CHAPTER 5.2
ACTIVE DISCRETE COMPONENTS

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POWER AND RECEIVING TUBES

George W. Taylor, Bernard Smith

Introduction

Power and receiving tubes are active devices using either the flow of free electrons in a vacuum or electrons and ions combined in a gas medium. The vast majority of uses for low-power electron tubes are found in the area of high vacuum with controlled free electrons. The source of free electrons is a heated material that is a thermionic emitter (cathode). The control element regulating the flow of electrons is called a *grid*. The collector element for the electron flow is the *anode*, or *plate*. Power tubes, in contrast to receiving-type tubes, handle relatively large amounts of power, and for reasons of economy, a major emphasis is placed on efficiency. The traditional division between the two tube categories is at the 25-W plate-dissipation rating level.

Receiving tubes traditionally provided essential active-device functions in electronic applications. Most receiving-type tubes produced at the present time are for replacement use in existing equipments. Electronic functions of new equipment designs are being handled by solid-state devices.

Power tubes are widely used as high-power-level generators and converters in radio and television transmitters, radar, sonar, manufacturing-process operations, and medical and industrial x-ray equipment.

Classification of Types

Power and receiving-type tubes can be separated into groups according to their circuit function or by the number of electrodes they contain. Table 5.2.1 illustrates these factors and compares some of the related features. The physical shape and location of the grid relative to the plate and cathode are the main factors that determine the amplification factor μ of the triode. The μ values of triodes generally range from about 5 to over 200. The mathematical relationships between the three important dynamic tube factors are

$$\text{Amplification factor } \mu = \Delta e_b/\Delta e_{c1}$$

$$\text{Dynamic plate resistance } r_p = \Delta e_b/\Delta i_b \qquad e_b, e_{cl}, i_b = \text{const}$$

$$\text{Transconductance } Sm \text{ or } Gm = \Delta i_b/\Delta e_{c1}$$

TABLE 5.2.1 Tube Classification by Construction and Use

Tube type	No. of active electrodes	Typical use	Relative features and advantages
Diode	2	Rectifier	High back resistance
Triode	3	Low- and high-power amplifier, oscillatgor, and pulse modulator	Low cost, circuit simplicity
Tetrode	4	High-power amplifier and pulse modulator	Low drive power, low feedback
Pentode	5	Low-power amplifier	High gain, low drive, low feedback, low anode voltage
Hexode, etc.	6 or more	Special applications	Multiple-input mixers, converters

where e_b = total instantaneous plate voltage
e_{c1} = total instantaneous control grid voltage
i_b = total instantaneous plate current

Note that $\mu = Gmr_p$. Figure 5.2.1 shows the curves of plate and grid current as a function of plate voltage at various grid voltages for a typical triode with a μ value of 30.

The tetrode, a four-element tube, is formed when a second grid (screen grid) is mounted between grid 1 (control grid) and the anode (plate). The plate current is almost independent of plate voltage. Figure 5.2.2 shows the curves of plate current as a function of plate voltage at a fixed screen voltage and various grid voltages for a typical power tetrode.

Cooling Methods

Cooling of the tube envelope, seals, and anode, if external, is a major factor affecting tube life. The data sheets provided by tube manufacturers include with the cooling requirements a maximum safe temperature for the various external surfaces. The temperature of these surfaces should be measured in the operating equipment. The temperature can be measured with thermocouples, optical pyrometers, a temperature-sensitive paint such as Tempilaq, or temperature-sensitive tapes.

The envelopes and seals of most tubes are cooled by convection of air around the tube or by using forced air. The four principal methods used for cooling external anodes of tubes are by air, water, vapor, and heat

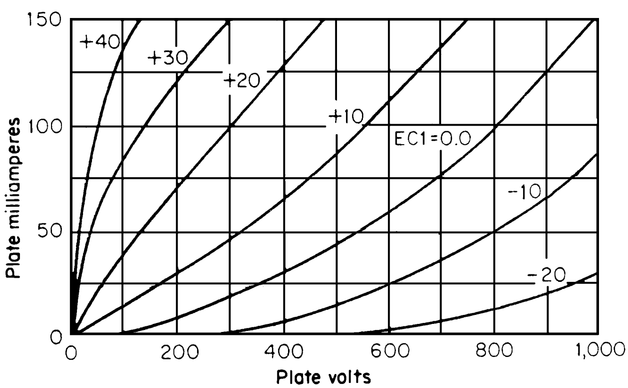

FIGURE 5.2.1 Typical triode plate characteristics.

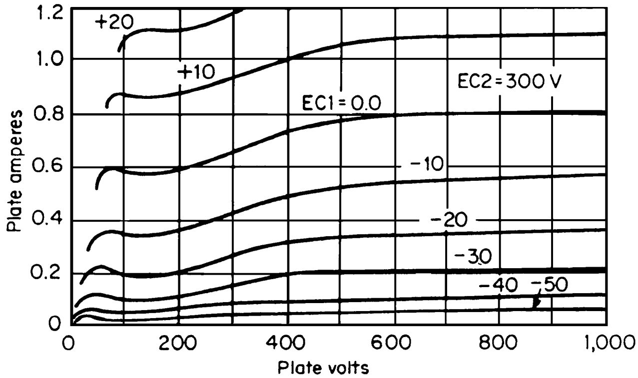

FIGURE 5.2.2 Typical tetrode plate characteristics.

sinks. Other cooling methods occasionally used are oil, heat pipes, refrigerants, such as Freon, and gases, such as sulfahexafluoride.

Protective Circuits

Arcs can damage or destroy electron tubes, which may significantly increase the equipment operating cost. In low- or medium-power operation, the energy stored in the circuit is relatively small and the series impedance is high, which limits the tube damage. In these circuits, the tube will usually continue to work after the fault is removed; however, the life of the tube will be reduced. Since these tubes are normally low in cost, economics dictates that inexpensive slow-acting devices, e.g., circuit breakers and common fuses, be used to protect the circuit components.

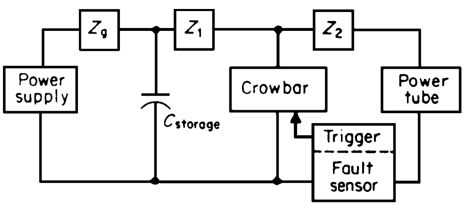

FIGURE 5.2.3 Energy-diverter circuit.

High-power equipment has large stored energy, and the series impedance is usually low. Arcs in this type of equipment will often destroy expensive tubes, and slow-acting protective devices offer insufficient protection. The two basic techniques used to protect tubes are *energy diverters* and special *fast-blow fuses*. The term *crowbar* is commonly used for energy diverters. The typical circuit for a crowbar is shown in Fig. 5.2.3. In the event of a tube arc, the trigger-fault sensor unit "fires" to a crowbar, which is a very-low-impedance gas-discharge device. The firing time can be less than 2 μs. The low impedance in the crowbar arm is in shunt with the Z_2 and tube arm and diverts current from the tube during arcs. The impedance Z_2, which is in series with the tube, is used to ensure that most of the current is diverted through the crowbar. The value of Z_2 is primarily limited by efficiency considerations during normal operation. The impedance Z_1 is required to limit the fault current in the storage condenser to the maximum current rating of the condenser. The impedance Z_g is the internal power-supply impedance. Devices used as crowbars are thyratrons, ignitrons, triggered spark gaps and plasmoid-triggered vacuum gaps.

Fast Fuses

Two types of fast-blow fuses are used to protect power tubes. They are *exploding-wire* and *exothermic* fuses. Exploding-wire fuses require milliseconds to operate and are limited in their ability to protect the tube. Exothermic fuses, although faster-acting than exploding wires, are significantly slower than crowbars in clearing the fault current in the tube. A second disadvantage of fuses is that after each fault the power supply must be turned off and the fuse replaced. For this reason, fuses are limited to applications where the tubes seldom arc. The major advantage of fuses is low cost.

CATHODE-RAY STORAGE AND CONVERSION DEVICES

I. Reingold, Munsey E. Crost

Storage Tubes

Electronic charge-storage tubes are divided into four broad classes: electrical-input-electrical-output types, electrical-input-visual-output types, visual-input-electrical-output types, and visual-input-visual-output types. An example of each class is cited in Table 5.2.2.

Tubes under these classes in which storage is merely incidental, such as camera tubes and image converters, are classed under conversion devices.

Electrical-Input Devices

Electrical-Output Types. The *radechon*, or *barrier-grid storage tube*, is a single-electron-gun storage tube with a fine-mesh screen in contact with a mica storage surface. The metal screen, called the *barrier grid*, acts as a very-close-spaced collector electrode, and essentially confines the secondary electrons to the apertures of the grid in which they were generated. The very thin mica sheet is pressed in contact with a solid metal backplate. A later model was developed with a concave copper bowl-shaped backplate and a fritted-glass dielectric storage surface. A similarly shaped fine-mesh barrier grid was welded to the partially melted glass layer. The tube is operated with backplate modulation; i.e., the input electrical signal is applied to the backplate while the constant-current electron beam scans the mica storage surface. The capacitively induced voltage on the beam side of the mica dielectric is neutralized to the barrier-grid potential at each scanned elemental area by collection of electrons from the beam and/or by secondary electron emission (equilibrium writing). The current involved in recharging the storage surface generates the output signal.

In a single-electron-gun *image-recording storage tube* (Fig. 5.2.4) information can be recorded and read out later. The intended application is the storage of complete halftone images, such as a television picture, for later readout. In this application, write-in of information is accomplished by electron-beam modulation, in time-sharing sequence with the readout mode. Reading is accomplished nondestructively, i.e., without intentionally changing the stored pattern, by not permitting the beam to impinge upon the storage surface. The electron-gun potentials are readjusted for readout so that none of the electrons in the constant-current beam can reach the storage surface, but divide their current between the storage mesh and the collector in proportion to the stored charge. This process is called *signal division*.

One type of double-ended, multiple-electron-gun *recording storage tube* with nondestructive readout operates by recording halftone information on an insulating coating on the bars of a metal mesh grid, which can be penetrated in both directions by the appropriate electron beams. Very high resolution and long storage time with multiple readouts, including simultaneous writing and reading, are available with this type of tube. Radio-frequency separation or signal cancellation must be used to suppress the writing signal in the readout during simultaneous operation.

Figure 5.2.5 is a representative schematic drawing of a double-ended, multiple-electron-gun *membrane-target storage tube* with nondestructive readout, in which the writing beam and the reading beam are separated by

TABLE 5.2.2 Storage-Tube Classes

Type of input	Type of output	Subclass	Representative example
Electrical	Electrical	Single-gun	Radechon
		Multiple-gun	Graphechon
	Visual	Bistable	Memotron
		Halftone	Tonotron
Visual	Electrical	Nonscanned	Correlatron
	Visual	Time-sharing	Storage image tube

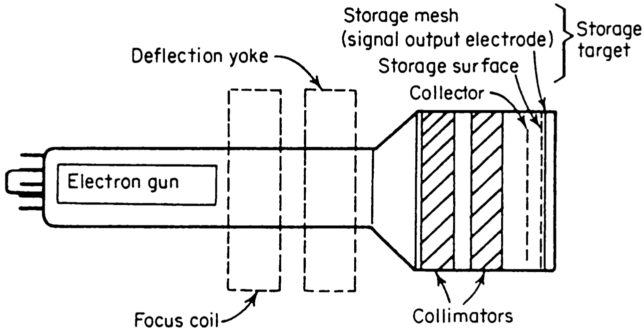

FIGURE 5.2.4 Electrical-signal storage tube, basic structure. (*Hughes Aircraft Corp.*)

the thin insulating film of the storage target. In this case there is a minimal interference of the writing signal with the readout signal in simultaneous operation, except for capacitive feed-through, which can readily be canceled. Writing is accomplished by beam modulation, while reading is accomplished by signal division. Very high resolution and long storage time with multiple readouts are available with this group of tubes.

The *graphechon* differs from the two groups of tubes just described in that its storage target operates by means of electron-bombardment-induced conduction (EBIC). Halftones are not available from tubes of this type in normal operation. The readout is of the destructive type, but since a large quantity of charge is transferred through the storage insulator during writing, a multitude of readout copies can be made before the signal displays noticeable degradation. In simultaneous writing and reading, signal cancellation of the writing signal in the readout is generally accomplished at video frequencies.

Visual-Output Types. This class comprises the *display storage tubes (DSTs)* or *direct-view storage tubes (DVSTs)*. Figure 5.2.6 shows a schematic diagram of a typical DVST with one electrostatic focus-and-deflection writing gun (other types may have electromagnetic focus and/or deflection) and one flood gun, which is used to provide a continuously bright display and may also establish bistable equilibrium levels. The storage surface is an insulating layer deposited on the bars of the metal-mesh backing electrode. The view screen is an aluminum-film-backed phosphor layer.

The *memotron* is a DST that operates in the bistable mode; i.e., areas of the storage surface may be in either the cutoff condition (flood-gun-cathode potential) or in the transmitting condition (collector potential), either of which is stable. The focusing and deflection are electrostatic. Normally, the phosphor remains in the unexcited

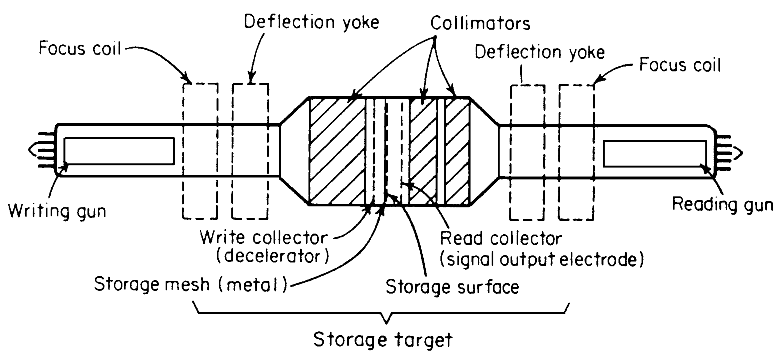

FIGURE 5.2.5 Typical double-ended scan converter, basic structure. (*Hughes Aircraft Corp.*)

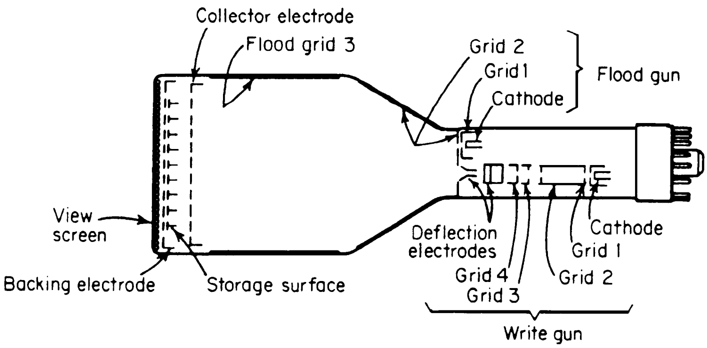

FIGURE 5.2.6 Cross-sectioned view of direct-view storage tube. (*Westinghouse Electric Corp.*)

condition until a trace to be displayed is written into storage; then this trace is displayed continuously until erased, so long as the flood beam is maintained in operation.

The *tonotron* is typical of a large number of halftone DSTs. These operate in the nondestructive readout mode, with the storage surface at or below flood-cathode potential. Writing is accomplished by depositing halftone charge patterns by electron-beam modulation.

Visual-Input Devices

Electrical-Output Types. The *correlatron* is a storage tube that receives a visual input to a photoemissive film, focuses the photoelectron image upon a transmission-grid type of storage target, where it is stored, and later compares the original image with a similar image. A single total output current is read out for the entire image, with no positional reference. The purpose of this comparison is to ascertain whether the first and second images correlate.

Visual-Output Types. In the *storage image tube*, a positive electron image can be stored upon the insulated bars of the storage mesh. Then, if the photocathode is uniformly flooded with light to produce a flood electron cloud, a continuously bright image of the stored charge pattern can be obtained on the phosphor screen in the following section of the tube. A high degree of brightness gain can be achieved with this type of tube, or a single snapshot picture of a continuous action can be "frozen" for protracted study.

Conversion Devices

The conversion devices discussed receive images in visible or infrared radiation and convert them by internal electronic processes into a sequence of electrical signals or into a visible output image. Some of these devices may employ an internal storage mechanism, but this is generally not the primary function in their operation. These tubes are characterized by a photosensitive layer at their input ends that converts a certain region of the quantum electromagnetic spectrum into electron-hole pairs. Some of these layers are photoemissive; i.e., they emit electrons into the vacuum if the energy of the incoming quantum is high enough to impart at least enough energy to the electron to overcome the work function at the photosurface-vacuum interface. Others do not emit electrons into the vacuum but conduct current between the opposite surfaces of the layer by means of the electron-hole pairs; i.e., they are photoconductive. The transmission characteristics of the material of the entrance window of the tube can greatly modify the effective characteristics of any photosurface. If the material is photoemissive, the total active area is called a *photocathode*.

The types of conversion devices discussed are divided into visual-input devices, electrical-output and visual-output types. An example of each type is cited in Table 5.2.3.

TABLE 5.2.3 Conversion Devices

Type of input	Type of output	Subclass	Representative example
Visual	Electrical	Photoemissive	Image orthicon
		Photoconductive	Vidicon
	Visual	Photoemissive	Image amplifier

Visual-Input Conversion Devices

Electrical-Output Types. This class covers the large group of devices designated camera tubes. The defining attributes of the *vidicon* are a photoconductive rather than photoemissive image surface or target, a direct readout from the photosensitive target rather than by means of a return beam, and a much smaller size than the above camera tubes. The original vidicons used coincident electromagnetic deflection and focusing. Many later versions employ either or both electrostatic focusing and deflection.

A very important group of tubes is the *semiconductor diode-array vidicons*. In place of the usual photoconductive target, these tubes include a very thin monolithic wafer of the semiconductor, usually single-crystal silicon. On the beam side of this wafer a dense array of junction photodiodes has been generated by semiconductor diffusion technology. These targets are very sensitive compared with the photoconductors, and they have very low leakage, low image lag, and low blooming from saturation.

Visual-Output Types. The *image tube*, or *image amplifier*, with input in the visible spectrum is used principally to increase the light level and dynamic range of a very low light-level image to a level and contrast acceptable to a human observer, a photographic plate, or a camera tube. The image tube consists basically of a photoemissive cathode, a focusing and accelerating electron-optical system, and a phosphor screen.

Since the photocathode would be illuminated by light returning from the phosphor screen, the internal surface of the phosphor is covered with a very thin film of aluminum that can be penetrated by the high-energy image electrons. The aluminum film also serves as the tube anode and as a reflector for the light that would otherwise be emitted back into the tube.

SEMICONDUCTOR DIODES AND CONTROLLED RECTIFIERS

Gregory J. Malinowski, John F. Donlon

Semiconductor Materials and Junctions

Diodes and controlled rectifiers are fabricated from semiconductor materials, a form of matter situated between metals and insulators in their ability to conduct electricity. Typical values of electrical resistivity of conductors, semiconductors, and insulators are 10^{-6} to 10^{-5}, 10 to 10^4, and 10^{12} to 10^{16} $\Omega \cdot$ cm, respectively. Silicon is the most widely used semiconductor material. Other semiconductor materials such as germanium, gallium arsenide, selenium, cadmium sulfide, copper oxide, and silicon carbide have electrical properties that make them useful in special applications.

Semiconductor devices develop current flow from the motion of *charge carriers* within a crystalline solid. The conduction process in semiconductors is most easily visualized in terms of silicon. The silicon atoms have four electrons in the outer shell (valence shell). These electrons are normally bound in the crystalline lattice structure. Some of these valence electrons are free at room temperature, and hence can move through the crystal; the higher the temperature, the more electrons are free to move. Each vacancy, or hole, left in the lattice can be filled by an adjacent valence electron. Since a hole moves in a direction opposite to that of an electron, a hole may be considered as a positive-charge carrier. Electrical conduction is a result of the motion of holes and electrons under the influence of an applied field.

Intrinsic (pure) semiconductors exhibit a negative coefficient of resistivity, since the number of carriers increases with temperature. Conduction owing to thermally generated carriers, however, is usually an undesirable effect, because it limits the operating temperature of the semiconductor device.

At a given temperature, the concentration of thermally generated carriers is related to the energy gap of the material. This is the minimum energy (stated in electron volts) required to free a valence electron (1.1 eV for silicon and 0.7 eV for germanium). Silicon devices perform at higher temperatures because of the wider energy gap.

The conductivity of the semiconductor material can be altered radically by doping with minute quantities of *donor* or *acceptor impurities*. Donor (*n*-type) impurity atoms have five valence electrons, whereas only four are accommodated in the lattice structure of the semiconductor. The extra electron is free to conduct at normal operating temperatures. Common donor impurities include phosphorus, arsenic, and antimony. Conversely, acceptor (*p*-type) atoms have three valence electrons; a surplus of holes is created when a semiconductor is doped with them. Typical acceptor dopants include boron, gallium, and indium.

In an *extrinsic (doped) semiconductor*, the current-carrier type introduced by doping predominates. These carriers, electrons in *n*-type material and holes in *p*-type, are called *majority carriers*. Thermally generated carriers of the opposite type are also present in small quantities and are referred to as *minority carriers*. Resistivity is determined by the concentration of majority carriers.

Lifetime is the average time required for excess minority carriers to recombine with majority carriers. Recombination occurs at "traps" caused by impurities and imperfections in the semiconductor crystal. Semiconductor junctions are formed in material grown as a single continuous crystal to obtain the lattice perfection required, and extreme precautions are taken to ensure exclusion of unwanted impurities during processing. However, in some applications the characteristics associated with short lifetime are desirable. In these cases electron and/or proton irradiation and/or heavy metal doping such as gold are used to create recombination sites and lower the life time.

Carrier mobility is the property of a charge carrier that determines its velocity in an electric field. Mobility also determines the velocity of a minority carrier in the diffusion process. High mobility yields a short transit time and good frequency response.

pn Junctions

If *p*- and *n*-type materials are formed together, a unique interaction takes place between the two materials, and a *pn* junction is formed. In the immediate vicinity of this junction (in the *depletion region*), some of the excess electrons of the *n*-type material diffuse into the *p* region, and likewise holes diffuse into the *n*-type region. During this process of recombination of holes and electrons, the *n* material in the depletion region acquires a slightly positive charge and the *p* material becomes slightly negative. The space-charged region thus formed repels further flow of electrons and holes, and the system comes into equilibrium. Figure 5.2.7 shows a typical *pn* junction.

To keep the system in equilibrium, two related phenomena constantly occur. Because of thermal energy, electrons and holes diffuse from one side of the *pn* junction to the other side. This flow of carriers is called *diffusion current*. When a current flows between two points, a potential gradient is produced. This potential gradient across the depletion region causes a flow of charge carriers; drift current, in the opposite direction to the diffusion current. As a result, the two currents cancel at equilibrium, and the net current flow is zero through the region. An energy barrier is erected such that further diffusion of charge carriers becomes impossible without the addition of some external energy source. This energy barrier formed at the interface of the *p*- and *n*-type materials provides the basic characteristics of all junction semiconductor devices.

pn Junction Characteristics

When a dc power source is connected across a *pn* junction, the quantity of current flowing in the circuit is determined by the polarity of the applied voltage and its effect on the depletion layer of the diode. Figure 5.2.8 shows the classical condition for a reversed-biased *pn* junction. The negative terminal of the power supply is connected to the *p*-type material, and the positive terminal to the *n*-type material. When a *pn* junction is reverse-biased, the

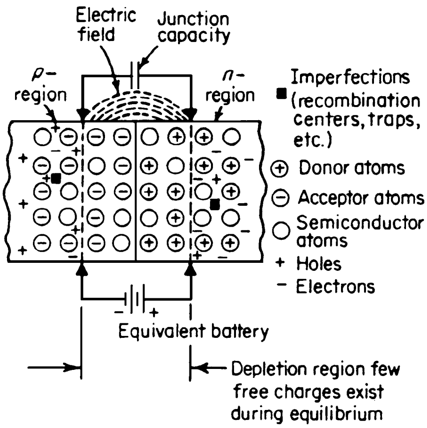

FIGURE 5.2.7 *pn* junction.

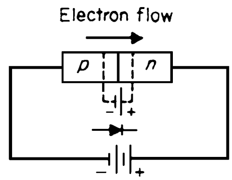

FIGURE 5.2.8 Reversed-biased diode.

free elections in the *n*-type material are attracted toward the positive terminal of the power supply and away from the junction. At the same time, holes from the *p*-type material are attracted toward the negative terminal of the supply and away from the junction. As a result, the depletion layer becomes effectively wider, and the potential gradient increases to the value of the supply. Under these conditions the current flow is very small because no electric field exists across either the *p* or *n* region.

Figure 5.2.9 shows the positive terminal of the supply connected to the *p* region and the negative terminal to the *n* region. In this arrangement, electrons in the *p* region near the positive terminal of the supply break their electron-pair bonds and enter the supply, thereby creating new holes. Concurrently, electrons from the negative terminal of the supply enter the *n* region and diffuse toward the junction. This condition effectively decreases the depletion layer, and the energy barrier decreases to a small value. Free electrons from the *n* region can then penetrate the depletion layer, flow across the junction, and move by way of the holes in the *p* region toward the positive terminal of the supply. Under these conditions, the *pn* junction is said to be *forward-biased.*

A general plot of voltage and current for a *pn* junction is shown in Fig. 5.2.10. Here both the forward- and reverse-biased conditions are shown. In the forward-biased region, current rises rapidly as the voltage is increased and is quite high. Current in the reverse-biased region is usually much smaller and remains low until the breakdown voltage of the diode is reached. Thereupon the current increases rapidly. If the current is not limited, it will increase until the device is destroyed.

Junction Capacitance. Since each side of the depletion layer is at an opposite charge with respect to each other, each side can be viewed as the plate of a capacitor. Therefore a *pn* junction has capacitance. As shown in Fig. 5.2.11, junction capacitance changes with applied voltage.

DC Parameters of Diodes. The most important of these parameters are as follows:

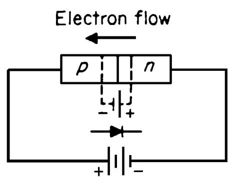

FIGURE 5.2.9 Forward-biased diode.

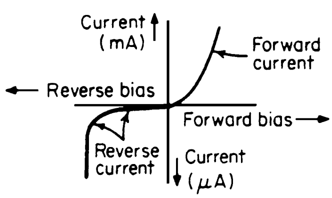

FIGURE 5.2.10 Voltage-current characteristics for a *pn* junction.

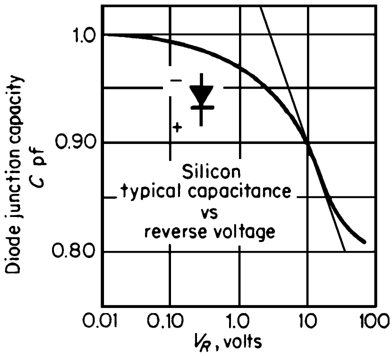

FIGURE 5.2.11 Diode junction capacitance vs. reverse voltage.

Forward voltage V_F is the voltage drop at a particular current level across a diode when it is forward-biased.

Breakdown voltage BV is the voltage drop across the diode at a particular current level when the device is reverse-biased to such an extent that heavy current flows. This is known as *avalanche*.

Reverse current I_R is the leakage current specified at a voltage less than BV when the diode is reverse-biased.

AC Parameters of Diodes. The most important of these parameters are as follows:

Capacitance C_0 is the total capacitance of the device, which includes junction and package capacitance. It is measured at a particular frequency and bias level.

Rectification efficiency R_E is defined as the ratio of dc output (load) voltage to the peak of the input voltage, in a detector circuit. This provides an indication of the capabilities of the device as a high-frequency detector.

Forward recovery time t_{fr} is the time required for the diode voltage to drop to a specified value after the application of a given forward current.

Reverse recovery time t_{rr} is the time required for the diode principle current to recover to a specified value after switching from the on state to the reverse blocking state. *Reverse Recovery Charge Qrr* and *recovery softness factor RSF* are also characteristics of the diode turn-off process that are important to the proper application of a rectifier diode.

Transient thermal impedance provides data on the instantaneous junction temperature rise above a specified reference point such as the device case as a function of time with constant power applied. This parameter is essential in ensuring reliable operation of diodes in pulse applications.

Small-Signal Diodes

Small-signal diodes are the most widely used discrete semiconductor devices. The capabilities of the general-purpose diode as a switch, demodulator, rectifier, limiter, capacitor, and nonlinear resistor suit it to many low power applications.

The most important characteristics of all small-signal diodes are forward voltage, reverse breakdown voltage, reverse leakage current, junction capacitance, and recovery time.

Silicon Rectifier Diodes

Silicon rectifier diodes are *pn* junction devices that have average forward current carrying capability ratings upward of 8000A and reverse blocking voltage ratings upward of 10,000 V. An ideal rectifier has an infinite reverse resistance, infinite breakdown voltage, and zero forward resistance. The silicon rectifier approaches these ideal specifications in that the forward resistance can be on the order of a few thousandths of an ohm, while the reverse resistance is in the megohm range.

Since silicon rectifiers are primarily used in power supplies, thermal dissipation must be adequate. To avoid excessive heating of the junction, the heat generated must be efficiently transferred to a heat sink. The relative efficiency of this heat transfer is expressed in terms of the thermal resistance of the device. The thermal-resistance range is typically 0.1 to 1°C/W for stud mount diodes and 0.009 to 0.1°C/W for double side cooled disc diodes.

Zener Diodes

Zener diodes are primarily used as voltage reference or regulator elements. This performance is based on the avalanche characteristics of the *pn* junction. When a source of voltage is applied to the diode in the reverse direction (anode negative), a reverse current I_r is observed. As the reverse potential is increased beyond the knee of the current-voltage curve, avalanche-breakdown current becomes well developed. This occurs at the zener voltage V_z. Since the resistance of the device drastically drops at this point, it is necessary to limit the current flow by means of an external resistor. Avalanche breakdown of the operating zener diode is not destructive as long as the rated power dissipation of the junction is not exceeded. The ability of the zener diode to maintain a desired operating voltage is limited by its temperature coefficient and impedance. The design of zener diodes permits them to absorb overload surges and thereby serve as transient voltage protection.

Varactor Diodes

The varactor diode is a *pn* junction device that has useful nonlinear voltage-dependent variable-capacitance characteristics. Varactor diodes are useful in microwave amplifiers and oscillators when employed with the proper filter and impedance-matching circuitry. The voltage-dependent capacitance effect in the diode permits its use as an electrically controlled tuning capacitor in radio and television receivers.

Tunnel Diodes

The tunnel diode is a semiconductor device whose primary use arises from its negative conductance characteristic. In a *pn* junction, a *tunnel* effect is obtained when the depletion layer is made extremely thin. Such a depletion layer is obtained by heavily doping both the *p* and *n* regions of the device. In this situation it is possible for an electron in the conduction band on the *n* side to penetrate, or tunnel, into the valence band of the *p* side. This gives rise to an additional current in the diode at a very small forward bias, which disappears when the bias is increased. It is this additional current that produces the negative resistance of the tunnel diode.

Typical applications of tunnel diodes include oscillators, amplifiers, converters, and detectors.

Schottky Barrier Diodes

This diode (also known as the surface-barrier diode, metal-semiconductor diode, and hot-carrier diode) consists of a rectifying metal-semiconductor junction in which majority carriers carry the current flow. When the diode is forward-biased, the carriers are injected into the metal side of the junction, where they remain majority carriers at some energy greater than the Fermi energy in the metal; this gives rise to the name *hot carriers*. The diode can be switched to the OFF state in an extremely short time (in the order of picoseconds). No stored minority-carrier charge exists.

The reverse dc current-voltage characteristics of the device are very similar to those of conventional *pn*-junction diodes. The reverse leakage current increases with reverse voltage gradually, until avalanche breakdown is reached.

Schottky barrier diodes used in detector applications have several advantages over conventional *pn*-junction diodes. They have a lower noise and better conversion efficiency, and hence have greater overall detection sensitivity.

Light Sensors (Photodiodes)

When a semiconductor junction is exposed to light, photons generate hole-electron pairs. When these charges diffuse across the junction, they constitute a photocurrent. Junction light sensors are normally operated with a load resistance and a battery that reverse-biases the junction. The device acts as a source of current that increases with light intensity.

Silicon sensors are used for sensing light in the visible and near-infrared spectra. They can be fabricated as phototransistors in which the collector-base junction is light-sensitive. Phototransistors are more sensitive than photodiodes because the photon-generated current is amplified by the current gain of the transistor.

Light-Emitting Diodes (LEDs)

These devices have found wide use in visual displays, isolators, and as digital storage elements.

LEDs are principally manufactured from gallium arsenide. When biased in the avalanche-breakdown region, *pn* junctions emit visible light at relatively low power levels. LEDs are capable of providing light of different wavelengths by varying their construction.

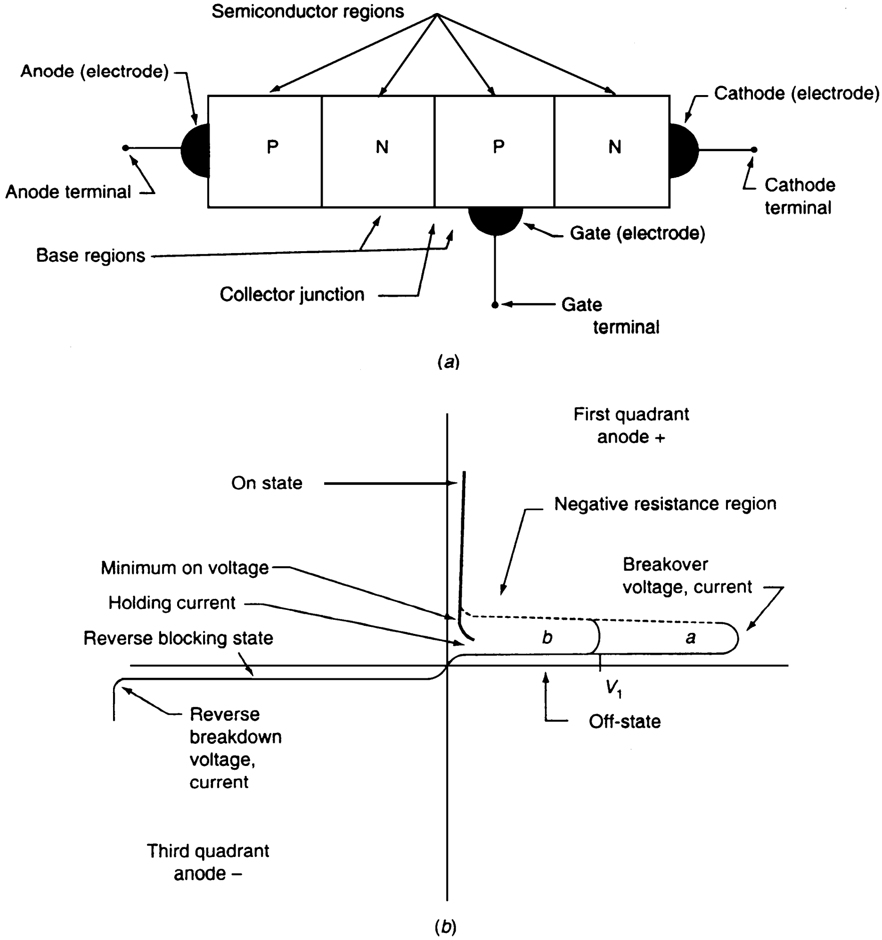

FIGURE 5.2.12 (*a*) SCR junction diagram; (*b*) typical SCR voltage-current characteristics. Curve *a* applies for zero-gate current; curve *b* applies when minimum gate current to trigger is present and the off-state voltage is V_1. (Electronic Industries Association)

Silicon Controlled Rectifiers (SCRs)

A silicon controlled rectifier is basically a four-layer *pnpn* device that has three electrodes (a cathode, an anode, and a control electrode called the *gate*). Figure 5.2.12 shows the junction diagram and voltage-current characteristics for an SCR.

When an SCR is reverse-biased (anode negative with respect to the cathode), it is similar in characteristics to that of a reverse-biased silicon rectifier or other semiconductor diode. In this bias mode, the SCR exhibits a very high internal impedance, and only a very low reverse current flows through the *pnpn* device. This current remains small until the reverse voltage exceeds the reverse breakdown voltage; beyond this point, the reverse current increases rapidly.

During forward-bias operation (anode positive with respect to the cathode), the *pnpn* structure of the SCR is electrically bistable and may exhibit either a very high impedance (OFF *state*) or a very low impedance (ON *state*). In the forward-blocking state (OFF), a small forward current, called the *forward* OFF-*state or leakage current*, flows through the SCR. The magnitude of this current is approximately the same as that of the reverse-blocking current that flows under reverse-bias conditions. As the forward bias is increased, a voltage point is reached at which the forward current increases rapidly, and the SCR switches to the ON state. This voltage is called the *forward breakover voltage*.

When the forward voltage exceeds the breakover value, the voltage drop across the SCR abruptly decreases to a very low value, the forward ON-state voltage. When the SCR is in the ON state, the forward current is limited primarily by the load impedance. The SCR will remain in this state until the current through the SCR decreases below the holding current and then reverts back to the OFF state.

The breakover voltage of an SCR can be varied or controlled by injection of a signal at the gate. When the gate current is zero, the principal voltage must reach the breakover value of the device before breakover occurs. As the gate current is increased, however, the value of breakover voltage becomes less until the device goes to the ON state. This enables an SCR to control a high-power load with a very-low-power signal and makes it suitable for such applications as phase control and high power conversion.

The most important SCR parameters are forward or ON-state voltage V_{τ}, OFF-state and reverse breakover voltage V_{BO} and $V_{(BR)R}$, gate trigger current I_{GT}, rate of application of OFF-state voltage dv/dt, circuit commutated turn-off time t_q, and transient thermal impedance.

Gate-turn-off thyristors (GTOs) are basically SCRs that are specially fabricated so that the gate does not completely lose control when the GTO is in the latched conducting state. It can be restored to the blocking state by the application of reverse bias to the gate. The GTO finds application in dc control, dc-to-dc converters, and self-commutated ac-to-dc, dc-to-ac, and ac-to-ac converters where the fact that it does not need an external force-commutating circuit is an advantage. The GTO finds primary application in very high power circuits where the other turn-off devices (bipolar transistors, IGBTs, MOSFETs, and so forth) do not have the necessary current and/or voltage ratings.

TRANSISTORS

Edward B. Hakim

Introduction

A bipolar transistor consists of two junctions in close proximity within a single crystal. An *npn* transistor is shown in Fig. 5.2.13. In normal bias conditions, the emitter-base junction is forward-biased and the collector-base junction is reversed-biased.

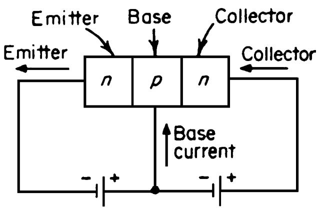

FIGURE 5.2.13 An *npn* junction transistor.

Forward bias of the emitter-base junction causes electrons to be injected into the base region, producing an excess concentration of minority carriers there. These carriers move by diffusion to the collector junction, where they are accelerated into the collector region by the field in the depletion region of the reverse-biased collector junction. Some of the electrons recombine before reaching the collector. Current flows from the base terminal to supply the holes for this recombination process. Another component of current flows in the emitter-base circuit because of the injection of holes from the base into the emitter.

Practical transistors have narrow bases and high lifetimes in the base to minimize recombination. Injection of holes from the base into the emitter is made negligible by doping the emitter much more heavily than the base. Thus the collector current is less than, but almost equal to, the emitter current.

In terms of the emitter current I_E, the collector current I_C is

$$I_C = \alpha I_E + I_{CBO}$$

where α is the fraction of the emitter current that is collected and I_{CBO} is a result of the reverse-current characteristic of the collector-base junction. Increase of I_{CBO} with temperature sets the maximum temperature of operation.

High-frequency transistors are fabricated with very narrow bases to minimize the transit time of minority carriers across the base region. Although germanium has a higher carrier mobility, silicon is the preferred material because of its availability and superior processing characteristics.

ACTIVE DISCRETE COMPONENTS 5.41

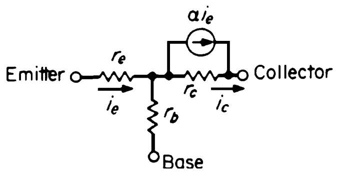

FIGURE 5.2.14 Common-base T-equivalent circuit.

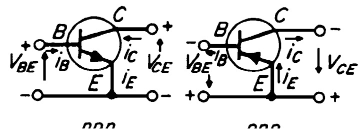

FIGURE 5.2.15 Transistor symbols.

Circuit Models of the Transistor

Performance of the transistor as an active circuit element is analyzed in terms of various small-signal equivalent circuits. The low-frequency T-equivalent circuit (Fig. 5.2.14) is closely related to the physical structure. This circuit model is used here to illustrate the principle of transistor action. Carriers are injected into the base region by forward current through the emitter-base junction. A fraction α (near unity) of this current is collected. The incremental change in collector current is determined essentially by the current generator αi_e, where i_e is the incremental change of emitter current. The collector resistance r_c in parallel with the current generator accounts for the finite resistance of the reverse-biased collector-base junction. The input impedance is a result of the dynamic resistance r_e of the of the forward-biased emitter-base junction and the ohmic resistance r_b of the base region.

The room temperature value of r_e is about $26/I_E$ Ω, where I_E is the dc value of emitter current in milliamperes. Typical ranges of the other parameters are as follows: r_b varies from tens of ohms to several hundred ohms; α varies from 0.9 to 0.999; and r_c ranges from a few hundred ohms to several megohms. The symbolic representations of an *npn* and *pnp* transistor are shown in Fig. 5.2.15. The direction of conventional current flow and terminal voltage for normal operation as an active device are indicated for each. The voltage polarities and current for the *pnp* are reversed from those of the *npn*, since the conductivity types are interchanged.

Transistors may be operated with any one of the three terminals as the common, or grounded, element, i.e., common base, common emitter, or common collector. These configurations are shown in Fig. 5.2.16 for an *npn* transistor.

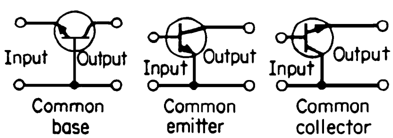

FIGURE 5.2.16 Circuit connections for *npn* transistor.

Common Base. The transistor action shown at the left in Fig. 5.2.16 is that of the common-base connection whose current gain (approximately equal to α) is slightly less than 1. Even with less than unity current gain, voltage and power amplification can be achieved, since the output impedance is much higher than the input impedance.

Common Emitter. For the common-emitter connection, only base current is supplied by the source. Base current is the difference between emitter and collector currents and is much smaller than either; hence current gain I_c/I_b is high. Input impedance of the common-emitter state is correspondingly higher than it is in the common-base connection.

Common Collector. In the common-collector connection, the source voltage and the output voltage are in series and have opposing polarities. This is a negative-feedback arrangement, which gives a high input impedance and approximately unity voltage gain. Current gain is about the same as that of the common-emitter connection. The common-base, common-emitter, and common-collector connections are roughly analogous to the grounded-grid, grounded-cathode, and grounded-plate (cathode-follower) connections, respectively, of the vacuum tube.

h *Parameters.* Low-frequency performance of transistors is commonly specified in terms of the small-signal *h* parameters listed in Table 5.2.4. In the notation system used, the second subscript designates the circuit connection (*b* for common-base and *e* for common-emitter). The forward-transfer parameters (h_{fb} and h_{fe}) are current gains measured with the output short-circuited. The current gains for practical load conditions are not greatly different. The input parameters h_{ib} and h_{ie}, although measured for short-circuit load, approximate the input impedance of practical circuits. The output parameters h_{ob} and h_{oe} are the output admittances.

TABLE 5.2.4 Transistor Small-Signal *h* Parameters

	Input parameter	Transfer parameter	Output parameter
Common-base	$h_{ib} \approx r_e + (1 - \alpha)r_b$	$h_{fb} \approx \alpha$	$h_{ob} \approx 1/r_c$
Common-emitter	$h_{ie} \approx r_e/(1 - \alpha) + r_b$	$h_{fe} \approx \alpha/(1 - \alpha)$	$h_{oe} \approx 1/r_c(1 - \alpha)$

The current gain of the common-base stage is slightly less than unity; common-emitter current gains may vary from ten to several hundred. Input impedance and output admittance of the common-emitter stage are higher than those of the common-base circuit by approximately h_{fe}. Nomenclature and units for *h* parameters are given in Table 5.2.5.

Although matched power gains of the common-base and common-emitter connections are about the same, the higher input impedance and lower output impedance of the common-emitter stage are desirable for most applications. For these reasons, the common-emitter stage is more commonly used. For example, the voltage gain of cascaded common-base stages cannot exceed unity unless transformer coupling is used.

The common-collector circuit has a higher input impedance and lower output impedance than either of the other connections. It is used primarily for impedance transformation.

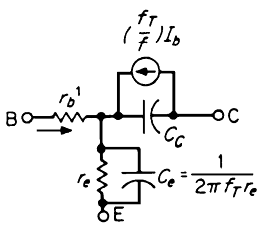

FIGURE 5.2.17 High-frequency common-emitter equivalent circuit.

High-Frequency Limit. The current gain of a transistor decreases with frequency, principally because of the transit time of minority carriers across the base region. The frequency f_T at which h_{fe} decreases to unity is a measure of high-frequency performance. Parasitic capacitances of junctions and leads also limit high-frequency capabilities. These high-frequency effects are shown in the modified equivalent circuit of Fig. 5.2.17. The maximum frequency f_{max} at which the device can amplify power is limited by f_T and the time constant $\dot{r}_b C_C$, where $\dot{r}_b$ is the ohmic base resistance and C_C is that portion of the collector-base junction capacitance which is under the emitter stripe. Values of f_T greater than 2 GHz and f_{max} exceeding 10 GHz are obtained by maintaining very thin bases (<30 μm) and narrow emitters (<3 μm).

Transistor Voltampere Characteristics

The performance of a transistor over wide ranges of current and voltage is determined from static characteristic curves, e.g., the common-emitter output characteristics of Fig. 5.2.18. Collector current I_C is plotted as a function of collector-to-emitter voltage V_C for constant values of base current I_B. Maximum collector voltage for grounded emitter is limited by either punch-through or avalanche breakdown, whichever is lower, depending on the base resistivity and thickness. When a critical electric field is reached, avalanche occurs because of intensive current multiplication. At this point current increases rapidly with little increase in voltage. The common-emitter breakdown voltage BV_{CEO} is always less than the collector-junction breakdown voltage BV_{CBO}. Another

TABLE 5.2.5 *h*-Parameter Nomenclature

Parameter	Nomenclature	Unit
h_{ib}	Input impedance (common-base)	Ω
h_{ie}	Input impedance (common-emitter)	Ω
h_{fb}	Forward-current transfer ratio (common-base)	Dimensionless
h_{fe}	Forward-current transfer ratio (common-emitter)	Dimensionless
h_{ob}	Output admittance (common-base)	S
h_{oe}	Output admittance (common-emitter)	S

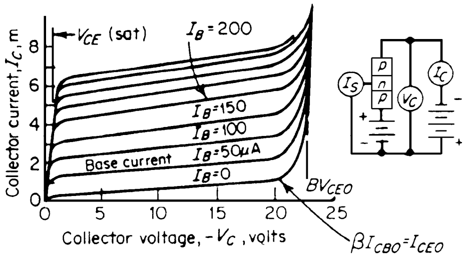

FIGURE 5.2.18 V_C-I_C characteristic for grounded-emitter junction transistor.

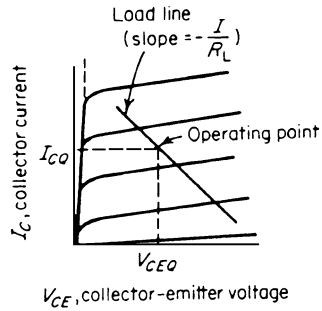

FIGURE 5.2.19 Load line for linear-transistor-amplifier circuit.

characteristic evident from Fig. 5.2.18 is the grounded-emitter saturation voltage $V_{CE,\text{sat}}$. This parameter is especially important in grounded-emitter switching applications.

Two additional parameters, both related to the emitter junction, are BV_{EBO} and V_{BE}. The breakdown voltage emitter to base with the collector open-circuited BV_{EBO} is the avalanche-breakdown voltage of the emitter junction. The base-to-emitter forward voltage of the emitter junction V_{BE} is simply the junction voltage necessary to maintain the forward-bias emitter current.

The leakage current I_{CBO} in the common-base connection is the reverse current of the collector-base junction; common-emitter leakage is higher by the factor $1/(1 - \alpha)$ because of transistor amplification. In either case, the leakage current increases exponentially with temperature. Maximum junction temperatures are limited to about 100°C in germanium and 250°C in silicon. The locus of maximum power dissipation is a hyperbola on the voltampere characteristic curve. Power dissipation must be decreased when higher ambient temperatures exist. Large-area devices and physical heat sinks of high thermal dissipation are used to extend power ratings.

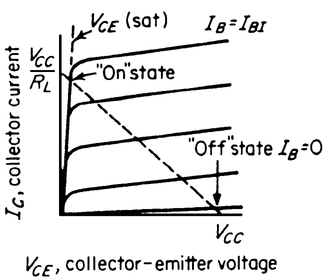

FIGURE 5.2.20 Switching states for common-emitter circuit.

Dynamic variations of voltage and current are analyzed by a load line on the characteristic curves, as in vacuum tubes. For a linear transistor amplifier with load resistance R_L, the output varies along a load line of slope $-1/R_L$ about the dc operating point (Fig. 5.2.19). Since the minimum voltage $V_{CE,\text{sat}}$ is quite low, good efficiencies can be obtained with low values of supply voltage. The operating point on the V_{CE}-I_C coordinates is established by a dc bias current in the input circuit. Transistor circuits should be biased for a fixed emitter current rather than a fixed base current to maintain a stable operating point, since the lines of constant base current are variable between devices of a given type and with temperature.

The common-emitter circuit can also be used as an effective switch, as shown by the load line of Fig. 5.2.20. When the base current is zero, the collector circuit is effectively open-circuited and only leakage current flows in the collector circuit. The device is turned on by applying base current I_{Bl}, which decreases the collector voltage to the saturation value.

Field-Effect (Unipolar) Transistors

There are two general types of field-effect transistors (FET): junction (JFET) and insulated-gate (IGFET). The IGFET has a variety of structures, known as the metal-insulator-semiconductor (MISFET) and the metal-oxide-semiconductor (MOSFET).

The cross section of a *p*-channel JFET is shown in Fig. 5.2.21. Channel current is controlled by reverse-biasing the gate-to-channel junction so that the depletion region reduces the effective channel width. The input

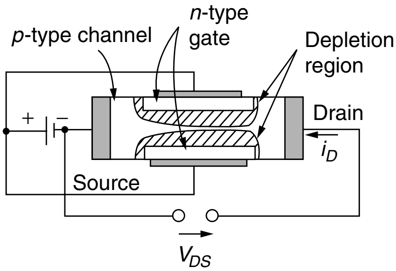

FIGURE 5.2.21 A *p*-channel junction field-effect transistor.

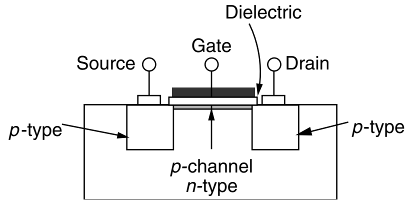

FIGURE 5.2.22 A *p*-channel MOS transistor.

impedance of these devices is high because of the reverse-biased diode in the input channel. In fact, the voltampere characteristics are quite similar to those of a vacuum tube. Another important feature of the junction FET is the excellent low-frequency noise characteristics, which surpass those of either the vacuum tube or conventional (bipolar) transistor.

The cross section of the *p*-channel MOSFET (or MOS transistor) is shown in Fig. 5.2.22. This device operates in the depletion mode. For zero gate voltage, there is no channel, and the drain current is small. A negative voltage on the gate repels the electrons from the surface and produces a *p*-type conduction region under the gate. Compared with the JFET, the MOS transistor has a wider gain-bandwidth product and a higher input impedance (>100 GΩ).

Power MOSFETs offer the major advantage over bipolar transistors in that they do not suffer from second breakdown. Their safe dc operating areas are determined by their rated power dissipation over the entire drain-to-source voltage range up to a rated voltage. This is not the case for bipolar transistors. The superiority in power handling capability of MOSFETs is also true for the pulsed-power operating mode.

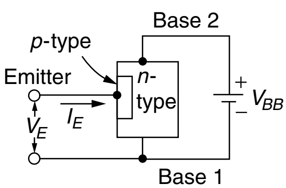

FIGURE 5.2.23 Unijunction transistor.

Further operational and reliability advantages of FETs over bipolar devices are obtained by the use of gallium arsenide (GaAs) in place of silicon (Si). The advantages include enhanced switching speeds resulting from electron velocity twice that of Si; lower operating voltages and lower ON resistance resulting from a five-fold greater electron mobility; and 350°C maximum operating temperature versus 175°C.

Unijunction Transistors

A unijunction transistor is shown in Fig. 5.2.23. The input diode is reverse-biased at low voltages owing to *IR* drop in the bulk resistance of the *n*-type region. When V_E exceeds this drop, carriers are injected and the resistance is lowered. As a result, the *IR* drop and V_E decrease abruptly. The negative-resistance characteristic is useful in such applications as oscillators and as trigger devices for silicon controlled rectifiers.