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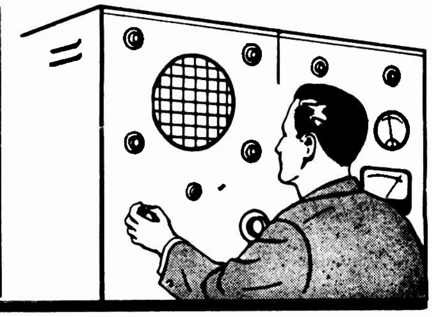

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Semiconductor Devices as Nonlinear Resistors

By the Engineering Department, Aerovox Corporation

Modern sophisticated electron design often calls for a nonohmic resistance element; i. e., one in which R varies nonlinearly with current or voltage (and sometimes which may vary approximately linearly but is dc-sensitive). This requirement is not recent in origin, however, as is attested by the article "Nonlinear Resistors" in the October-November 1953 issue of the *Research Worker*. That article was devoted only to the nonohmic resistance of thyrite, thermistors, tungsten-filament lamps, forward-biased germanium diodes, and miniature fuses. But during the ensuing decade, other components have become available, which extend the usefulness of nonlinear resistance.

Other components in which nonlinear resistance is available as a supplementary effect, and which merit present discussion, include silicon diodes and rectifiers, zener diodes, transistors, and tunnel diodes. The peculiar resistance characteristic of these components opens new vistas of application in control, computation, instrumentation, and communications. The performance of these components is discussed separately below.

SILICON DIODE

Forward-biased germanium small-signal diodes have long been used as nonlinear resistors to provide an average resistance variation of 100:1 (resistance decreases from 10,000 ohms to 100 ohms as the diode voltage drop is increased from 0.1 v to 1 v). Forward-biased small-signal silicon diodes provide similar nonlinear resistance change, with the added advantage of improved temperature characteristics.

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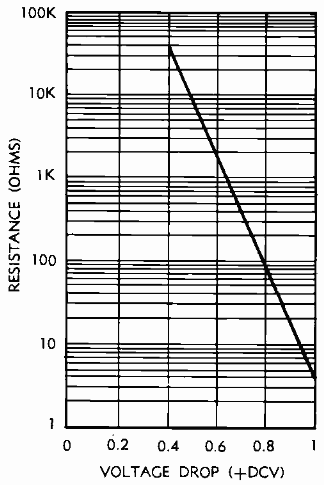


FIGURE 1
RESISTANCE CHARACTERISTIC OF PLANAR PASSIVATED EPITAXIAL SILICON DIODE

Figure 1 shows the resistance-vs-dc voltage characteristic of a forward-biased (i. e., anode positive, cathode negative) planar epitaxial passivated silicon diode (General Electric Type 1N3606) at 25°C. Note that the resistance decreases from 40K at 0.4 vdc to 4 ohms at 1 vdc, a resistance change of 1000:1 for a voltage change of 2.5:1. Corresponding current levels are 0.01 ma at 40,000 ohms, and 25 ma at 4 ohms. At +150°C, the resistance change, for the same voltage change, becomes 266 ohms to 3.3 ohms, and at −55°C, it becomes 4 megohms to 33 ohms.

SILICON RECTIFIERS

When a high value of current and/or voltage must be used in a nonlinear circuit, a silicon rectifier having suitable continuous dc ratings must be substituted for the small-signal diode.

Rectifiers (sometimes called *power diodes*) are supplied in a wide variety of current and voltage ratings — from less than 100 v to several kv, and from a few milliamperes to several hundred amperes. Correspondingly varied resistance values (both from a standpoint of absolute levels and range of variation) are provided by these rectifiers. Figure 3, for example, shows the resistance characteristic of an 850-ma rectifier (RCA Type CR101). Here, the resistance decreases from 1.8 ohm to 0.23 ohm (a resistance change of 7.84:1) as the forward d-c voltage is increased from 1.8v to 3.4v. (This corresponds to a current variation from 1 A to 15A. A rectifier may be selected to operate at the current and/or voltage available for the application, and the obtainable resistance range then may be determined from calculations of static d-c E/I values, the slope of the resulting curve resembling that given in Figure 2.

Like the small-signal silicon diode, the silicon rectifier has improved temperature ratings, compared with those of its germanium counterpart.

ZENER DIODE

Operation of the zener diode is characterized by its sharp reverse breakdown (rapid increase of current at a discrete reverse voltage). This peculiarity, which has been much exploited in voltage regulation, gives rise to a distinctive nonlinear resistance feature. The zener diode is reverse-biased; i. e., anode negative and cathode positive.

Figure 3 shows the resistance characteristic of a reverse-biased 3.9-volt zener diode (International Rectifier Type 1N1518). Here, the resistance decreases from 140K to 11 ohms as the voltage drop is increased from 0.6 v to 3.9 v (a resistance change of 12,700:1 for a voltage change of 6.5:1). The corresponding current increases from 4 microamperes to 250 milliamperes.

Zener diodes are available in a wide variety of current, voltage, and power ratings. As is true with small-signal diodes and rectifiers, a unit may be chosen to withstand current and/or voltage available in the circuit. The obtainable resistance range then may be determined from static d-c E/I calculations, the slope of the resulting curve resembling that given in Figure 3.

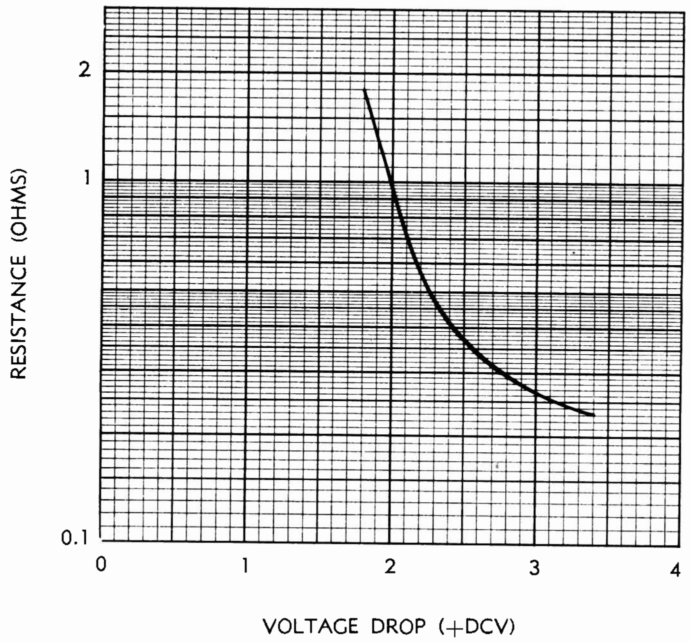


FIGURE 2. RESISTANCE CHARACTERISTIC OF SILICON POWER RECTIFIER (RCA CR101)

Figure 6 shows the circuit for a field effect transistor. Here, R is a 50,000-ohm ½-watt resistor, B a 1½-volt bias battery, and X the field effect transistor (Amelco Type FE200). The resistance available at terminals A and B (with A positive) increases from 10K to 41K as the applied voltage is increased from 5 v to 45 v (corresponding to a current change from 0.5 ma to 1.1 ma).

Selection of Transistor Resistance Range. Changing the emitter-base input bias will change the resistance of the transistor at any discrete value of collector voltage. Thus, the resistance range of any transistor, together with its absolute resistance limits, may be selected simply by changing the value of fixed bias — current bias in conventional small-signal and power types; voltage bias in the field effect type.

TUNNEL DIODE

The forward-biased tunnel diode provides not only nonlinear resistance, but also negative resistance over a portion of its E/I characteristic. Figure 7 shows how this resistance varies with low values of forward d-c voltage drop in a General Electric Type 1N2940 tunnel diode.

The diode resistance is positive and stable between its 10-mv and 55-mv values, negative and unstable from 55 mv to 350 mv, and positive and stable again from 350 mv to 400 mv and beyond. The current peak (1 ma) occurs at 55 mv, and the current valley (0.1 ma) at 350 mv, for the particular diode tested by the editors.

WHERE USED

Some of the automatic actions provided in a simple manner by nonlinear resistors include voltage regulation, frequency multiplication (harmonic generation), curve shaping, curve correction, amplitude stabilization, signal compression, signal expansion, modulation, bias control, signal damping, instrument protection, and transient suppression. The semiconductor devices discussed in this article have extended the range of usefulness of nonlinearity and are valuable additions to the stock of early nonlinear resistors.

Equipment in which nonlinear resistor action may be exploited include test instruments, control devices, communications apparatus, electromedical gear, and domestic and industrial electrical and electronic machinery.

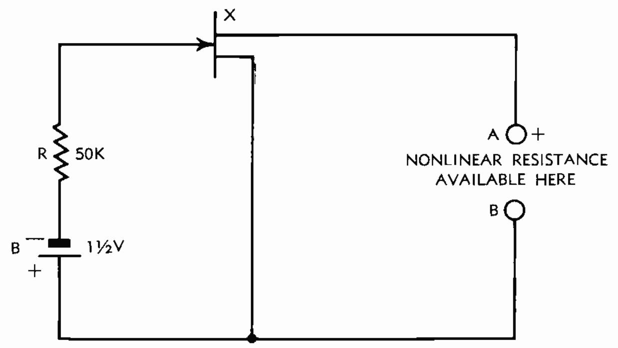


FIGURE 6. FIELD EFFECT TRANSISTOR AS NONLINEAR RESISTOR

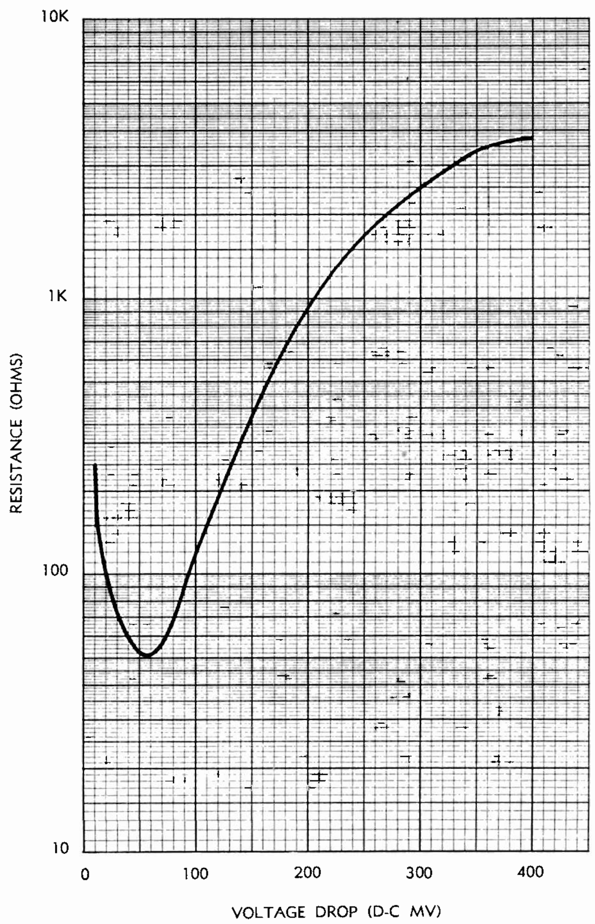


FIGURE 7. RESISTANCE CHARACTERISTIC OF TUNNEL DIODE

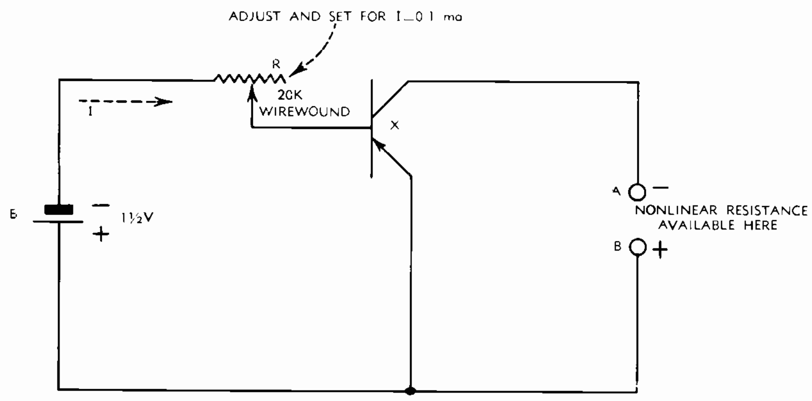


FIGURE 4. TRANSISTOR AS NONLINEAR RESISTOR

TRANSISTOR

The common-emitter - connected transistor will provide a nonlinear resistance in its collector-emitter (output) circuit when a small fixed bias current is supplied to its base-emitter (input) circuit. Figure 4 shows the circuit: X is the transistor, B a 1½-volt d-c bias source, and R a 20,000-ohm wirewound rheostat for setting the bias current to 0.1 milliampere. The internal collector-emitter resistance varies nonlinearly as a voltage applied to terminals A and B (with A negative) is varied linearly.

Conventional Small-Signal Transistor. For low-voltage applications (i. e., where the d-c voltage drop across the transistor will not exceed 22½ v), a conventional, small-signal transistor is satisfactory. Common-emitter response curves for various transistors may be inspected for the absolute resistance values and resistance variation desired. (Resistance may be calculated from the collector voltage and collector current values obtained from the curves: $R = Vc/Ic$.)

Figure 5 shows the collector resistance variation for the circuit given in Figure 4. When rheostat R is set for a bias current, I, of 0.1 ma, the resistance varies from 118 ohms at a collector-to-emitter voltage drop of 1 v to 1160 ohms at 12 volts. (This resistance change of 9.84:1 corresponds to a current change from 8.5 ma to 10.32 ma.) The transistor is RCA Type 2N109. Unlike the previous examples, here the resistance varies *directly* as the applied voltage; and although it is very nearly linear, it is voltage-dependent.

Power Transistor. When higher voltage and/or current must be used, a suitable power transistor must be chosen. The circuit is the same as Figure 4, except that B and R must be chosen for higher bias current. With a Delco Type 2N2827 transistor, biased at 1 ma, the resistance increases from 40 ohms to 156 ohms as the voltage is increased from 5 v to 25 v (corresponding to a current increase from 125 ma to 160 ma). When this transistor is biased at 4 ma, the resistance increases from 17.7 ohms at 5 v to 61.6 ohms at 20 v (corresponding to a current increase from 280 ma to 325 ma).

Field Effect Transistor. Operation of the unipolar field effect transistor (FET) approximates that of a vacuum tube more closely than is possible with a conventional transistor. In particular, the input impedance (resistance) of the FET is very high (similar to the tube grid input), so this device is essentially voltage operated as far as an input-bias signal is concerned.

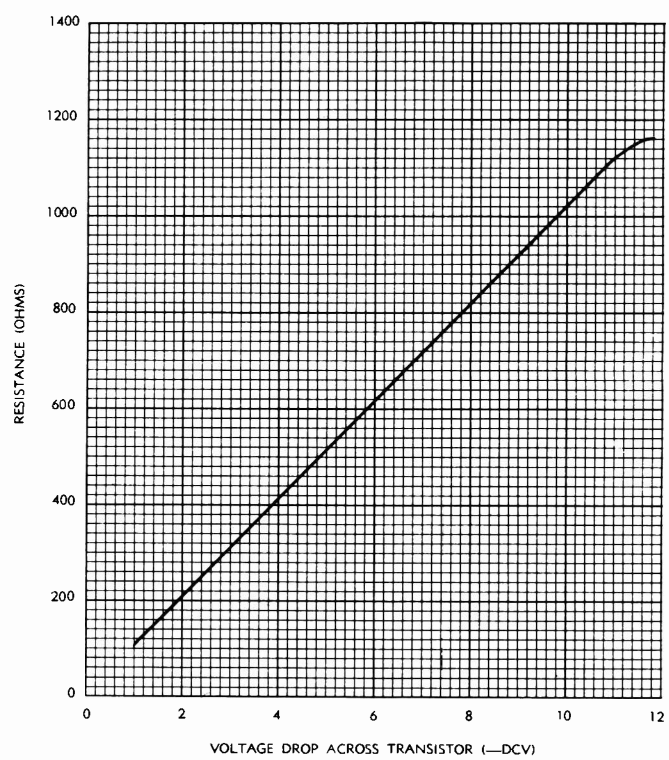


FIGURE 5. COLLECTOR RESISTANCE CHARACTERISTIC OF SMALL-SIGNAL TRANSISTOR

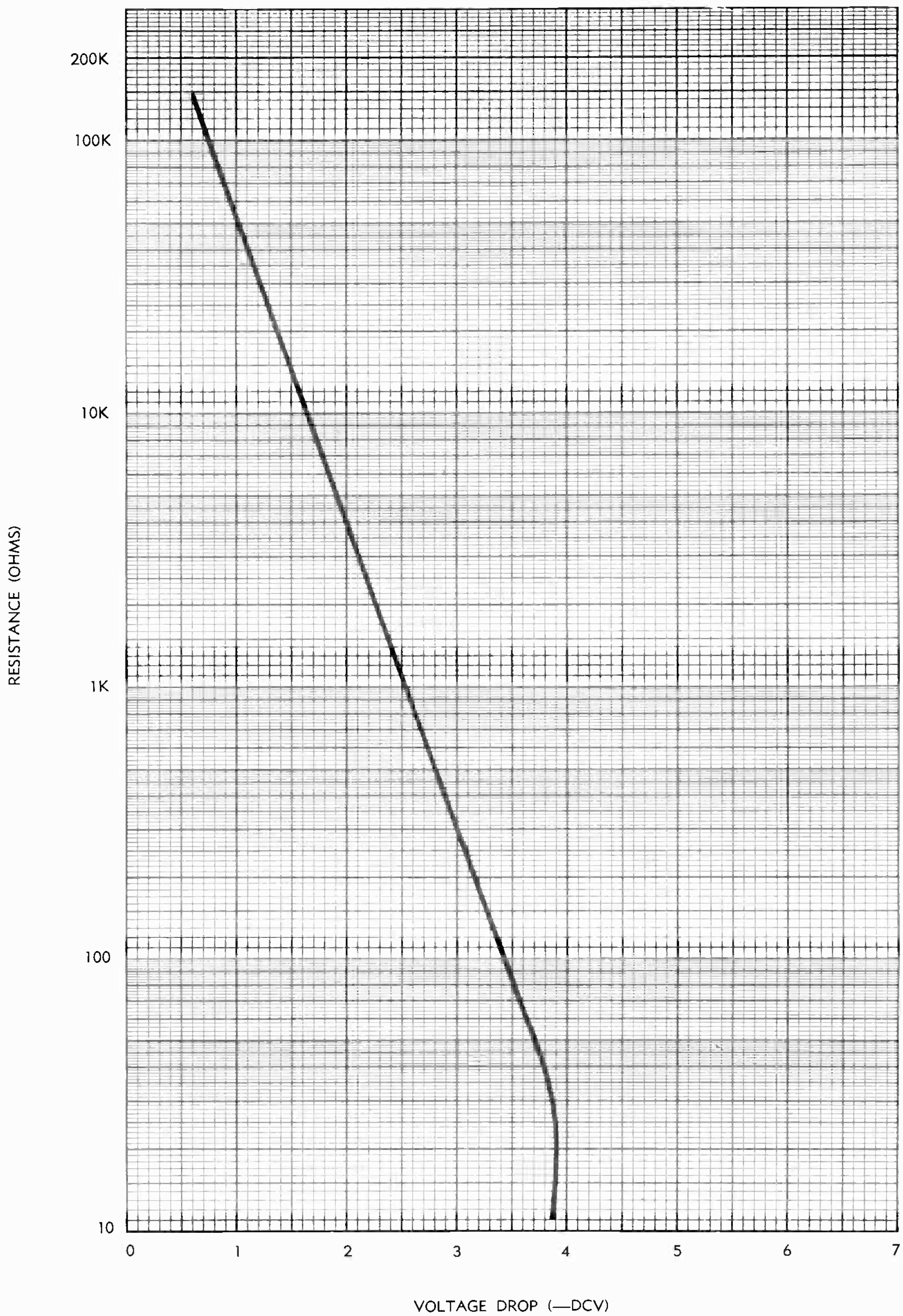
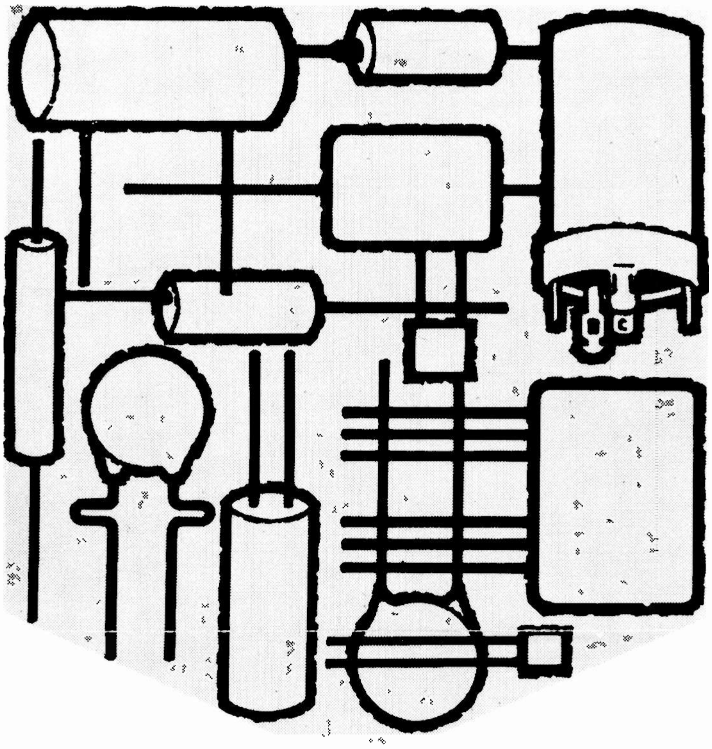


FIGURE 3. RESISTANCE CHARACTERISTIC OF ZENER DIODE



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