depends primarily on _________ a capacitor.

Q7-36. A positive dc restorer can be made from a negative dc restorer by _________ ___ ______.

Your Answers Should Be:

A7-34. Another name for shifting a waveform to a level above or below a certain voltage is **clamping.**

A7-35. Clamping depends primarily on **charging a capacitor.**

A7-36. A positive dc restorer can be made from a negative dc restorer by **reversing the diode.**

WHAT YOU HAVE LEARNED

1. Pulse circuits are operated by large signals that are a combination of a wide range of sine-wave frequencies.
2. This kind of operation places a tube or transistor in the nonlinear portion of its characteristic curve.
3. Tubes and transistors are often driven rapidly from cutoff to saturation; therefore, their transient response is quite important to circuit performance.
4. Pulses instead of sinusoidal inputs are usually the primary signal sources in pulse circuits.
5. Sine waves can be converted to pulses by Schmitt triggers or other shaping circuits.
6. Pulse circuits can be used to count, shape waveforms, switch circuits on and off rapidly, and perform logical functions.
7. Pulse circuits are used extensively in computers, radar, and television, and in applications requiring logic operations.
8. The dc restorers are used to maintain the relationship of a waveform to some reference voltage.

8

Special Semiconductor Devices

what you will learn

This chapter covers some additional solid-state devices sometimes referred to as special devices. The reason they are referred to as special is that they differ in some ways from diodes and transistors which might be considered conventional. The special devices that you will learn about include FETs (field effect transistors), MOSFETs (metal-oxide semiconductor FETs), dual-gate MOSFETs, enhancement-mode MOSFETs, depletion-mode MOSFETs, UJTs (unijunction transistors), thyristors (which include the triac and the diac), SCRs (silicon-controlled rectifiers), and ICs (integrated circuits). You will learn that the FET and the different versions of the FET offer some characteristics that are superior in some ways to conventional transistors which are now sometimes called bipolar transistors because they operate through the movement of both holes and electrons.

You will also learn that the UJT is a unique type of oscillator whose operation is based on something called negative resistance. You will also see how SCRs, diacs, and triacs are useful in the control of circuits carrying relatively large currents. Another device that you will be introduced to is the IC which can contain more circuits in a tiny volume than could be contained in racks full of electronic equipment back in the 1940s and 1950s.

FIELD EFFECT TRANSISTOR

Junction FET

An important advancement in solid-state technology has been the development of the FET. There are actually three types of FETs—one is the junction FET, or JFET; the other two types are both metal-oxide semiconductor FETs, called MOSFETs. One MOSFET is the enhancement-mode MOSFET; the other is the depletion-mode MOSFET. First, we will consider the regular FET or JFET, whose basic operation also applies to the MOSFETs.

The FET is a three-terminal device, like the conventional or bipolar transistor. The FET terminals are called *gate*, *source*, and *drain*. The FET includes a bar of n- or p-type semiconductor material called a *channel*, as shown in Fig. 8-1. The channel is electrically similar to a resistor. One end of the channel is called the *Source* (*S*). The other end is called the

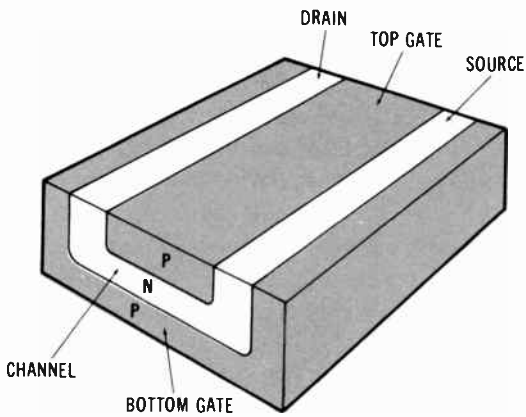


Fig. 8-1. Construction of n-channel FET.

Drain (*D*). Current carriers move along the bar and are controlled by an electric field which is applied by the *Gate* (*G*) electrode. The gate consists of two layers of semiconductor, one on each side of the channel. The current carriers in a FET are electrons if the channel is an n-type semiconductor. The gate is then p-type material. Conversely, the current carriers are holes if the FET channel is p-type material and the gate is n-type material.

A conventional transistor is referred to as a *bipolar* transistor because its current or charge carriers are both electrons and holes. The FET is called a *unipolar* transistor because its operation is based on the movement of only one polarity of carrier, either holes or electrons. As mentioned before, for an n-type carrier, the carriers are electrons; and for a p-type channel, the carriers are holes.

Q8-1. **The three types of FETs are the _________ FET, the _____________ mode MOSFET, and the ___________ mode MOSFET.**

Q8-2. **The three FET terminals are called the _____, the _______, and the ______.**

Q8-3. **In the n-channel FET, the current carriers are (holes, electrons).**

Q8-4. **The FET is a unipolar transistor because its carriers are of only one _________.**

Your Answers Should Be:

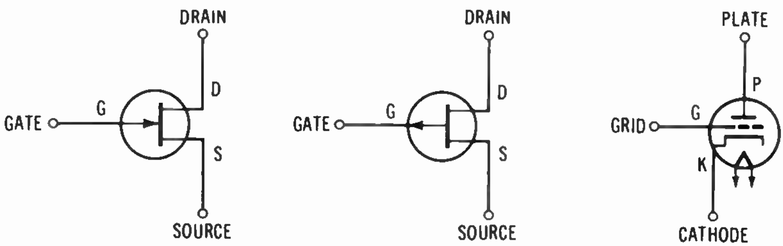
A8-1. The three types of FETs are the **junction** FET, the **enhancement-mode** MOSFET, and the **depletion-mode** MOSFET.

A8-2. The three FET terminals are called the **gate,** the **source,** and the **drain.**

A8-3. In the n-channel FET, the current carriers are **electrons.**

A8-4. The FET is a unipolar transistor because its carriers are of only one **polarity.**

The symbols for the n-channel and the p-channel FETs are shown in Fig. 8-2. Also shown is the symbol for the triode vacuum tube.



(A) N-channel. (B) P-channel. (C) Triode tube.

Fig. 8-2. Field effect transistors.

For the n-channel FET, biasing, voltage polarities, and operating characteristics are much like those for a triode vacuum tube. The gate corresponds to the grid of the triode tube, the drain corresponds to the plate, and the source corresponds to the cathode of the triode tube, as shown in Fig. 8-2. Like the triode, the gate of the n-channel FET is biased negative with respect to the source. This reverse biases the n-channel FET, cutting off any current flow across the gate-source junction. The drain is forward biased or positive with reference to the source. Performance and characteristics of a p-channel FET are exactly the same as for the n-channel FET, but voltage polarities are opposite—the gate is reverse-biased, but positive, for the p-channel FET; and the drain is forward biased (negative) in reference to the source.

The FET is widely used in electronics. It has lower noise generation due to the absence of any current flow in its input circuit than either the bipolar transistor or the vacuum tube. Also, the FET has a high-input resistance (hundreds of megohms) and is a voltage-amplifying device like the vacuum tube. The FET can provide high gain or amplification and is often used in small-signal circuits. A disadvantage is that if the gate becomes forward biased, the input resistance decreases sharply and the gain of the FET drops. Also, the FET becomes somewhat unstable due to increased leakage currents when subjected to increased temperatures. However, its advantages far outweigh these disadvantages.

Q8-5. **Voltage polarities and operative characteristics for the n-channel FET are much like those for the ______ vacuum tube.**

Q8-6. **The p-channel FET has its gate biased (negative, positive) with regard to its source.**

Q8-7. **The p-channel FET has its drain biased (negative, positive) with regard to its source.**

Q8-8. **Advantages of the FET are its low _____ generation, its high input __________, and its (high, low) gain.**

Q8-9. **Disadvantages of the FET are its loss of ____ if its gate becomes forward biased, and it becomes unstable with __________ temperatures.**

Your Answers Should Be:

A8-5. Voltage polarities and operative characteristics for the n-channel FET are much like those for the triode vacuum tube.

A8-6. The p-channel FET has its gate biased **positive** with regard to its source.

A8-7. The p-channel FET has its drain biased **negative** with regard to its source.

A8-8. Advantages of the FET are its low **noise** generation, its high input **impedance**, and its **high** gain.

A8-9. Disadvantages of the FET are its loss of **gain** if its gate becomes forward biased, and it becomes unstable with **increased** temperatures.

MOSFETS

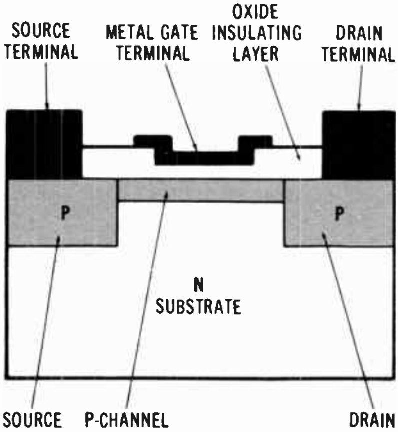
In most ways, the MOSFET is similar in construction and operation to the JFET, but in the MOSFET there is a thin insulating layer between the metal gate electrodes and the channel. For that reason, MOSFETs are sometimes called IGFETs (insulated-gate FETs). In the MOSFET, the conductance of the conducting path between gate and source is controlled by a reverse-biased pn junction. In the MOSFET, the thin insulating layer is silicon dioxide. The insulation between gate and transistor body effectively puts a resistor in series with the gate and the result is a very high input-resistance for the MOSFET, up to 10^{14} ohms. The gate and channel act the same as a capacitor—an insulating layer separating two conducting surfaces.

There are two types of MOSFETs as distinguished by their modes of operation. One type operates in the *depletion* mode; the other operates in the *enhancement* mode.

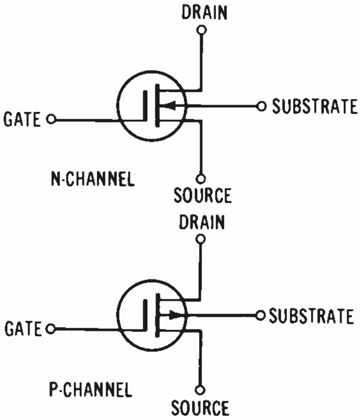
Depletion-Mode MOSFET

In the depletion-type MOSFET, a zero gate-to-source bias results in a conducting path between source and drain along the channel under the gate region.

Fig. 8-3 shows a p-channel depletion-type MOSFET; n-channel types are also available. When the gate is sufficiently reverse-biased, the channel can be depleted of charge carriers, or cut off. Reverse bias polarity is negative with respect to the source for *n*-channel MOSFETs and positive for p-channel MOSFETs.



(A) P-channel.



(B) Schematic symbols.

Fig. 8-3. Depletion-type MOSFET.

Depletion-type MOSFETs exhibit a unique property in that a forward bias applied to the gate can cause an increase in charge carriers in the channel making possible an increase in conduction in the channels. Furthermore, due to the insulating layer, the forward bias does not result in gate current which could cause reduced power output as would occur in the JFET.

Q8-10. In the MOSFET, a thin insulating layer separates the gate electrodes from the ________.

Q8-11. The MOSFET conducting path between gate and source is controlled by a ________ biased pn junction.

Q8-12. There are two types of MOSFET—the ___________ mode MOSFET and the _____________ mode MOSFET.

Q8-13. When the depletion-type MOSFET is sufficiently ________ biased, the channel can be cut off.

Your Answers Should Be:

A8-10. In the MOSFET, a thin insulating layer separates the gate electrodes from the **channel.**

A8-11. The MOSFET conducting path between gate and source is controlled by a **reverse-biased** pn junction.

A8-12. There are two types of MOSFETs—the **depletion**-mode MOSFET and the **enhancement**-mode MOSFET.

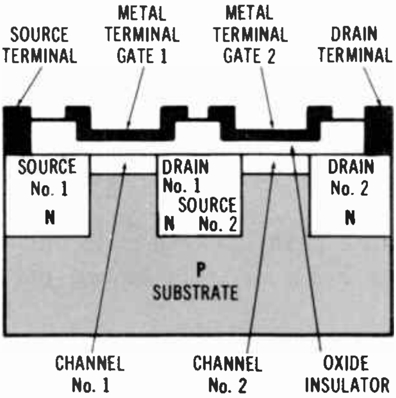
A8-13. When the depletion-type MOSFET is sufficiently **reverse-biased,** the channel can be cut off.

Dual Gate MOSFET

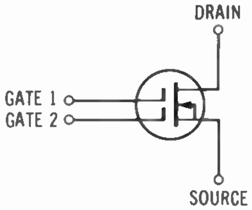
Depletion-mode MOSFETs are also available having two separate and independent gates, as shown in Fig. 8-4. These are called dual-gate MOSFETs and they provide unique advantages in a number of applications including being used as rf amplifiers, mixers or converters, demodulators, and gain-controlled amplifiers that extend into the uhf spectrum. The device shown is an n-channel type, along with its schematic symbol; p-channel types are also available.

Enhancement-Mode MOSFET

The enhancement-mode MOSFET exhibits zero conductivity between source and drain for both zero bias and reverse bias.



(A) N-channel dual-gate MOSFET.

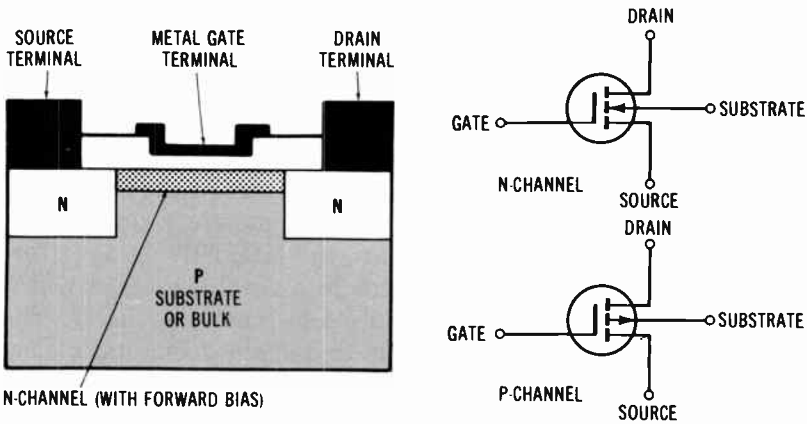


(B) Schematic symbol (includes substrate and case).

Fig. 8-4. Dual gate MOSFET and schematic symbol.

With zero current, no channel actually exists. When forward bias is applied to the gate-source junction, it produces an electric field that attracts minority carriers from the substrate or bulk thus increasing the total number of carriers and the source-to-drain current conduction. The enhancement-mode MOSFET finds greatest use in digital or pulse-type circuits and in switching applications.

Fig. 8-5 shows the structure of the n-channel enhancement-type MOSFET and schematic symbols for both the n-channel and p-channel enhancement MOSFETs.



(A) N-channel.

(B) Schematic symbols.

Fig. 8-5. Enhancement type MOSFET.

Q8-14. A MOSFET of the depletion-mode type and having two separate and independent gates is known as a ____ ____ MOSFET.

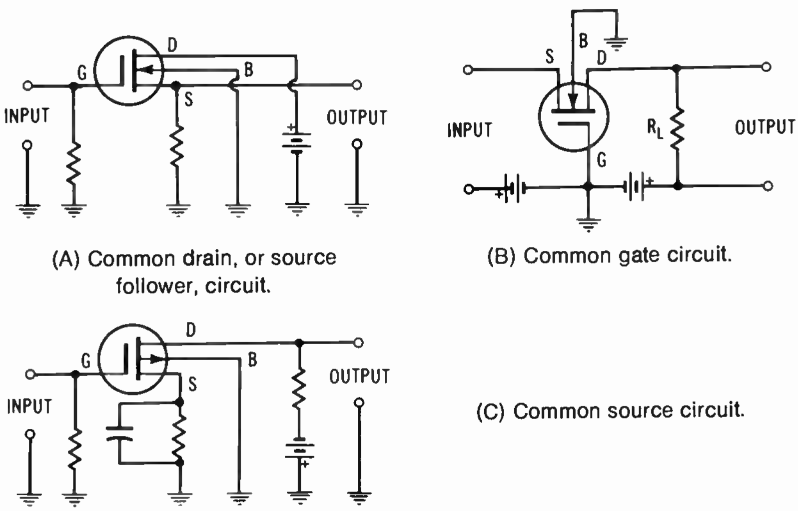
Q8-15. In the enhancement-mode MOSFET, zero bias and reverse bias result in ____ conductivity between source and drain.

Q8-16. The enhancement-mode MOSFET is used mainly in ________ or _____ type circuits.

> **Your Answers Should Be:**
>
> A8-14. A MOSFET of the depletion-mode type and having two separate and independent gates is known as a **dual-gate** MOSFET.
>
> A8-15. In the enhancement-mode MOSFET, zero bias and reverse bias both result in zero conductivity between source and drain.
>
> A8-16. The enhancement-mode MOSFET is used mainly in **digital-** or **pulse-type** circuits.

MOSFET Applications

MOSFETs in general can operate effectively at higher frequencies and higher temperatures than bipolar transistors, and they also require less protection from overvoltages. They are also less costly to manufacture. However, where both high-frequency and high-power rf applications are required, the bipolar transistor is superior. Also, the MOSFET is less "forgiving" than the bipolar transistor to excessive voltage which can cause puncturing of the thin oxide insulating layer. The MOSFET is also more susceptible to damage from static electricity as is often generated during manufacture, handling, and shipping.



(A) Common drain, or source follower, circuit.

(B) Common gate circuit.

(C) Common source circuit.

Fig. 8-6. Basic MOSFET circuits.

JFETs and MOSFETs can be connected in the basic configurations, the same as bipolar transistors. Shown in Fig. 8-6 are circuits representing the MOSFET connected in the common-drain, or source-follower, the common-gate, and the common source configurations.

Also shown here is a comparison of how MOSFET and JFET basic configurations correspond to equivalent bipolar-transistor circuits.

Bipolar Configuration	FET Configuration
Common Collector or Emitter Follower	Common Drain or Source Follower
Common Base	Common Gate
Common Emitter	Common Source

The common-source circuit is the most-used FET circuit because it provides high input impedance, medium to high output impedance, and actual voltage gains exceeding unity (one). The common-gate FET circuit can convert a low impedance applied to its input to a high impedance at its output, and thus can be used as a transformer. The common-gate circuit is useful at high frequencies and it can provide high gain.

The common-drain (also called source follower) circuit has a fairly high input impedance and low output impedance. The input signal is applied between drain and gate and has the same phase as the output signal which is between drain and source. Gain of the common-drain circuit is always less than one.

Q8-17. MOSFETs can operate effectively at higher temperatures than can ________ transistors.

Q8-18. Puncturing of the thin oxide insulating layer of the MOSFET can be caused by excessive ________.

Q8-19. The MOSFET is susceptible to damage from ______ electricity.

Q8-20. The bipolar emitter follower configuration is equivalent to the FET ______ follower.

Q8-21. The FET configuration having low input and high output impedance is the common ____ circuit.

Your Answers Should Be:

A8-17. MOSFETs can operate effectively at higher temperatures than can bipolar transistors.

A8-18. Puncturing of the thin oxide insulating layer of the MOSFET can be caused by excessive voltage.

A8-19. The MOSFET is susceptible to damage from static electricity.

A8-20. The bipolar emitter follower configuration is equivalent to the FET source follower.

A8-21. The FET configuration having low input and high output impedance is the common gate circuit.

FET FAMILY OF CURVES

The JFET and the MOSFET having operating characteristics that are similar to those of the vacuum-tube triode.

A response curve for a typical JFET with a gate-to-source bias of zero is shown in Fig. 8-7.

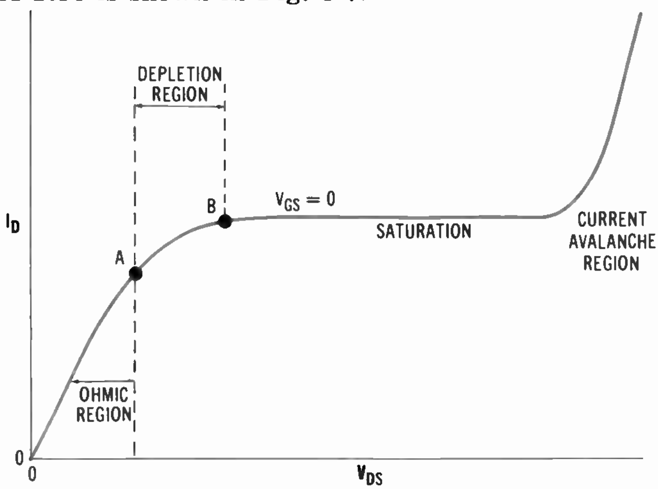


Fig. 8-7. JFET response curve, zero gate-source bias.

From 0 to point A, drain current I_D increases steadily as drain-source voltage V_{DS} is increased. Between points A and B, a *pinch-off* effect in the depletion region causes a tapering off in current. The point at which the current increase drops off significantly is called the pinch-off drain current. Further increases in voltage cause only a slight increase in drain current and this relatively horizontal part of the response curve is referred to as the *saturation* region. If the voltage between drain and source is increased further, a point of current avalanche is reached where there is a sharp rise in current. Normal operation of the FET does not include the avalanche area.

The FET channel conductance is related to both drain voltage and gate voltage. The channel current can be reduced in the n-channel FET by a negative bias voltage between the gate and the source. Such a dc bias sets up a larger depletion area and, therefore, increases the channel resistance for a given drain-source voltage. The effect is that it pinches off at a lower drain-source voltage.

With a high enough gate-bias voltage, channel current can be reduced to zero, just as a vacuum tube control grid can cut off plate current.

By using various values of gate bias, and plotting drain voltage versus drain current for each bias, a family of JFET curves can be set up as shown in Fig. 8-8. Note that there are three main regions for each curve. In the ohmic region, the drain current rises quickly with an increase in drain-source voltage. But in the depletion region, as drain voltage is increased, the current rise is less, and finally the curve bends

Q8-22. The JFET and the MOSFET have operating characteristics that are similar to those of the vacuum tube _______.

Q8-23. The JFET response curve shown was drawn using values of drain current versus drain-to-source voltage while the gate-to-source bias was kept at ____.

Q8-24. The region between *A* and *B* on the response curve is called the __________ region.

Q8-25. The part of the response curve above *B* is called the ___________ region.

Q8-26. The drop off in current in the saturation region is due to the _________ effect.

Q8-27. The FET is not normally operated in the __________ area.

Your Answers Should Be:

Q8-22. The JFET and the MOSFET have operating characteristics that are similar to those of the vacuum **triode.**

A8-23. The JFET response curve shown was drawn using values of drain current versus drain-to-source voltage while the gate-to-source bias was kept at **zero.**

A8-24. The region between *A* and *B* on the response curve is called the **depletion** region.

A8-25. The part of the response curve above *B* is called the **saturation** region.

A8-26. The drop off in current in the saturation region is due to the **pinch-off** effect.

A8-27. The FET is not normally operated in the **avalanche** area.

to reach saturation. In the saturation region, there is a very slow increase in drain current with increased drain voltage. This saturation region is the normal operating section of a JFET.

The FET can provide voltage, current, and power gains. The I_{DSS} point indicated in the figure is usually specified for the drain-source voltage that corresponds to the beginning of

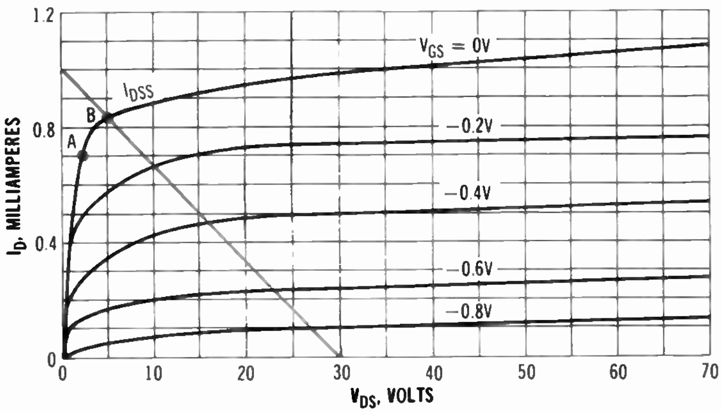


Fig. 8-8. JFET family of curves.

the constant-current saturation region of the zero-bias curve.

The gate-source pinch-off voltage V_P is defined as that gate-bias voltage V_{GS} at which the drain current is practically zero for a specified drain voltage. At a specified V_{DS} of 5 volts, you can interpret the curve to indicate that the pinch-off voltage is approximately 0.8 volt.

FET OPERATION WITH AC INPUT SIGNAL

The operation of the common-source n-channel JFET with an ac input signal applied is described as follows, with reference to Fig. 8-9.

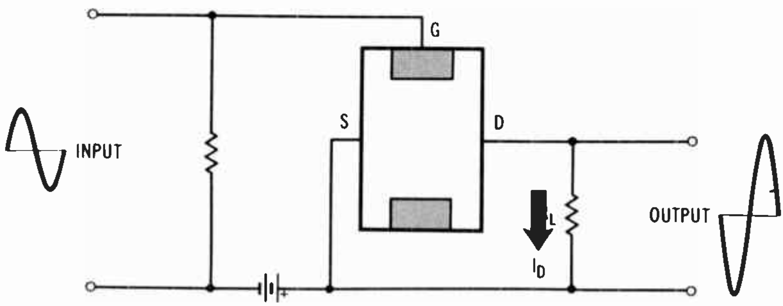


Fig. 8-9. JFET with an ac input signal.

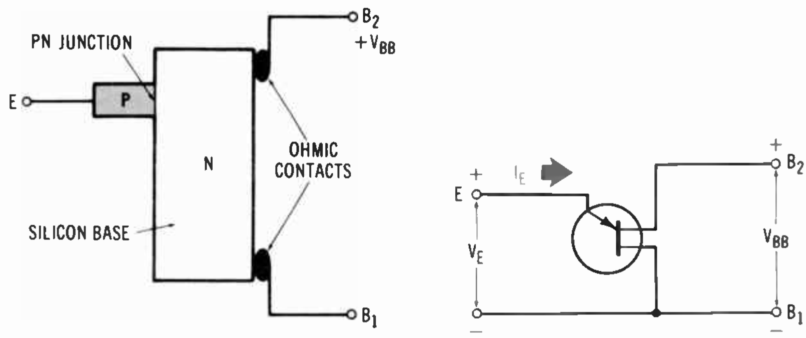
An ac signal applied between gate and source causes the depletion area in the channel to vary with that signal and, at the same time, there are corresponding changes in the resistivity of the channel. Therefore, the charge motion varies. This produces a like change in the external drain current I_D. A small signal-voltage change at the input produces a substantial change in the drain current. As a result the drain voltage change will be an amplified version of the input signal.

A positive swing of the input signal causes the depletion area to decrease and the drain current to increase. The increased drain current results in a drop in the drain voltage, producing the negative excursion of the output signal.

The negative sweep of the input signal increases the depletion region and results in a decrease in drain current and the drain voltage swings positive. Therefore, the output voltage and input voltage are out of phase in this common-source circuit.

THE UNIJUNCTION TRANSISTOR

The UJT (unijunction transistor) is sometimes called a double-base diode, is a single-junction semiconductor device with three terminals. Its special characteristics make the UJT useful in certain types of oscillator, switching, and trigger circuits. The construction of the UJT is shown in Fig. 8-10, along with the circuit symbol and the appropriate circuit voltage-current relations. The base structure of a UJT is lightly doped n-type silicon, which has high resistance. The ordinary contact base connections at each end, B_1 and B_2, are not rectifying connections. They allow current flow in both directions. The one rectifying connection is the pn junction between the emitter and the base. The resistance of the silicon base between B_1 and B_2 is called the interbase resistance, R_{BB}. The value of R_{BB} varies from about 4 to 10 thousand ohms. Internally, the base resistance acts like a voltage divider distributing the bias voltage V_{BB} along the length of the base.



(A) Basic construction. (B) Circuit symbol, including voltage-current relations.

Fig. 8-10. Basic construction of unijunction transistor.

UJT Negative Resistance

The interbase resistance can be considered as two resistances. One resistance, between B_2 and E, is shown in Fig. 8-11. Because the emitter was shown in the previous figure closer to base 2 than to base 1, R_{B2} is less than R_{B1} if the emitter is open circuited so that no emitter current flows. Base 1 resistance varies with emitter current. That is why it is shown as a potentiometer in the equivalent circuit. The diode represents the emitter-base rectifying junction.

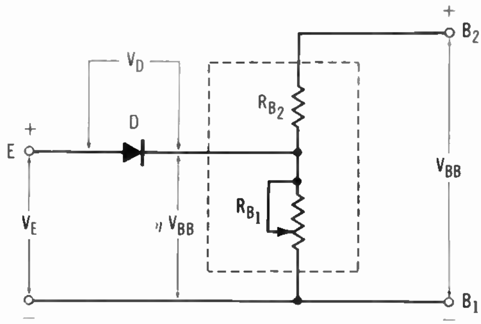


Fig. 8-11. Unijunction transistor equivalent circuit.

In Typical Operation of the UJT

The emitter junction of the UJT is forward biased, by applying a positive voltage to emitter E and a positive bias voltage V_{BB} to base B_2. Base 1 is common to both the input and the output. The voltage appearing at the emitter-to-base 1 region due to voltage-divider action is determined by the formula

$$V_{B1} = \frac{R_{B1}}{R_{B1} + R_{B2}} V_{BB}$$

The intrinsic standoff (resistance) ratio of the two regions is η (Greek letter *Eta*) and is found by the formula

$$\eta = \frac{R_{B1}}{R_{B1} + R_{B2}} = \frac{R_{B1}}{R_{BB}}$$

Q8-28. An ac signal applied to the FET input causes the depletion areas in the channel to vary and, at the same time, produces a like change in the external _ _ _ _ _ current.

Q8-29. Because of the changes in drain current corresponding with the changes in the input voltage, the _ _ _ _ _ voltage change will be an amplified version of the input signal.

Q8-30. Another name for the unijunction transistor is _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _.

Q8-31. The only junction in the unijunction transistor is between base and _ _ _ _ _ _ _ _.

Your Answers Should Be:

A8-28. An ac signal applied to the FET input causes the depletion areas in the channel to vary and, at the same time, produces a like change in the external **drain** current.

A8-29. Because of the changes in drain current corresponding with changes in the input voltage, the **drain** voltage change will be an amplified version of the input signal.

A8-30. Another name for the unijunction transistor is **double-base diode.**

A8-31. The only junction in the unijunction transistor is between base and **emitter.**

The response curve of the UJT is shown in Fig. 8-12. Notice that for the condition of reverse bias at cutoff, a small leakage current flows. As reverse bias is decreased (increase in V_E), emitter current I_E becomes less negative.

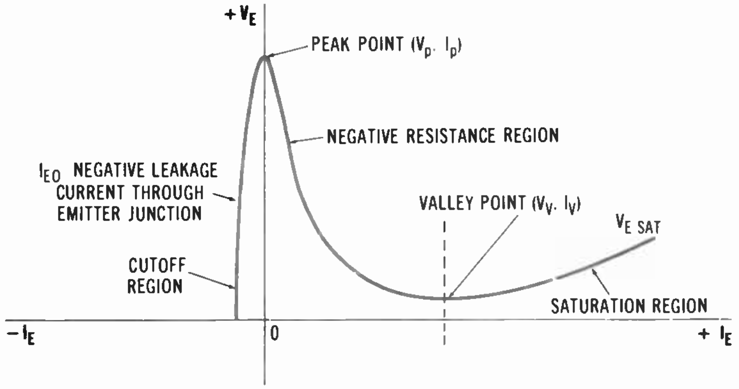


Fig. 8-12. Unijunction transistor voltage-current characteristic.

Near the zero-current value for I_E, V_E is of sufficient amplitude to cause at least a portion of the emitter junction to be forward biased. The emitter then injects holes into the base bar and these holes are attracted toward base B_1 by the relatively negative voltage at B_1, and the resistivity of the base bar between the emitter and base B_1 is lowered. The result is that the distribution of base voltage is altered, with the end of the pn junction nearest base B_1 becoming biased even more in the forward direction so that even more holes are injected into the base. This action is equivalent to positive feedback: the conductivity of the base region increases rapidly. There has been an increase in conductivity; V_E decreases as I_E increases. Since this behavior is just the opposite of that expected from Ohm's law, the UJT is exhibiting negative resistance.

This negative-resistance characteristic of the UJT makes it well suited to use in oscillator, timing, and multivibrator circuits.

Interpreting the Negative Resistance Characteristic

In the characteristic curve for the UJT, notice that the point of transition from cutoff to conduction is called the peak point. The peak-point emitter voltage, V_P, depends on the interbase voltage V_{BB}. The peak-point emitter current, I_P, corresponds to the emitter current at the peak point. It represents the minimum current required to turn on the UJT, and is inversely proportional to the interbase voltage V_{BB}.

The negative-resistance region continues until saturation is reached, and this point on the emitter V-I characteristic is called the valley point. The valley voltage V_v which is the emitter voltage at the valley point, increases as V_{BB} increases. Also it decreases in series with base B_1. The valley current I_v is the emitter current at the valley point. The valley current increases as V_{BB} increases, and decreases with resistance in series with base B_1 or base B_2.

Q8-32. In the UJT, base B_1 resistance varies with ________ current.

Q8-33. For the UJT circuit shown, the emitter junction is forward biased by applying a positive voltage to the ________ and a _________ bias voltage V_{BB} to base B_2.

Q8-34. As the UJT reverse bias is decreased, the ________ current becomes less negative.

Q8-35. If the operation of the UJT is such that V_E decreases as I_E increases, the UJT is exhibiting _________ resistance.

Your Answers Should Be:

A8-32. In the UJT, base B_1 resistance varies with **emitter** current.

A8-33. For the UJT circuit shown, the emitter junction is forward biased by applying a positive voltage to the **emitter** and a **positive** bias voltage V_{BB} to base B_2.

A8-34. As the UJT reverse bias is decreased, the **emitter** current becomes less negative.

A8-35. If the operation of the UJT is such that V_E decreases as I_E increases, the UJT is exhibiting **negative** resistance.

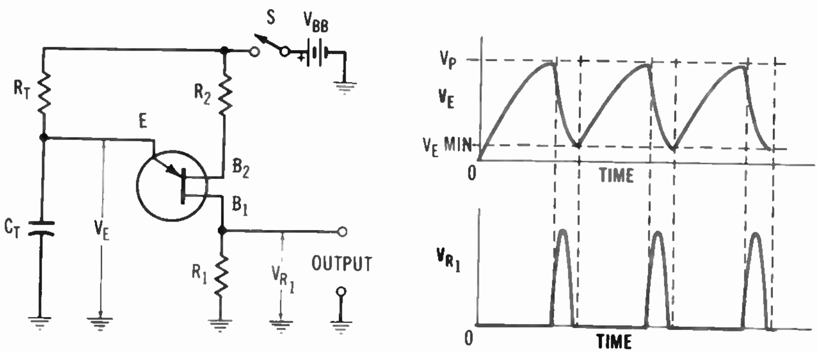
For current above the valley point (saturation), the voltage increases slowly. The emitter saturation voltage V_{Esat} indicates the forward drop across the UJT from the emitter to base B_1, when it is conducting the maximum-rated emitter current.

As the amplitude of the input pulse decays toward zero, the number of holes that the emitter injects into the base decreases, increasing the voltage drop in the base. This causes that end of the pn junction nearest to base B_1 to be biased in reverse again. As more and more of the junction is cut off, the injection falls off rapidly and another positive-feedback process is initiated and the whole junction area is cut off suddenly.

A wide variation in emitter-input impedance of the UJT occurs between the two operating regions. At cutoff, the impedance is that of a reverse-biased junction diode and ranges from several hundred thousand ohms to several million ohms. In the negative-resistance region, the impedance is of the order of thousands of ohms. In the saturation region, the impedance is hundreds of ohms.

UJT Relaxation Oscillator

The UJT is frequently used as a relaxation oscillator in sawtooth and pulse generators, triggering circuits, and timing circuits. An example of the UJT relaxation oscillator is shown in Fig. 8-13. Operation of the circuit is explained briefly as follows: When switch S is closed, timing capacitor C_T charges through timing resistor R_T. At that time emitter-B_1 resistance becomes small and C_T discharges rapidly through R_1, B_1, and emitter. Thus, the emitter voltage rises toward V_{BB}, the supply voltage. As soon as emitter voltage V_E reaches the peak-point voltage of the UJT, the UJT triggers *on* as a result of the emitter diode becoming forward biased. There is now a low-resistance path between emitter and B_1, allowing C_T to discharge and V_E to decrease quickly. When V_E decreases to where UJT conduction ceases, the discharge path is opened. The charging cycle then begins again and will repeat over and over producing a series of pulses at the output across R_1.



(A) Relaxation oscillator. (B) Waveforms.

Fig. 8-13. Unijunction transistor relaxation oscillator and waveforms.

Q8-36. In the UJT characteristic curve, the point of transition from ______ to conduction is called the peak point.

Q8-37. The peak-point ________ ________ is the minimum current required to turn *on* the UJT.

Q8-38. In the UJT negative-resistance region, the impedance is of the order of __________ of ohms.

Q8-39. In the UJT relaxation oscillator, the UJT triggers (on, off) as soon as the emitter voltage reaches the peak-point voltage.

Your Answers Should Be:

A8-36. In the UJT characteristic curve, the transition point from **cutoff** to conduction is called the peak point.

A8-37. The peak-point **emitter current** is the minimum current required to turn *on* the UJT.

A8-38. In the UJT negative-resistance region, the impedance is of the order of **thousands** of ohms.

A8-39. In the UJT relaxation oscillator, the UJT triggers **on** as soon as the emitter voltage reaches the peak-point voltage.

UJT Frequency and Waveforms

Frequency F of the UJT relaxation oscillator is determined approximately by the formula

$$F \cong \frac{1}{R_T C_T \ln \frac{1}{1-\eta}}$$

where,

ln is the natural logarithm,
η is the intrinsic standoff ratio of the UJT.

The waveform at the emitter is sawtooth in shape while narrower pulses are at the base terminals. For the circuit shown in Fig. 8-13, a B_1 output will be a positive pulse, while there will be a negative pulse output at B_2.

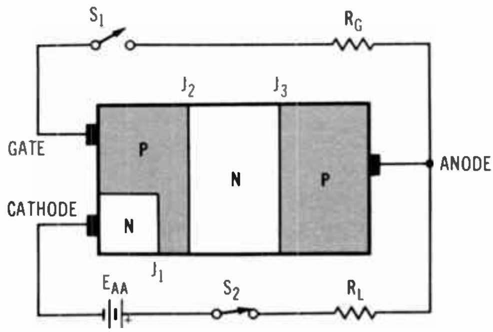
THYRISTORS

Types of Thyristors

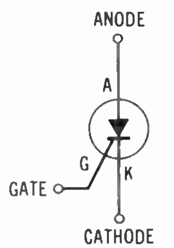
Thyristors are a group of semiconductor devices that include the *SCR* (silicon controlled rectifier), the *triac*, and the *diac*. Thyristors are used widely in the switching and triggering of large-signal and power circuits. Thyristors consist of three-layer or four-layer semiconductors and have from two to four terminals.

SCRs

The SCR is an npnp multiple-layer semiconductor. In the SCR there are four layers and three junctions. The construction is shown in Fig. 8-14, along with its use in a *dc* circuit to demonstrate its operation.



(A) Structure and dc circuit.



(B) Symbol.

Fig. 8-14. Silicon controlled rectifier.

In this circuit, the objective is to supply load R_L with current from voltage source E_{AA}. The supply circuit is from E_{AA} to the cathode of the SCR, through the SCR and its anode, through load R_L and back to E_{AA}.

Q8-40. In the UJT relaxation oscillator shown, the waveform on the emitter is a _________ and a narrower (positive, negative) pulse will be at B_2.

Q8-41. The SCR, the triac, and the diac are classified as ___________.

Q8-42. In the SCR, there are ____ layers and _____ junctions.

Your Answers Should Be:

A8-40. In the UJT relaxation oscillator shown, the waveform on the emitter is a **sawtooth** and a narrow **negative pulse** will be at B_2.

A8-41. The SCR, the triac, and the diac are classified as **thyristors**.

A8-42. In the SCR there are **four** layers and **three** junctions.

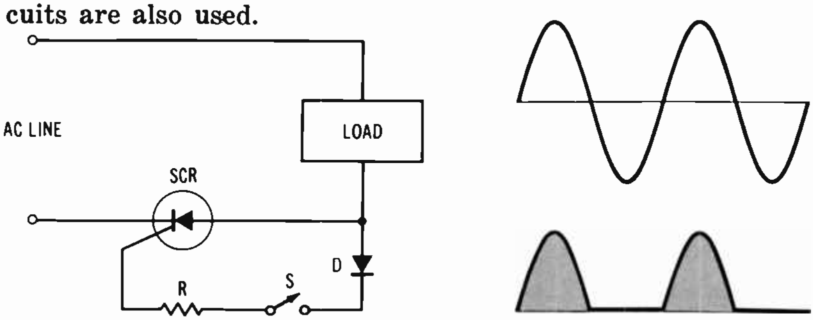
SCR in a DC Circuit

Refer to Fig. 8-14 for the following analysis of operation. At the start, if E_{AA} is less than the forward breakover voltage of the SCR no useful current flows. Now let's suppose switch S_1 is closed; the gate is then forward biased from E_{AA} through load R_L and gate resistance R_G. This allows current to flow through junction J_2. Junction J_3, already forward biased by G_{AA}, then provides a path for current from E_{AA}, through the SCR from cathode to anode, and load R_L, accomplishing the objective. It is important to understand that even though the circuit through S_1 to the gate is now opened, current will continue through R_L because J_2 has lost control of current carriers. Further, reverse-biasing of the gate will not stop the current. Only by reducing the anode voltage E_{AA} to almost zero will the current stop.

Another important factor is that if E_{AA} polarity is reversed and S_1 is closed to forward bias the gate, no current will flow. The conclusion is that the SCR can act as a rectifier and is equivalent to a thyratron tube in which the grid can cause the tube to conduct on positive half cycles, but cannot cut the tube off once it conducts. Only when the negative half cycles appear on the plate does current flow stop.

SCR Control in an AC Circuit

An example of how the SCR is used to control power to an ac load is shown in Fig. 8-15. Current of several amperes to the load is controlled by the SCR which is activated by switch S. Current through switch S is normally only a few milliamperes. The value of resistor R is set to limit the peak current through the gate to 2 amperes or less. Closing switch S connects the gate to the anode and turns on, or "fires," the SCR. As soon as the load current starts, the gate voltage drops and gate current ceases. Diode D prevents the flow of reverse gate current. In this circuit, current flows only during those half cycles when the anode is positive. Full-wave SCR control circuits are also used.



(A) Circuit. (B) Waveform.

Fig. 8-15. Use of SCR to control ac load and waveform.

Q8-43. Once the SCR conducts it can be turned off only by removing the _____ voltage or reducing it to nearly zero.

Q8-44. The SCR is turned on by forward biasing the ____.

Q8-45. In the ac control circuit shown, switch S controls only a few (amperes, milliamperes).

Q8-46. Reverse gate current through the SCR in the circuit shown is prevented by the _____.

Your Answers Should Be:

A8-43. Once the SCR conducts it can be turned off only by removing the **anode** voltage or reducing it to nearly zero.

A8-44. The SCR is turned on by forward biasing the **gate.**

A8-45. In the ac control circuit shown, switch S controls only a few **milliamperes.**

A8-46. Reverse gate current through the SCR in the circuit shown is prevented by the **diode.**

Half-Wave Phase Control of SCR

In Fig. 8-16, an SCR circuit is shown for dimming one or more lamps.

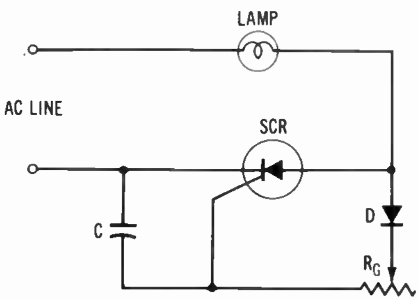


Fig. 8-16. SCR circuit for dimming a lamp by phase control.

The degree of dimming is accomplished by controlling the phase of the ac triggering voltage which is applied to the gate. During the half cycle when the SCR anode is positive and the SCR can turn on, capacitor C charges through the lamp and through resistance R_G. When C is charged to enough voltage, the SCR turns on, or fires.

If the slider of R_G is set for a high resistance, capacitor C charges slowly and the firing of the SCR is delayed. This results in current flow through the load, for only a few degrees of the ac positive half cycle, as shown in Fig. 8-17.

A medium setting of R_G results in current flow during approximately half, or 90 degrees, of each positive alternation of the ac wave. Setting R_G at a low value lets C charge very quickly and allows current to flow during nearly the full 180 degrees of the positive half cycle. As in the previous circuit, diode D prevents reverse voltage from being applied to the SCR gate when the ac reverses polarity.

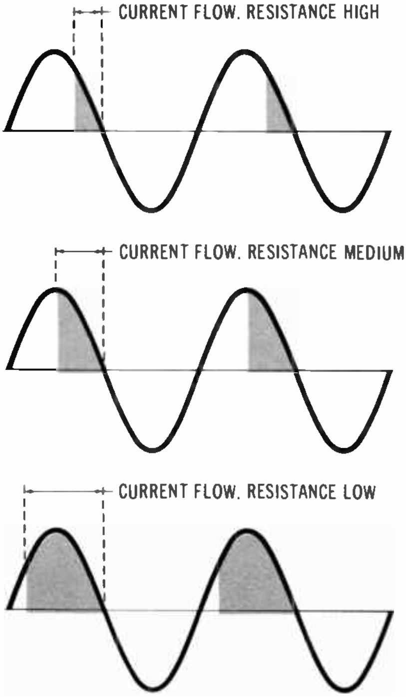


Fig. 8-17. Phase control of current through a load.

Q8-47. The brightness of the lamp shown in the SCR dimming circuit is controlled by the _____ of the ac triggering voltage applied to the gate.

Q8-48. In the SCR half-wave phase control circuit, if R_G is set at its midresistance point, current will flow through the load during approximately __ degrees of the positive half cycles.

Q8-49. The purpose of diode D in the SCR phase-control circuit is to prevent ________ voltage from reaching the gate during negative half cycles.

Your Answers Should Be:

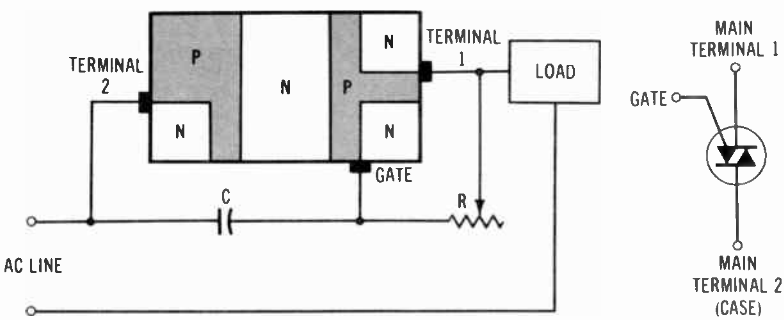
A8-47. The brightness of the lamp shown in the SCR dimming circuit is controlled by the **phase** of the ac triggering voltage applied to the gate.

A8-48. In the SCR half-wave phase control circuit, if R_G is set at its midresistance point, current will flow through the load during approximately **90** degrees of the positive half cycles.

A8-49. The purpose of diode D in the SCR phase-control circuit is to prevent **reverse** voltage from reaching the gate during negative half cycles.

The Triac

The *triac* (*tri*ggers on *ac*) is effectively a two-way SCR which will provide for control of ac current in both directions. The principle of the triac is shown in Fig. 8-18. The triac symbol is also shown.



(A) Principle and circuit.

(B) Schematic symbol.

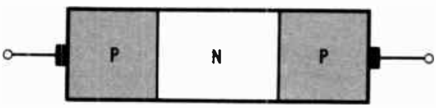
Fig. 8-18. Triac circuit and symbol.

The three connections or electrodes are called terminal 1, terminal 2, and the gate. Either a positive or a negative voltage on the gate can cause the triac to conduct for either polarity of the voltage across terminals 1 and 2. The gate has no further control once conduction starts. The triac cannot be turned off as with the SCR by reversing the voltage across the main terminals. This would only reverse the current. To turn off the triac it is necessary to reduce the current through the main terminals to a point where conduction ceases. Variable resistor R and capacitor C constitute a phase control which operates in a manner similar to phase control of the SCR.

The Diac

The diac (*di*ode *ac* switch) is a three-layer two-terminal semiconductor device. It can be switched from the off state to the on state for either polarity of voltages connected across it. The junction arrangement and symbol are shown in Fig. 8-19.

An ac voltage applied across the terminals of the diac causes a small leakage current to flow. As the ac reverse voltage is increased and the avalanche point is reached (usually 25 V to 35 V), current flow suddenly increases. The sudden increase occurs during both halves of the cycle; therefore, the diac is



(A) Junction arrangement.


(B) Schematic symbol.

Fig. 8-19. Diac junction arrangement and symbol.

a full-wave device. The diac is used mainly to trigger triacs and other devices.

Q8-50. The triac allows for control of ac current in (one, both) direction(s).

Q8-51. The triac connections consist of two __________ and a _____.

Q8-52. Either a positive or a negative voltage on the ____ can cause the triac to conduct.

Q8-53. The diac is a ___ terminal, _____ layer device.

Q8-54. In the diac, the avalanche point is reached during (one, both) half (halves) of the ac cycle.

Your Answers Should Be:

A8-50. The triac allows for control of ac current in *both* directions.

A8-51. The triac connections consist of two **terminals** and a **gate.**

A8-52. Either a positive or a negative voltage on the **gate** can cause the triac to conduct.

A8-53. The diac is a **two**-terminal, **three**-layer device.

A8-54. In the diac, the avalanche point is reached during **both** halves of the ac cycle.

INTEGRATED CIRCUITS

The IC (integrated circuit) has had a greater effect on revolutionizing the field of electronics than any device since the introduction of the transistor. The IC is a device which includes all the basic components in a single package to perform a designated function. An IC may contain up to dozens, hundreds, or thousands of components, such as resistors, transistors, ca-

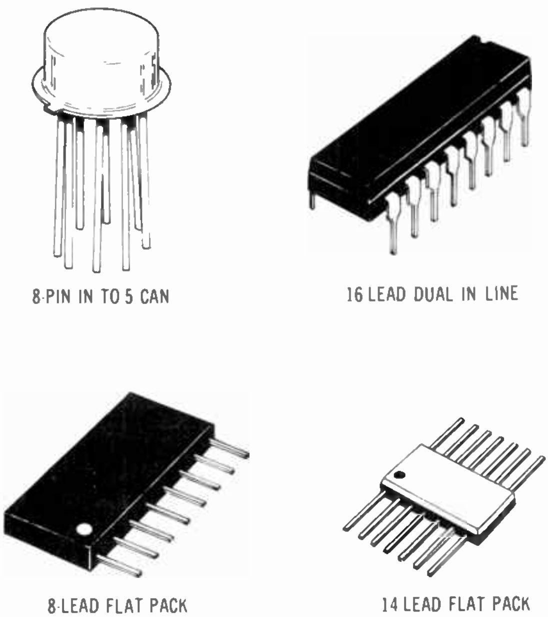


Fig. 8-20. Examples of ICs showing different packaging styles.

pacitors, coils, diodes, and so on. All these components are interconnected as required for the particular need, and all of these are contained within a very small package. Most rectangular-shaped ICs measure about an inch long, by about one-quarter inch in width, and an eighth inch in thickness. Other ICs are disk shaped and yet others are square. Fig. 8-20 shows some examples.

Some ICs are made up of actual discrete, or physically separate, parts interconnected and sealed into a package with the needed external terminals or pins protruding. The pins provide connecting points for input, output, ground, power sources, and so on.

Other ICs are circuits that are built up by depositing a series of thin layers of film on a base material. The base material is usually a thin disk or wafer of germanium or silicon. The required number of layers of film are deposited on the base and the surface of the wafer is divided into a large number of tiny squares. Each square is then arranged into a complete electronic circuit. As the final steps, each wafer is cut into sections and the sections are installed in their individual cases with the required protruding pins.

ICs are widely used in radios, industrial control systems, computers, test instruments, calculators, tv sets, intruder alarms, and practically all other types of electronic equipment. The ICs have made it possible to reduce room-size computers to units that can fit in a small briefcase. Some computers are now available that can be held easily in the palm of one's hand.

There are ICs, which are also called chips, available that contain all the basic interconnected components for a complete radio receiver, a calculator, a digital counter, and so on.

The ICs may be either wired and soldered into a circuit board, or the IC may be plugged into a socket that is wired into the board; therefore, the IC can be easily removed and replaced.

Q8-55. The device which contains all the basic components to perform a given function is called a/an ___________ circuit.

Q8-56. Some ICs are built up by depositing thin layers of film on a base material of _______ or __________.

Your Answers Should Be:

A8-55. The device which contains all the basic components to perform a given function is called an **integrated circuit.**

A8-56. Some ICs are built up by depositing thin layers of film on a base material of **silicon** or **germanium.**

Types of ICs

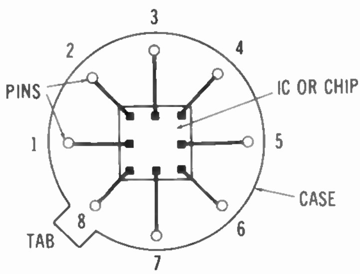
According to function, there are two types of ICs: *linear* ICs and *digital* ICs.

Linear ICs are used where the output is proportional to the input. Typically, this means that the output is a reproduction of the input, but the output may be amplified or enlarged. Also, a linear IC may combine, or mix, two or more inputs or separate inputs without affecting their shapes.

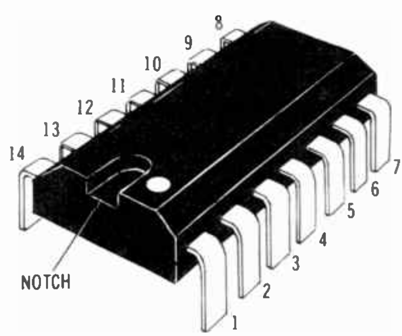
Digital ICs are used in switching-, pulse-, and computer-type circuits. The digital IC is a switching-type integrated circuit that processes electrical signals that have only two states, such as "on" or "off," "high" or "low," or "positive" or "negative." For example, 5 volts or 0 volts.

IC Terminal Identification

The IC pins are identified by numbering systems that have been standardized. Two examples are shown in Fig. 8-21. The ICs enclosed in a TO-5 can normally have a tab for location of the number (pin which looking from the bottom or lead end of the transistor is the first pin in a clockwise direction



(A) TO-5 type, bottom view.



(B) Dual in-line type.

Fig. 8-21. Pin numbering systems.

from the tab). The dual in-line IC has either a notch in its case, or a small dimple, at the end of the IC where the number 1 pin starts. Hold the transistor so the notch or dimple is at the left. The numbers then progress left to right, then directly to the other side of the transistor in a right to left direction as shown, looking from the top.

OPTOELECTRONIC DEVICES

Optoelectronic devices include those devices which can convert light energy to a change in an electrical condition. Other optoelectronic devices convert electrical energy to light energy. Examples of these latter devices are light-emitting diodes (LEDs), liquid-crystal displays (LCDs), and lasers.

These devices whose electrical condition is changed when light strikes them are called light-sensitive devices, and they are of three types: *photoemissive*, *photoconductive*, and *photoelectric*. Photoemissive devices emit electrons when light strikes them. Photoconductive devices show a change in resistance when struck by light and a photovoltaic device develops on output voltage when struck by light.

Lasers are electronic devices that convert input power to a narrow, intense beam of a visible or infrared light. The applications of lasers include microsurgery, cutting, drilling, welding, surveying, communications, and tracking of moving objects.

Light-emitting diodes (LEDs) and liquid crystal displays (LCDs) are used as readout devices in calculators and other digital readout devices.

Q8-57. There are two kinds of ICs according to function. They are _______ ICs and ________ ICs.

Q8-58. The ________ IC is used in switching and pulse circuits.

Q8-59. A dual in-line IC should be held so that the notch in the case is at the (left, right) in order to identify the number 1 pin.

Q8-60. The optoelectronic device that changes resistance when light strikes it is the ________________ device.

Your Answers Should Be:

A8-57. There are two kinds of ICs according to function. They are **linear** ICs and **digital** ICs.

A8-58. The **digital** IC is used in switching and pulse circuits.

A8-59. A dual in-line IC should be held so that the notch in the case is at the **left** in order to identify the number 1 pin.

A8-60. The optoelectronic device that changes resistance when light strikes it is the **photoconductive** device.

SUMMARY

1. The FET represents an important advancement in solid-state technology.
2. The three types of FETs are the JFET, the enhancement-mode MOSFET, and the depletion-mode MOSFET.
3. The three electrodes of the FET are called the source, the gate, and the drain.
4. The FET is called a unipolar transistor because its carriers are of only one polarity, either holes or electrons, but not both.
5. Operating characteristics of the FET are much like those of the vacuum-tube triode.
6. The enhancement-mode MOSFET is used mainly in digital- or pulse-type circuits. The depletion-mode MOSFET is frequently used in linear circuits.
7. The MOSFET is subject to damage from static electricity, so care in handling is required.
8. The FET source-follower circuit is equivalent to the emitter-follower circuit of the bipolar type of transistor.
9. The FET common-gate circuit has low-input impedance and high-output impedance.
10. The FET family of characteristic curves is much like the characteristic curves for the vacuum-tube triode.
11. In the FET, changes in drain current are caused by changes in the input voltage; therefore, the drain voltage changes will be an amplified version of the input signal.

12. In the unijunction transistor, the only junction is between base and emitter.
13. Base B_1 resistance varies with the UJT emitter current.
14. A positive voltage applied to the UJT emitter causes the emitter junction to become forward biased.
15. The UJT exhibits a negative resistance characteristic if V_E increases as I_E increases.
16. The UJT is very useful as a pulse and sawtooth oscillator.
17. The SCR is used in many industrial control circuits as a trigger device. A positive voltage applied to the gate will cause it to conduct.
18. Once it conducts, it can be turned off only by removing the anode voltage or by reducing it to nearly zero.
19. The triac is a two-way SCR which provides for control of ac current in both directions.
20. The diac is a three-layer two-terminal semiconductor which can be switched from the off state to the on state for either polarity of voltage connected across it.
21. The IC, or integrated circuit, combines many components and functions into one tiny electronic chip.
22. ICs can perform jobs formerly requiring electronic components taking up many times the space now taken by ICs.
23. The basic material of the IC is a thin base of silicon or germanium.

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