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SEMICONDUCTORS AND TRANSISTORS

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Each year semiconductor devices become increasingly important in the general field of electronics. For this reason it has become desirable that secondary school students in Australia, in the course of their study of physics, should gain some familiarity with semiconductors as well as with the valve, which has a somewhat longer history. The following notes were originally prepared for such students and their teachers, with the aim of alleviating the difficulties encountered in their approach to a relatively new subject. Some emphasis has been placed on practical matters, and descriptions of useful experiments are included. In the belief that this treatment of the subject may well be of interest to a somewhat wider audience, the notes and descriptions of experiments are reprinted here.*

In the first part, "Semiconductors and Transistors," there is to be found a non-mathematical description of those physical properties of semiconducting materials which are relevant to the fundamentals of operation of semiconductor rectifiers and transistors. This is followed by a graduated series of nine experiments, using simple equipment, in which some useful properties of semiconductor devices may be measured. In the second part, "Further Experiments in Electronics," five additional experiments are described in which, with the aid of semiconductor devices, an investigation may be made of the properties of inductors and capacitors, and of techniques such as modulation, transmission and reception which find everyday application in electronic communications.

The authors are grateful to Dr. A. A. Hukins and Mr. D. M. Henderson, Sydney Teachers' College, for their valuable comments on the material presented here, and to colleagues in Amalgamated Wireless Valve Company Pty. Ltd. for assistance in the measurements on which the experiments are based.

** A kit of transistors and diodes required to undertake the full range of experiments is available from Sales Department, Amalgamated Wireless Valve Company Pty. Ltd., Victoria Road, Rydalmere, N.S.W., Australia.*

1. SEMICONDUCTOR PHYSICS

1.1 CONDUCTION BY ELECTRONS AND HOLES

In the metals, of which copper is an example, there are many conduction electrons available to carry an electric current at all temperatures, and the conductivity is high. Semiconductors contain far fewer mobile charge carriers than metals, and furthermore the number of such charge carriers available to carry current may depend quite strongly on the temperature. Thus semiconductors are materials whose conductivity is temperature-dependent, and very much less than that of the metals. Values of the conductivity at 27°C of two well-known semiconductors are compared with those of a metal and an insulator (glass) in Table 1.

Table 1

Values of Electrical Conductivity at 27°C (Units ohm.$^{-1}$ cm.$^{-1}$.)

Copper	6×10^5
Pure Germanium	0.02
Pure Silicon	4×10^{-6}
Glass	approx. 10^{-15}

Most semiconductors are valence crystals, that is to say "giant" molecules in which each atom is covalently bound to its nearest neighbours. The semiconductors silicon and germanium are elements, which solidify with the valence-crystal structure illustrated in Fig. 1. This structure, or "lattice", in which each atom has four nearest neighbours, arises from the circumstance that germanium and silicon atoms have four valence electrons each. One electron from each of two neighbouring atoms forms a covalent bond between them, thus localizing the electrons in the lattice.

At very low temperatures, near the absolute zero (—273°C), there are no electrons free to move through the crystal and carry a current; the crystal is thus an insulator near —273°C. At room temperature however, a small fraction of the covalent bonds are disrupted by thermal vibrations of the atoms of the lattice; conduction electrons are thus produced which are free to move through the crystal and to contribute to the electrical conductivity. This fraction amounts to 5×10^{-10} in germanium at 27°C, compared with approximately one electron for each atom in metallic crystals. Thus the conductivity of a semiconductor is very much less than that of a metal principally because of the much smaller density of mobile charge carriers.

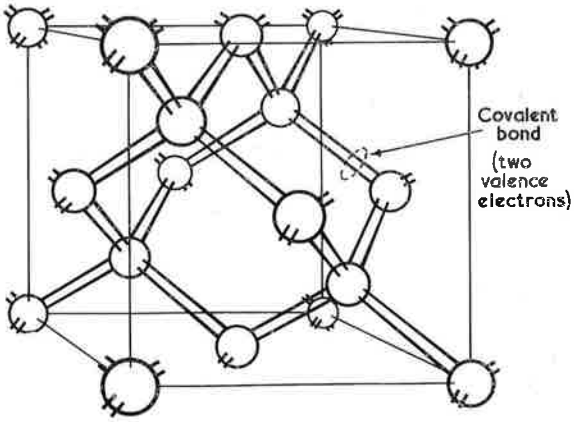


FIG. 1—The crystal structure of germanium and silicon.

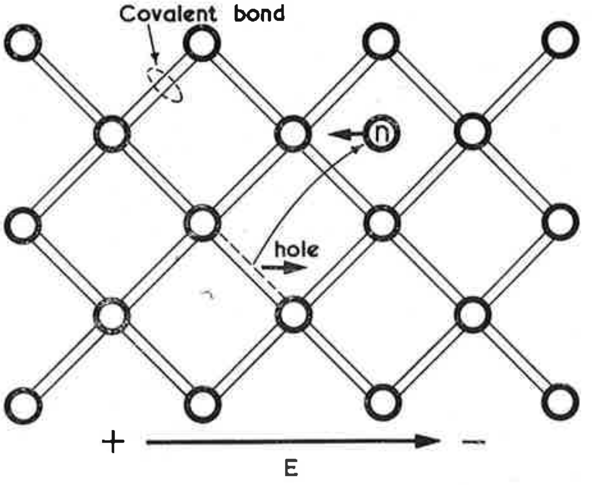


FIG. 2—Creation of electron-vacancy pair, and movement in electric field E.

There is in addition an important additional mechanism for the transport of current in semiconductors. Imagine the structure of the valence crystal of Fig. 1 to be deformed, for the purpose of discussion, into the structure shown in Fig. 2. It can be seen from this diagram that the disruption of a valence bond not only creates a conduction electron (n), but also leaves a vacancy in the covalent bond structure.

When an electric field E is set up in the crystal by the application of an external potential difference the conduction electron is caused to move from right to left in Fig. 2, thus transporting a current. An additional independent mechanism for current transport is associated with the vacant covalent bond. In the presence of the field E one of the valence electrons to the right of the vacancy may be moved from its position to fill the vacancy; we can describe this situation just as well by saying that the vacancy is moved from left to right by the field E. The vacancies are called holes; since they move oppositely to the electrons, they have an effective positive charge.

In any semiconductor we may have conduction both by electrons and holes, quite independently of each other. In a pure semiconductor the electron and hole conductivities are comparable, since the densities of electrons and holes are equal.

1.2 N-TYPE AND P-TYPE SEMICONDUCTORS

The conductivity of a semiconductor can be very greatly increased by the presence in the crystal of small amounts of impurity. For example, let us consider the effects of an arsenic atom, with its five valence electrons. As shown in Fig. 3, four of these form covalent bonds; the weakly-bound fifth electron is normally detached from the arsenic atom at room temperature, so that each arsenic atom in the crystal gives rise to a conduction electron.

Atoms with five valence electrons are known as "donor" impurities in semiconductors. A donor concentration of as little as one part in ten million in germanium gives rise to a density of conduction electrons some 200 times greater than that in pure germanium at 27°C; the conductivity is also increased by the large factor of 200. Since conduction now takes place almost entirely by the movement of conduction electrons (negative charge carriers) the semiconductor is said to be n-type.

Impurity elements with three valence electrons also increase the conductivity when incorporated in an otherwise pure semiconductor, but in this case do so by increasing the density of holes. An atom of indium, for example, incorporated in the crystal as shown in Fig. 3, has associated with it a vacancy in the valence-bond structure which is easily detached to yield a mobile hole. Semiconductors which contain such "acceptor" impurities are said to be p-type, as their conductivity arises almost entirely from the movement of holes (positive charge carriers.)

1.3 P-N JUNCTION DIODES

A very interesting situation arises when we consider the properties of a semiconductor which contains adjacent p-type and n-type regions. Such p-n junctions in germanium or silicon can be produced quite readily by suitable control of donor and acceptor impurities.

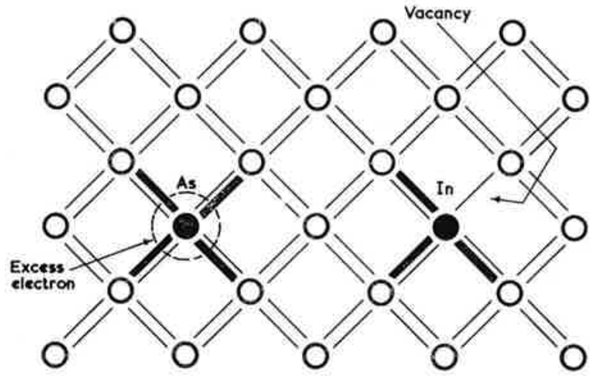


FIG. 3—Arsenic and indium impurity atoms in germanium crystal, before detachment of excess electron and hole respectively.

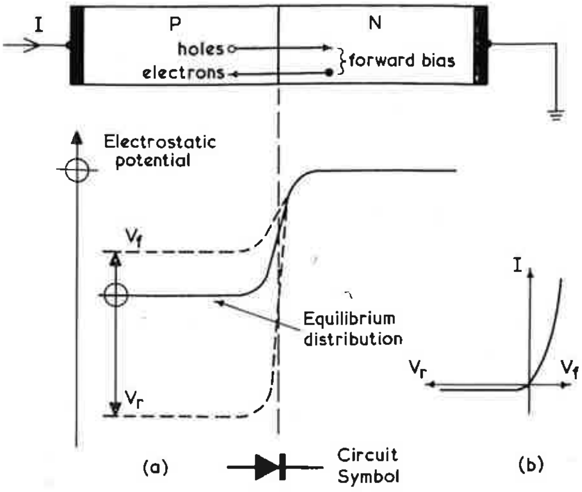


FIG. 4—(a) Distribution of electrostatic potential in a p-n junction; (b) current-voltage characteristic of junction.

There exists a "contact" potential difference between p-type and n-type material such that the p-type is slightly negative with respect to the other. The electrostatic potential in a p-n junction in equilibrium is plotted in Fig. 4(a); the resulting potential barrier counteracts the tendency of holes to diffuse into the n-region, and of electrons to diffuse into the p-region, and in this way ensures that there is no current in the equilibrium situation.

The n-region is taken to be at zero (earth) potential. When a potential difference V_f is applied so as to make the p-region more positive with respect to the n-region, the height of the potential barrier in Fig. 4(a) is reduced. We describe this as the forward-biased condition. Electrons and holes are then able to surmount the barrier and diffuse into the p-type and n-type material respectively on the opposite side of the junction; the directions of flow are shown in Fig. 4(a). The resultant current rises very rapidly with increase in V_f in this "easy" direction of current flow, as shown in Fig. 4(b).

If the junction is biased in reverse by the application of a potential difference V_r in the opposite direction the height of the barrier is increased, and no electrons and holes can now surmount it. The junction consequently acts as a rectifier, i.e., a device passing current in one direction only. In practice there is a small leakage current in the reverse direction as shown in Fig. 4(b), which increases very strongly with increasing temperature; this may also be augmented by a surface leakage current, which is substantially independent of temperature. Commercial junction rectifiers such as the silicon type 1N3194 have a form similar to that shown in Fig. 4; the p- and n-regions however are separated by a thin region of nearly pure silicon in order to increase the capability of the diode to withstand reverse voltages as high as 400 volts.

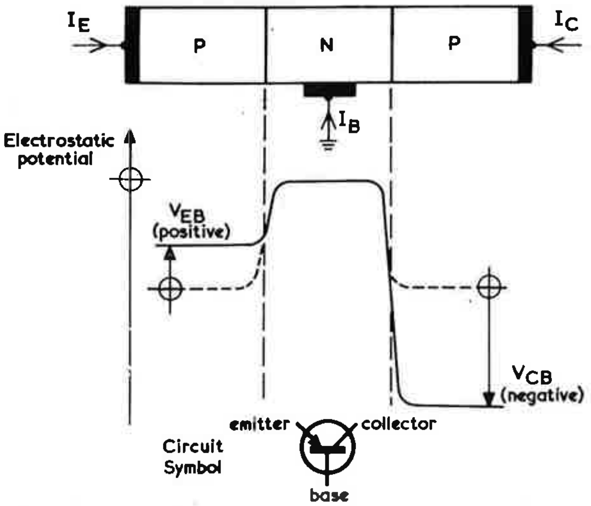


FIG. 5—Distribution of potential in a p-n-p transistor biased for operation.

Junction diodes are also good detectors of light. Light which falls on a semiconductor creates electron-hole pairs by disruption of the valence bonds; the electrons and holes produced near a p-n junction are "collected" by the junction when it is biased in the reverse direction, and the light thus increases the current through the junction. This effect may be observed in silicon and germanium with light extending into the infra-red.

1.4 JUNCTION TRANSISTORS

Junction transistors are semiconductor amplifiers, and may be of two types. Transistors with adjacent p-, n- and p-type regions (Fig. 5), in which the current in the device is carried by holes, are known as p-n-p transistors; alternatively one may have an n-p-n structure in which the current is carried by electrons. We restrict our discussion here to the p-n-p transistor of Fig. 5, in which we suppose the n-region (the base) to be at zero (earth) potential.

The electrostatic potential in the device is given by the dotted line of Fig. 5 under equilibrium conditions, when no current flows. There is a potential barrier at each of the two p-n junctions. If a negative bias of a few volts (—V_{CB}) is applied to the right-hand p-region (the collector), only a small leakage current flows initially. However when a positive bias voltage ($+V_{EB}$) is subsequently applied to the left-hand p-region (the emitter), the holes which surmount the diminished barrier at the emitter junction can pass into the n-region and be collected at the right-hand junction, if the base be sufficiently narrow, thus augmenting the collector current. The current flow I_C in the collector can thus be controlled by the current I_E which is caused to flow through the emitter junction.

In a well-designed transistor the currents in emitter and collector circuits are very nearly equal —that is, the current I_E through the emitter junction consists almost entirely of holes, almost all of which reach the collector junction successfully after passage through the base. Departures from perfection in this respect lead to a small base current I_B in actual devices. If we take a p-n-p transistor in the "common-emitter" configuration of Fig. 6, and produce small variations in the input (base) current I_B, these can lead to large changes in the output (collector) current I_C—approximately 100-fold in practice. A transistor is therefore a useful current amplifier in the common-emitter configuration.

2. SEMICONDUCTOR DEVICES AND CIRCUITS

2.1 INTRODUCTION

A circuit, in its most common form, is made up of examples of both "passive" and "active" devices. The former comprise resistors, capacitors, inductors and diodes. The latter are split into two main groups:— (a) The vacuum valve consisting of a heated filament and a mechanical assembly of a grid or grids and a plate—all operating in a near vacuum. (b) The transistor, which can be small, is light in weight and is a rugged solid-state device; furthermore it has no heater and therefore can operate for very many hours with a high electrical efficiency.

We are here concerned with the semiconductor device in two forms, the diode and the transistor.

Both have two particular properties which may limit their performance and which determine the values of associated components:— (1) Important characteristics are sensitive to comparatively small changes in operating temperature; (2) They both have relatively low internal resistance.

In the case of the simple diode, changes in temperature will affect its resistance when conducting in the forward direction and also its leak-

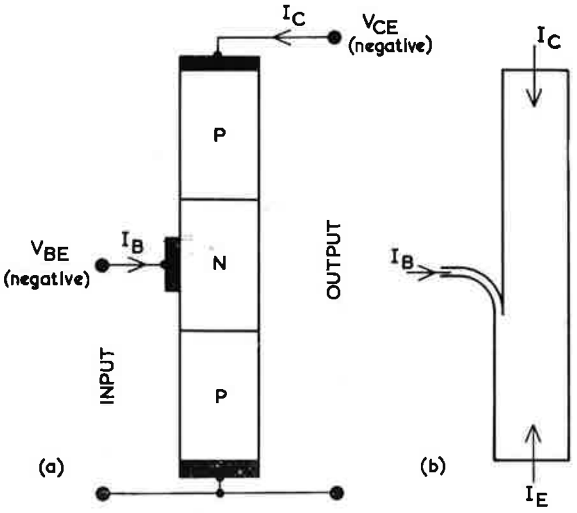
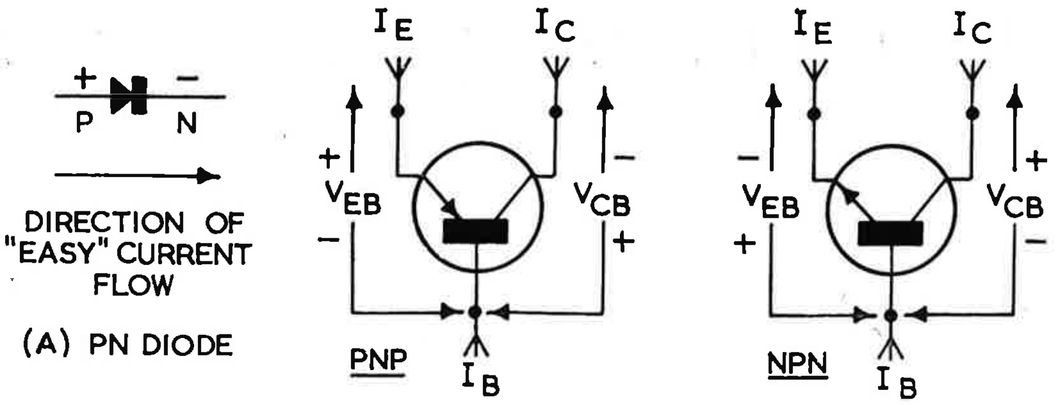


FIG. 6—(a) p-n-p transistor with base input; (b) corresponding current distribution.



(A) PN DIODE

(B) JUNCTION TRANSISTOR

Fig. 7

age current when a potential difference is applied in the reverse direction. Since a transistor may be considered as a special combination of two diodes, a change in operating temperature produces more complicated effects.

2.2 CONVENTIONS FOR SYMBOLS AND FLOW OF CURRENT

(a) **Symbols.** Symbols commonly used to indicate a diode and the classes of junction transistor are shown in Fig. 7.

(b) **Flow of Current.** The closed arrow in each diagram of Fig. 7 indicates the direction of easy current flow or forward conduction.

The figure shows the sign of the applied voltage, in the case of the diode, for forward conduction and, in the case of the transistor, for normal operation, i.e., with the emitter-base diode biased for forward conduction and the collector-base diode biased in the reverse direction.

The convention adopted for the direction of the flow of current into the transistor is that current flowing into the device is called positive and flowing out is called negative so that we have:

$$I_C + I_B + I_E = 0.$$

The open arrows indicating current in Fig. 7 show positive flow of current. For a p-n-p transistor the actual collector current is in the same direction as that of flow to the negatively biased collector; it thus constitutes a current **out** of the transistor and therefore negative in sign. A small percentage of the available holes "escape" to the base producing a small base current which is **out** of the transistor and therefore carries the negative sign.

It should be noted here that the universally adopted convention for the direction of current flow is that it is in the opposite direction to the flow of electrons.

(c) **Circuit Configuration.** The basic type of circuit in which a transistor is used is described by the terminal which is common to both the input and output circuits; e.g., a common-emitter connection is one in which the emitter is common to both circuits. See Fig. 8.

2.3 EXPERIMENTS

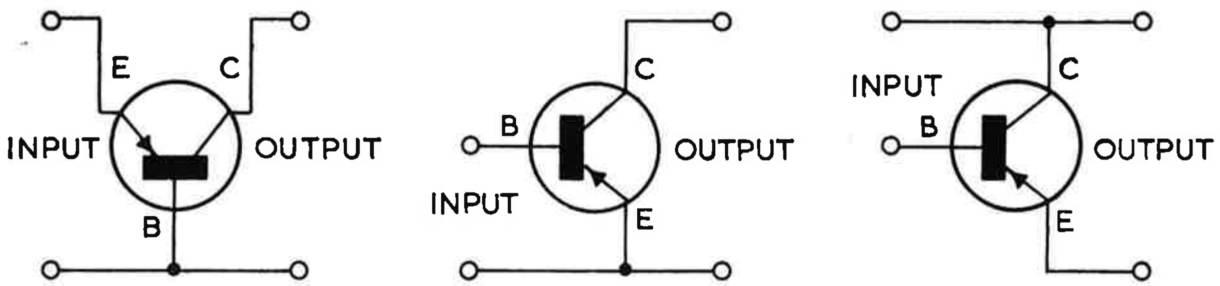
2.3.1 Properties of Devices

Experiment No. 1

Germanium Junction Diode

Aim. To measure the forward and reverse characteristics of the emitter-base junction of the germanium p-n-p alloy transistor type 2N218.

Method. Connect the emitter and base leads of the transistor as shown in the circuit of Fig. 9.



COMMON BASE

COMMON EMITTER

COMMON COLLECTOR

Fig. 8

Adjust the potentiometer to increase the voltage V, in a series of steps of approximately 0.1 volt, from zero to 0.5 volt and record the current corresponding to each voltage.

Plot on squared paper the measured values and draw the curve showing the **forward** characteristic of the junction.

Reconnect the emitter and base leads in the circuit as shown in Fig. 10.

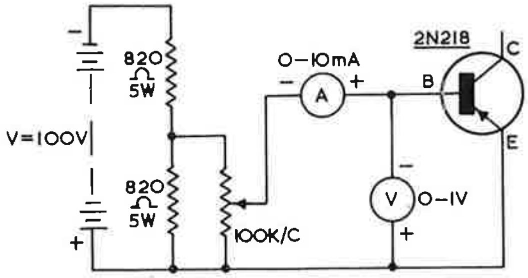


Fig. 9

Adjust the potentiometer to increase the voltage V, in a series of steps of approximately 5 volts, from zero to 50 volts and record the current corresponding to each step.

Plot all measured valves on squared paper (using scales for each axis different from those first used) and draw the curve showing the **reverse** characteristic of the junction.

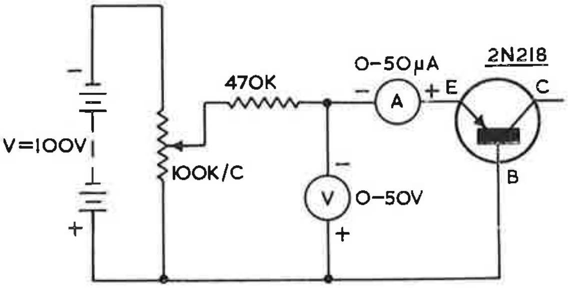


Fig. 10

Experiment No. 2

Silicon Junction Diode

Aim. To measure the forward and reverse characteristics of the silicon junction diode type 1N3194.

Method. Connect the diode as shown in the circuit of Fig. 11.

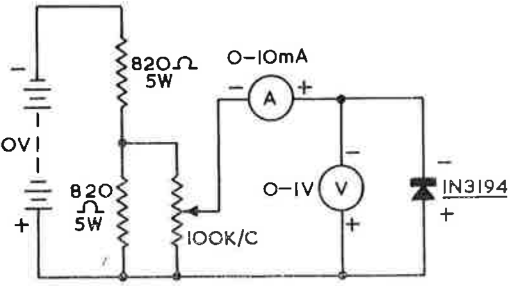


Fig. 11

Adjust the potentiometer to increase the voltage V, in a series of steps from zero to 0.7 volt and record the current corresponding to each step.

Plot on the same graph as used for Experiment No. 1 all measured values and draw the **forward** characteristic of the diode.

Reconnect the diode as shown in Fig. 12.

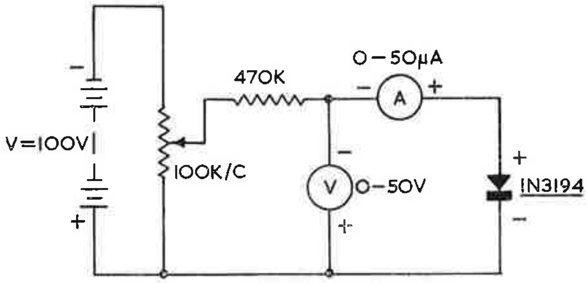


Fig. 12

Adjust the potentiometer as carried out in Experiment No. 1. Plot on the same graph all measured values and draw the curve showing the **reverse** characteristics of the diode. (Note the very low reverse or leakage current of the silicon diode.)

Note. The voltmeter of Figs. 10 and 12 is a high-resistance instrument (>500K-ohm). If a voltmeter of lower resistance is used in these two circuits, the 470K-ohm resistor should be reduced to 100K-ohm.

Experiment No. 3

Germanium Alloy p-n-p Transistor

Aim. To plot the characteristics in the form of the collector family of curves for the p-n-p transistor type 2N218.

Method. Connect the transistor as shown in Fig. 13 and with the switch in the "base disconnected" position, adjust the potentiometer to increase the collector-to-emitter voltage V_{CE} in a series of steps of 2 volts from zero until a point is reached where the collector current I_C increases rapidly. The measurements made to this point will allow the collector characteristic to be drawn up to the region of collector-to-emitter "breakdown". The continuation of the characteristic into the breakdown region should be plotted by first reducing V_{CE} below the commencement of breakdown and then increasing in small steps (say 0.2V) to allow the curve to be drawn. Plot on squared paper all values of V_{CE} and corresponding I_C and draw the first member of the collector family of curves, i.e. the curve relating V_{CE} and I_C for base current $I_B = O$.

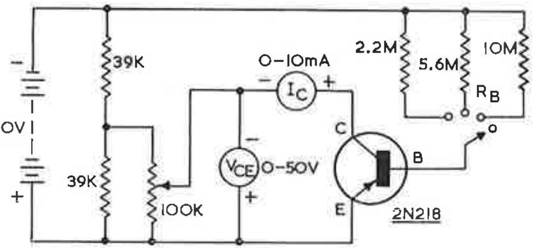


Fig. 13

Repeat the above procedure with the base switch on the 10M-ohm, 5.6M-ohm and 2.2M-ohm positions. Each position produces a different base current given by V/R_B. For example, using $R_B = 2.2$M-ohm, $I_B = 100/(2.2 \times 10^6) = 45.5$ μA.

Note. The direct current gain of the transistor for a given value of V_{CE} is indicated by the large ratio between the collector or output current and the base or input current. Similarly, the alternating current gain is shown by the ratio $\Delta I_C/\Delta I_B$ for a given value of V_{CE}.

The breakdown region is generally unusable and operation here may damage the transistor. Conditions normally are arranged to avoid this area.

When adjusting V_{CE} check that $V_{CE} \times I_C$ is always less than 30×10^{-3} watts. (Power dissipation at the transistor junction causes heating and may change characteristics.)

Experiment No. 4

Current Gain Characteristic of a Transistor

Aim. To plot the "transfer" or current gain characteristic of the p-n-p transistor type 2N218.

Method. Connect the transistor as shown in Fig. 14 and, with the slider "Y" of the potentiometer set to the "X" end, measure the collector-to-emitter voltage V_{CE}.

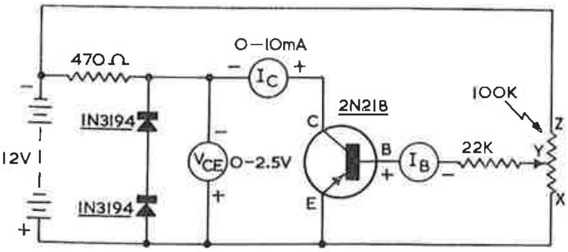


Fig. 14

Adjust the slider "Y" of the potentiometer to increase the base current I_B in a series of steps from zero to a value which produces a collector current $I_C = 10$mA. Record the corresponding values of base and collector currents and plot I_C as a function of I_B on squared paper. Trace the "transfer" characteristic by drawing a curve through all points.

Note. The curve relates collector and base currents and hence current gain for the measured collector-to-emitter voltage. In this experiment the two silicon diodes (1N3194) supply a source of low voltage for the collector which is reasonably and current for diodes of this type, and check the value of V_{CE} measured in this experiment with that expected from the 1N3194 characteristic for two diodes in series.)

The current through the two diodes in the circuit used here will vary between approximately 23 and 13mA.

Experiment No. 5

Effect of Heat on Transistor Characteristics

Aim. To measure the change in collector leakage current with changes in temperature for the p-n-p transistor type 2N218.

Method. Place a mixture of water and broken ice and a thermometer in a beaker. Stir to maintain uniform temperature throughout the water. Fit the transistor with a tubular heat fin and with it connected in the circuit shown in Fig. 15 place in the ice-water. (Avoid water contacting the leads of the transistor.) Allow a few minutes for the temperature of the transistor junction to stabilize and record the value of leakage current at this temperature (0°C.). Remove ice and slowly heat the water to about 50°C. by means of a bunsen burner; stirring constantly, record the increasing values of collector current and the corresponding water temperature.

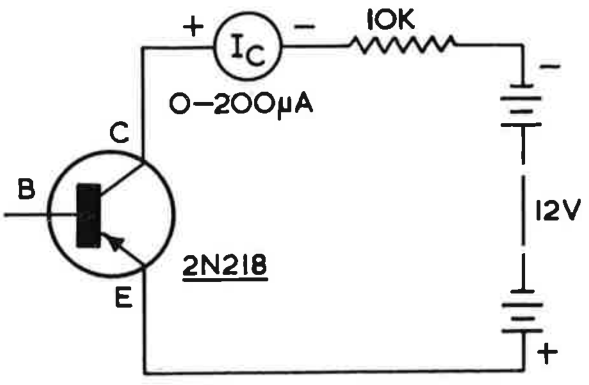


Fig. 15

Plot all values on squared paper and draw the curve relating collector-to-emitter leakage current and junction temperature.

2.3.2 Circuits

Experiment No. 6

Diode as a Rectifier

Aim. To demonstrate the "one-way" property of a semiconductor diode and its use as a rectifier of an alternating voltage.

Method. Connect the 1N3194 diode as shown in Fig. 16 and by alternately connecting the "Y" amplifier of the cathode ray oscilloscope to points A and B show first the sinusoidal shape of the alternating voltage at the secondary of the transformer and then the "half" sine waves appearing across the 1000-ohm resistor. (The horizontal time base of the c.r.o. should be set to a frequency of 20 c/s, or a speed of 10 ms/cm.)

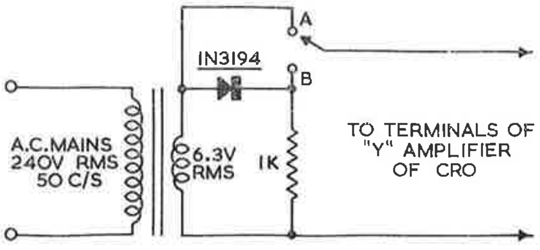


Fig. 16

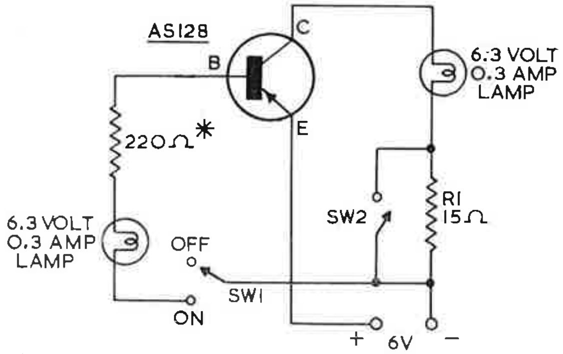
The generation of a direct voltage from the half sine waves can be demonstrated by connecting a large capacitor across the 1000-ohm resistor. The larger the capacitor the nearer the rectified voltage approaches the "direct" value. The use of a 32μF (12V) capacitor will provide a wave-form containing a 3-volt ripple.

Experiment No. 7

Transistor as a Switch

Aim. To demonstrate the use of a transistor as a switch.

Method. Connect as shown in Fig. 17, and by switching the base current of the transistor from "off" to "on" by means of switch SW1 cause the collector current to turn on and so light the lamp. Resistor R_1 serves as protection for the transistor and may be short-circuited by means of SW2 after the circuit is known to be operating correctly (indicated by the lamp lighting at approximately half brilliance).



* 56Ω 1W WILL PRODUCE SLIGHT GLOW IN BASE LAMP

Fig. 17

In this experiment the small current switched by SW1 in the base circuit is used to control the very much larger current in the collector circuit. The "on-off" action of a transistor, i.e., the change in collector-to-emitter resistance from a very high to a very low value by a small current supplied to the base-to-emitter junction, enables it to operate in many applications as a true switch: e.g., to replace a relay, to convert a direct into an alternating voltage and to operate "go and no go" circuits in computers and automatic test equipment.

Note. For some transistors the base current limited by the 220-ohm resistor may be insufficient to cause a detectable glow in the base lamp. In such a case the value of the resistor may be reduced to not less than 56 ohms and if necessary the supply voltage increased to not greater than 10 volts.

When this experiment is conducted in an ambient temperature >35°C a flag type heat fin should be fitted to the case of the transistor.

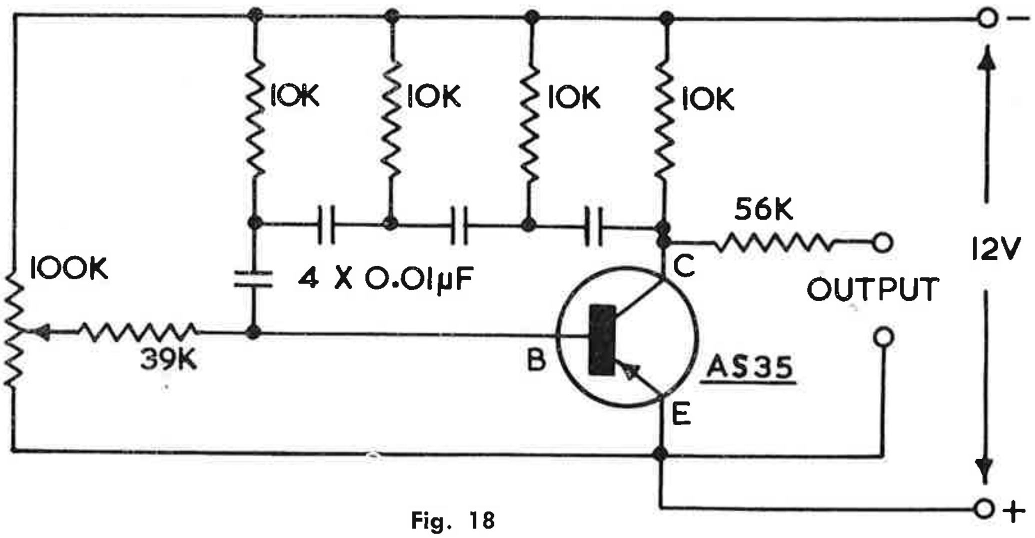


Fig. 18

Experiment No. 8

Phase Shift Oscillator

Aim. To demonstrate the use of a transistor in an oscillator circuit to generate an audio frequency signal.

Method. Connect the transistor as shown in Fig. 18. With the headphones and/or the terminals of the "Y" amplifier of the c.r.o. connected at the output, a signal will be indicated. The potentiometer allows the amplitude of the signal to be varied.

The circuit oscillates because the network of resistors and capacitors between the collector and the base of the transistor is able to "feedback" to the base a part of any signal appearing at the collector. The network produces a "phase shift" in the feedback component such that when amplified by the transistor it is able to "reinforce" the signal at the collector. This is positive feedback and the circuit oscillates. Using the values shown the frequency of the signal produced will be approximately 1000 c/s.

Experiment No. 9

Audio Frequency Amplifier

Aim. To demonstrate the amplification of audio frequency signals by means of a transistor.

Method. Wire the transistor in the circuit as shown in Fig. 19, and connect the output of the oscillator (constructed in Experiment No. 8) to the input. By alternately connecting headphones and/or the "Y" terminals of the c.r.o. to the input and the output terminals of the circuit demonstrate the audio frequency amplification of the transistor.

Although the output of the oscillator is reduced by the 56K-ohm resistor shown in Experiment No. 8 it may be necessary to adjust the potentiometer of the oscillator to provide a signal no larger than is necessary to hear or see a "clean" signal at the output of the amplifier.

2.4 PRECAUTIONS WHEN USING TRANSISTORS

All supply voltages **must** be switched "off" before connecting or disconnecting a transistor.

Semiconductor devices are damaged by excessive heat and it is necessary when using a soldering iron on the leads to the device to make sure that little heat is transferred along the lead to the semiconductor junction. The iron should be held

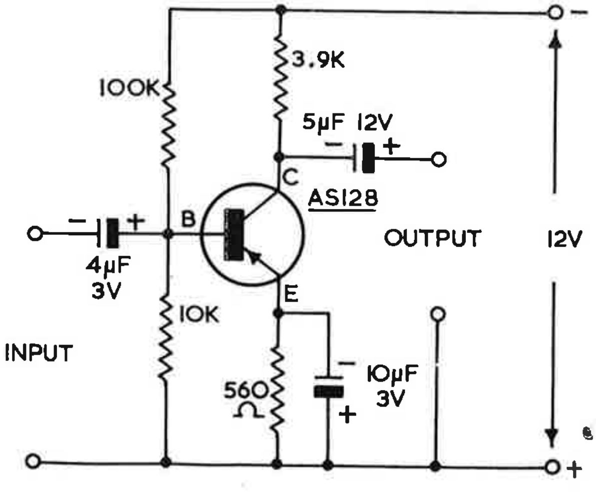


Fig. 19

Fig. 20

in contact with the lead for as short a time as possible and **never** should be allowed to touch the case of the transistor. Where the leads are short (say less than 1″) a pair of pliers, preferably with copper-clad jaws, should be used to hold the lead at a point between the case and the soldered point.

Terminal connections for the transistors used in these experiments are shown in Fig. 20.

List of parts required for Experiments 1-9 inclusive.

Semiconductors

Qty.	Item
1	2N218
2	1N3194
1	AS35
1	AS128

Resistors

Qty.	Item
1	15 Ω 1 W
1	56 Ω ½ W
1	220 Ω ½ W
1	470 Ω ½ W
1	560 Ω ½ W
2	820 Ω 5 W
1	1 kΩ 1 W
1	3.9 kΩ ½ W
4	10 kΩ ½ W
1	22 kΩ ½ W
2	39 kΩ 1 W
1	56 kΩ ½ W
1	100 kΩ ½ W
1	470 kΩ ½ W
1	2.2 MΩ ½ W
1	5.6 MΩ ½ W
1	10 MΩ ½ W
1	100 kΩ Pot.

Capacitors

Qty.	Item
4	0.01 μF 25 V
1	4 μF 3 V
1	5 μF 15 V
1	10 μF 6 V

Miscellaneous

Qty.	Item
2	6.3 V 0.3A Lamp
2	Heat sink—flag type

The second part, "Further Experiments in Electronics", by H. R. Wilshire, will appear in a subsequent issue of Radiotronics.

EDITOR'S NOTE

The paper, "Plate and Grid Voltage Display Unit for Deflection Valves", by G. N. Taylor, published in the April issue of "Radiotronics", was based on a paper contributed to the Institution of Radio and Electronics Engineers Australia and will be published in full in "Proceedings I.R.E.E. Australia", Vol. 26, No. 7, July, 1965.

NUCLEAR POWER IN THE SKY

Unique Device Developed by RCA Converts Nuclear Heat Directly Into Electricity in SNAP 10A Space Vehicle

The SNAP 10A space power system will be literally a nuclear power plant in the sky. With the successful launching of the Atlas Agena carrying a SNAP 10A power unit, space nuclear power became a reality.

Unlike conventional nuclear power plants on earth, the SNAP 10A space power system utilizes silicon-germanium thermoelectric power conversion modules which operate without moving mechanical parts to convert the nuclear reactor heat directly into electricity—producing 500 watts of usable electric power.

RCA Electronic Components and Devices were selected to develop and fabricate the thermoelectric modules for the SNAP 10A power system in January 1962, following an accelerated programme in the latter months of 1961 to demonstrate the feasibility of achieving system objectives utilizing RCA-developed thermoelectric materials. The SNAP 10A system, utilizing these modules, was designed and assembled for the Atomic Energy Commission by the Atomics International Division of North American Aviation, Inc.

The flight of the SNAP (an acronym for Systems for Nuclear Auxiliary Power) 10A system represents the first orbital test of a nuclear reactor powered thermoelectric converter system and opens the door to a new generation of spaceborne power supplies.

The conical structure of the SNAP 10A power converter is made up of 120 thermoelectric modules arranged in 40 strips around the periphery of the spacecraft. The nuclear reactor is at the apex of this cone. Heat from the reactor is transferred to the thermoelectric modules by means of a closed loop system containing a liquid sodium potassium alloy. Each module contains 12 thermoelectric couples, which individually produce 0.37 watt at 0.04 volt. These couples are connected in series-parallel circuits to yield more than 500 watts at approximately 30 volts.

Technical Details

The thermoelectric principle, discovered in 1821 by Seebeck, is based on the phenomenon that a current flows in a closed circuit formed by the junctions of two dissimilar metals if one junction is maintained at a higher temperature than the other. In modern power-generating thermocouples, carefully controlled p-type and n-type semiconductors replace the dissimilar metals originally employed by Seebeck and result in significantly improved thermocouple performance. The new thermoelectric material used in SNAP 10A, silicon-germanium, was developed by RCA Laboratories, in a programme sponsored by the U.S. Navy Bureau of Ships.

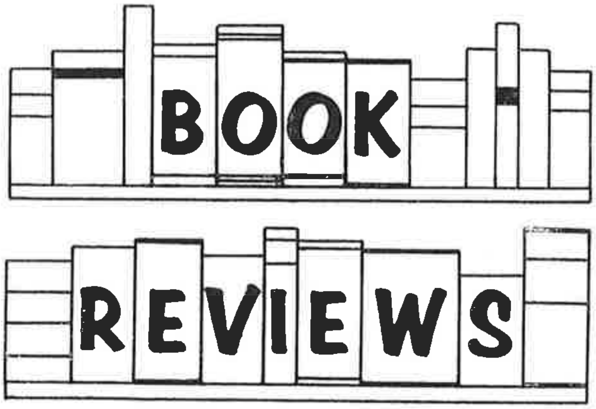
The SNAP 10A thermoelectric converter is heated with a 78% sodium - 22% potassium liquid alloy which is pumped through the reactor core where it picks up fission heat. This liquid-metal coolant flows through stainless steel tubes which are joined to the hot junctions of the thermocouple elements. The cold junctions of the thermocouples are joined to individual aluminium radiators which form the outer surface of the conical section of the SNAP 10A vehicle. The resultant temperature differential across the thermo-elements produces the required electrical power.

The entire SNAP 10A system successfully passed a series of flight-qualification ground tests late in January 1965 in a pre-flight check-out of the system by Atomics International.

The objective of the flight test is to establish the feasibility of operating nuclear reactor power system in space.

The RCA-developed module structure employing silicon-germanium thermoelectric material is unique in that all components are metallurgically bonded. This feature, made possible by the superior mechanical and chemical properties of silicon-germanium, minimizes extraneous losses in temperature resulting in maximum utilization of the power-generating capabilities of the thermoelectric material. The development of the technology for producing metallurgical bonds represents a major technical breakthrough in the construction of thermoelectric modules having high reliability and extreme ruggedness.

Recent technological advances concurrent with the development of SNAP 10A thermoelectric modules have extended the capability of silicon-germanium power generation devices permitting reliable long-life operation with hot junction temperatures of up to 900-1000°C, in air, in vacuum, or in combustion products, for applications utilizing nuclear or non-nuclear heat sources.



BOOK REVIEWS

"Handbook of Electron Tube and Vacuum Techniques," F. Rosebury, Addison-Wesley Publishing Co. Inc., size 9¼" x 6½", 597 pages.

Even to someone who has been associated with the manufacture of electron valves and has come to know some of the factors involved, this volume makes an immediate impact, both by reason of its size and scope and by reason of the immense amount of effort that has obviously gone into making it. The standard of documentation is high, and a refreshing note is the frankness with which the author refers to proprietary names, components and materials, thus making the references maximally useful to readers. Sources of supply are also quoted.

It is implicit in the title of this book, and obvious on other grounds, that whilst much of the book is devoted to techniques useful in making electron valves, by the same token a great deal of the material will also be of interest and assistance to those who employ vacuum techniques in other fields. The present volume is a new version of the "Tube Laboratory Manual" produced by the Research Laboratory of Electronics at the Massachusetts Institute of Technology, and is the first public edition of this work, and the author is the Supervisor of the Electron Tube Laboratory, Research Laboratory of Electronics, at M.I.T.

It may perhaps be necessary to point out to readers of "Radiotronics" that this is a manufacturing handbook, and does not deal with the use and application of electron tubes.

* * *

A GENERAL DISCUSSION OF LOW NOISE TRANSISTOR RF AMPLIFIER CIRCUIT DESIGN AND MEASUREMENT TECHNIQUES

T. ROBE

INTRODUCTION

Degradation of signal-to-noise ratio is of primary concern in the design of low-level amplifiers or receivers, especially in applications where input signals are in the one-microvolt region. This Note reviews the signal-to-noise ratio problem and describes the techniques of designing transistor receivers for the lowest noise-figure. Design considerations such as the selection of transistors, operating conditions and circuit design considerations are discussed and a number of noise-figure measuring techniques are described. Data are presented for specific RCA amplifier transistors.

NOISE-FACTOR

A measure of the degradation mentioned above is the receiver noise-factor defined by the equation:

$$\text{Noise Factor} = \frac{\text{Signal-To-Noise Ratio at Receiver Input}}{\text{Signal-To-Noise Ratio at Receiver Output}} = \frac{(S/N)\ \text{In}}{(S/N)\ \text{Out}} \qquad (1)$$

There are generally two sources of noise in an RF transistor amplifier, (1) thermally generated noise due to the base spreading resistance of the transistor and resistance of the source termination, and (2) shot noise due to the DC current flow in the transistor junctions. Accordingly, the minimum noise power at the amplifier output is that due to the input termination alone. This condition would only exist if the receiver were ideal in that it contributed no noise to the system. In view of this, the noise-factor as previously defined can also be expressed by:

$$\text{Noise-Factor} = \frac{\text{Output Noise Power Due To Input Term.} + \text{Output Noise Power Due To Receiver}}{\text{Output Noise Power Due To Input Term.}} \qquad (2)$$

If the receiver were ideal, this ratio would be "1" and there would be no signal-to-noise degradation. Since noise-factor is actually a noise power ratio, it can be expressed in decibels. It is then called "Noise-figure" (F).

$$F = 10 \log_{10} (\text{Noise Factor})$$

DESIGN CONSIDERATIONS

Design considerations here will be divided into 3 areas, (1) selecting the transistor, (2) selecting the operating conditions, and (3) circuit design.

Selection of the transistor (first RF) is of prime importance since the noise performance of a well-designed amplifier circuit depends almost entirely upon the noise-figure of the first transistor. This transistor should be a type specifically designed for low-noise. Nielsen has shown that the noise factor of a transistor amplifier is related to it equivalent circuit parameters and external circuit conditions by:

$$\text{Noise-Factor} = 1 + \frac{r_{bb}'}{R_g} + \frac{r_e}{2R_g} + \frac{(r_{bb}' + r_e + R_g)^2}{2r_e R_g h_{feo}} \left[1 + \left(\frac{f}{f\alpha}\right)^2 (1 + h_{feo})\right] \qquad (3)$$

Where

rbb' - transistor base spreading resistance

re - emitter diode dynamic resistance $= \frac{26}{I_E\ (MA)}$

fa - transistor alpha cutoff frequency

h_{feo} - low frequency value of h_{fe}

f - frequency of operation

Rg - source resistance as seen by the transistor

Equation (3) indicates that the transistor $r_{bb'}$ is of prime importance and should be as low as possible. The alpha cut-off frequency should be high compared to the frequency of operation and the low frequency value of hfe should be reasonably high. Another highlight of the equation is the dependance of noise-factor on the source resistance seen by the transistor. Specifications sheets written around low-level amplifier transistors will invariably include a specification of maximum noise-figure measured at a frequency in the intended range of device use. In addition to its usefullness in selecting the proper transistor, this specification generally reflects the optimum bias conditions and source resistance for best performance at the frequency specified.

When selecting the operating conditions, the following should be considered. For most low-level RF transistors, the optimum collector bias current for low-noise operation is about 1 ma when working at frequencies below approximately 0.2 f_a. At higher operating frequencies, it may be necessary to use larger bias currents to increase the high frequency current gain, thereby reducing the effects of the last term in equation (3). A good method for determining the optimum bias conditions at a given frequency and source resistance is to set up a noise-figure test using an automatic noise-figure indicator (ANFI) and observe the variation in noise-figure indication while varying the bias current and voltage. A description of this type of measurement is given under "Noise-Figure Measurements."

The source resistance giving minimum noise-figure for a given transistor and bias condition can be determined by differentiating equation (3) with respect to Rg and equating the derivative to zero.

$$R_g\,(F_{min.}) = \left[(r_{bb}' + r_e)^2 + \frac{(r_{bb}' + 0.5\,r_e)\,(2 h_{feo}\, r_e)}{1 + \left(\frac{f}{f\alpha}\right)^{(2)} (1 + h_{feo})} \right]^{1/2} \tag{4}$$

The value of Rg given by equation (4) is normally close to the value of Rg giving maximum power gain in the common-emitter configuration. Maximum power gain in either of the other two configurations (common-base or common-collector) is obtained when the source resistance is substantially different from that of equation (4). Consequently, the common-emitter configuration is the one predominantly used for low-noise applications.

If selectivity and image rejection are more important than noise-figure in a particular design, it may be desirable to terminate the transistor input with a source resistance other than Rg (Fmin.). Consider the antenna-to-RF amplifier coupling circuit shown in Figure 1.

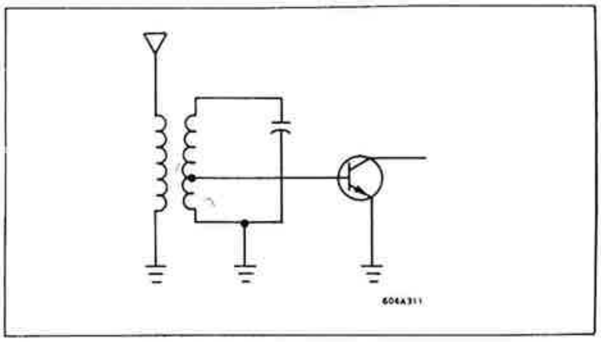


FIGURE 1

To have good selectivity in the input tuned circuit, the base of the RF amplifier transistor must be connected at a point on the transformer secondary which is near the signal ground end. This tap may not reflect Rg (Fmin.) to the transistor, but, since noise-figure does not degrade too rapidly with Rg in the vicinity of Rg(Fmin.), it is often desirable to sacrifice a small degradation in noise performance for a large improvement in selectivity.

Besides terminating the input of the first stage with a resistance close to Rg(Fmin.) it is necessary to insure that the input matching and tuning circuitry is very efficient since all losses in these circuits add directly to the amplifier noise-figure, i.e., if the input losses are 2 db, the receiver noise-figure will be 2 db greater than could otherwise be achieved. To meet this requirement, it is necessary that the unloaded Q_u of the input tank circuit be much greater than the loaded Q_L since the tank loss in db is:

$$\text{loss (db)} = 10 \log_{10} \left(1 - \frac{Q_L}{Q_\mu}\right)^2 \tag{5}$$

Losses due to the input bias resistors should be eliminated by connecting them through an RF choke to the input circuit or by making their connection through the ground end of the tank coil. This technique is shown in Figures 2a and 2b.

The effect of cascaded stages on the over-all system noise-factor is expressed by:

$$NF = NF_1 + \frac{NF_2}{G_1} + \frac{NF_3}{G_1\,G_2} +$$

where NF_1 and G_1 are the noise-factor and power gain (in numerics) of the first stage; NF_2 and G_2

those of the second stage and so on. The equation shows that with sufficient gain in the first stage, the system noise-figure is almost entirely determined by NF_1. Therefore it is desirable to use at least one low-noise RF amplifier stage in a heterodyne receiver if good sensitivity is to be achieved. The equation also indicates the advantage of a transistor mixer over a diode mixer since the attenuation of the diode mixer (G_2 less than 1) makes the G_1 G_2 product small and magnifies the effect of the third stage or IF noise factor on the overall system noise-factor.

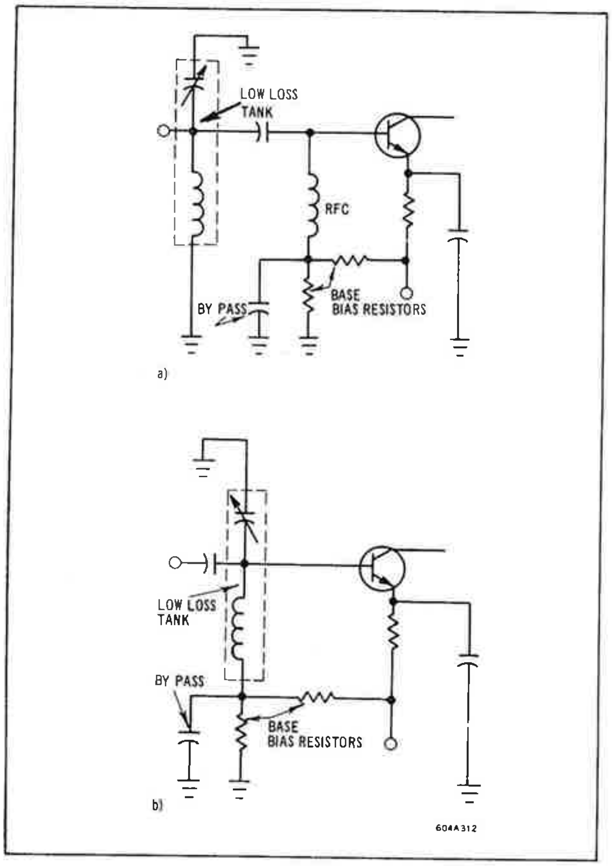


FIGURE 2

In summary - the important design considerations include:

1. Choice of a low noise transistor
2. Choice of optimum bias and source resistance conditions.
3. Low loss input circuitry.
4. Use of transistor RF amplifier and mixer stages in heterordyne receivers.

TECHNIQUES OF NOISE FIGURE MEASUREMENT

The receiver to be tested can be considered an ideal (noiseless) receiver with an associated noise voltage (e_r) at the input. The source termination Rg and its associated noise voltage (e_T) are included at the input as shown in Figure 3.

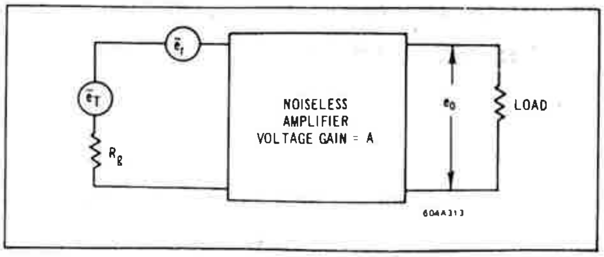


FIGURE 3

Source resistance noise voltage (e_T) is independent of frequency but is directly proportional to noise bandwidth. From statistical theory -

$e_T = \sqrt{4K\ T\ B\ R_g}$ - where K is Boltzmann's Constant

$(1.38 \times 10^{-23}\ \frac{\text{Joule}}{^\circ K})$,

T is the absolute temperature in degrees Kelvin, and B is the effective noise bandwidth in c.p.s.

Since noise power is proportional to the square of true RMS noise voltage, equation (2) can be extended to give noise-factor in terms of the above noise voltages.

$$NF = \frac{\overline{Ae_T}^2 + \overline{Ae_r}^2}{(\overline{Ae_T})^2} = \frac{\overline{e_o}^2}{(\overline{Ae_T})^2} \qquad (7)$$

Signal Generator Method of Measurement

From equation (7)

$$NF = \frac{\overline{e_o}^2}{A^2\ 4K\ T\ B\ R_g}$$

The connections for this measurement are shown in Figure 4.

With the signal generator output set to zero, note the RMS noise voltage e_o on a power meter or RMS voltmeter (sufficient gain, A, is required to detect low noise levels), then apply, at the test frequency, a signal V_g sufficient to increase the meter indication by exactly 3 db. The quantity AV_g is then equal to e_o so the noise-factor can be calculated from:

$$NF = \frac{(AV_g)^2}{A^2\ 4K\ T\ B\ R_g} = \frac{V_g^2}{4K\ T\ B\ R_g} \qquad (8)$$

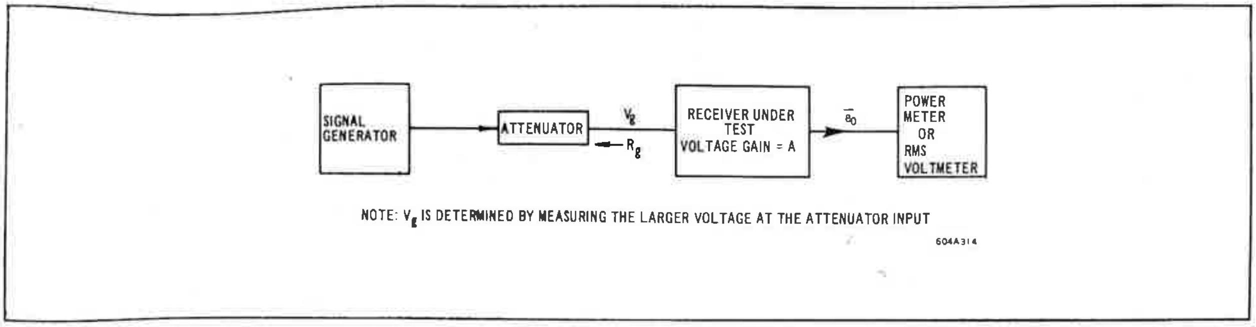


FIGURE 4

The disadvantage of this technique is that B, the effective noise bandwidth, is difficult to determine accurately. This bandwidth is not the 3 db bandwith of the amplifier resonance curve but is the width of an idealized rectangular bandpass curve which has the same area and peak value as the power gain versus frequency curve.

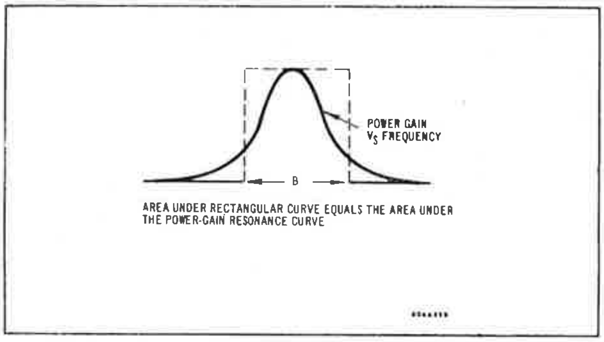


FIGURE 5

This technique is also inferior to others when a large number of measurements are to be made due to the time consuming calculations necessary.

Calibrated Diode Method

If a broadband noise source, such as a temperature limited diode, is used in place of the signal generator it is not necessary to determine the noise bandwith. The noise voltage V_n of such a source is a function of the diode direct current, the noise bandwidth and the source resistance.

$$V_n = (3.18 \times 10^{-19} I_b B)^{1/2} R_g$$

If one proceeds with the measurement in the same manner as above and increases the diode current from zero so as to increase the detected noise level by 3 db, i.e.

$AV_n = e_o$, the noise factor is:

$$NF = \frac{\overline{AV_n}^2}{\overline{Ae_T}^2} = \frac{3.18 \times 10^{-19} I_b B R_g^2}{4K\,T\,B\,R_g}$$

Which at T = + 298°K is $NF = 20 I_b R_g$

This shows that for a given value of Rg, the noise-factor or its logarithmic equivalent noise-figure can be calibrated directly in terms of the diode direct current I_b. Commercial diode noise sources are available with controls for varying I_b. They also have a current meter which is calibrated to indicate noise-figure directly in decibels.

A variation of the methods mentioned above uses an attenuator between the noise level detector and the receiver under test. The output reference noise level is noted as before. The attenuation is then increased 3 db and the noise diode or signal generator output is raised to bring the meter reading back to the initial reference point. This technique tends to eliminate errors due to inaccuracies in the meter. This is because the meter is being used as a reference level indicator only and not to make an absolute noise-power measurement.

Y Factor Method of Measurement

If a known amount of excess noise, relative to termination noise, is introduced at the input of the receiver and the relative change in output noise level is detected, a determination of noise-factor can be made without an accurate knowledge of gain and bandwidth.

By definition Y factor is:

The ratio of total output noise power with the excess noise source activated to the total output noise power with only the source termination connected.

If we define

N_T - output noise power due to the input termination

N_R - output noise power due to the imperfect receiver

N_{ex} - noise power at the output in excess of N_T due to the noise source at the input

then from equation (2)

$$NF = \frac{N_T + N_R}{N_T} => N_T + N_R = (NF)\,N_T$$

Also by definition

$$Y = \frac{N_T + N_R + N_{ex}}{N_T + N_R} \tag{10}$$

$$Y = 1 + \frac{N_{ex}}{(NF)\,N_T} = 1 + \frac{1}{NF}\left(\frac{N_{ex}}{N_T}\right)$$

The term $\left(\frac{N_{ex}}{N_T}\right)$ is the relative excess noise power of the broadband noise source and is usually expressed in db.

From equation (10), the noise factor is calculated as

$$NF = \frac{(N_{ex}/N_T)}{Y - 1}$$

In db this is

$$F = \left(\frac{N_{ex}}{N_T}\right) - 10 \log_{10} (Y-1) \qquad (11)$$

Thus if the change in output noise level (Y) is detected when a wideband noise source of known $\left(\frac{N_{ex}}{N_T}\right)$, ratio is connected at the input, it is a simple matter to calculate receiver noise-figure.

Typical excess noise-sources include:

1. Temperature Limited Diodes - useful for measurements up through the VHF band of frequencies.
2. Argon Discharge Tubes - useful from VHF through extremely high microwave frequencies.
3. Hot-Cold Noise Sources - useful into the gigacycle range of frequencies for very accurate NF measurements. Not adapted to automatic measurements.

Automatic Noise-Figure Measurements

Commercially available automatic noise-figure meters (hp Model 342A or AIL Model 74) convert a Y-factor measurement to a direct reading of noise-figure. A typical test block diagram for automatic noise-figure measurement of a UHF receiver is shown in Figure 6.

The noise source, which for UHF is normally a gas discharge tube, is pulsed on and off by the noise-figure meter power supply. This allows detection of the Y-ratio. The fixed attenuator at the input is used to minimize source standing wave ratio changes when going from the un-fired to the fired condition. The amount of attenuation in the pad must be subtracted from the measurement to obtain the correct noise-figure. The IF amplifier is necessary only if there is insufficient gain in the receiver for operating the AGC in the noise-figure meter. Normally, a minimum of 50 db gain from the receiver input to the meter input is necessary.

The automatic method of measurement is convenient when a determination of optimum bias is desired since changes in noise-figure can be observed simultaneously with changes in bias.

Typical noise-figure tests circuits used by RCA are shown in Figures 7, 8, and 9. These tests are at 60mc, 200 mc, and 450 mc respectively. The 60 mc circuit is followed by a 60 mc IF amplifier. This is used to obtain adequate gain for the test. The 200 mc and 450 mc circuits are each followed by a transistor mixer and an IF amplifier operating at 30 mc. Typical performance data on two, new RCA low-noise, silicon planar transistors tested in these circuits are shown in Table 1. Plots of NF versus I_C at 60 mc are shown in Figure 10.

TRANSISTOR TYPE	Rg	BIAS CONDITIONS	60MC NF	200MC INSERTION GAIN	200MC NF	450MC INSERTION GAIN	450MC NF
2N2857	400Ω	V_{CE} = 6V, I_C = 1ma	2 db	–	–	–	–
	*50Ω	V_{CE} = 6V, I_C = 1.5ma	–	21 db	3 db	14 db	4 db
2N2708	400Ω	V_{CE} = 6V, I_C = 1ma	3.5 db	–	–	–	–
	50Ω	V_{CE} = 15V, I_C = 2ma	–	16 db	5 db	–	–

*FOR THE 2N2857 C_1 IS CONNECTED TO THE TOP OF L_1 AS SHOWN BY THE DOTTED LINE IN FIGURE 8

604A321

TABLE I

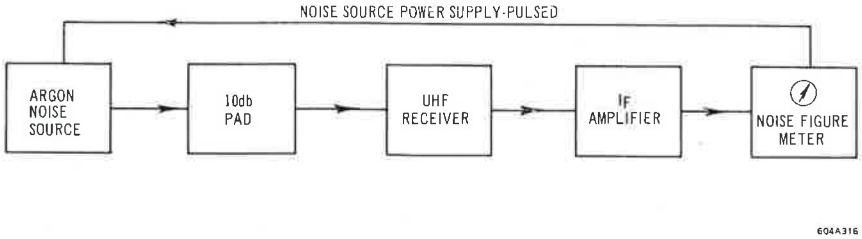


FIGURE 6

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Martin, Thomas P. "Electronic Circuits", Prentice Hall, 1956

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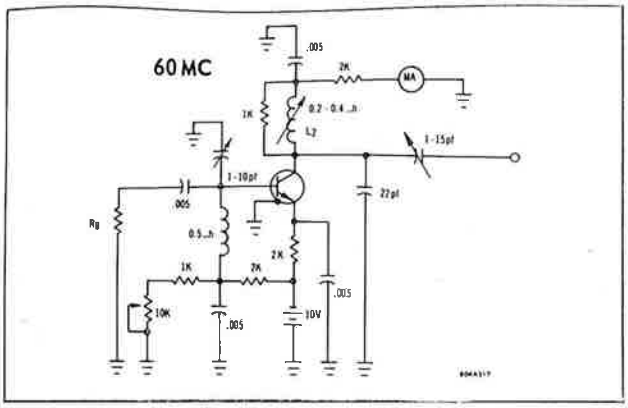
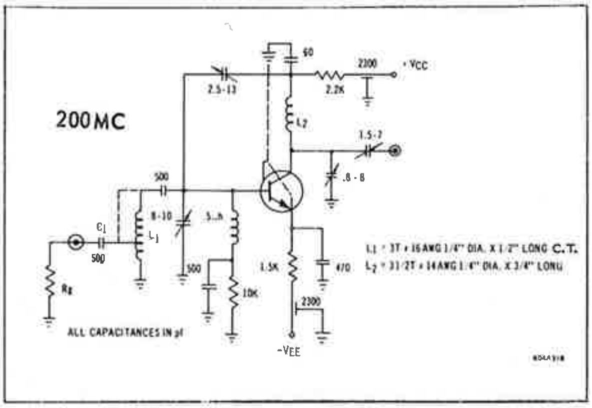


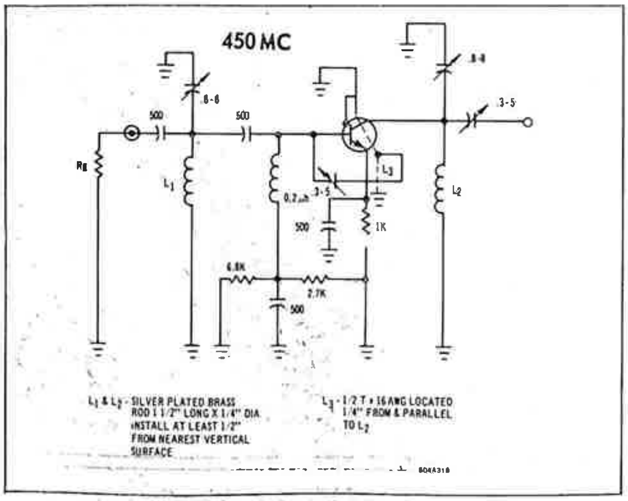
FIGURE 7



ALL CAPACITANCES IN pf

L1 = 3T # 16AWG 1/4" DIA. X 1/2" LONG C.T.
L2 = 3 1/2T # 14AWG 1/4" DIA. X 3/4" LONG

FIGURE 8



L1 & L2 - SILVER PLATED BRASS ROD 1 1/2" LONG X 1/4" DIA INSTALL AT LEAST 1/2" FROM NEAREST VERTICAL SURFACE

L3 - 1/2 T # 16 AWG LOCATED 1/4" FROM & PARALLEL TO L2

FIGURE 9

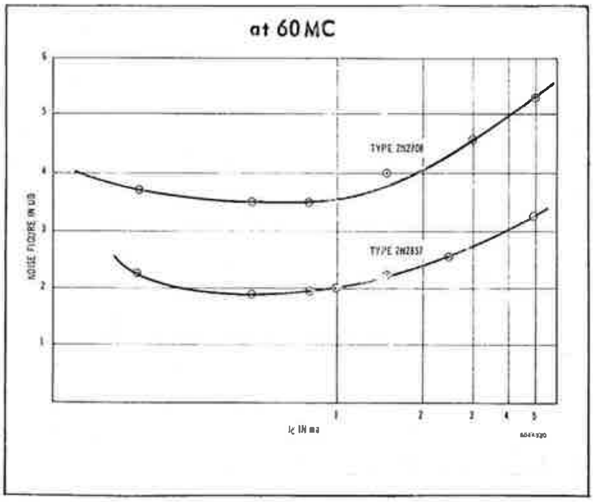


FIGURE 10

(With acknowledgements to RCA.)

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