pnpn and Other Devices

17

CHAPTER OBJECTIVES

To become familiar with the characteristics and areas of application of

- Silicon-controlled rectifiers (SCRs)
- Silicon-controlled switches (SCSs)
- Gate turn-off switches (GTO)
- Light-activated SCRs (LSCR)
- Shockley diodes and diacs
- Triacs
- Phototransistors and opto-isolators
- Unijunction and programmable unijunction transistors

17.1 INTRODUCTION

In Chapter 17, a number of important devices not discussed in detail in earlier chapters are introduced. The two-layer semiconductor diode has led to three-, four-, and even five-layer devices. A family of four-layer *pnpn* devices will first be considered: the SCR (silicon-controlled rectifier), the SCS (silicon-controlled switch), the GTO (gate turn-off switch), the LASCR (light-activated SCR), and then an increasingly important device—the UJT (unijunction transistor). Those four-layer devices with a control mechanism are commonly referred to as *thyristors*, although the term is most frequently applied to the SCR. The chapter closes with an introduction to the phototransistor, opto-isolators, and the PUT (programmable unijunction transistor).

pnpn DEVICES

17.2 SILICON-CONTROLLED RECTIFIER

Within the family of *pnpn* devices, the silicon-controlled rectifier is of greatest interest. It was first introduced in 1956 by Bell Telephone Laboratories. Some of the more common areas of application for SCRs include relay controls, time-delay circuits, regulated power suppliers, static switches, motor controls, choppers, inverters, cycloconverters, battery chargers, protective circuits, heater controls, and phase controls.

In recent years, SCRs have been designed to *control* powers as high as 10 MW with individual ratings as high as 2000 A at 1800 V. Its frequency range of application has also been extended to about 50 kHz, permitting some high-frequency applications such as induction heating and ultrasonic cleaning.

17.3 BASIC SILICON-CONTROLLED RECTIFIER OPERATION

As the terminology indicates, the SCR is a rectifier constructed of silicon material with a third terminal for control purposes. Silicon was chosen because of its high temperature and power capabilities. The basic operation of the SCR is different from that of the fundamental two-layer semiconductor diode in that a third terminal, called a *gate*, determines when the rectifier switches from the open-circuit to the short-circuit state. It is not enough to simply forward-bias the anode-to-cathode region of the device. In the conduction region, the dynamic resistance of the SCR is typically 0.01 Ω to 0.1 Ω. The reverse resistance is typically 100 kΩ or more.

The graphic symbol for the SCR is shown in Fig. 17.1 with the corresponding connections to the four-layer semiconductor structure. As indicated in Fig. 17.1a, if forward conduction is to be established, the anode must be positive with respect to the cathode. This is not, however, a sufficient criterion for turning the device on. A pulse of sufficient magnitude must also be applied to the gate to establish a turn-on gate current, represented symbolically by I_{GT}.

A more detailed examination of the basic operation of an SCR is best effected by splitting the four-layer *pnpn* structure of Fig. 17.1b into two three-layer transistor structures as shown in Fig. 17.2a and then considering the resultant circuit of Fig. 17.2b.

Note that one transistor for Fig. 17.2 is an *npn* device, whereas the other is a *pnp* transistor. For discussion purposes, the signal shown in Fig. 17.3a will be applied to the gate of the circuit of Fig. 17.2b. During the interval $0 \rightarrow t_1$, $V_{gate} = 0$ V, the circuit of Fig. 17.2b will appear as shown in Fig. 17.3b ($V_{gate} = 0$ V is equivalent to the gate terminal being grounded as shown in the figure). For $V_{BE_2} = V_{gate} = 0$ V, the base current $I_{B_2} = 0$, and I_{C_2} will be approximately I_{CO}. The base current of Q_1, $I_{B_1} = I_{C_2} = I_{CO}$, is too small to turn Q_1 on. Both transistors are therefore in the "off" state, resulting in a high impedance between the collector and the emitter of each transistor and the open-circuit representation for the controlled rectifier as shown in Fig. 17.3c.

At $t = t_1$, a pulse of V_G volts will appear at the SCR gate. The circuit conditions established with this input are shown in Fig. 17.4a. The potential V_G was chosen sufficiently large to turn Q_2 on ($V_{BE_2} = V_G$). The collector current of Q_2 will then rise to a value sufficiently large to turn Q_1 on ($I_{B_1} = I_{C_2}$). As Q_1 turns on, I_{C_1} will increase, resulting in a corresponding increase in I_{B_2}. The increase in base current for Q_2 will result in a further increase in I_{C_2}. The net result is a regenerative increase in the collector current of each transistor. The resulting anode-to-cathode resistance ($R_{SCR} = V/I_A$) is then small because I_A is large, resulting in the short-circuit representation for the SCR as indicated in Fig. 17.4b. The regenerative action described above results in SCRs having typical turn-on times of 0.1 μs to 1 μs. However, high-power devices in the range 100 A to 400 A may have 10- to 25-μs turn-on times.

In addition to gate triggering, SCRs can also be turned on by significantly raising the temperature of the device or raising the anode-to-cathode voltage to the breakover value shown on the characteristics of Fig. 17.7.

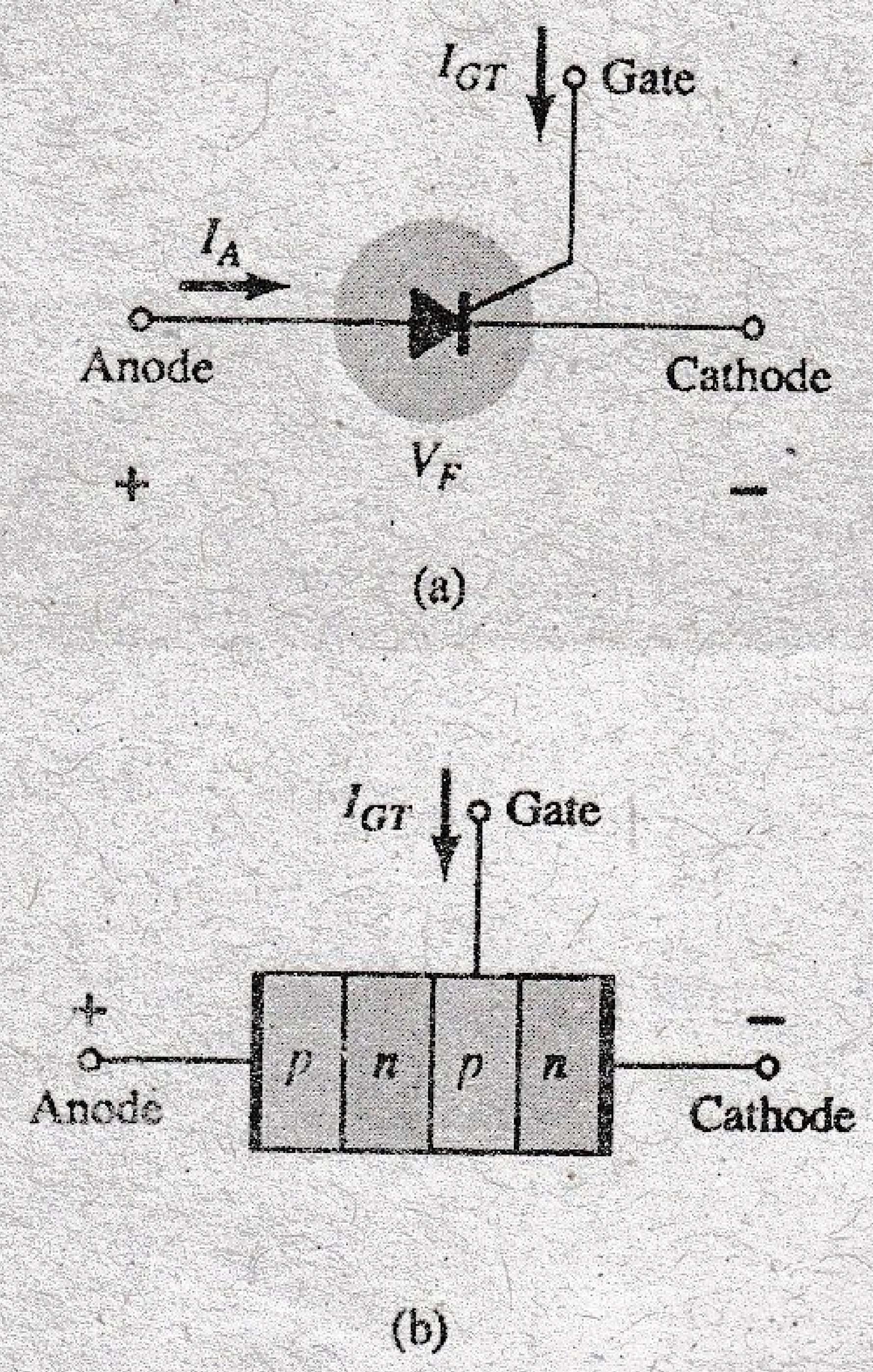


FIG. 17.1
(a) SCR symbol; (b) basic construction.

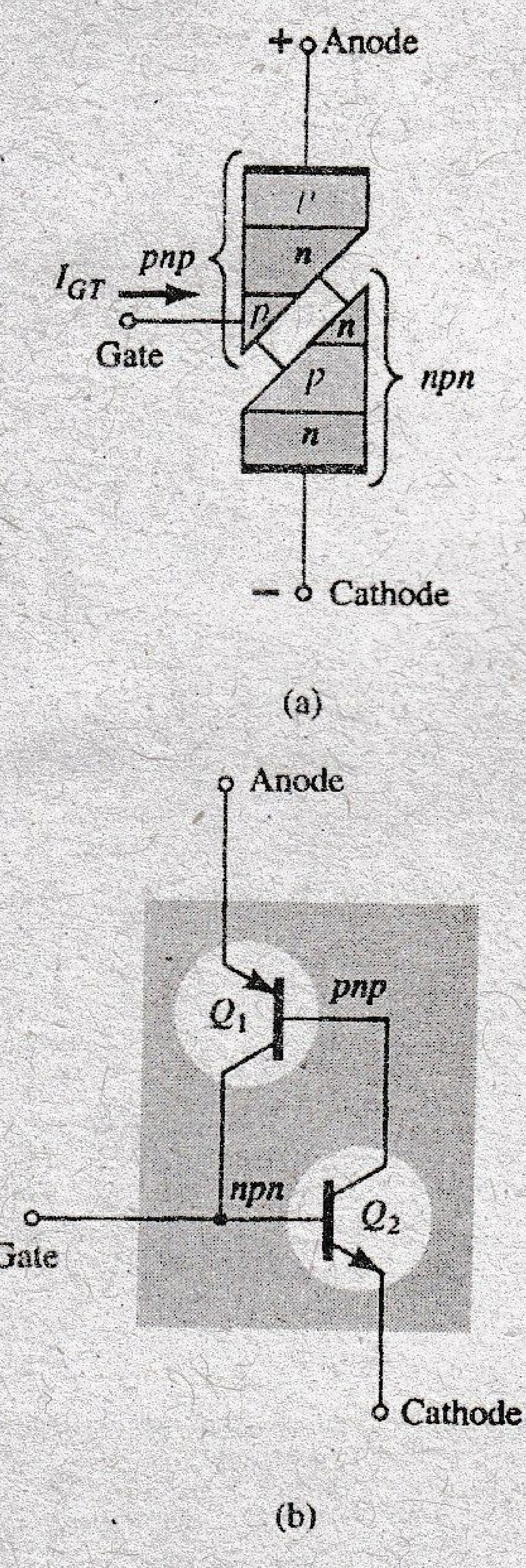


FIG. 17.2
SCR two-transistor equivalent circuit.

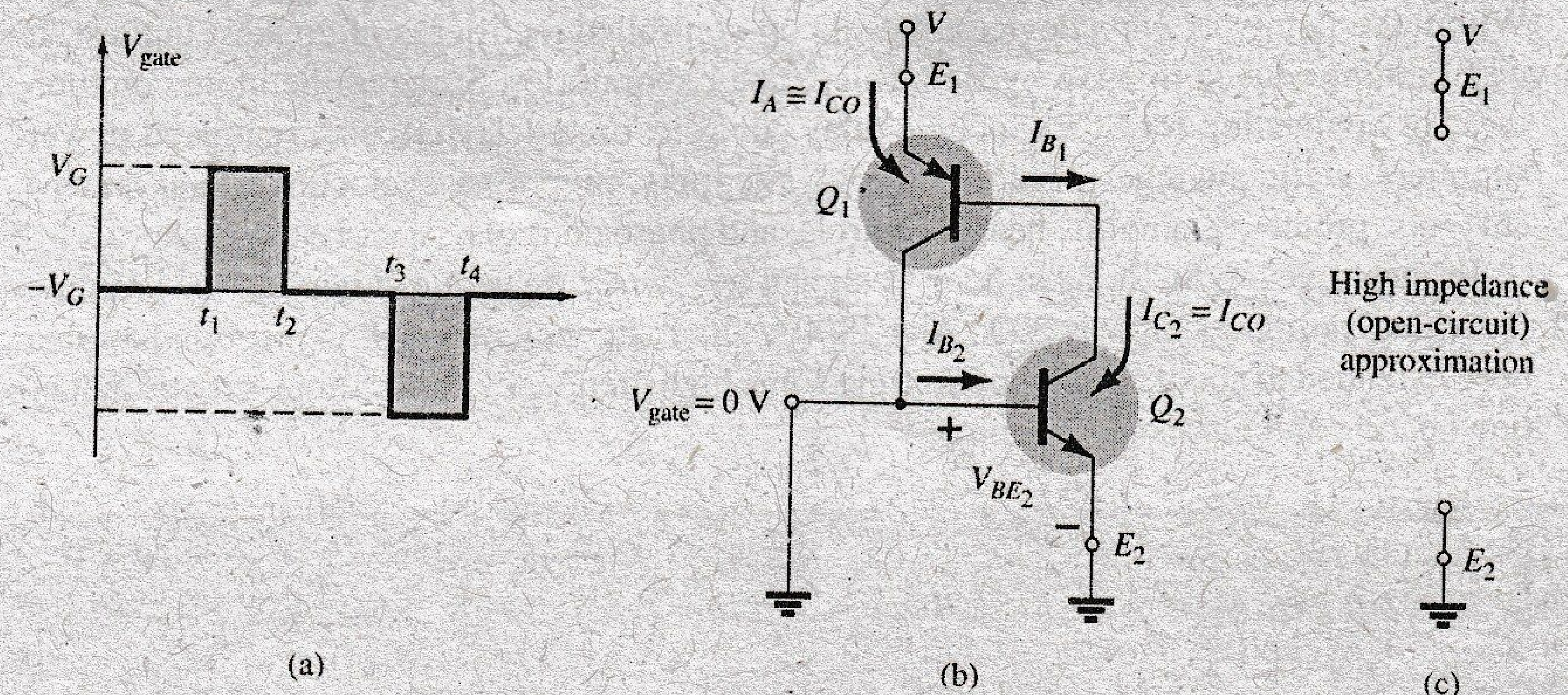


FIG. 17.3
"Off" state of the SCR.

The next question of concern is: How long is the turn-off time and how is turn-off accomplished? An SCR *cannot* be turned off by simply removing the gate signal, and only a special few can be turned off by applying a negative pulse to the gate terminal as shown in Fig. 17.3a at $t = t_3$.

The two general methods for turning off an SCR are categorized as anode current interruption and forced commutation.

The two possibilities for current interruption are shown in Fig. 17.5. In Fig. 17.5a, I_A is zero when the switch is opened (series interruption), whereas in Fig. 17.5b, the same condition is established when the switch is closed (shunt interruption).

Forced commutation is the "forcing" of current through the SCR in the direction opposite to forward conduction. There is a wide variety of circuits for performing this function, a number of which can be found in the manuals of major manufacturers in this area. One of the more basic types is shown in Fig. 17.6. As indicated in the figure, the turn-off circuit consists of an *npn* transistor, a dc battery V_B, and a pulse generator. During SCR conduction, the transistor is in the "off" state, that is, $I_B = 0$, and the collector-to-emitter impedance is very high (for all practical purposes an open circuit). This high impedance will isolate the turn-off circuitry from affecting the operation of the SCR. For turn-off conditions, a positive pulse is applied to the base of the transistor, turning it heavily on, resulting in a very low impedance from collector to emitter (short-circuit representation). The battery potential will then appear directly across the SCR as shown in Fig. 17.6b, forcing current through it in the reverse direction for turn-off. Turn-off times of SCRs are typically 5 μs to 30 μs.

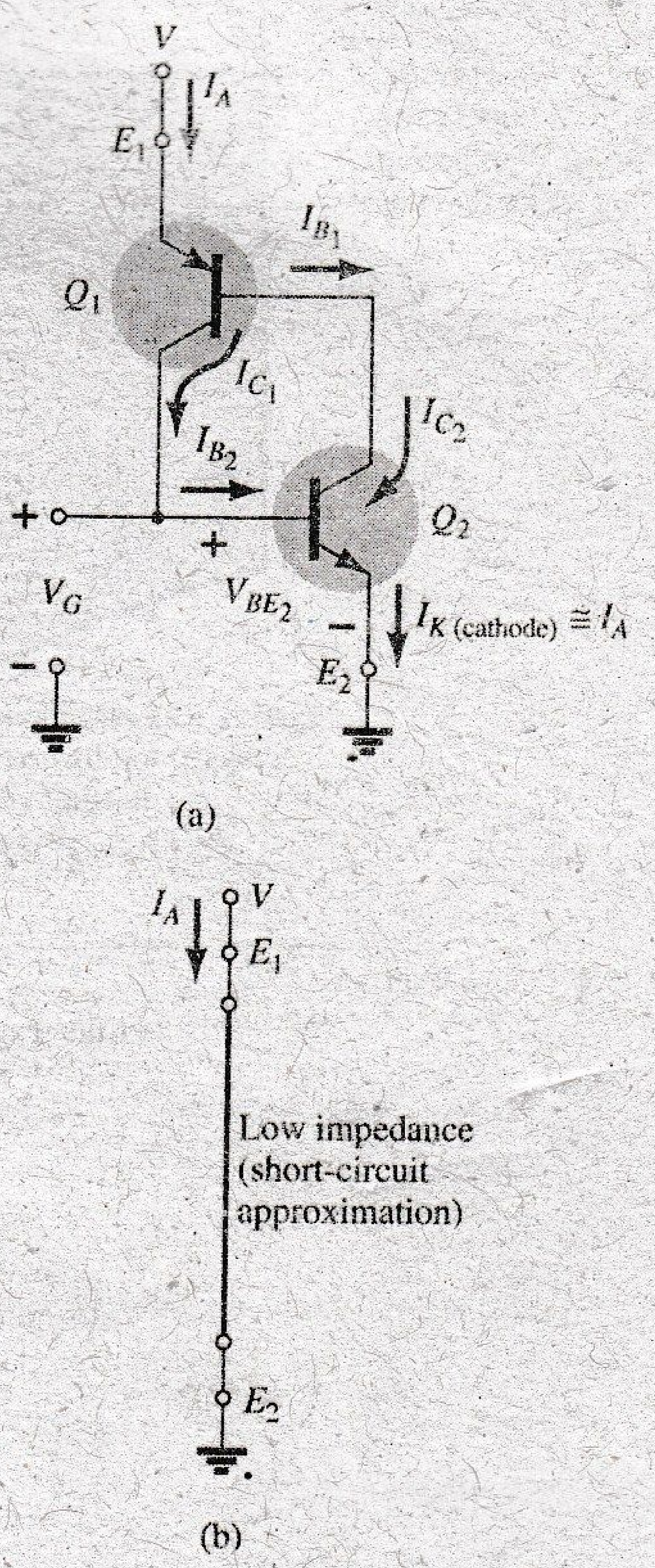


FIG. 17.4
"On" state of the SCR.

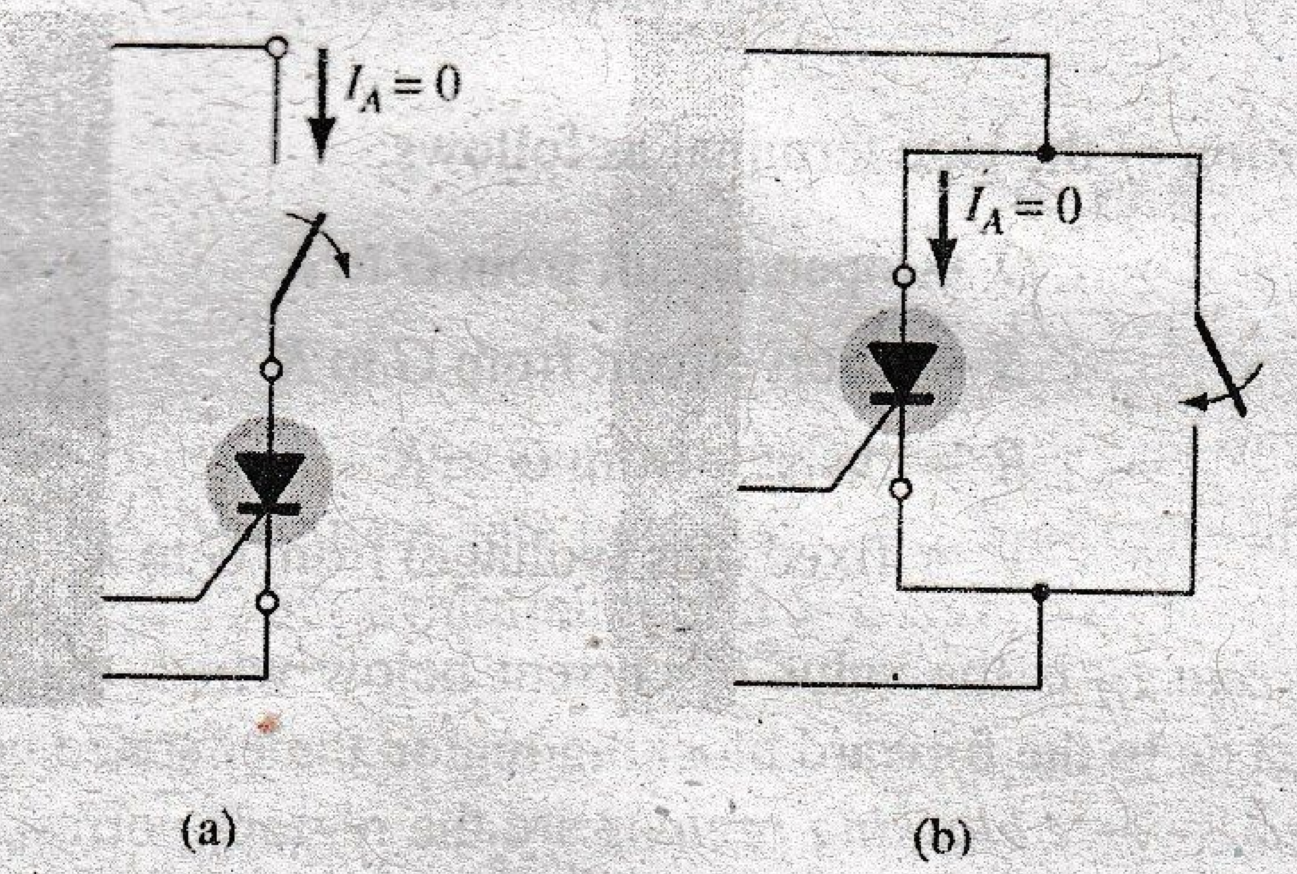


FIG. 17.5
Anode current interruption.

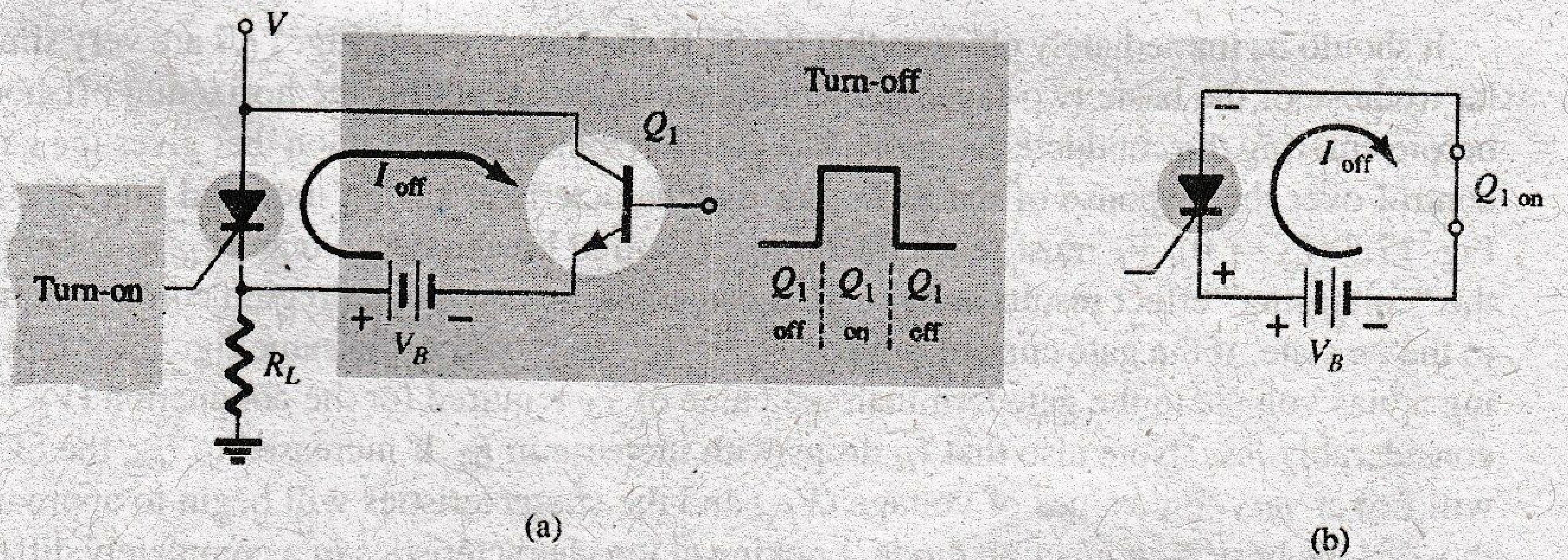


FIG. 17.6
Forced-commutation technique.

17.4 SCR CHARACTERISTICS AND RATINGS

The characteristics of an SCR are provided in Fig. 17.7 for various values of gate current. The currents and voltages of usual interest are indicated on the characteristic. A brief description of each follows.

1. *Forward breakover voltage* $V_{(BR)F^*}$ is the voltage above which the SCR enters the conduction region. The asterisk (*) denotes the letter to be added, which is dependent

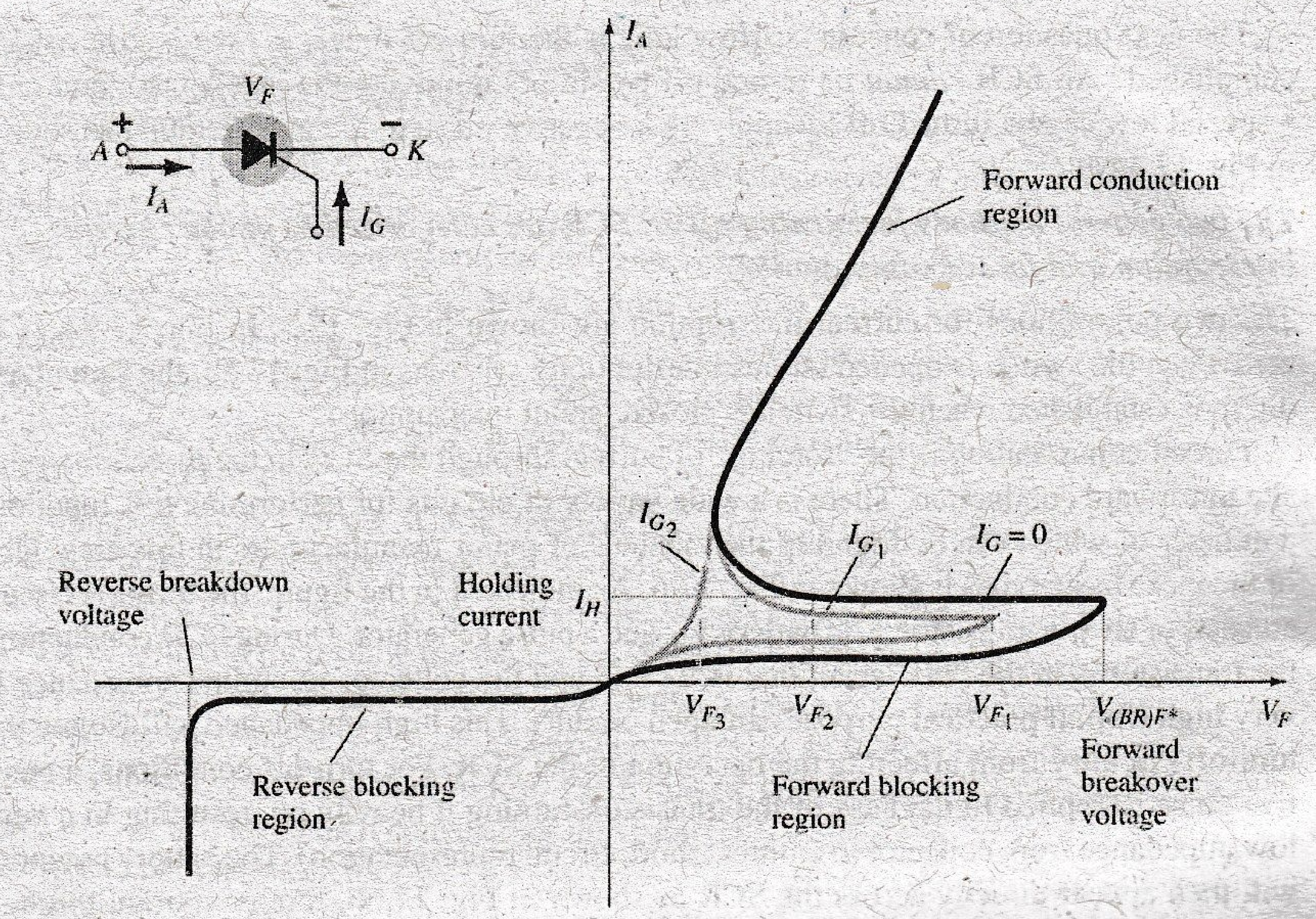


FIG. 17.7
SCR characteristics.

on the condition of the gate terminal as follows:

$$O = \text{open circuit from } G \text{ to } K$$
$$S = \text{short circuit from } G \text{ to } K$$
$$R = \text{resistor from } G \text{ to } K$$
$$V = \text{fixed bias (voltage) from } G \text{ to } K$$

2. *Holding current* I_H is the value of current below which the SCR switches from the conduction state to the forward blocking region under stated conditions.
3. *Forward and reverse blocking regions* are the regions corresponding to the open-circuit condition for the controlled rectifier that *block* the flow of charge (current) from anode to cathode.
4. *Reverse breakdown voltage* is equivalent to the Zener or avalanche region of the fundamental two-layer semiconductor diode.

It should be immediately obvious that the SCR characteristics of Fig. 17.7 are very similar to those of the basic two-layer semiconductor diode except for the horizontal offshoot before entering the conduction region. It is this horizontal jutting region that gives the gate control over the response of the SCR. For the characteristic having the solid blue line in Fig. 17.7 ($I_G = 0$), V_F must reach the largest required breakover voltage ($V_{(BR)F^*}$) before the "collapsing" effect results and the SCR can enter the conduction region corresponding to the *on* state. If the gate current is increased to I_{G_1}, as shown in the same figure by applying a bias voltage to the gate terminal, the value of V_F required for the conduction (V_{F_1}) is considerably less. Note also that I_H drops with increase in I_G. If increased to I_{G_2}, the SCR will fire at very low values of voltage (V_{F_3}) and the characteristics will begin to approach those of the basic *p–n* junction diode. Looking at the characteristics in a completely different sense, for a particular V_F voltage, say V_{F_2} (Fig. 17.7), we see that if the gate current is increased from $I_G = 0$ to I_{G_1} or more, the SCR will fire.

The gate characteristics are provided in Fig. 17.8. The characteristics of Fig. 17.8b are an expanded version of the shaded region of Fig. 17.8a. In Fig. 17.8a, the three gate ratings of greatest interest, P_{GFM}, I_{GFM}, and V_{GFM}, are indicated. Each is included on the characteristics in the same manner employed for the transistor. Except for portions of the shaded region, any combination of gate current and voltage that falls within this region will fire any SCR in the series of components for which these characteristics are provided. Temperature will determine which sections of the shaded region must be avoided. At −65°C the minimum current that will trigger the series of SCRs is 100 mA, whereas at +150°C only

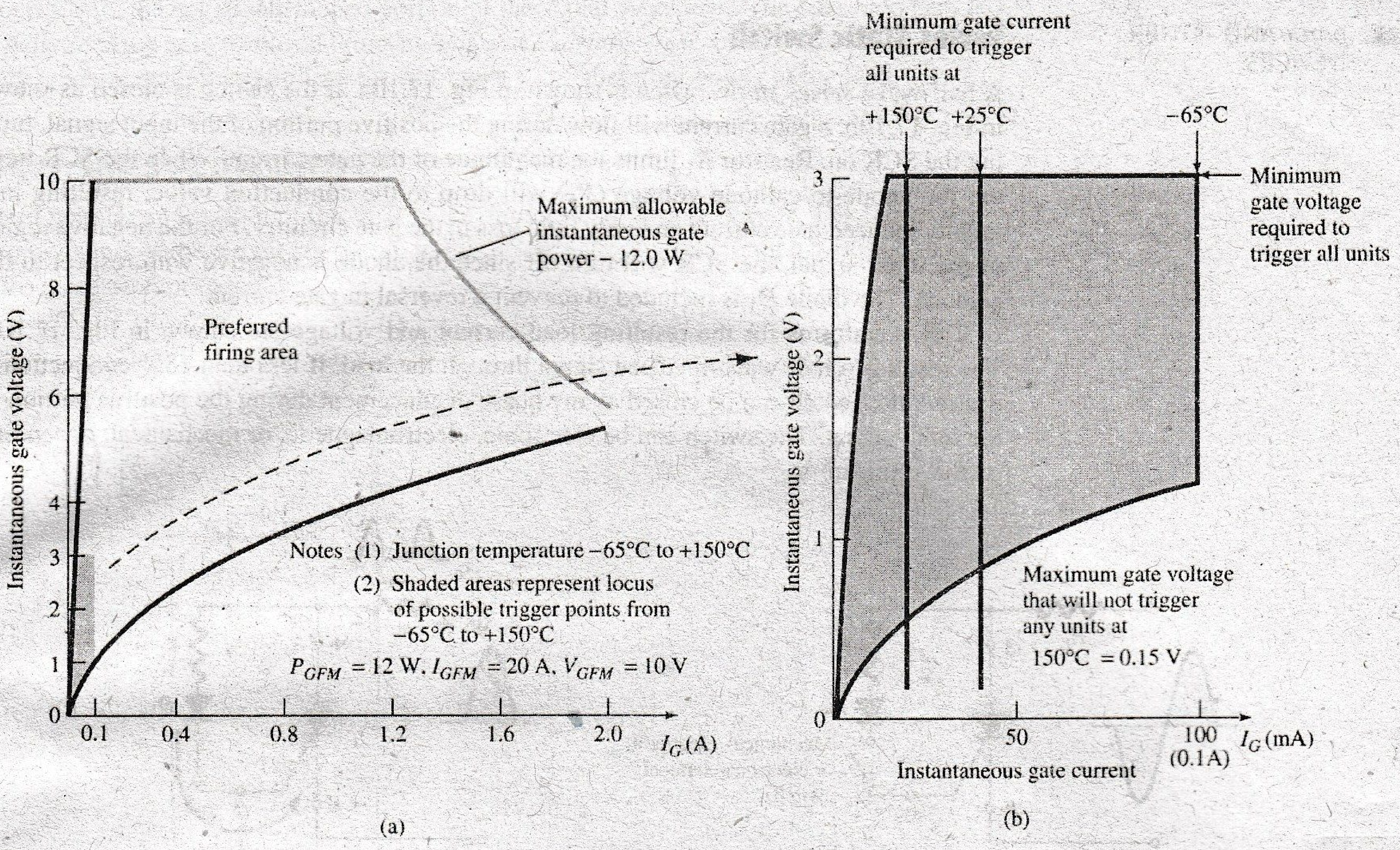


FIG. 17.8
SCR gate characteristics (GE series C38).

20 mA is required. The effect of temperature on the minimum gate voltage is usually not indicated on curves of this type since gate potentials of 3 V or more are usually obtained easily. As indicated on Fig. 17.8b, a minimum of 3 V is indicated for all units for the temperature range of interest.

Other parameters usually included on the specification sheet of an SCR are the turn-on time t_{on}, turn-off time t_{off}, junction temperature T_J, and case temperature T_C, all of which by now should be to some extent self-explanatory.

The case construction and terminal identification of SCRs vary with the application. The case-construction techniques and the terminal identification of a number of SCRs are provided in Fig. 17.9.

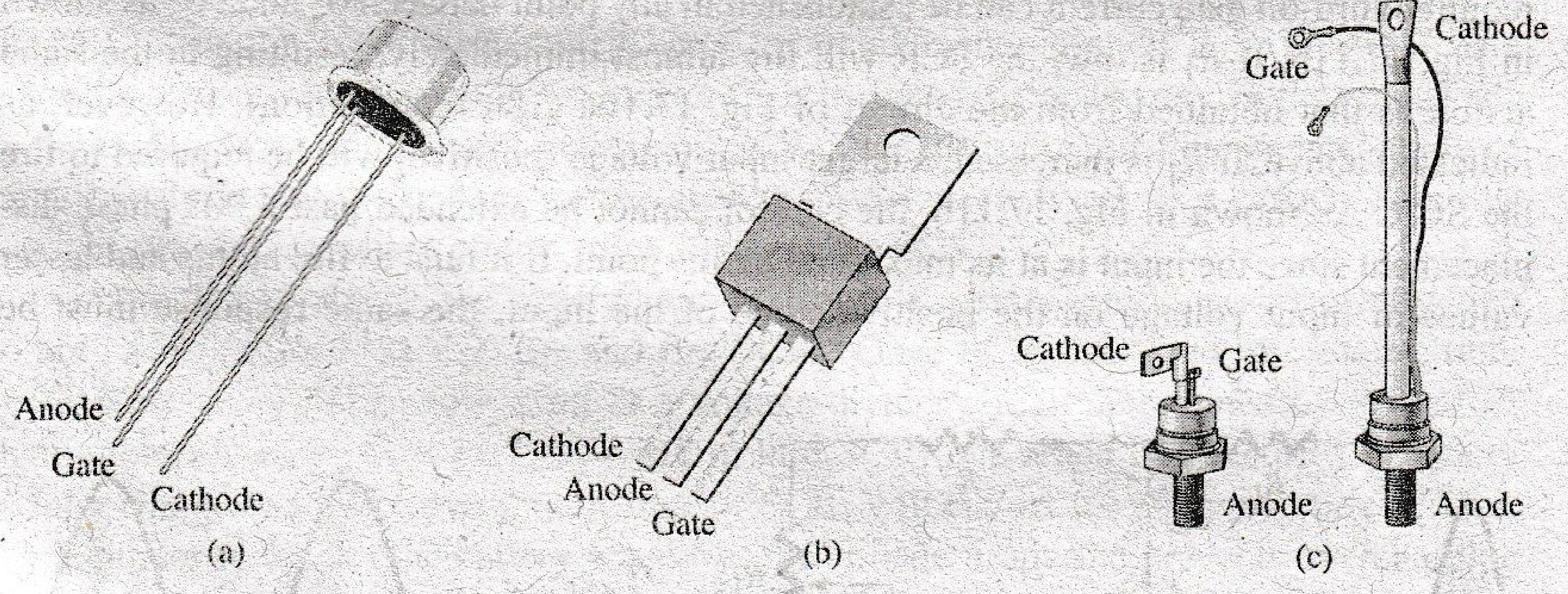


FIG. 17.9
SCR case construction and terminal identification.

17.5 SCR APPLICATIONS

Some of the possible applications for the SCR are listed in the introduction to the SCR (Section 17.2). In this section, we consider five: a static switch, a phase-control system, a battery charger, a temperature controller, and a single-source emergency-lighting system.

-55(A)

Series Static Switch

A half-wave *series static switch* is shown in Fig. 17.10a. If the switch is closed as shown in Fig. 17.10b, a gate current will flow during the positive portion of the input signal, turning the SCR on. Resistor R_1 limits the magnitude of the gate current. When the SCR turns on, the anode-to-cathode voltage (V_F) will drop to the conduction value, resulting in a greatly reduced gate current and very little loss in the gate circuitry. For the negative region of the input signal, the SCR will turn off since the anode is negative with respect to the cathode. The diode D_1 is included to prevent a reversal in gate current.

The waveforms for the resulting load current and voltage are shown in Fig. 17.10b. The result is a half-wave-rectified signal through the load. If less than 180° conduction is desired, the switch can be closed at any phase displacement during the positive portion of the input signal. The switch can be electronic, electromagnetic, or mechanical, depending on the application.

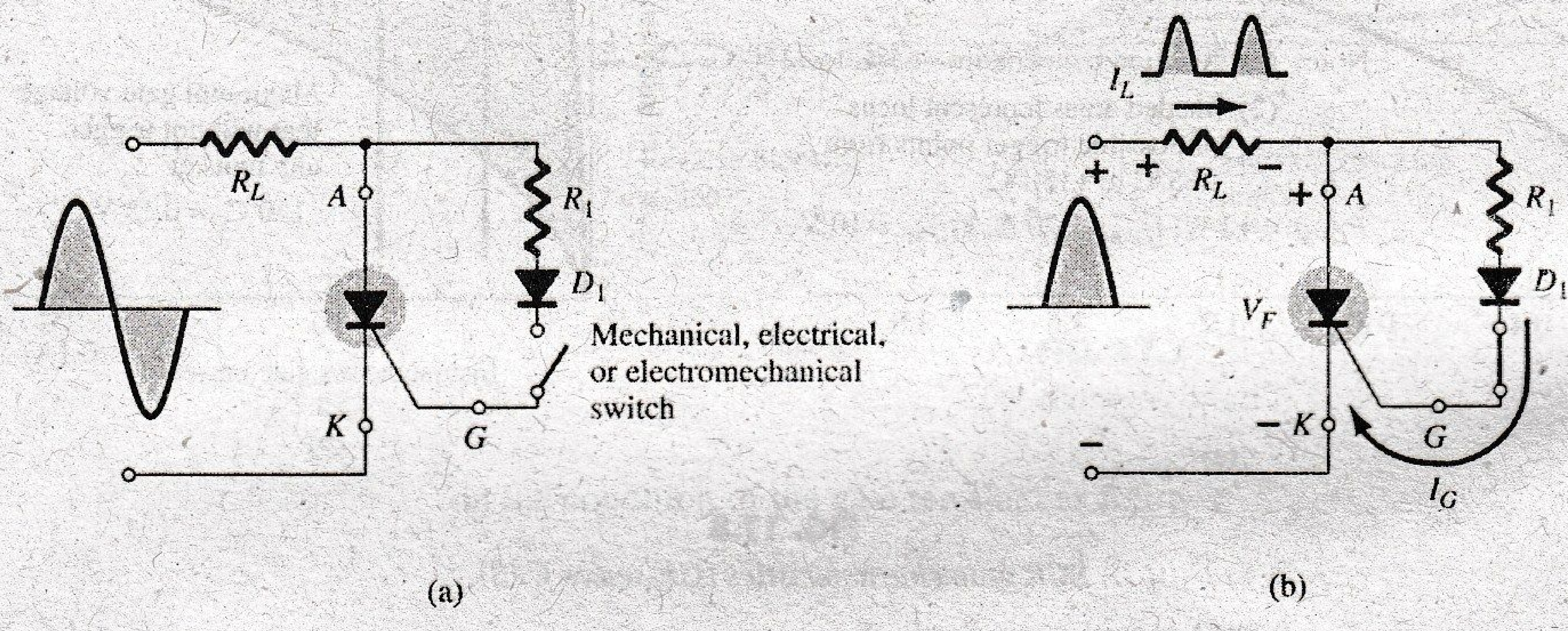


FIG. 17.10
Half-wave series static switch.

Variable-Resistance Phase Control

A circuit capable of establishing a conduction angle between 90° and 180° is shown in Fig. 17.11a. The circuit is similar to that of Fig. 17.10a except for the addition of a variable resistor and the elimination of the switch. The combination of the resistors R and R_1 will limit the gate current during the positive portion of the input signal. If R_1 is set to its maximum value, the gate current may never reach turn-on magnitude. As R_1 is decreased from the maximum, the gate current will increase from the same input voltage. In this way, the required turn-on gate current can be established in any point between 0° and 90° as shown in Fig. 17.11b. If R_1 is low, the SCR will fire almost immediately, resulting in the same action as that obtained from the circuit of Fig. 17.10a (180° conduction). However, as indicated above, if R_1 is increased, a larger input voltage (positive) will be required to fire the SCR. As shown in Fig. 17.11b, the control cannot be extended past a 90° phase displacement since the input is at its maximum at this point. If it fails to fire at this and lesser values of input voltage on the positive slope of the input, the same response must be

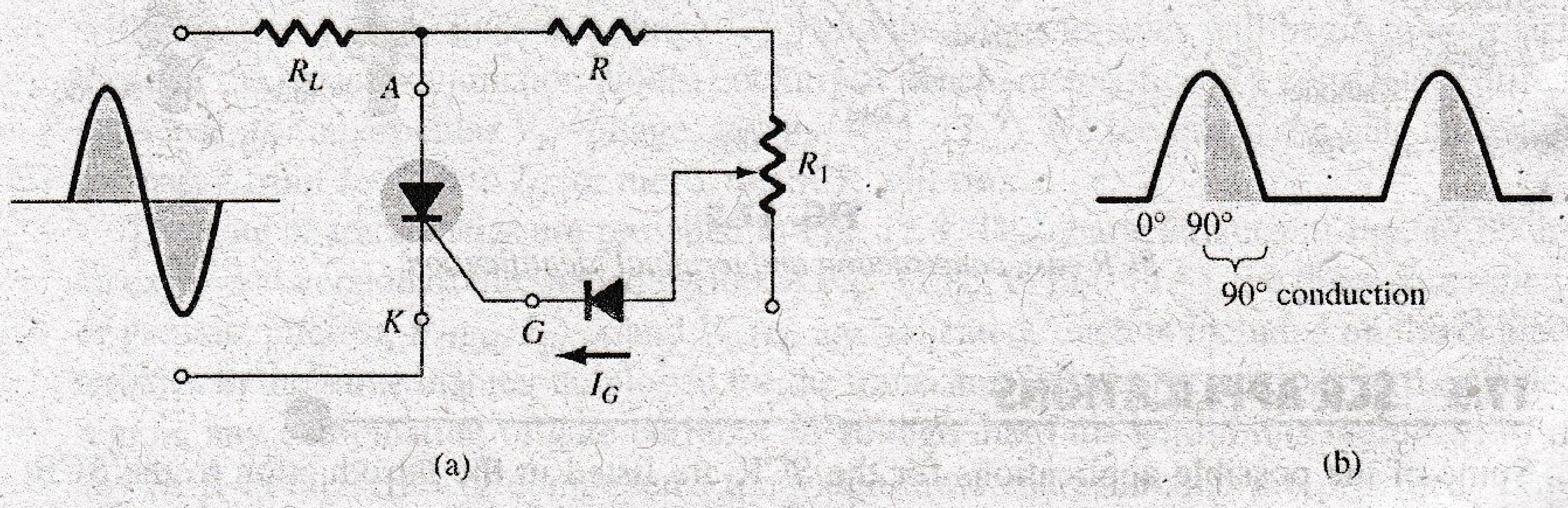


FIG. 17.11
Half-wave variable-resistance phase control.

-55(B)

expected from the negatively sloped portion of the signal waveform. The operation here is normally referred to in technical terms as *half-wave variable-resistance phase control.* It is an effective method of controlling the rms current and therefore power to the load.

Battery-Charging Regulator

A third popular application of the SCR is in a *battery-charging regulator.* The fundamental components of the circuit are shown in Fig. 17.12. The control circuit has been blocked off for discussion purposes.

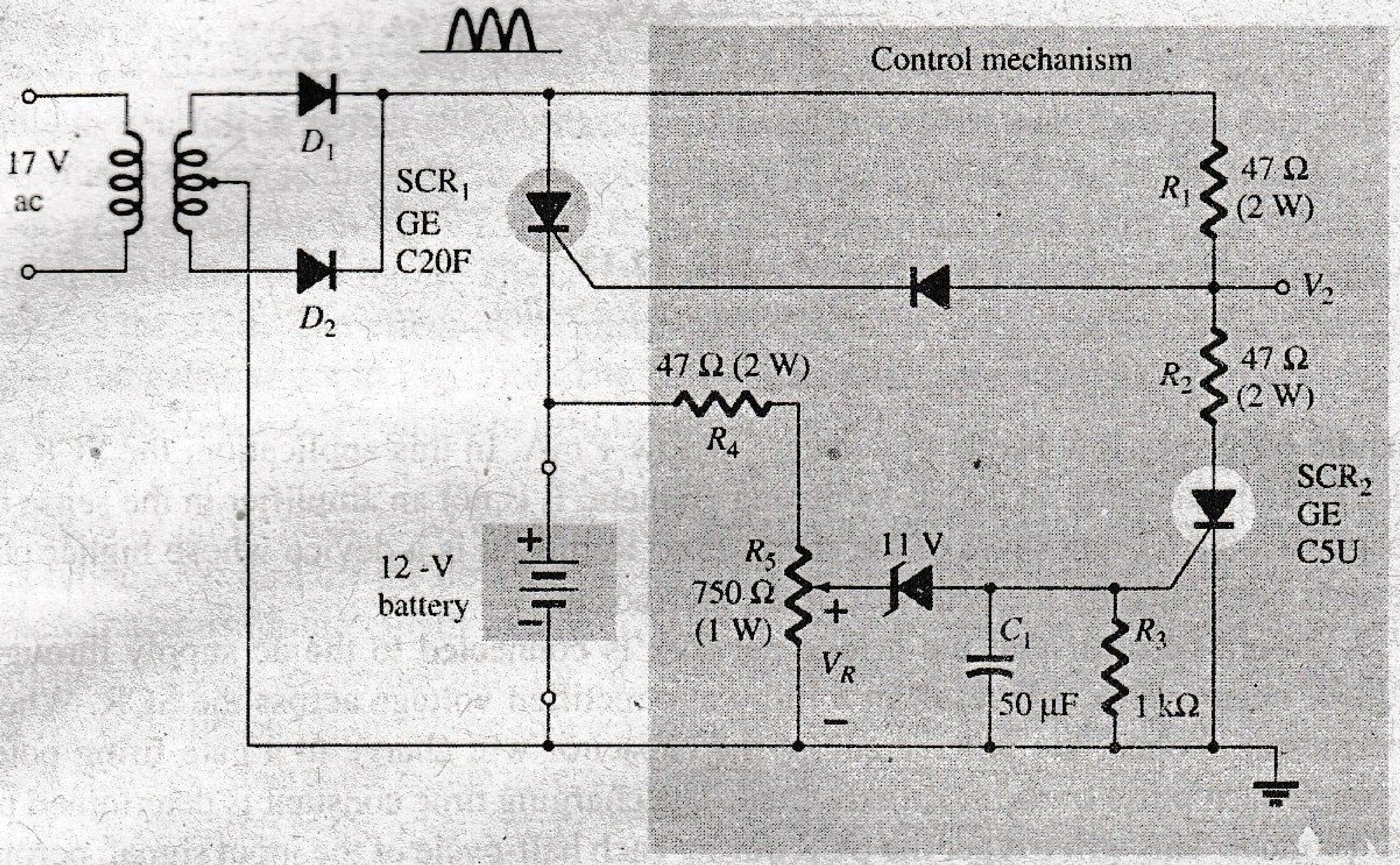


FIG. 17.12
Battery-charging regulator.

As indicated in the figure, D_1 and D_2 establish a full-wave-rectified signal across SCR$_1$ and the 12-V battery to be charged. At low battery voltages, SCR$_2$ is in the "off" state for reasons to be explained shortly. With SCR$_2$ open, the SCR$_1$ controlling circuit is exactly the same as the series static switch control discussed earlier in this section. When the full-wave-rectified input is sufficiently large to produce the required turn-on gate current (controlled by R_1), SCR$_1$ will turn on and charging of the battery will commence. At the start of charging, the low battery voltage will result in a low voltage V_R as determined by the simple voltage-divider circuit. Voltage V_R is in turn too small to cause 11.0-V Zener conduction. In the "off" state, the Zener is effectively an open circuit, maintaining SCR$_2$ in the "off" state since the gate current is zero. The capacitor C_1 is included to prevent any voltage transients in the circuit from accidentally turning on SCR$_2$. Recall from your fundamental study of circuit analysis that the voltage cannot change instantaneously across a capacitor. In this way, C_1 prevents transient effects from affecting the SCR.

As charging continues, the battery voltage rises to a point where V_R is sufficiently high to both turn on the 11.0-V Zener and fire SCR$_2$. Once SCR$_2$ has fired, the short-circuit representation for SCR$_2$ will result in a voltage-divider circuit determined by R_1 and R_2 that will maintain V_2 at a level too small to turn SCR$_1$ on. When this occurs, the battery is fully charged and the open-circuit state of SCR$_1$ will cut off the charging current. Thus the regulator recharges the battery whenever the voltage drops and prevents overcharging when it is fully charged.

Temperature Controller

The schematic diagram of a 100-W heater control using an SCR appears in Fig. 17.13. It is designed such that the 100-W heater will turn on and off as determined by thermostats. Mercury-in-glass thermostats are very sensitive to temperature change. In fact, they can sense changes as small as 0.1°C. They are limited in application, however, in that they can

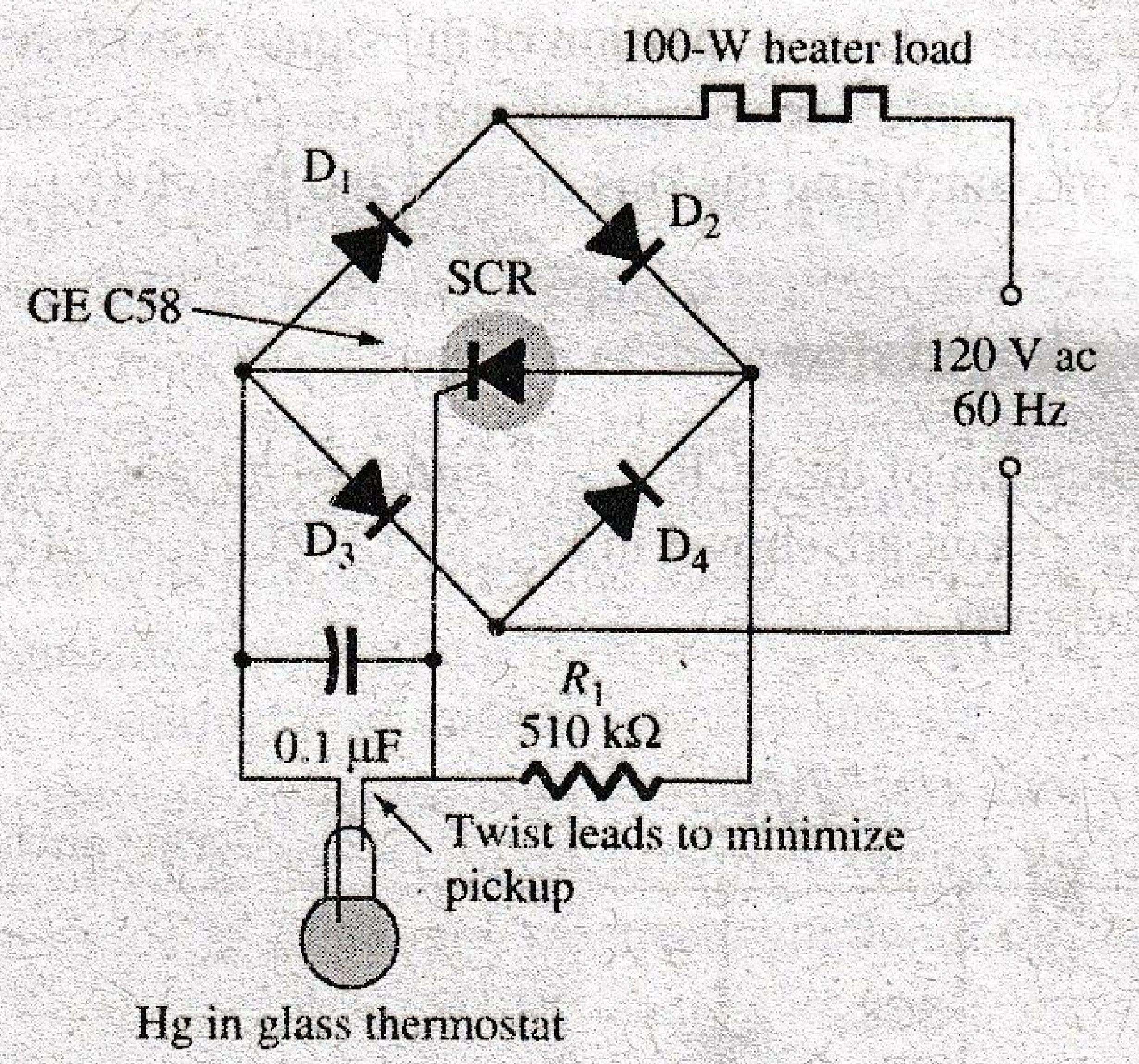


FIG. 17.13
Temperature controller.

handle only very low levels of current—below 1 mA. In this application, the SCR serves as a current amplifier in a load-switching element. It is not an amplifier in the sense that it magnifies the current level of the thermostat. Rather, it is a device whose higher current level is controlled by the behavior of the thermostat.

It should be clear that the bridge network is connected to the ac supply through the 100-W heater. This will result in a full-wave-rectified voltage across the SCR. When the thermostat is open, the voltage across the capacitor will charge to a gate-firing potential through each pulse of the rectified signal. The charging time constant is determined by the *RC* product. This will trigger the SCR during each half-cycle of the input signal, permitting a flow of charge (current) to the heater. As the temperature rises, the conductive thermostat will short-circuit the capacitor, eliminating the possibility of the capacitor charging to the firing potential and triggering the SCR. The 510-kΩ resistor will then contribute to maintaining a very low current (less than 250 μA) through the thermostat.

Emergency-Lighting System

The last application for the SCR to be described is shown in Fig. 17.14. It is a single-source emergency-lighting system that will maintain the charge on a 6-V battery to ensure its availability and also provide dc energy to a bulb if there is a power shortage. A full-wave-rectified signal will appear across the 6-V lamp due to diodes D_2 and D_1. The capacitor C_1 will charge to a voltage slightly less than a difference between the peak value of the full-wave-rectified signal and the dc voltage across R_2 established by the 6-V battery. In any event, the cathode of SCR_1 is higher than the anode, and the gate-to-cathode voltage is negative, ensuring that the SCR is nonconducting. The battery is charged

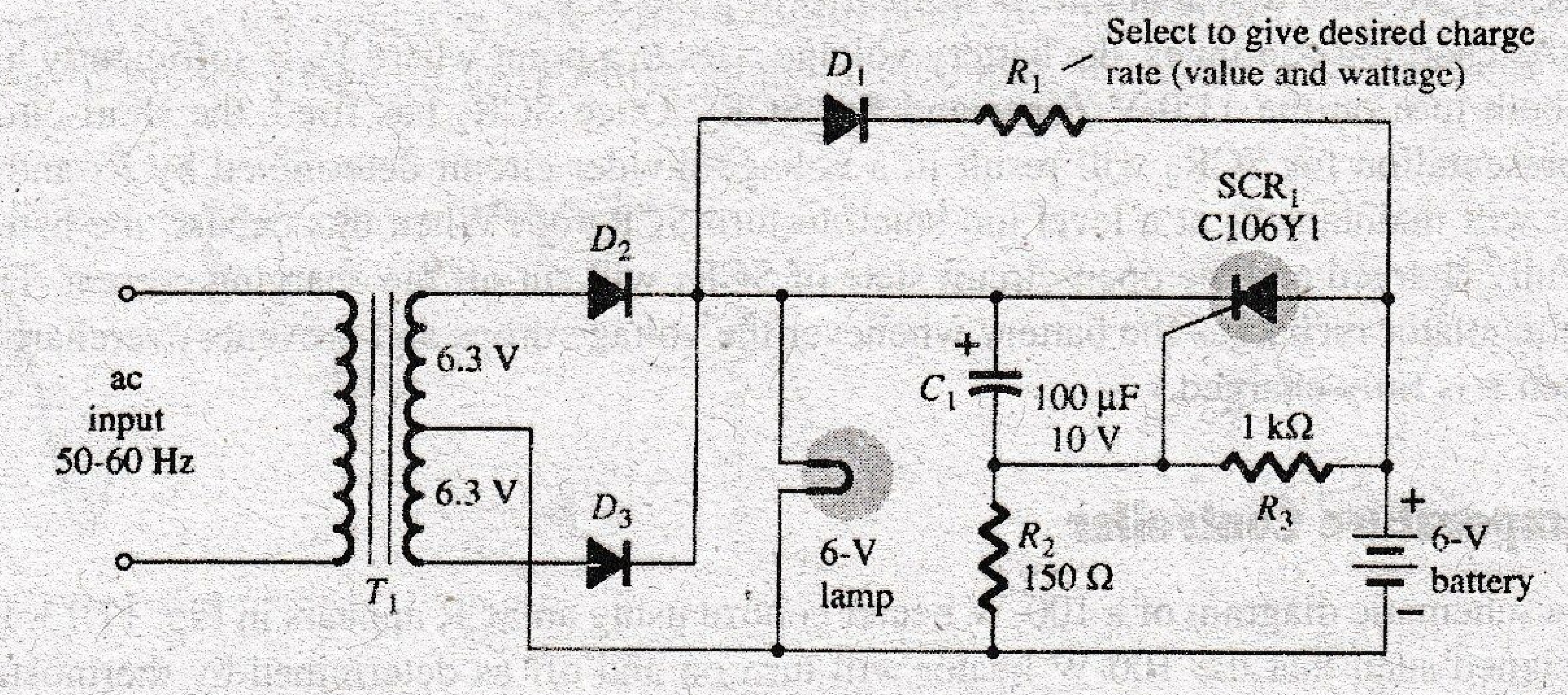


FIG. 17.14
Single-source emergency-lighting system.

through R_1 and D_1 at a rate determined by R_1. Charging will only take place when the anode of D_1 is more positive than its cathode. The dc level of the full-wave-rectified signal will ensure that the bulb is lit when the power is on. If the power should fail, the capacitor C_1 will discharge through D_1, R_1, and R_3 until the cathode of SCR_1 is less positive than the anode. At the same time, the junction of R_2 and R_3 will become positive and establish sufficient gate-to-cathode voltage to trigger the SCR. Once fired, the 6-V battery discharges through the SCR_1 and energizes the lamp and maintains its illumination. Once power is restored, the capacitor C_1 recharges and reestablishes the nonconducting state of SCR_1 as described above.

17.6 SILICON-CONTROLLED SWITCH

The silicon-controlled switch (SCS), like the silicon-controlled rectifier, is a four-layer *pnpn* device. All four semiconductor layers of the SCS are available due to the addition of an anode gate, as shown in Fig. 17.15a. The graphic symbol and transistor equivalent circuit are shown in the same figure. The characteristics of the device are essentially the same as those for the SCR. The effect of an anode gate current is very similar to that demonstrated by the gate current in Fig. 17.7. The higher the anode gate current, the lower is the required anode-to-cathode voltage to turn the device on.

The anode gate connection can be used to turn the device either on or off. To turn on the device, a negative pulse must be applied to the anode gate terminal, whereas a positive pulse is required to turn off the device. The need for the type of pulse indicated above can be demonstrated using the circuit of Fig. 17.15c. A negative pulse at the anode gate will forward-bias the base-to-emitter junction of Q_1, turning it on. The resulting heavy collector current I_{C_1} will turn on Q_2, resulting in a regenerative action and the "on" state for the SCS device. A positive pulse at the anode gate will reverse-bias the base-to-emitter junction of Q_1, turning it off, resulting in the open-circuit "off" state of the device. In general, the triggering (turn-on) anode gate current is larger in magnitude than the required cathode gate current. For one representative SCS device, the triggering anode gate current is 1.5 mA, whereas the required cathode gate current is 1 μA. The required turn-on gate current at either terminal is affected by many factors, including the operating temperature, the anode-to-cathode voltage, the load placement, and the type of cathode, gate-to-cathode, and anode gate-to-anode connection (short-circuit, open-circuit, bias, load, etc.). Tables, graphs, and curves are normally available for each device to provide the type of information indicated above.

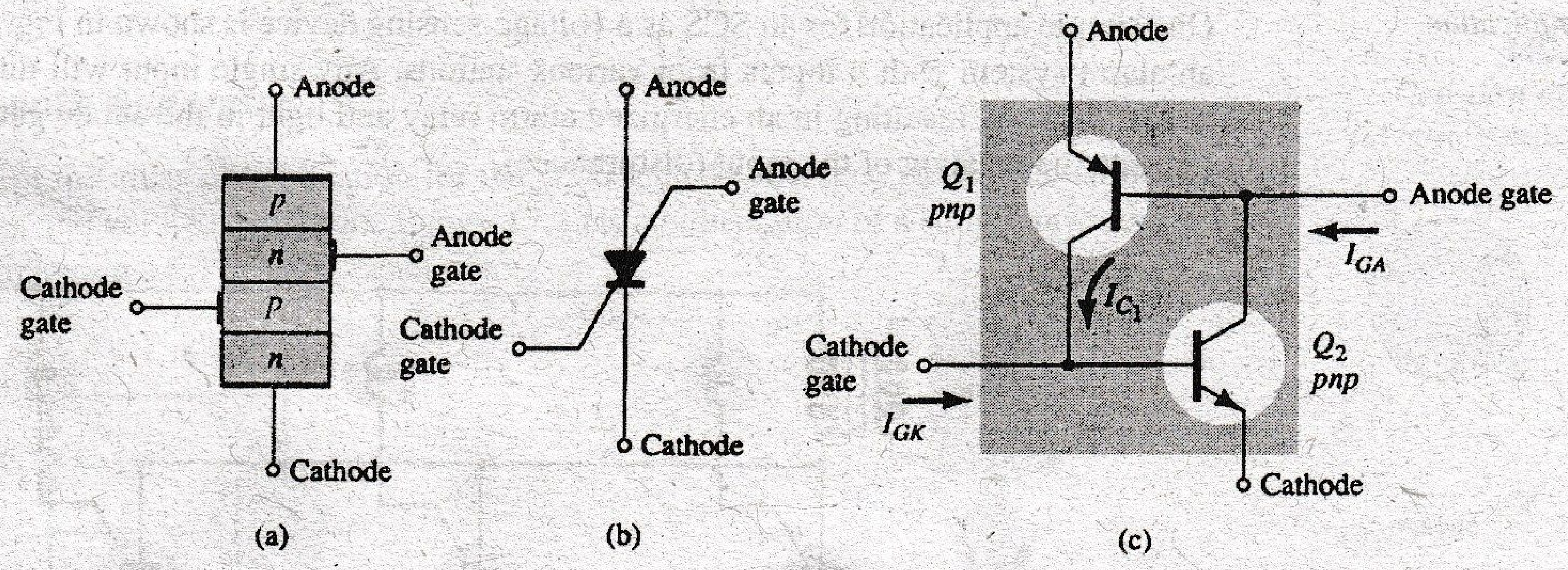


FIG. 17.15
Silicon-controlled switch (SCS): (a) basic construction; (b) graphic symbol; (c) equivalent transistor circuit.

Three of the more fundamental types of turn-off circuits for the SCS are shown in Fig. 17.16. When a pulse is applied to the transformer of Fig. 17.16a, the transistor conducts heavily, resulting in a low-impedance ($\cong$ short-circuit) characteristic between collector and emitter. This low-impedance branch diverts anode current away from the SCS, dropping it below the holding value and consequently turning it off. Similarly, the positive pulse at the anode gate of Fig. 17.16b will turn the SCS off by the mechanism described earlier in this section. The circuit of Fig. 17.16c can be turned either off *or* on by a pulse of the proper magnitude

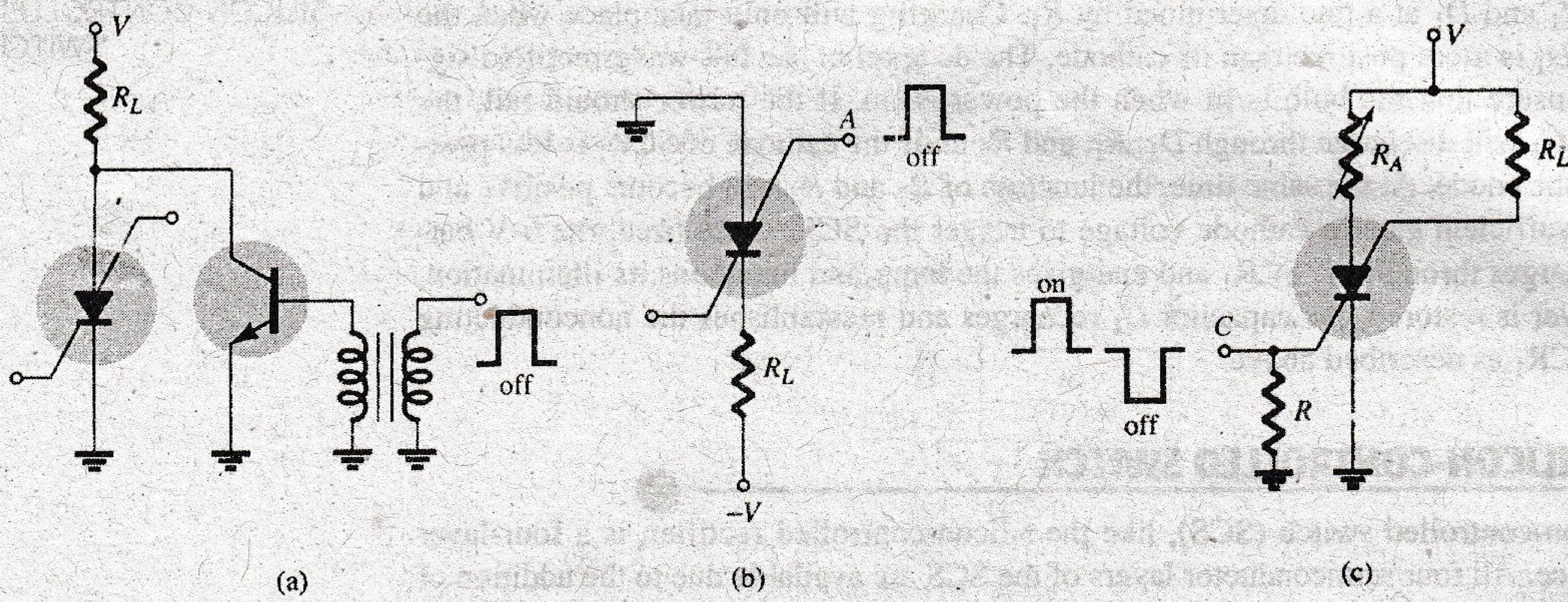


FIG. 17.16
SCS turn-off techniques.

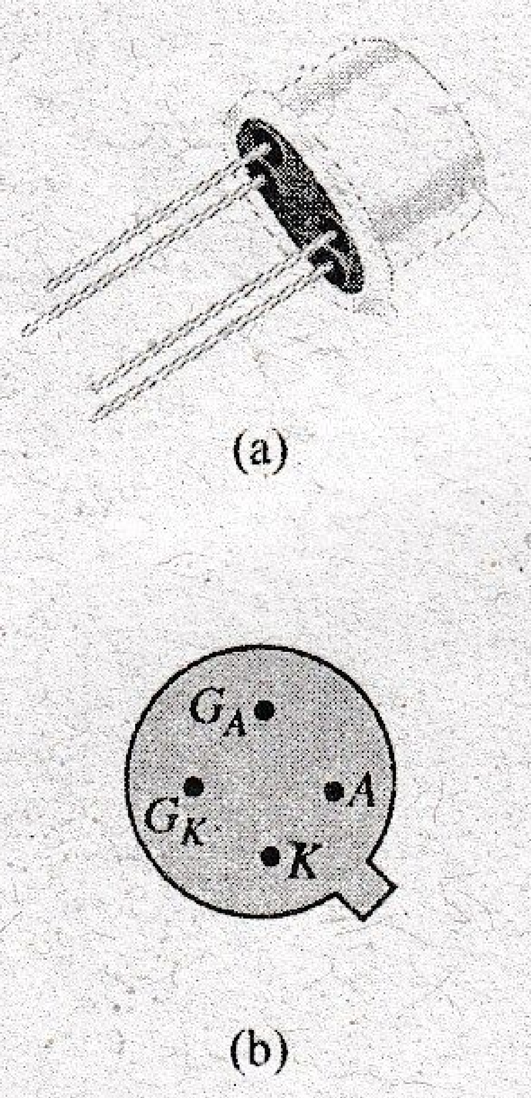


FIG. 17.17
Silicon-controlled switch (SCS): (a) device; (b) terminal identification.

at the cathode gate. The turn-off characteristic is possible only if the correct value of R_A is employed. It will control the amount of regenerative feedback, the magnitude of which is critical for this type of operation. Note the variety of positions in which the load resistor R_L can be placed. There are a number of other possibilities, which can be found in any comprehensive semiconductor handbook or manual.

An advantage of the SCS over a corresponding SCR is the reduced turn-off time, typically within the range 1 μs to 10 μs for the SCS and 5 μs to 30 μs for the SCR. Some of the remaining advantages of the SCS over an SCR include increased control and triggering sensitivity and a more predictable firing situation. At present, however, the SCS is limited to low power, current, and voltage ratings. Typical maximum anode currents range from 100 mA to 300 mA with dissipation (power) ratings of 100 mW to 500 mW.

The terminal identification of an SCS is shown in Fig. 17.17 with a packaged SCS.

Voltage Sensor

Some of the more common areas of application include a wide variety of computer circuits (counters, registers, and timing circuits), pulse generators, voltage sensors, and oscillators. One simple application for an SCS as a voltage-sensing device is shown in Fig. 17.18. It is an alarm system with n inputs from various stations. Any single input will turn that particular SCS on, resulting in an energized alarm relay and light in the anode gate circuit to indicate the location of the input (disturbance).

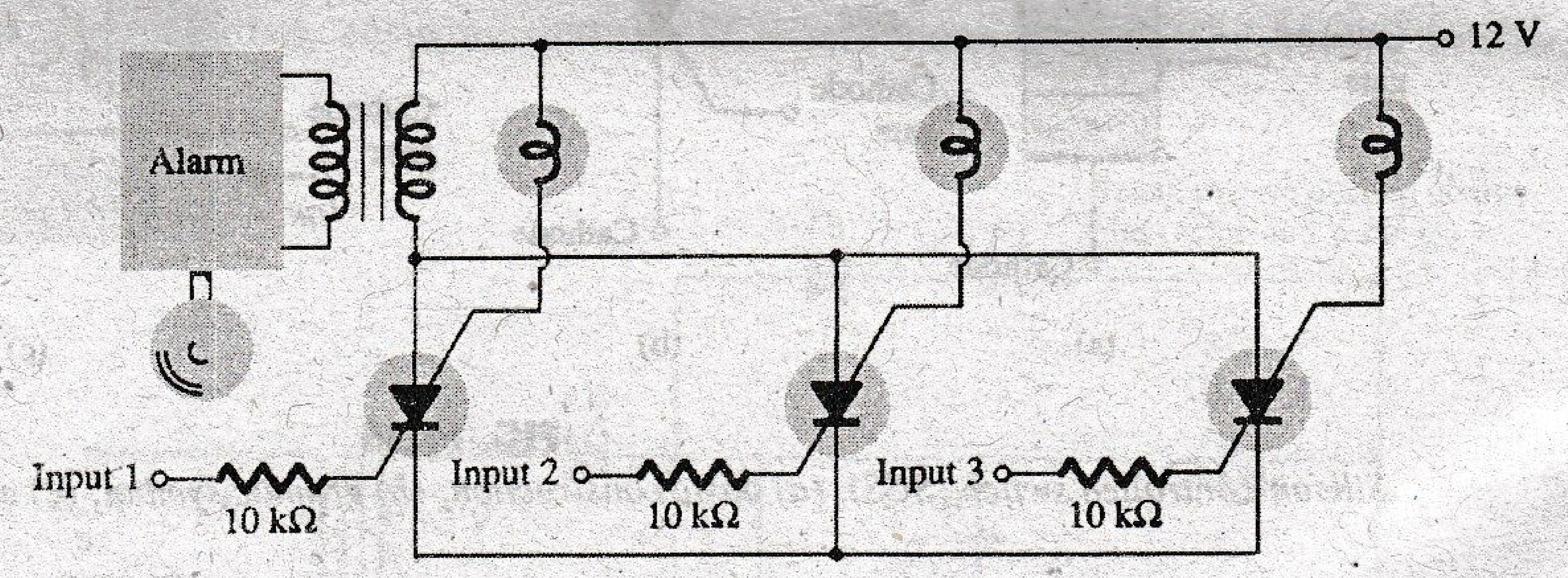


FIG. 17.18
SCS alarm circuit.

Alarm Circuit

One additional application of the SCS is in the alarm circuit of Fig. 17.19. R_S represents a temperature-, light-, or radiation-sensitive resistor, that is, an element whose resistance will decrease with the application of any of the three energy sources listed above. The cathode gate potential is determined by the divider relationship established by R_S and the variable resistor. Note that the gate potential is at approximately 0 V if R_S equals the value set by the variable resistor since both resistors will have 12 V across them. However, if R_S decreases, the potential of the junction will increase until the SCS is forward-biased, causing the SCS to turn on and energize the alarm relay.

The 100-kΩ resistor is included to reduce the possibility of an accidental triggering of the device through a phenomenon known as the *rate effect*. It is caused by the stray capacitance levels between gates. A high-frequency transient can establish sufficient base current to turn the SCS on accidentally. The device is reset by pressing the reset button, which opens the conduction path of the SCS and reduces the anode current to zero.

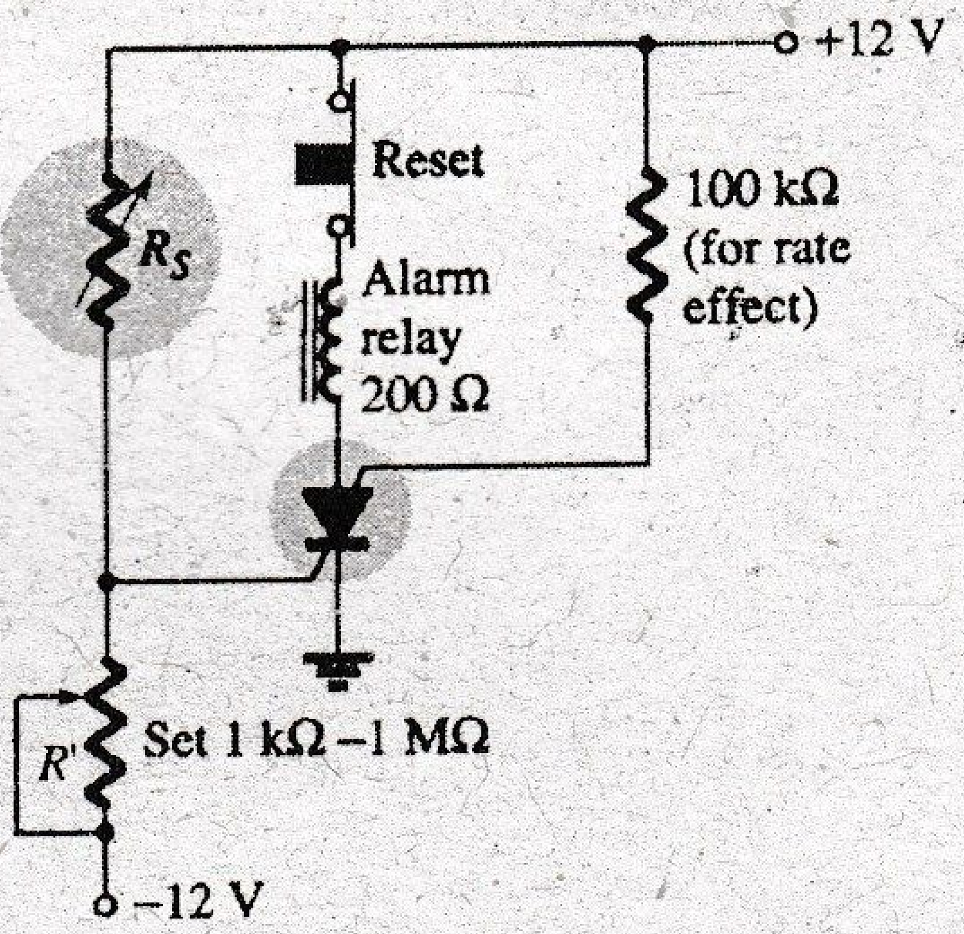


FIG. 17.19
Alarm circuit.

17.7 GATE TURN-OFF SWITCH

The gate turn-off switch (GTO) is the third *pnpn* device to be introduced in this chapter. Like the SCR, however, it has only three external terminals, as indicated in Fig. 17.20a. Its graphical symbol is shown in Fig. 17.20b. Although the graphical symbol is different from that of either the SCR or the SCS, the transistor equivalent is exactly the same and the characteristics are similar.

The most obvious advantage of the GTO over the SCR or SCS is the fact that it can be turned on *or* off by applying the proper pulse to the cathode gate (without the anode gate and associated circuitry required for the SCS). A consequence of this turn-off capability is an increase in the magnitude of the required gate current for triggering. For an SCR and GTO of similar maximum rms current ratings, the gate-triggering current of a particular SCR is 30 μA, whereas the triggering current of the GTO is 20 mA. The turn-off current of a GTO is slightly larger than the required triggering current. The maximum rms current and dissipation ratings of GTOs manufactured today are limited to about 3 A and 20 W, respectively.

A second very important characteristic of the GTO is improved switching characteristics. The turn-on time is similar to that of the SCR (typically 1 μs), but the turn-off time of about the *same* duration (1 μs) is much smaller than the typical turn-off time of an SCR (5 μs to 30 μs). The fact that the turn-off time is similar to the turn-on time rather than considerably larger permits the use of this device in high-speed applications.

A typical GTO and its terminal identification are shown in Fig. 17.21. The GTO gate input characteristics and turn-off circuits can be found in a comprehensive manual or specification sheet. The majority of the SCR turn-off circuits can also be used for GTOs.

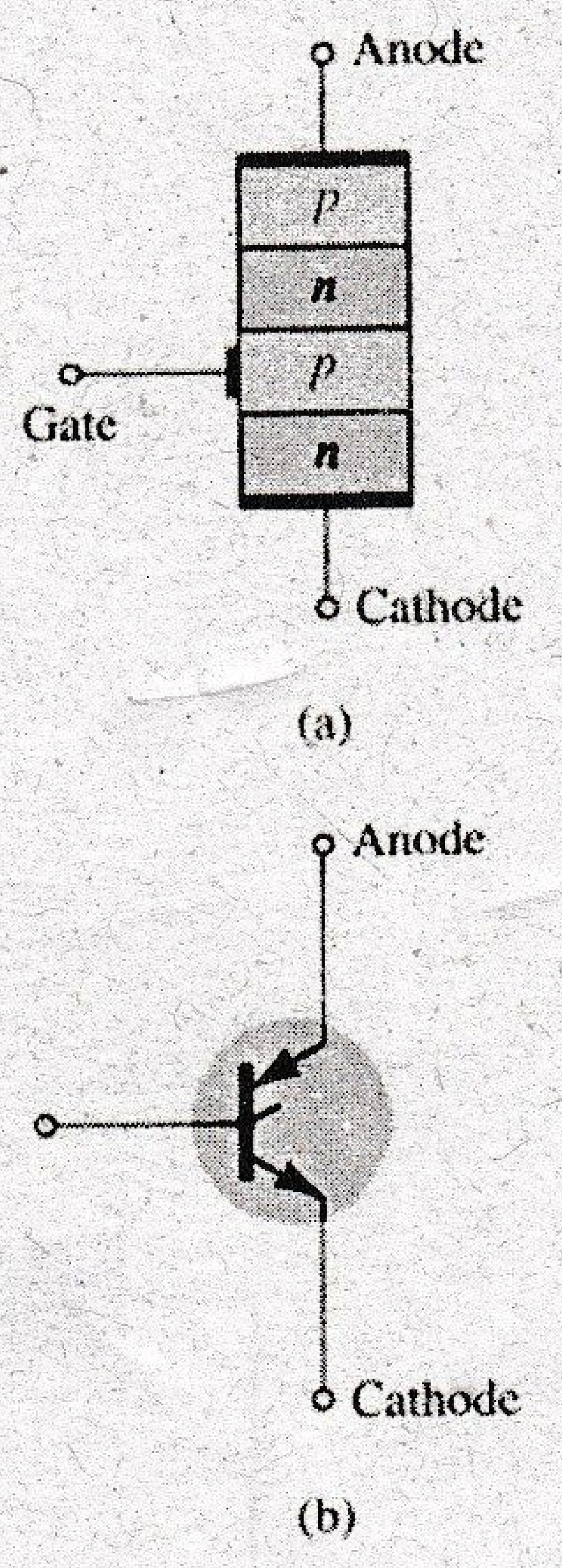


FIG. 17.20
Gate turn-off switch (GTO): (a) basic construction; (b) symbol.

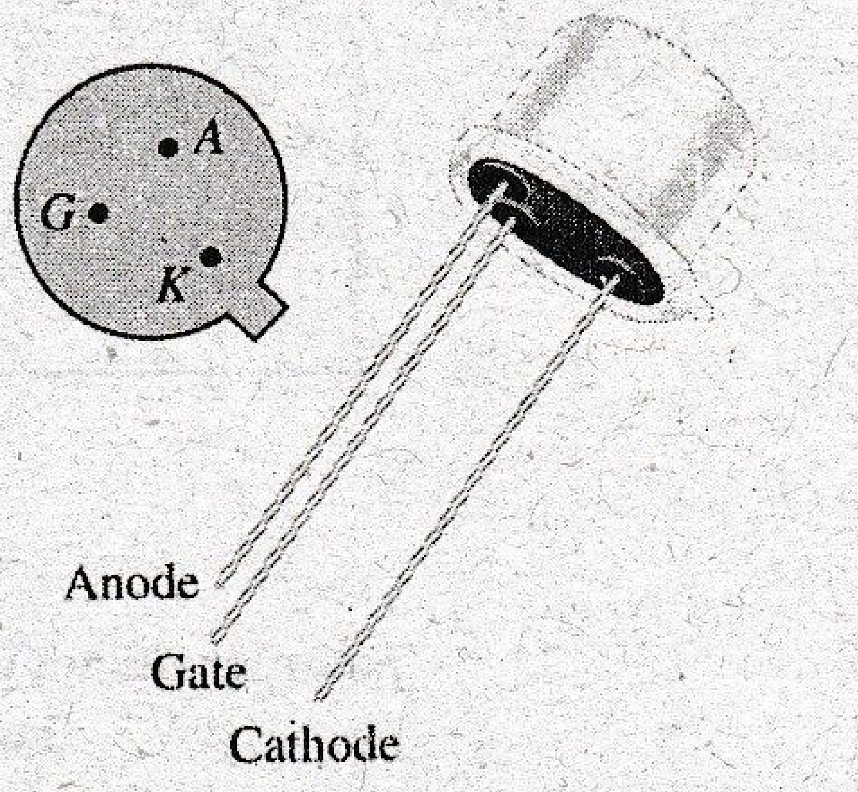


FIG. 17.21
Typical GTO and its terminal identification.

Sawtooth Generator

Some of the areas of application for the GTO include counters, pulse generators, multivibrators, and voltage regulators. Figure 17.22 is an illustration of a simple sawtooth generator employing a GTO and a Zener diode.

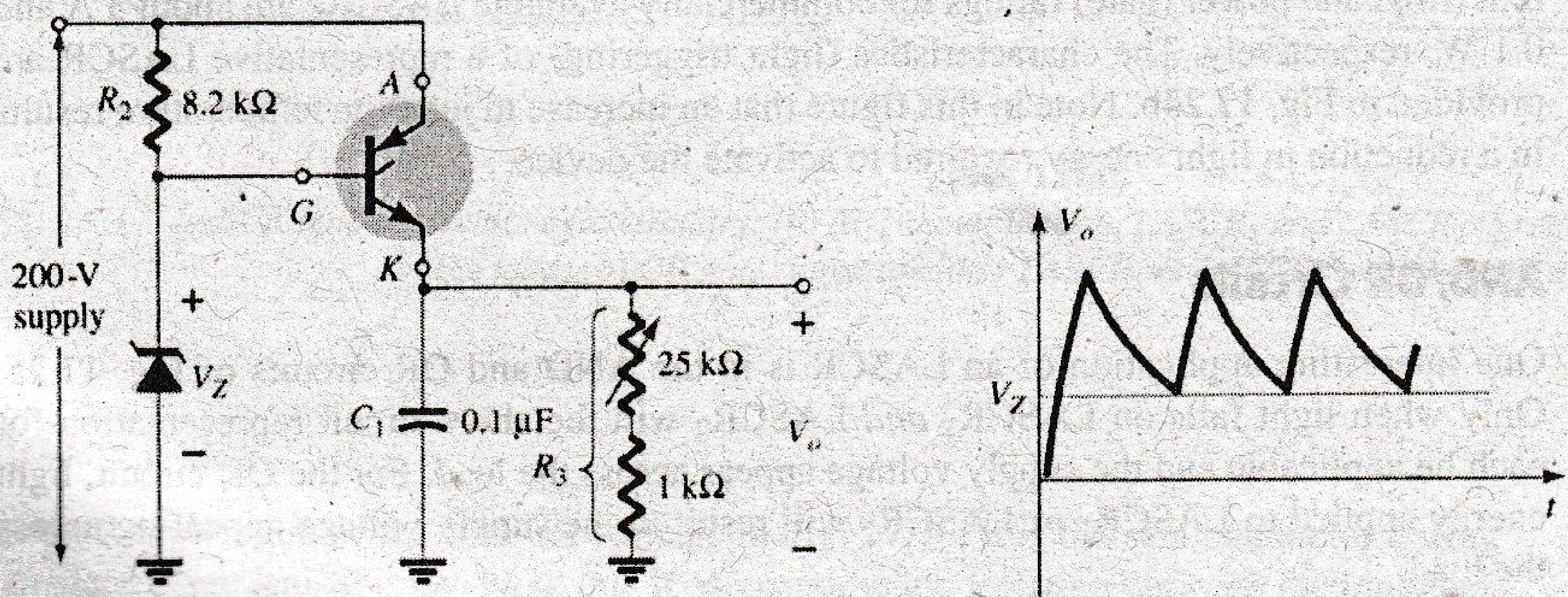


FIG. 17.22
GTO sawtooth generator.

When the supply is energized, the GTO will turn on, resulting in the short-circuit equivalent from anode to cathode. The capacitor C_1 will then begin to charge toward the supply voltage as shown in Fig. 17.22. As the voltage across the capacitor C_1 charges above the Zener potential, a reversal in gate-to-cathode voltage will result, establishing a reversal in gate current. Eventually, the negative gate current will be large enough to turn the GTO off. Once the GTO turns off, resulting in the open-circuit representation, the capacitor C_1 will discharge through the resistor R_3. The discharge time will be determined by the circuit time constant $\tau = R_3C_1$. The proper choice of R_3 and C_1 will result in the sawtooth waveform of Fig. 17.22. Once the output potential V_o drops below V_Z, the GTO will turn on and the process will repeat.

17.8 LIGHT-ACTIVATED SCR

The next in the series of *pnpn* devices is the light-activated SCR (LASCR). As indicated by the terminology, it is an SCR whose state is controlled by the light falling on a silicon semiconductor layer of the device. The basic construction of an LASCR is shown in Fig. 17.23a. As indicated in Fig. 17.23a, a gate lead is also provided to permit triggering the device using typical SCR methods. Note also in the figure that the mounting surface for the silicon pellet is the anode connection for the device. The graphical symbols most commonly employed for the LASCR are provided in Fig. 17.23b. The terminal identification and a typical LASCR appear in Fig. 17.24a.

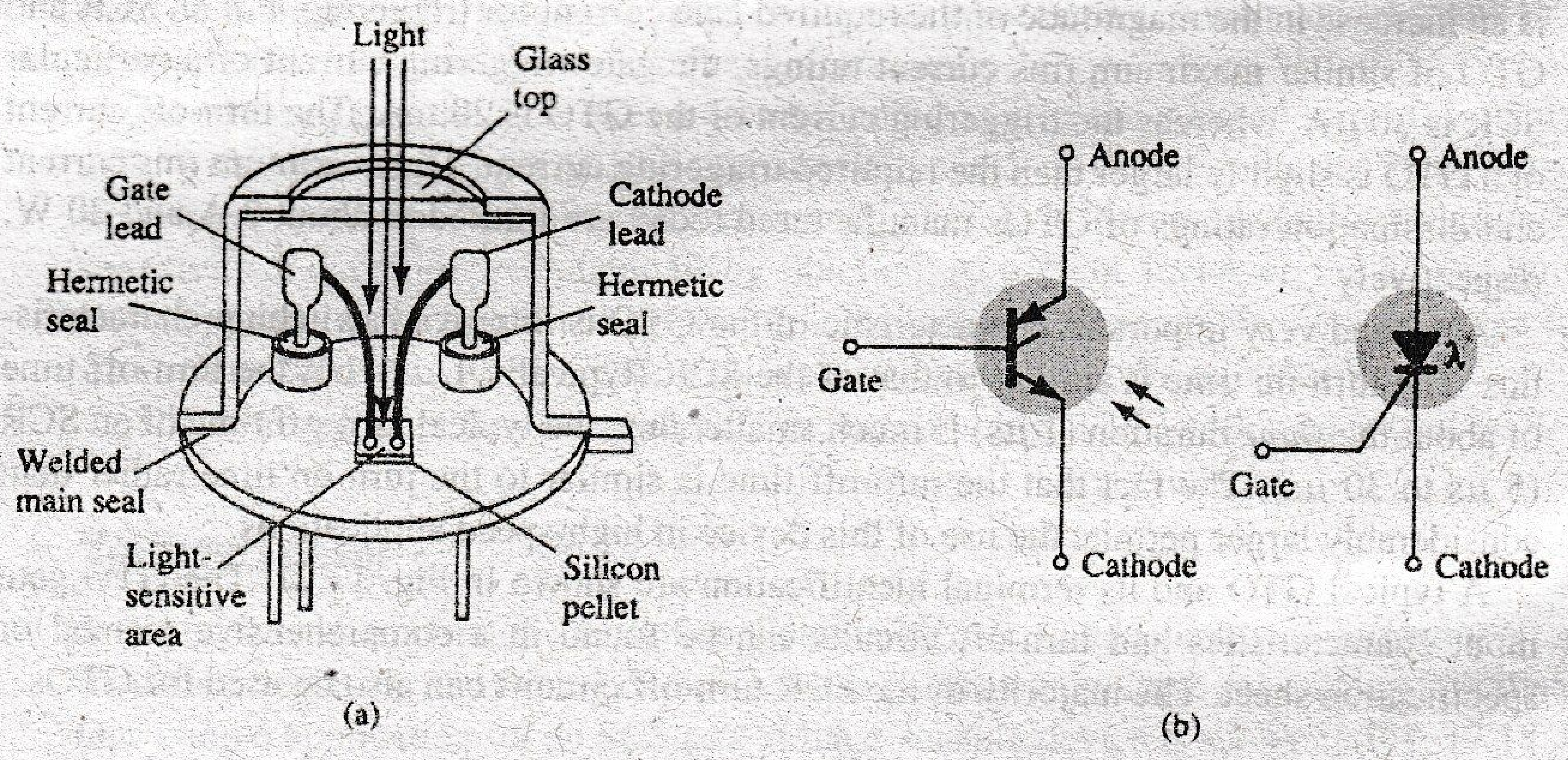


FIG. 17.23
Light-activated SCR (LASCR): (a) basic construction; (b) symbols.

Some of the areas of application for the LASCR include optical light controls, relays, phase control, motor control, and a variety of computer applications. The maximum current (rms) and power (gate) ratings for commercially available LASCRs are about 3 A and 0.1 W, respectively. The characteristics (light triggering) of a representative LASCR are provided in Fig. 17.24b. Note in this figure that an increase in junction temperature results in a reduction in light energy required to activate the device.

AND/OR Circuits

One interesting application of an LASCR is in the AND and OR circuits of Fig. 17.25. Only when light falls on $LASCR_1$ *and* $LASCR_2$ will the short-circuit representation for each be applicable and the supply voltage appear across the load. For the OR circuit, light energy applied to $LASCR_1$ *or* $LASCR_2$ will result in the supply voltage appearing across the load.

The LASCR is most sensitive to light when the gate terminal is open. Its sensitivity can be reduced and controlled somewhat by the insertion of a gate resistor, as shown in Fig. 17.25.

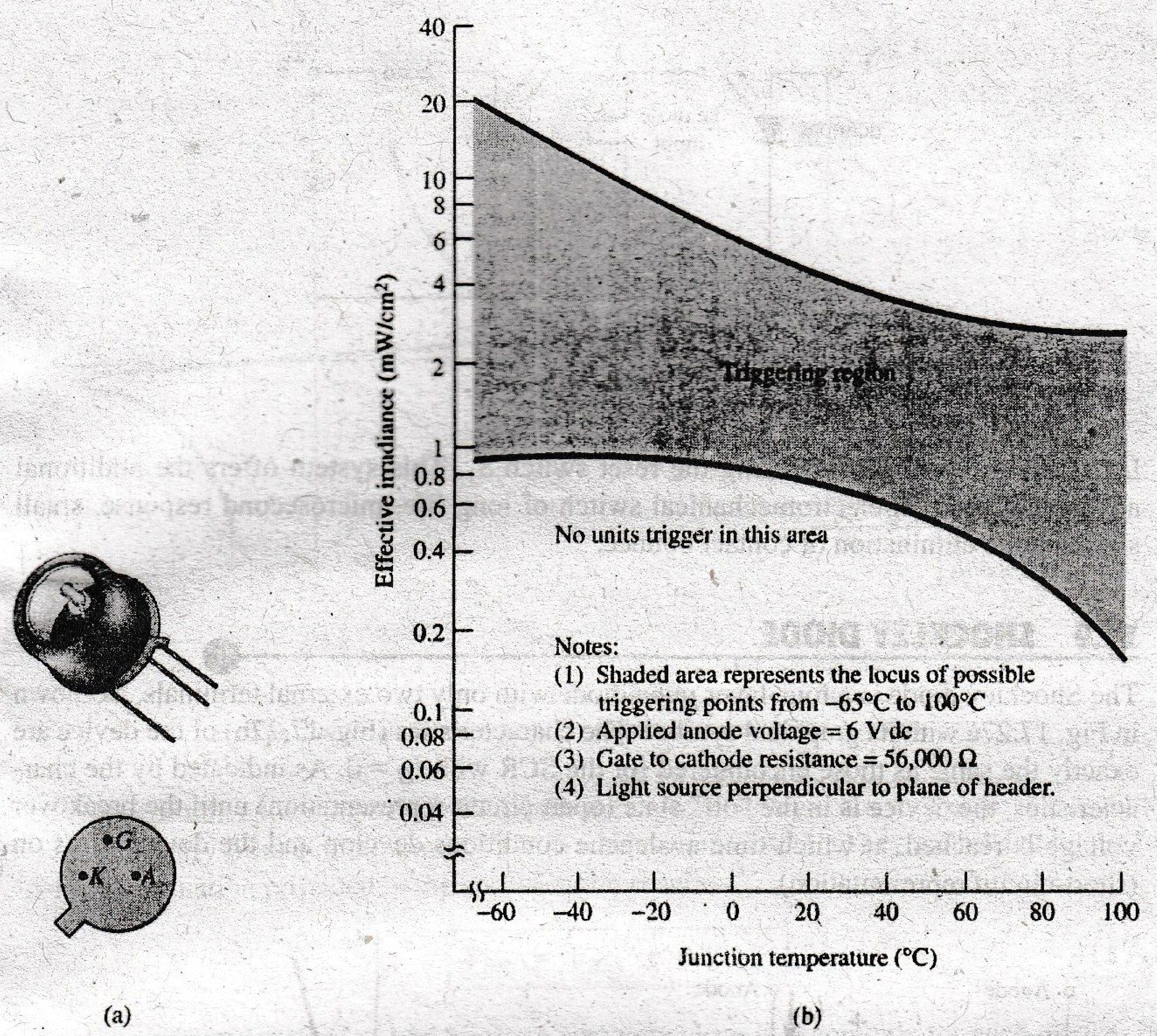


FIG. 17.24
LASCR: (a) appearance and terminal identification; (b) light-triggering characteristics.

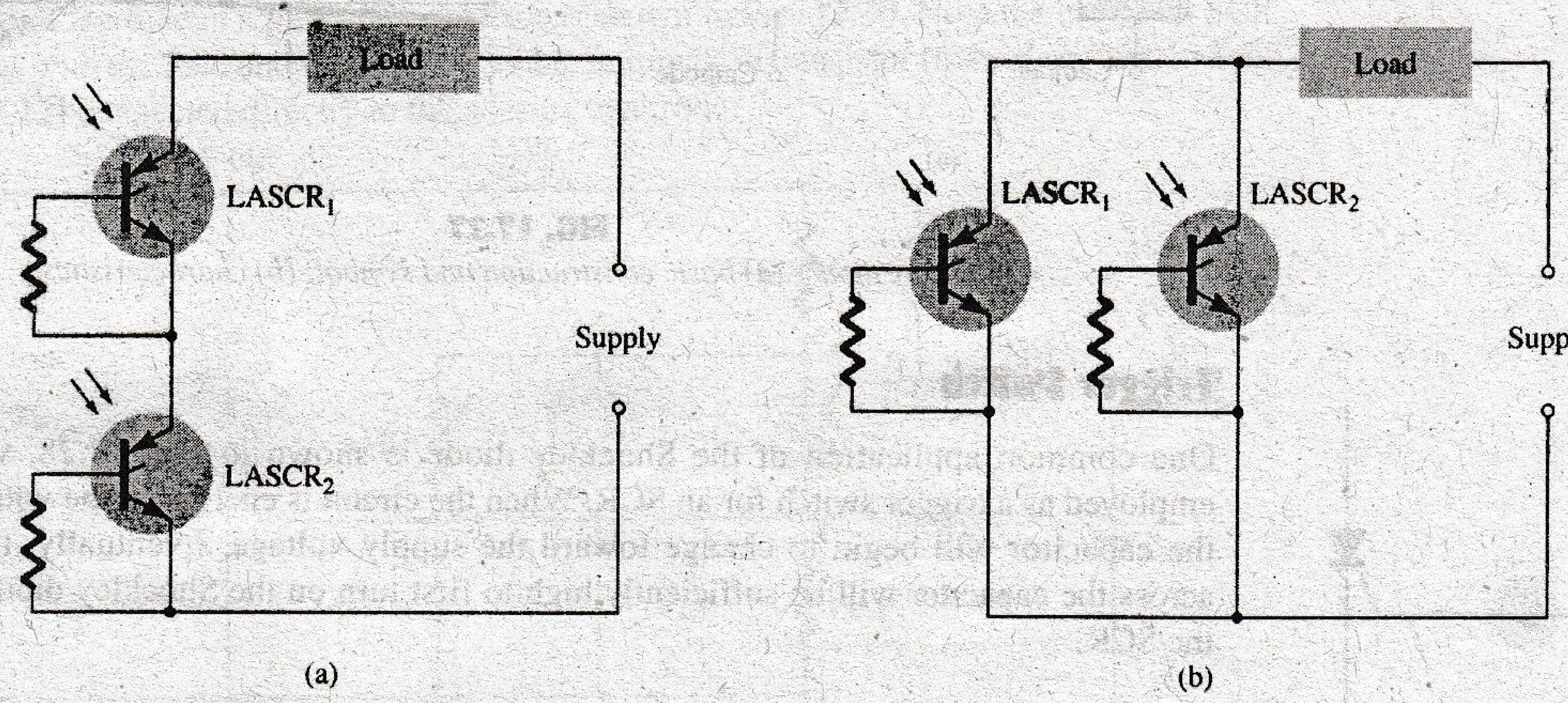


FIG. 17.25
LASCR optoelectronic logic circuitry: (a) AND gate: input to $LASCR_1$ and $LASCR_2$ is required for energization of the load; (b) OR gate: input to either $LASCR_1$ or $LASCR_2$ will energize the load.

Latching Relay

A second application of the LASCR appears in Fig. 17.26. It is the semiconductor analog of an electromechanical relay. Note that it offers complete isolation between the input and the switching element. The energizing current can be passed through a light-emitting diode or a lamp, as shown in the figure. The incident light will cause the LASCR to turn on and permit a flow of charge (current) through the load as established by the dc supply. The

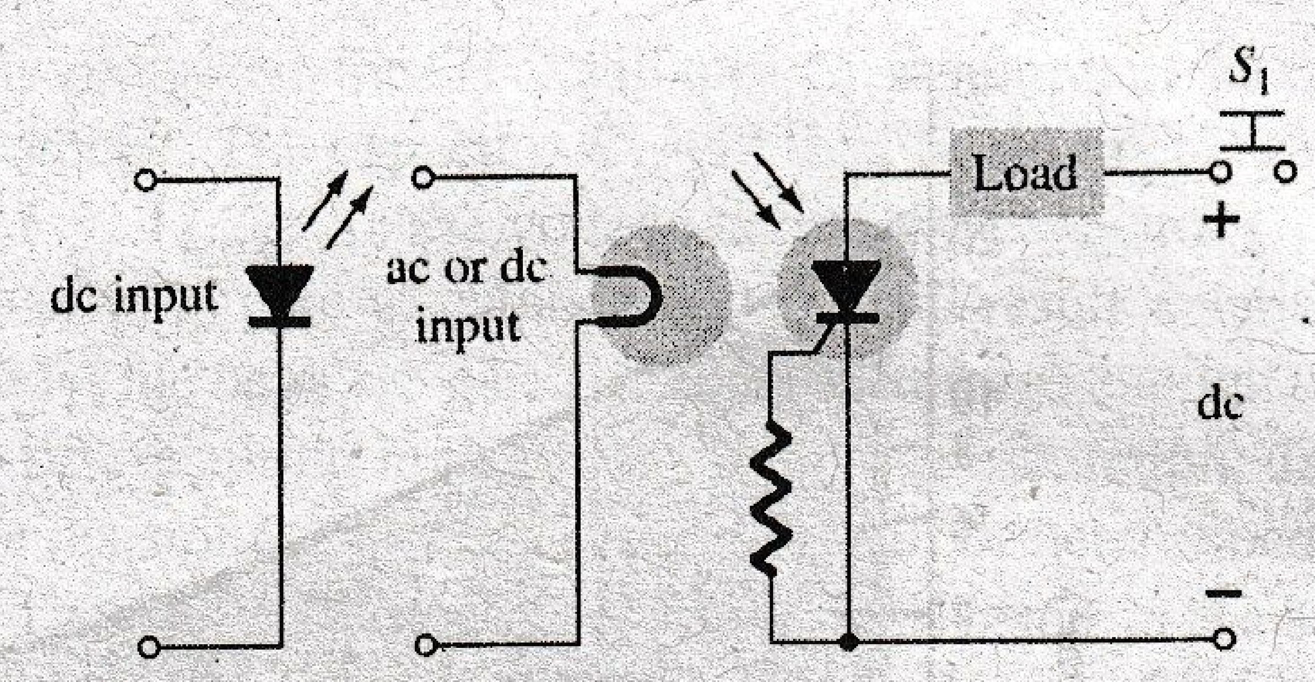


FIG. 17.26
Latching relay.

LASCR can be turned off using the reset switch S_1. This system offers the additional advantages over an electromechanical switch of long life, microsecond response, small size, and the elimination of contact bounce.

17.9 SHOCKLEY DIODE

The Shockley diode is a four-layer *pnpn* diode with only two external terminals, as shown in Fig. 17.27a with its graphical symbol. The characteristics (Fig. 17.27b) of the device are exactly the same as those encountered for the SCR with $I_G = 0$. As indicated by the characteristics, the device is in the "off" state (open-circuit representation) until the breakover voltage is reached, at which time avalanche conditions develop and the device turns on (short-circuit representation).

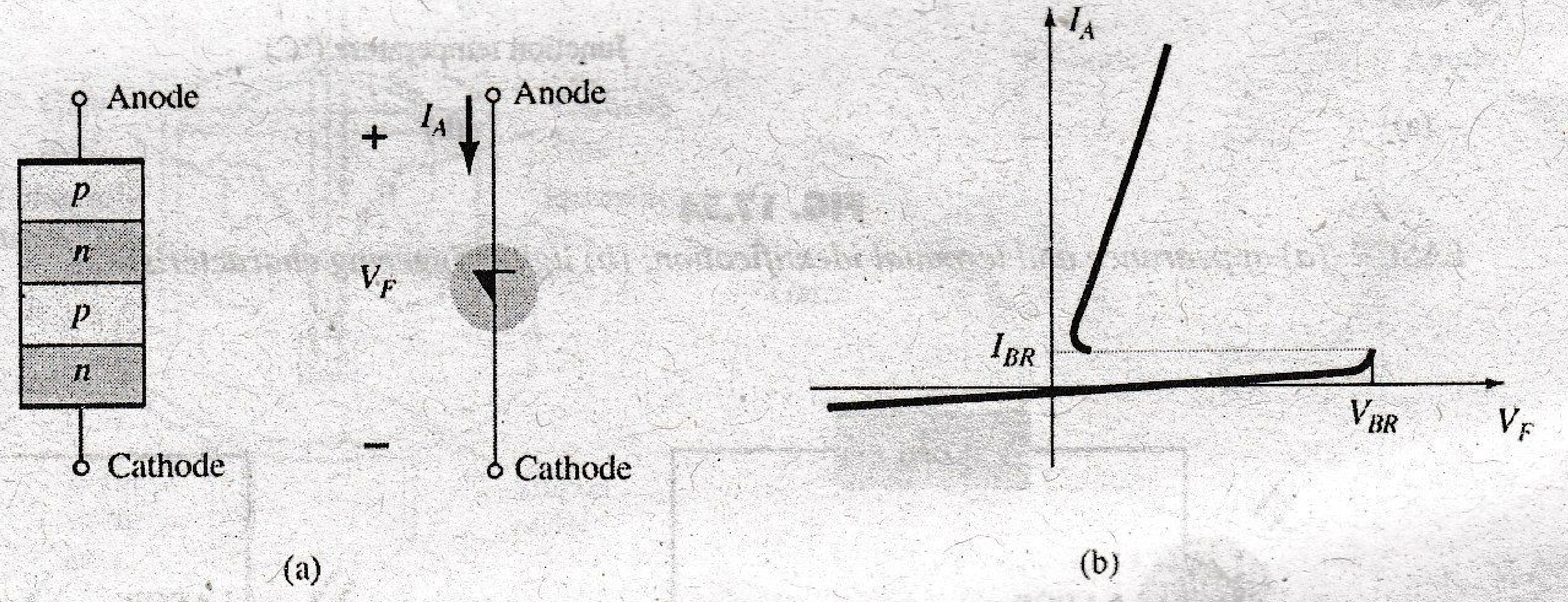


FIG. 17.27
Shockley diode: (a) basic construction and symbol; (b) characteristics.

Trigger Switch

One common application of the Shockley diode is shown in Fig. 17.28, where it is employed as a trigger switch for an SCR. When the circuit is energized, the voltage across the capacitor will begin to change toward the supply voltage. Eventually, the voltage across the capacitor will be sufficiently high to first turn on the Shockley diode and then the SCR.

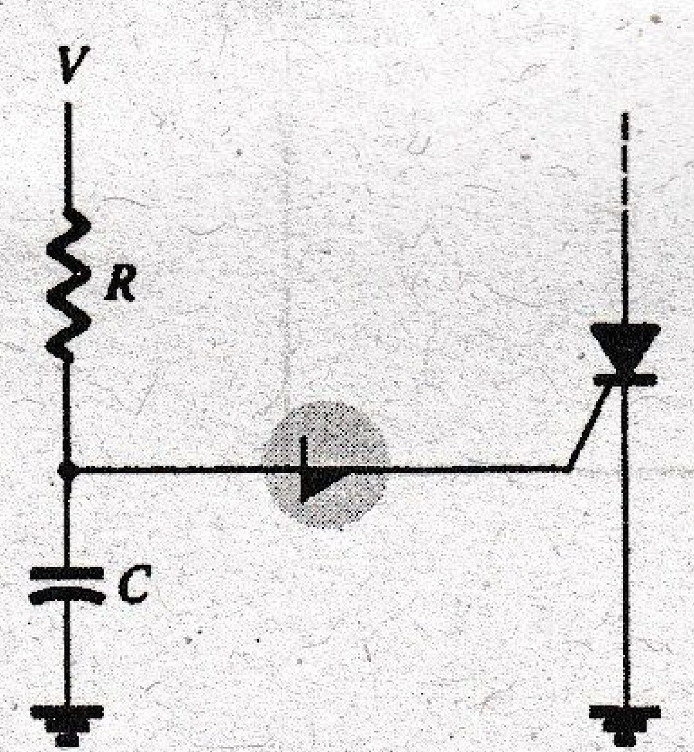


FIG. 17.28
Shockley diode application—trigger switch for an SCR.

17.10 DIAC

The diac is basically a two-terminal parallel-inverse combination of semiconductor layers that permits triggering in either direction. The characteristics of the device, presented in Fig. 17.29a, clearly demonstrate that there is a breakover voltage in either direction. This possibility of an *on* condition in either direction can be used to its fullest advantage in ac applications.

The basic arrangement of the semiconductor layers of the diac is shown in Fig. 17.29b, along with its graphical symbol. Note that neither terminal is referred to as the cathode. Instead, there is an anode 1 (or electrode 1) and an anode 2 (or electrode 2). When anode 1 is positive with respect to anode 2, the semiconductor layers of particular interest are $p_1n_2p_2$ and n_3. For anode 2 positive with respect to anode 1, the applicable layers are $p_2n_2p_1$ and n_1.

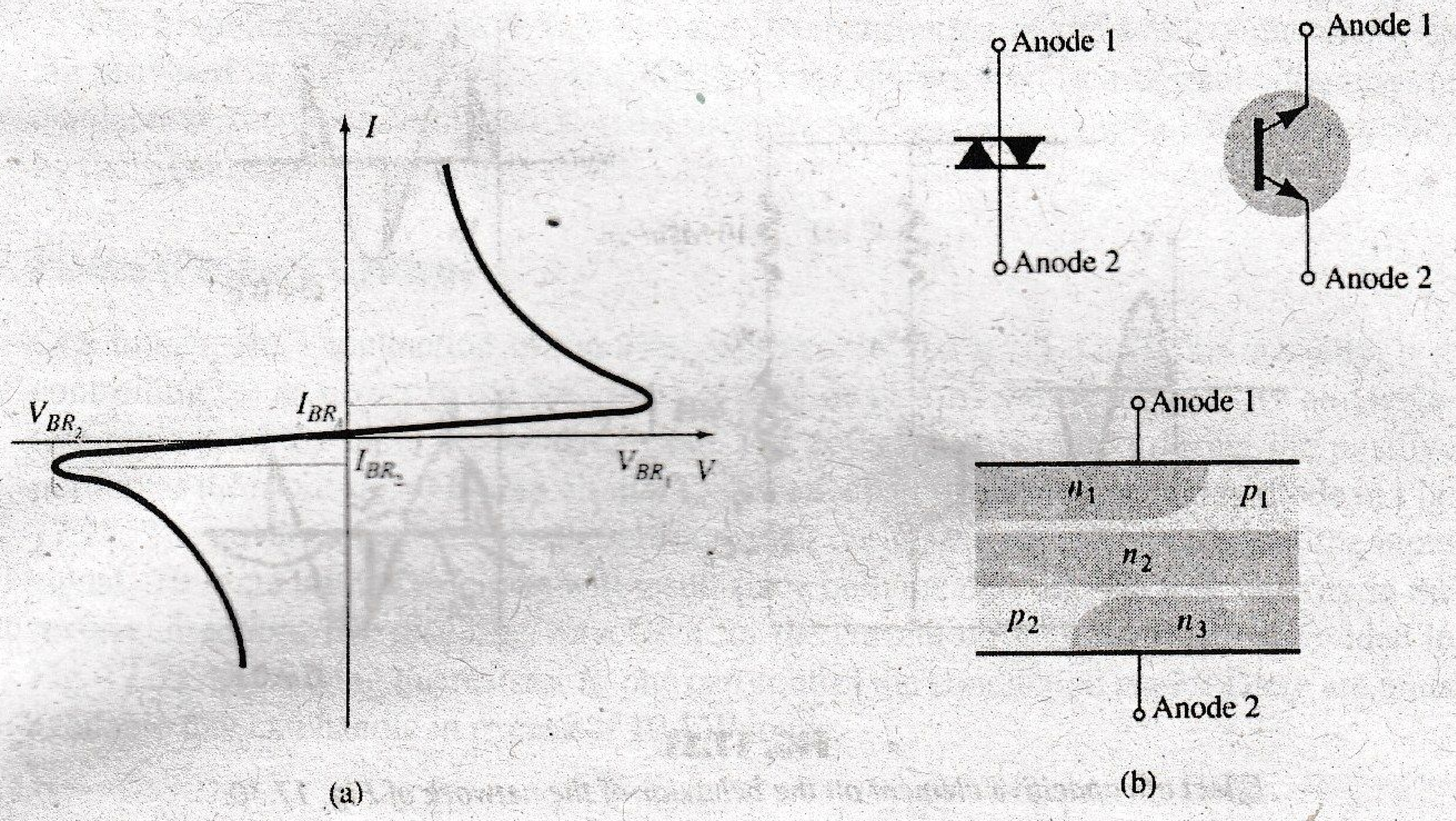


FIG. 17.29
The diac: (a) characteristics; (b) symbols and basic construction.

For the unit appearing in Fig. 17.29, the breakdown voltages are very close in magnitude but may vary from a minimum of 28 V to a maximum of 42 V. They are related by the following equation provided in the specification sheet:

$$\boxed{V_{BR_1} = V_{BR_2} \pm 0.1V_{BR_2}} \tag{17.1}$$

The current levels (I_{BR_1} and I_{BR_2}) are also very close in magnitude for each device. For the unit of Fig. 17.29, both current levels are about 200 μA = 0.2 mA.

Proximity Detector

The use of the diac in a proximity detector is shown in Fig. 17.30. Note the use of an SCR in series with the load and the programmable unijunction transistor (to be described in Section 17.12) connected directly to the sensing electrode.

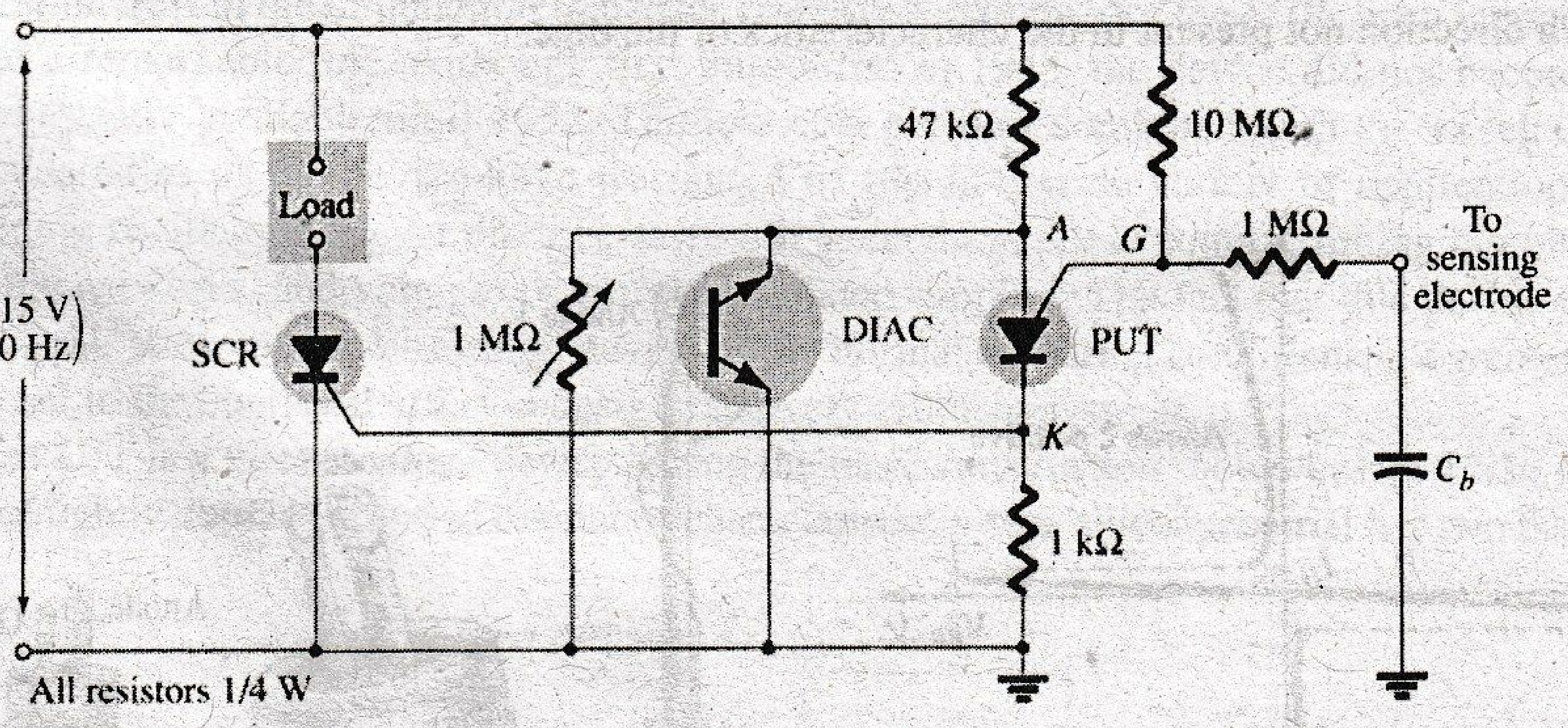


FIG. 17.30
Proximity detector or touch switch.

As a human body approaches the sensing electrode, the capacitance between the electrode and the ground (C_b) increases. The programmable UJT (PUT) is a device that will fire (enter the short-circuit state) when the anode voltage (V_A) is at least 0.7 V (for silicon) greater than the gate voltage (V_G). Before the programmable device turns on, the system is essentially as shown in Fig. 17.31. As the input voltage rises, the diac voltage v_A will follow as shown in the figure until the firing potential is reached. It will then turn on and the diac voltage will drop substantially, as shown. Note that the diac is in essentially an open-circuit state until it fires. Before the capacitive element is introduced, the voltage v_G will be the

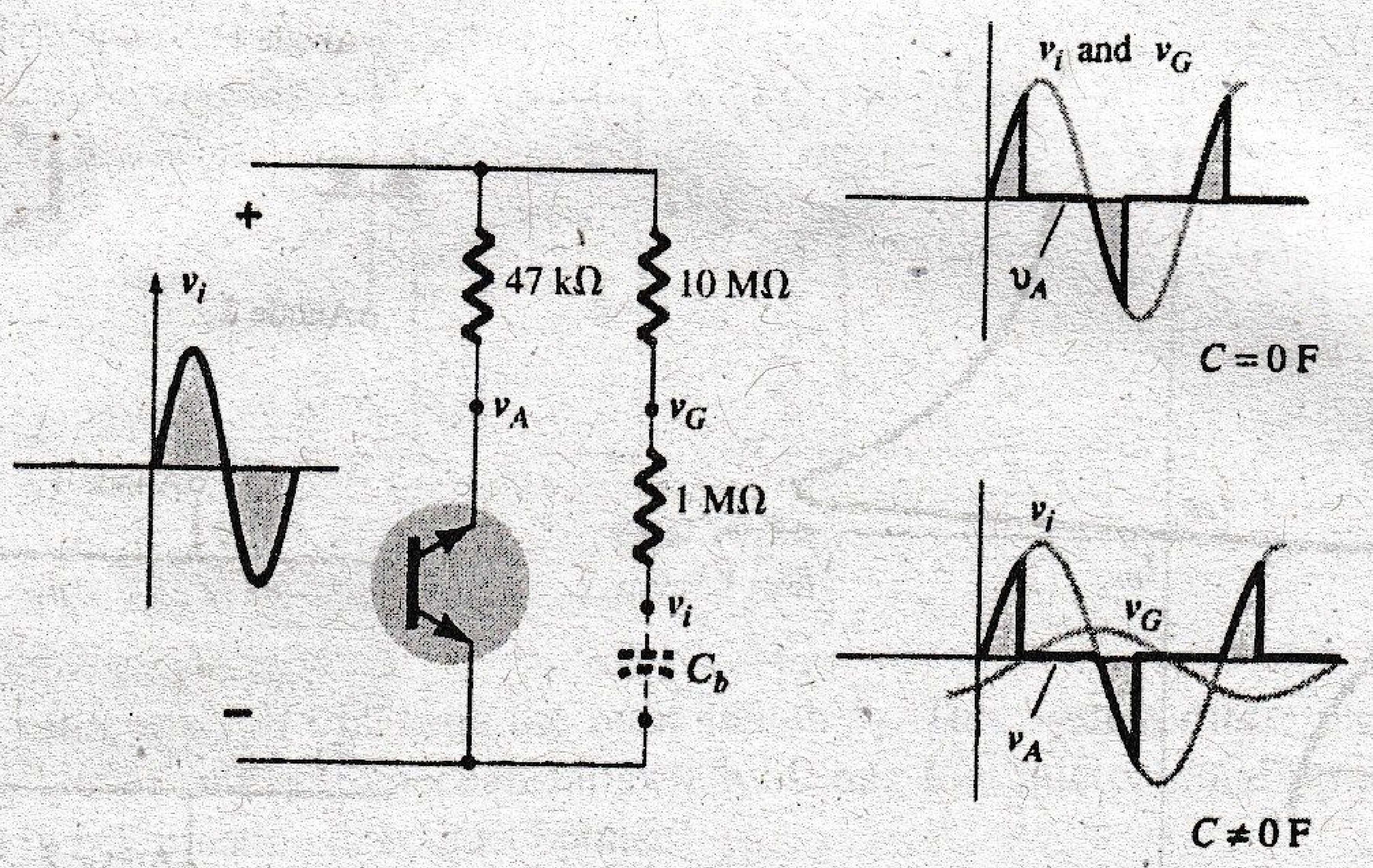


FIG. 17.31
Effect of capacitive element on the behavior of the network of Fig. 17.30.

same as the input. As indicated in the figure, since both v_A and v_G follow the input, v_A can never be greater than v_G by 0.7 V and turn on the device. However, as the capacitive element is introduced, the voltage v_G will begin to lag the input voltage by an increasing angle, as indicated in the figure. There is therefore a point established where v_A can exceed v_G by 0.7 V and cause the programmable device to fire. A heavy current is established through the PUT at this point, raising the voltage v_G and turning on the SCR. A heavy SCR current will then exist through the load, reacting to the presence of the approaching person.

A second application of the diac appears in the next section (Fig. 17.33) as we consider an important power-control device: the triac.

17.11 TRIAC

The triac is fundamentally a diac with a gate terminal for controlling the turn-on conditions of the bilateral device in either direction. In other words, for either direction the gate current can control the action of the device in a manner very similar to that demonstrated for an SCR. The characteristics, however, of the triac in the first and third quadrants are somewhat different from those of the diac, as shown in Fig. 17.32c. Note the holding current in each direction not present in the characteristics of the diac.

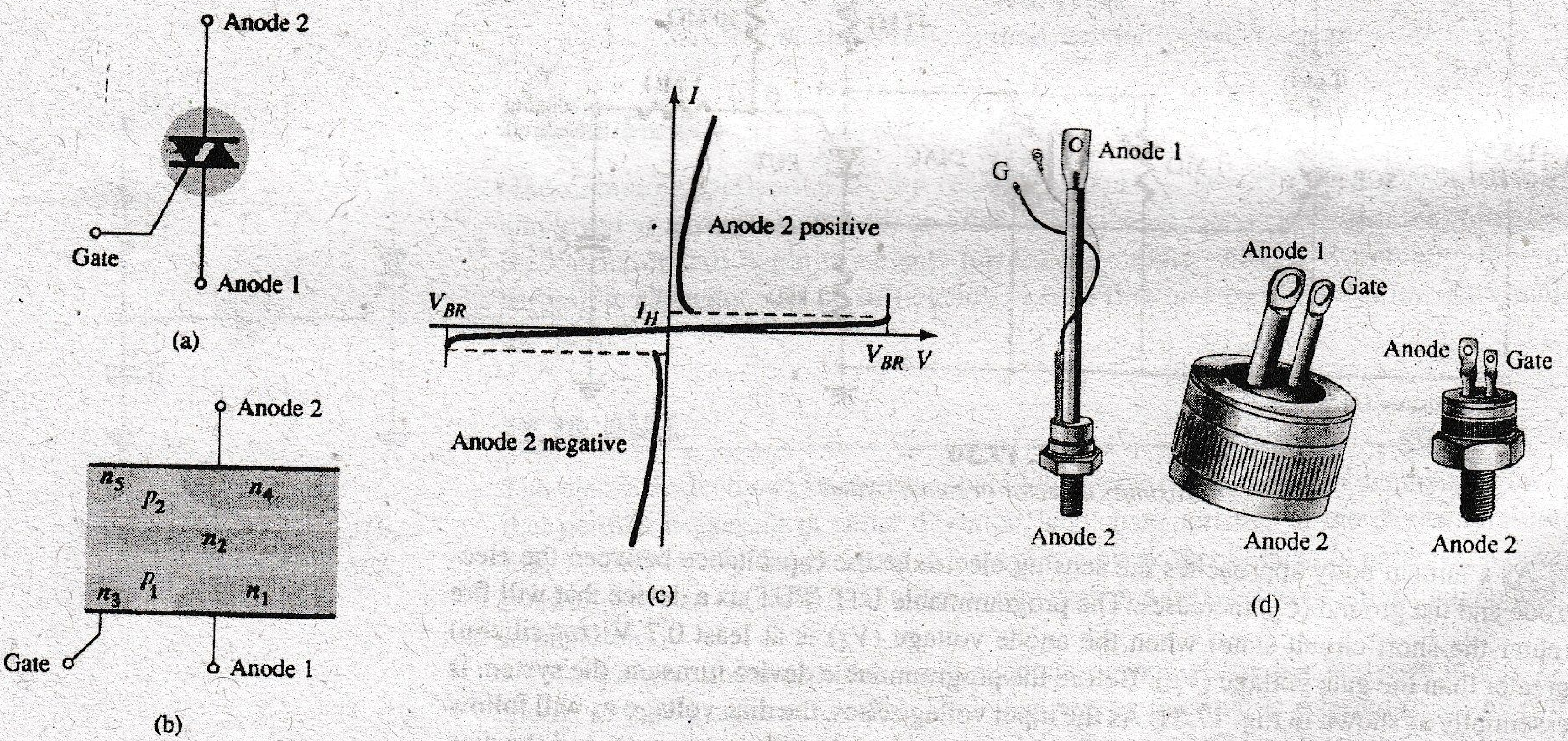


FIG. 17.32
The triac: (a) symbol; (b) basic construction; (c) characteristics; (d) drawings.

The graphical symbol for the device and the distribution of the semiconductor layers are provided in Fig. 17.32 with photographs of the device. For each possible direction of conduction, there is a combination of semiconductor layers whose state will be controlled by the signal applied to the gate terminal.

Phase (Power) Control

One fundamental application of the triac is presented in Fig. 17.33. In this capacity, it is controlling the ac power to the load by switching on and off during the positive and negative regions of the input sinusoidal signal. The action of this circuit during the positive portion of the input signal is very similar to that encountered for the Shockley diode in Fig. 17.28. The advantage of this configuration is that during the negative portion of the input signal, the same type of response will result since both the diac and the triac can fire in the reverse direction. The resulting waveform for the current through the load is provided in Fig. 17.33. By varying the resistor R, one can control the conduction angle. There are units available that can handle in excess of 10-kW loads.

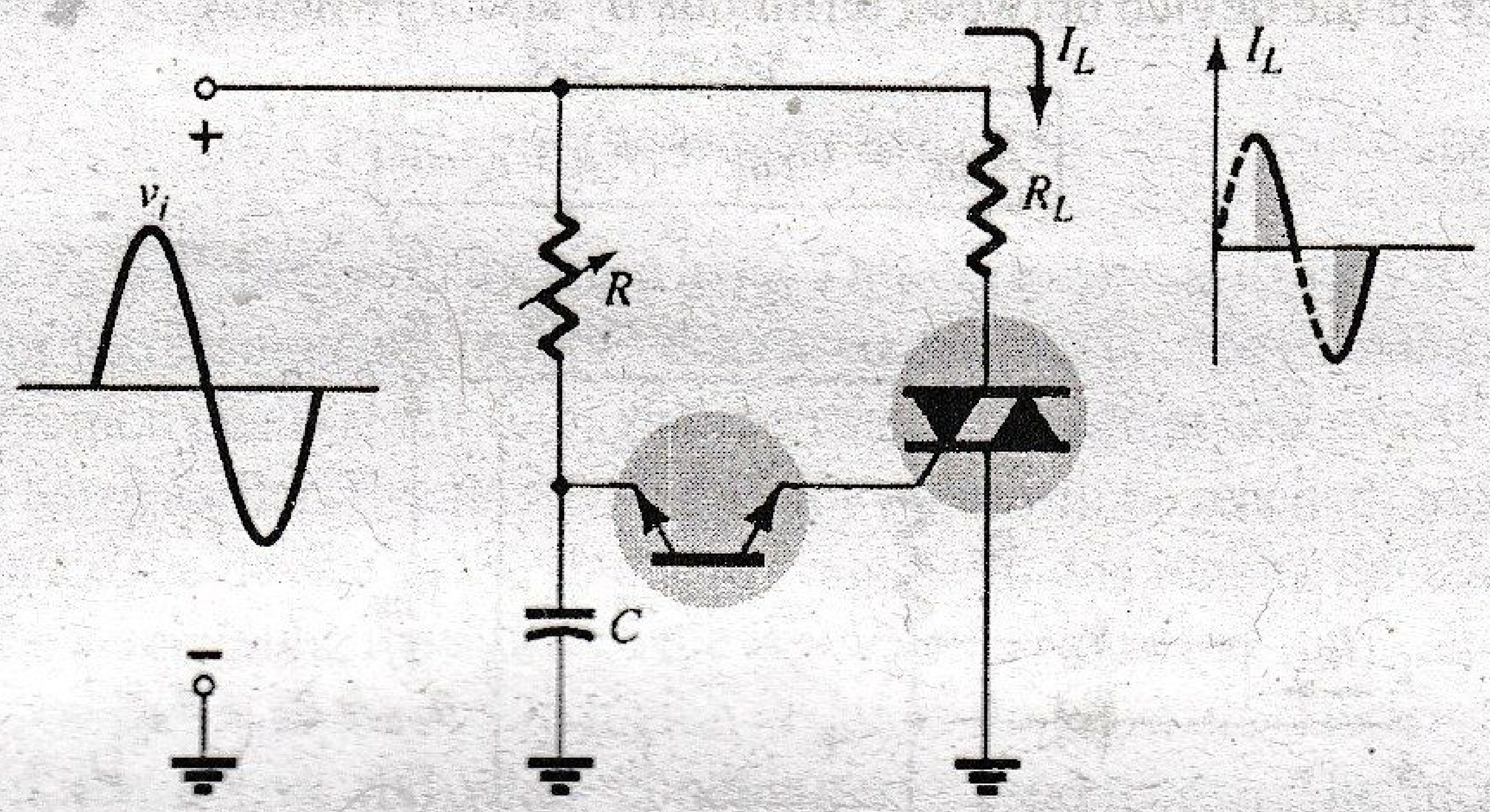


FIG. 17.33
Application of a triac: phase (power) control.

OTHER DEVICES

17.12 UNIJUNCTION TRANSISTOR

Recent interest in the unijunction transistor (UJT) has, like that for the SCR, been increasing at a remarkable rate. Although first introduced in 1948, the device did not become commercially available until 1952. The low cost per unit combined with the excellent characteristics of the device have warranted its use in a wide variety of applications, including oscillators, trigger circuits, sawtooth generators, phase control, timing circuits, bistable networks, and voltage- or current-regulated supplies. The fact that this device is, in general, a low-power-absorbing device under normal operating conditions is a tremendous aid in the continual effort to design relatively efficient systems.

The UJT is a three-terminal device having the basic construction shown in Fig. 17.34. A slab of lightly doped (increased resistance characteristic) n-type silicon material has two base

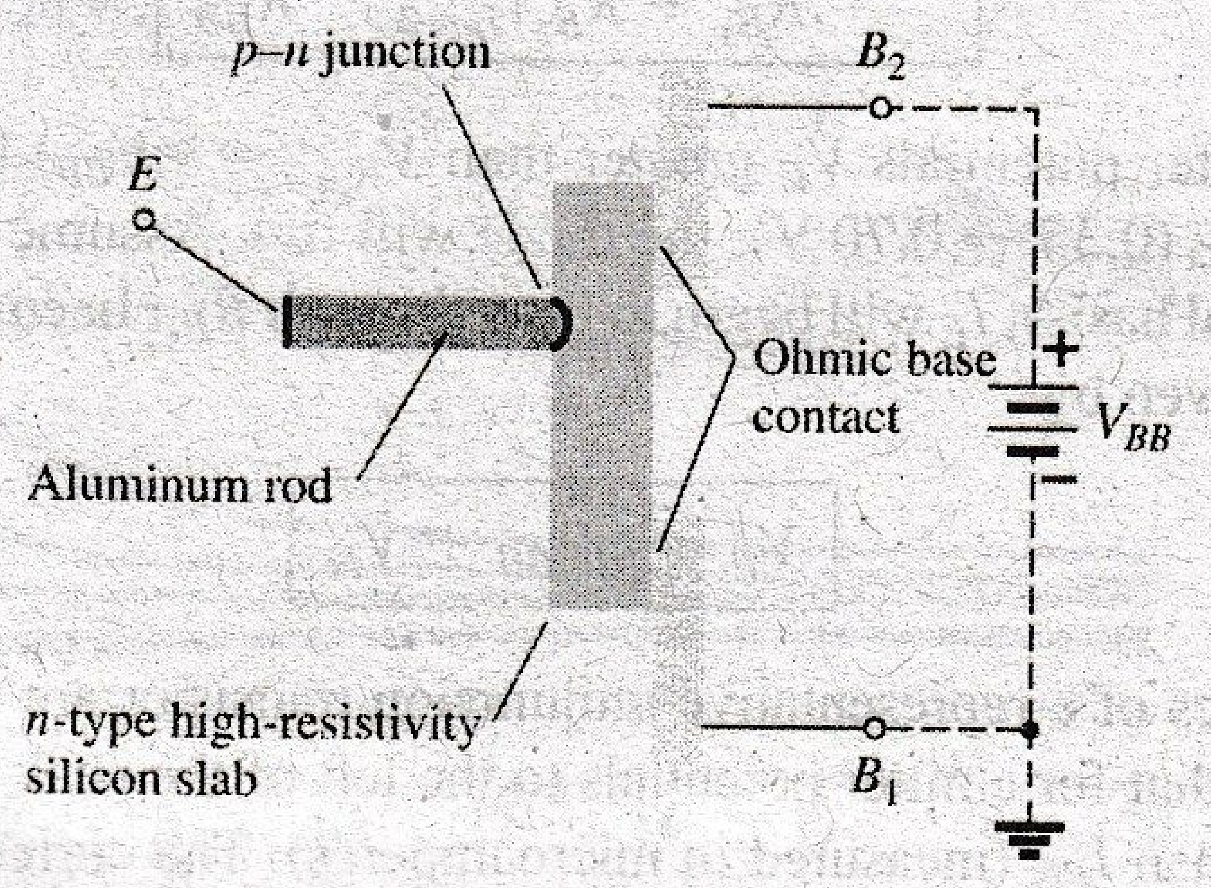


FIG. 17.34
Unijunction transistor (UJT): basic construction.

contacts attached to both ends of one surface and an aluminum rod alloyed to the opposite surface. The *p–n* junction of the device is formed at the boundary of the aluminum rod and the *n*-type silicon slab. The single *p–n* junction accounts for the terminology *unijunction*. It was originally called a duo (double) base diode due to the presence of two base contacts. Note in Fig. 17.34 that the aluminum rod is alloyed to the silicon slab at a point closer to the base 2 contact than the base 1 contact and that the base 2 terminal is made positive with respect to the base 1 terminal by V_{BB} volts. The effect of each will become evident in the paragraphs to follow.

The symbol for the unijunction transistor is provided in Fig. 17.35. Note that the emitter leg is drawn at an angle to the vertical line representing the slab of *n*-type material. The arrowhead is pointing in the direction of conventional current (hole) flow when the device is in the forward-biased, active, or conducting state.

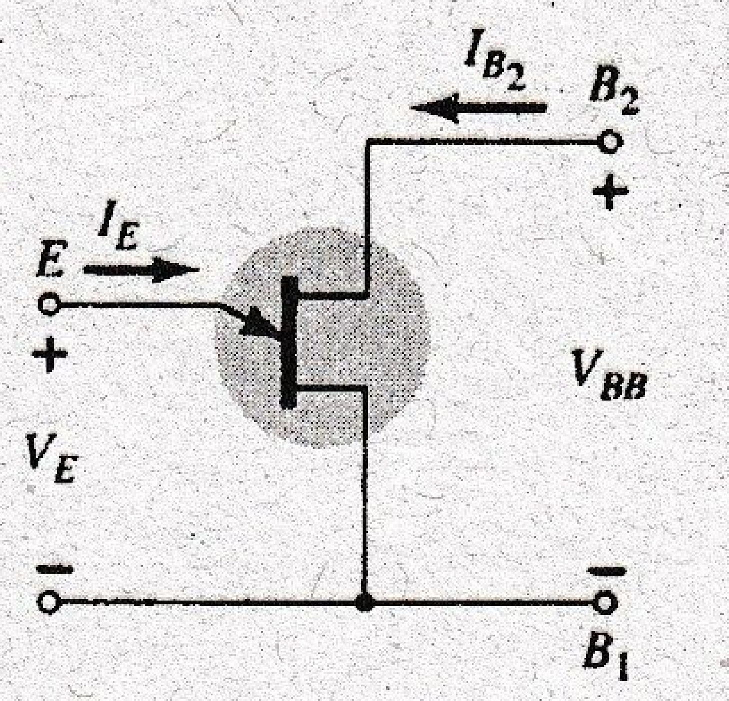


FIG. 17.35
Symbol and basic biasing arrangement for the unijunction transistor.

The circuit equivalent of the UJT is shown in Fig. 17.36. Note the relative simplicity of this equivalent circuit: two resistors (one fixed, one variable) and a single diode. The resistance R_{B_1} is shown as a variable resistor since its magnitude will vary with the current I_E. In fact, for a representative unijunction transistor, R_{B_1} may vary from 5 kΩ down to 50 Ω for a corresponding change of I_E from 0 μA to 50 μA. The interbase resistance R_{BB} is the resistance of the device between terminals B_1 and B_2 when $I_E = 0$. In equation form,

$$R_{BB} = (R_{B_1} + R_{B_2})\big|_{I_E=0} \tag{17.2}$$

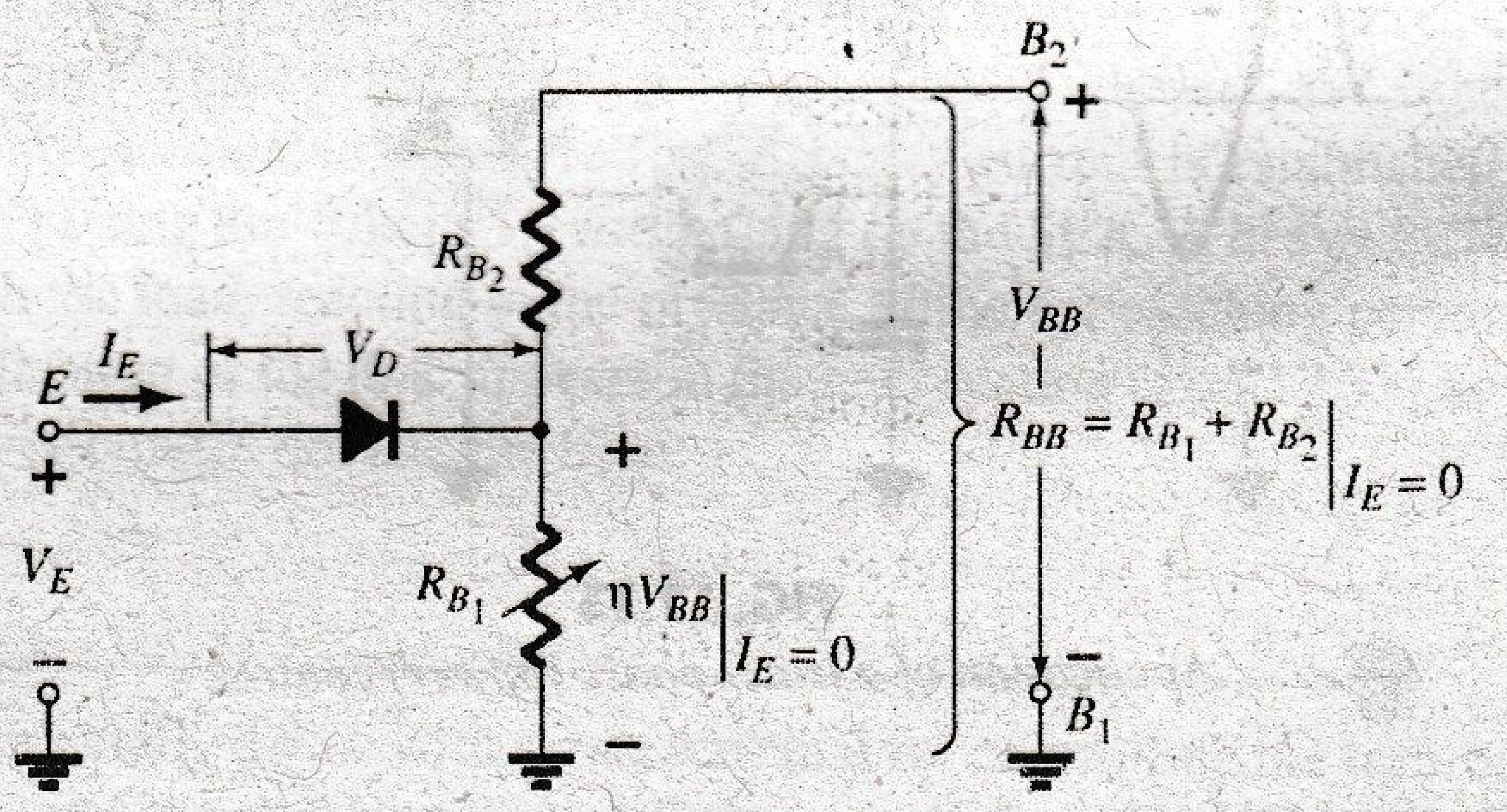


FIG. 17.36
UJT equivalent circuit.

(R_{BB} is typically within the range of 4 kΩ to 10 kΩ.) The position of the aluminum rod of Fig. 17.34 will determine the relative values of R_{B_1} and R_{B_2} with $I_E = 0$. The magnitude of $V_{R_{B1}}$ (with $I_E = 0$) is determined by the voltage-divider rule in the following manner:

$$V_{R_{B1}} = \frac{R_{B_1}}{R_{B_1} + R_{B_2}} \cdot V_{BB} = \eta V_{BB}\Big|_{I_E=0} \tag{17.3}$$

The Greek letter η (eta) denotes the *intrinsic stand-off* ratio of the device, which is defined by

$$\eta = \frac{R_{B_1}}{R_{B_1} + R_{B_2}}\Big|_{I_E=0} = \frac{R_{B_1}}{R_{BB}} \tag{17.4}$$

For applied emitter potentials V_E greater than $V_{R_{B1}} (= \eta V_{BB})$ by the forward voltage drop of the diode V_D (0.35 → 0.70 V), the diode will fire. Assume the short-circuit representation (on an ideal basis); I_E will begin to flow through R_{B_1}. In equation form, the emitter firing potential is given by

$$V_P = \eta V_{BB} + V_D \tag{17.5}$$

The characteristics of a representative unijunction transistor are shown for $V_{BB} = 10$ V in Fig. 17.37. Note that for emitter potentials to the left of the peak point, the magnitude of I_E is never greater than I_{EO} (measured in microamperes). The current I_{EO} corresponds very closely to the reverse leakage current I_{CO} of the conventional bipolar transistor. This region, as indicated in the figure, is called the cutoff region. Once conduction is established at $V_E = V_P$,

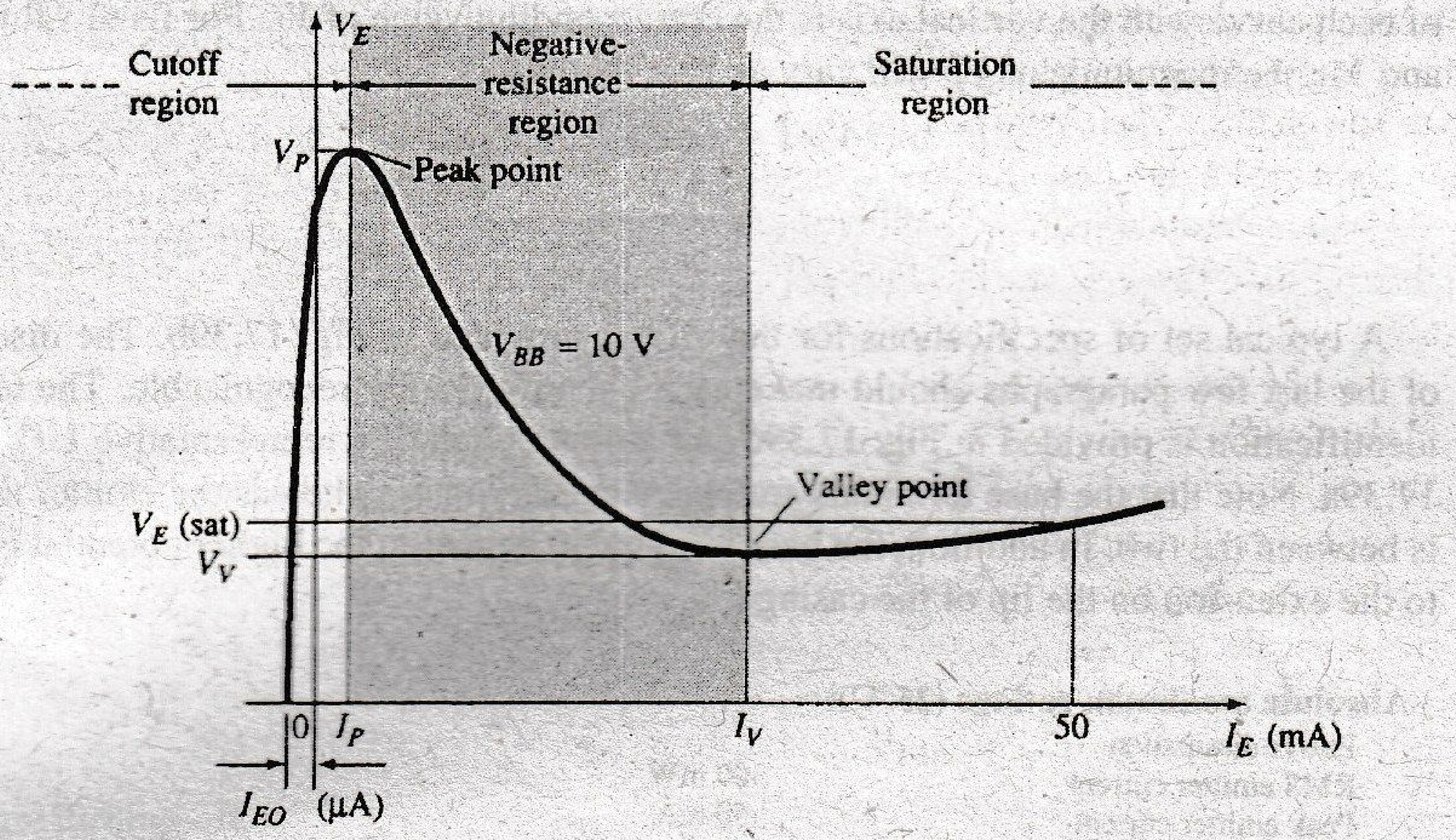


FIG. 17.37
UJT static emitter characteristic curve.

the emitter potential V_E will drop with increase in I_E. This corresponds exactly to the decreasing resistance R_{B_1} for increasing current I_E, as discussed earlier. This device, therefore, has a *negative-resistance* region that is stable enough to be used with a great deal of reliability in the areas of application listed earlier. Eventually, the valley point will be reached, and any further increase in I_E will place the device in the saturation region. In this region, the characteristics approach those of the semiconductor diode in the equivalent circuit of Fig. 17.36.

The decrease in resistance in the active region is due to the holes injected into the n-type slab from the aluminum p-type rod when conduction is established. The increased hole content in the n-type material will result in an increase in the number of free electrons in the slab, producing an increase in conductivity G and a corresponding drop in resistance ($R \downarrow = 1/G \uparrow$). Three other important parameters for the unijunction transistor are I_P, V_V, and I_V. Each is indicated on Fig. 17.37. They are all self-explanatory.

The emitter characteristics as they normally appear are provided in Fig. 17.38. Note that I_{EO} (μA) is not in evidence since the horizontal scale is in milliamperes. The intersection

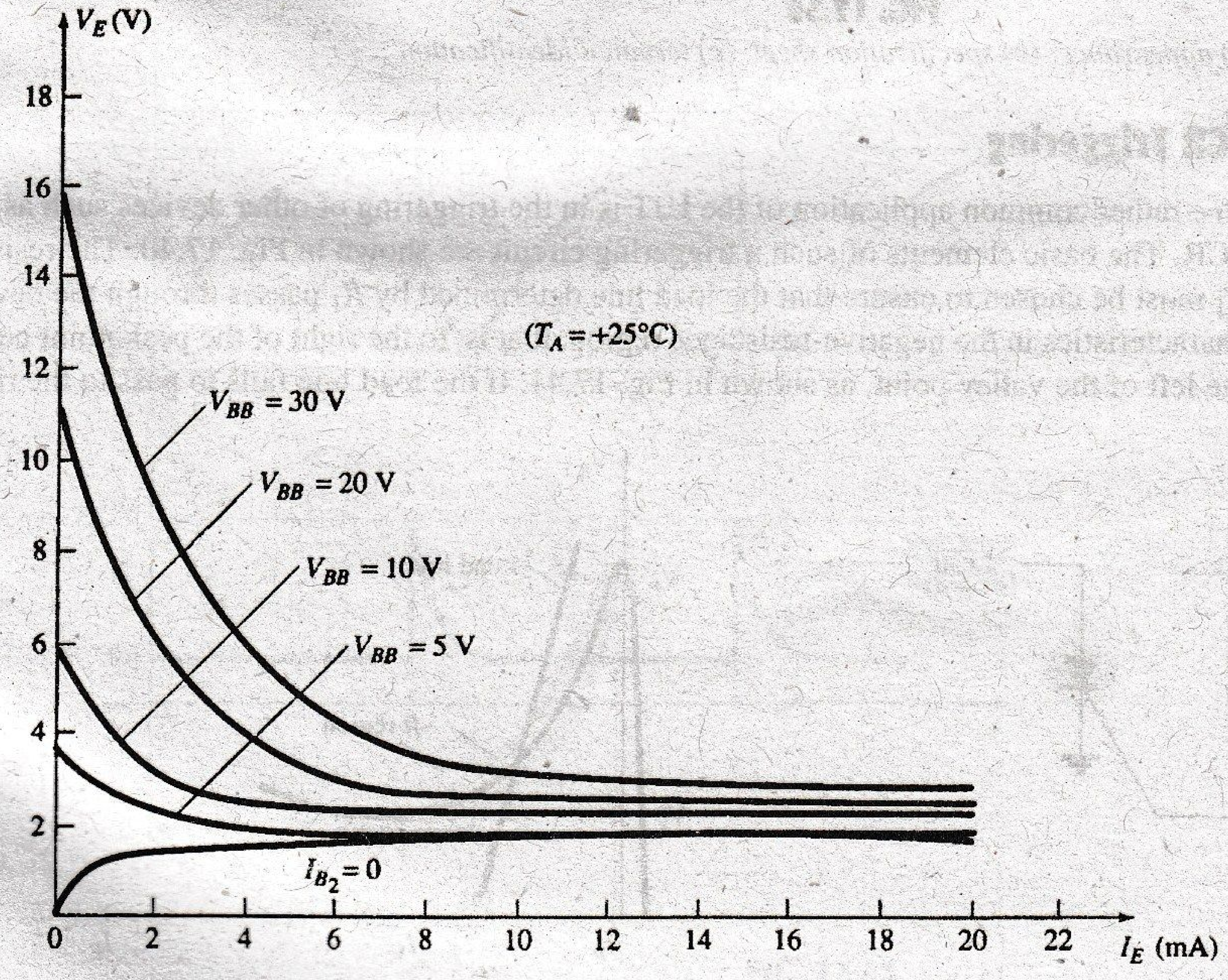
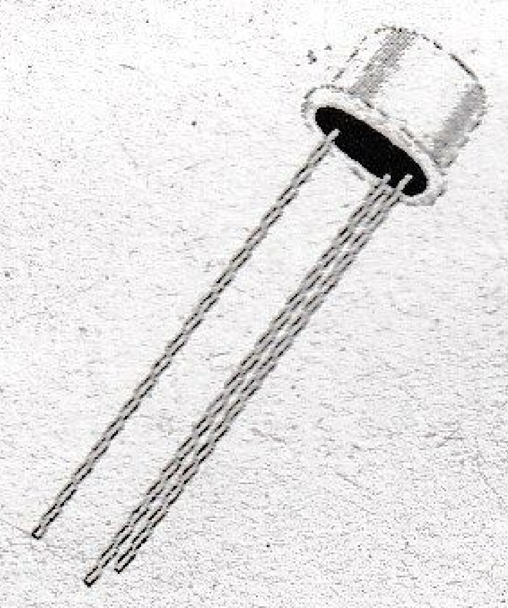


FIG. 17.38
Typical static emitter characteristic curves for a UJT.

of each curve with the vertical axis is the corresponding value of V_P. For fixed values of η and V_D, the magnitude of V_P will vary as V_{BB}, that is,

$$V_P \uparrow = \underbrace{\eta}_{\text{fixed}} V_{BB}\uparrow + \underbrace{V_D}_{\text{fixed}}$$

A typical set of specifications for the UJT is provided in Fig. 17.39b. The discussion of the last few paragraphs should make each quantity readily recognizable. The terminal identification is provided in Fig. 17.39c and a photograph of a representative UJT in Fig. 17.39a. Note that the base terminals are opposite each other, whereas the emitter terminal is between the two. In addition, the base terminal to be tied to the higher potential is closer to the extension on the lip of the casing.



(a)

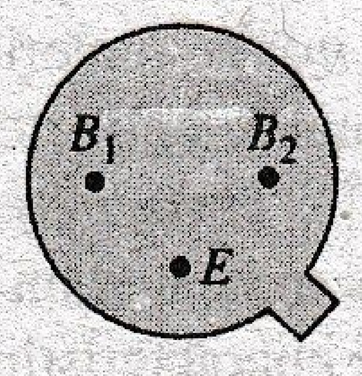
Absolute maximum ratings (25°C):

Power dissipation	
RMS emitter current	300 mW
Peak emitter current	50 mA
Emitter reverse voltage	2 A
Interbase voltage	30 V
Operating temperature range	35 V
Storage temperature range	−65°C to +125°C

Electrical characteristics (25°C):

		Minimum	Typical	Maximum
Intrinsic standoff ratio		0.56	0.65	
(V_{BB} = 10 V)	η	0.56	0.65	0.75
Interbase resistance (kΩ)				
(V_{BB} = 3 V, I_E = 0)	R_{BB}	4.7	7	9.1
Emitter saturation voltage				
(V_{BB} = 10 V, I_E = 50 mA)	$V_{E(\text{sat})}$		2	
Emitter reverse current				
(V_{BB} = 3 V, I_{B1} = 0)	I_{EO}		0.05	12
Peak point emitter current	I_P (μA)		0.04	5
(V_{BB} = 25 V)				
Valley point current				
(V_{BB} = 20 V)	I_V (mA)	4	6	

(b)



(c)

FIG. 17.39
UJT: (a) appearance; (b) specification sheet; (c) terminal identification.

SCR Triggering

One rather common application of the UJT is in the triggering of other devices such as the SCR. The basic elements of such a triggering circuit are shown in Fig. 17.40. The resistor R_1 must be chosen to ensure that the load line determined by R_1 passes through the device characteristics in the negative-resistance region, that is, to the right of the peak point but to the left of the valley point, as shown in Fig. 17.41. If the load line fails to pass to the right

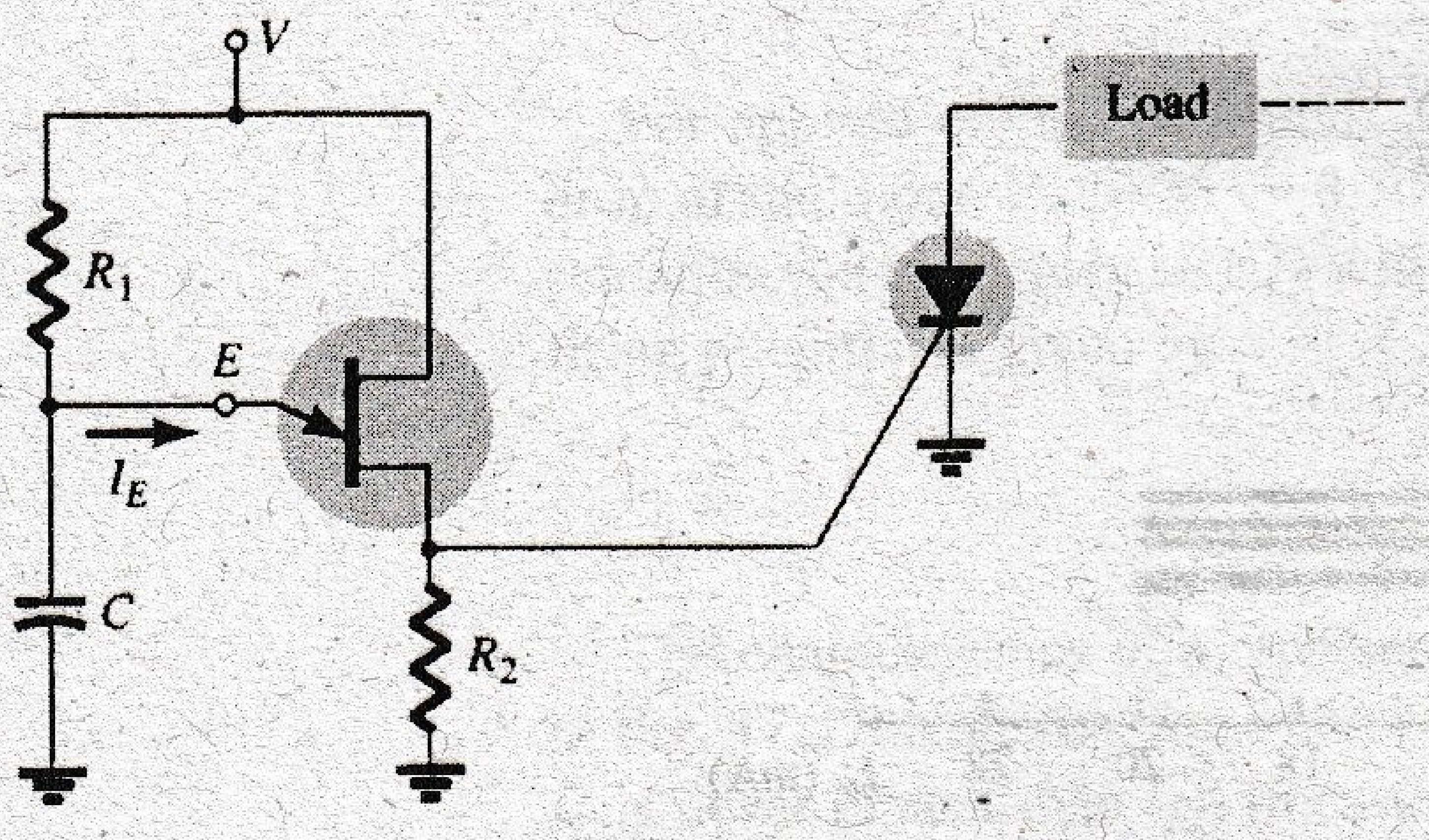


FIG. 17.40
UJT triggering of an SCR.

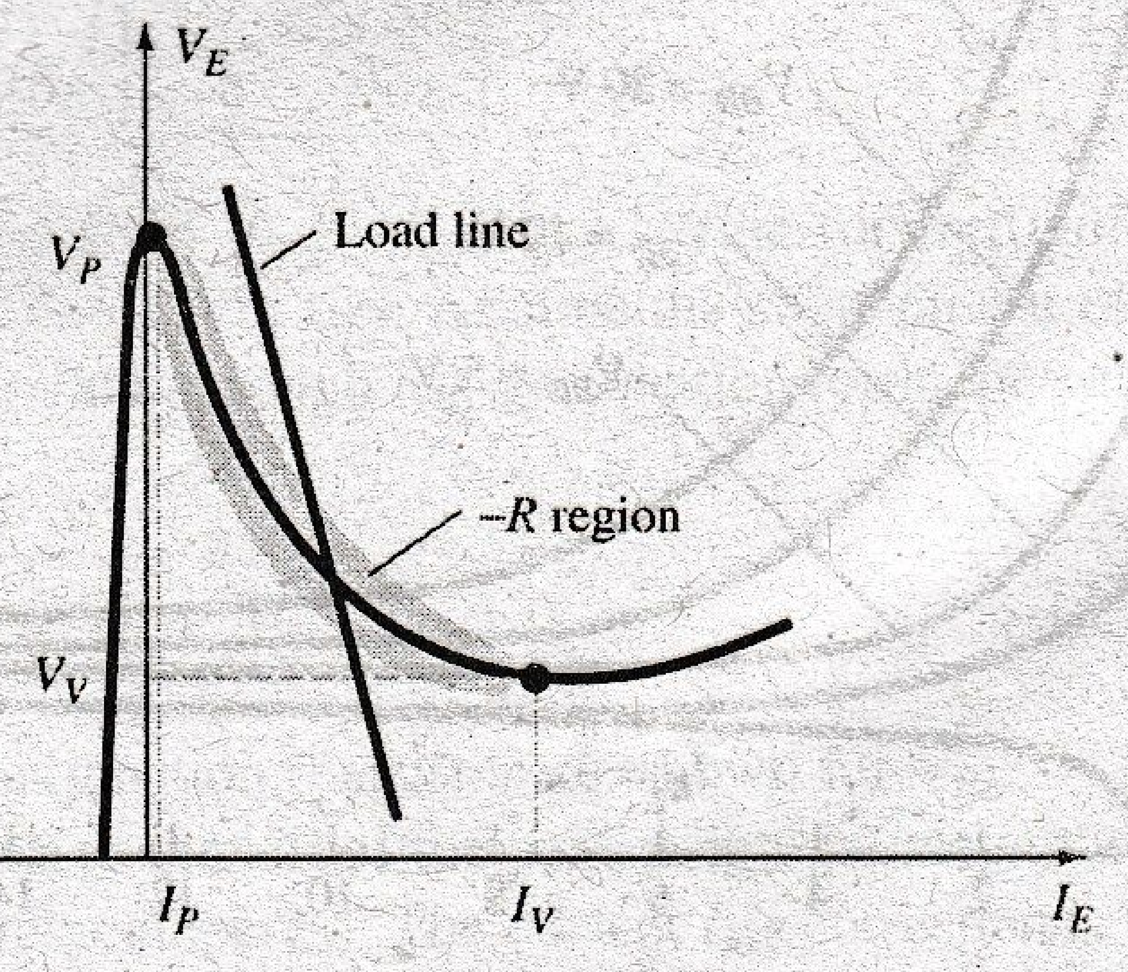


FIG. 17.41
Load line for a triggering application.

A representative set of characteristics for a phototransistor is provided in Fig. 17.49 along with the symbolic representation of the device. Note the similarities between these curves and those of a typical bipolar transistor. As expected, an increase in light intensity corresponds to an increase in collector current. To provide a greater degree of familiarity with the light-intensity unit of measurement, milliwatts per square centimeter, we give a curve of base current versus flux density in Fig. 17.50a. Note the exponential increase in base current with increasing flux density. In the same figure, a sketch of the phototransistor is provided with the terminal identification and the angular alignment.

Some of the areas of application for the phototransistor include computer logic circuitry, lighting control (highways, etc.), level indication, relays, and counting systems.

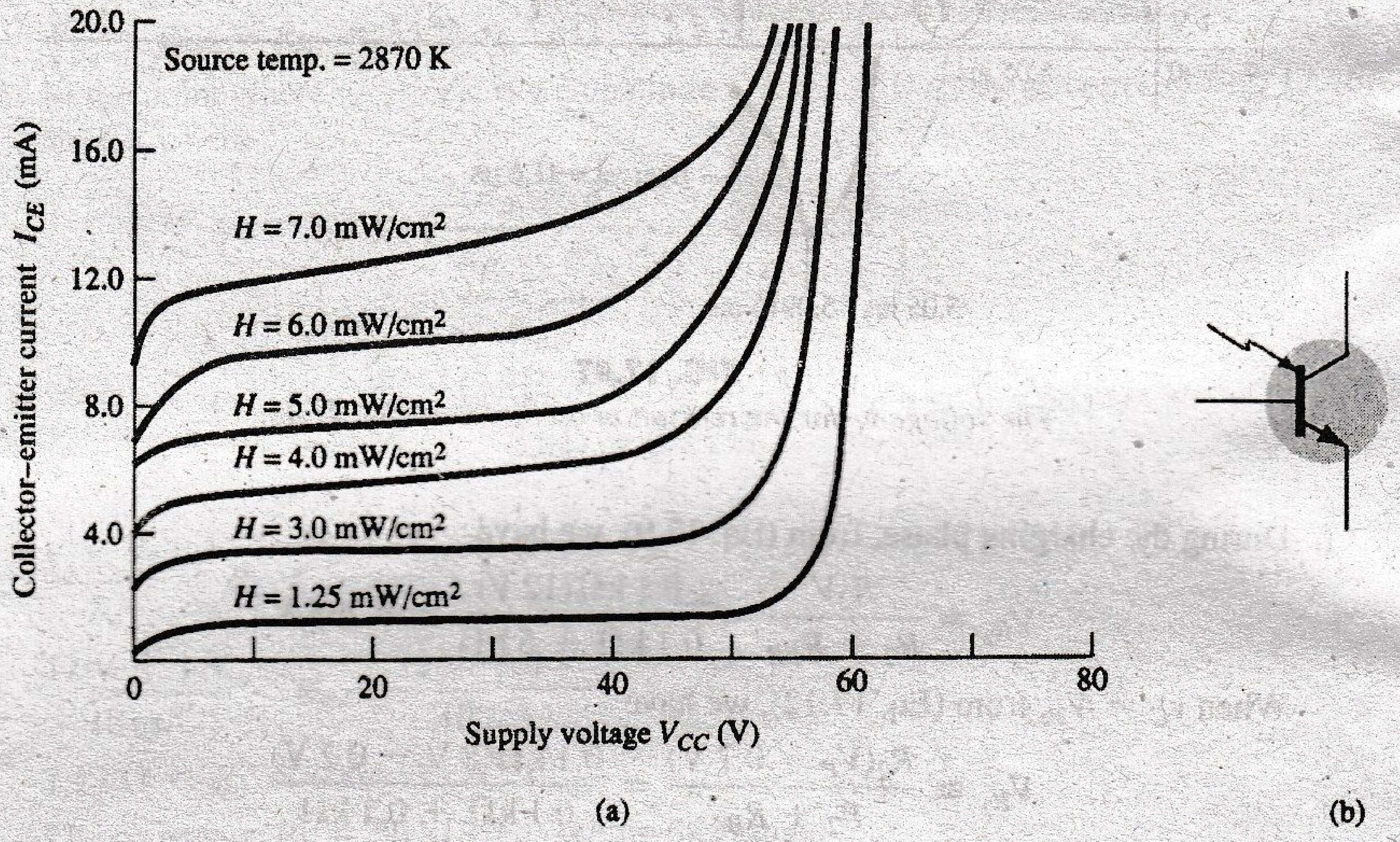


FIG. 17.49
Phototransistor: (a) collector characteristics; (b) symbol.

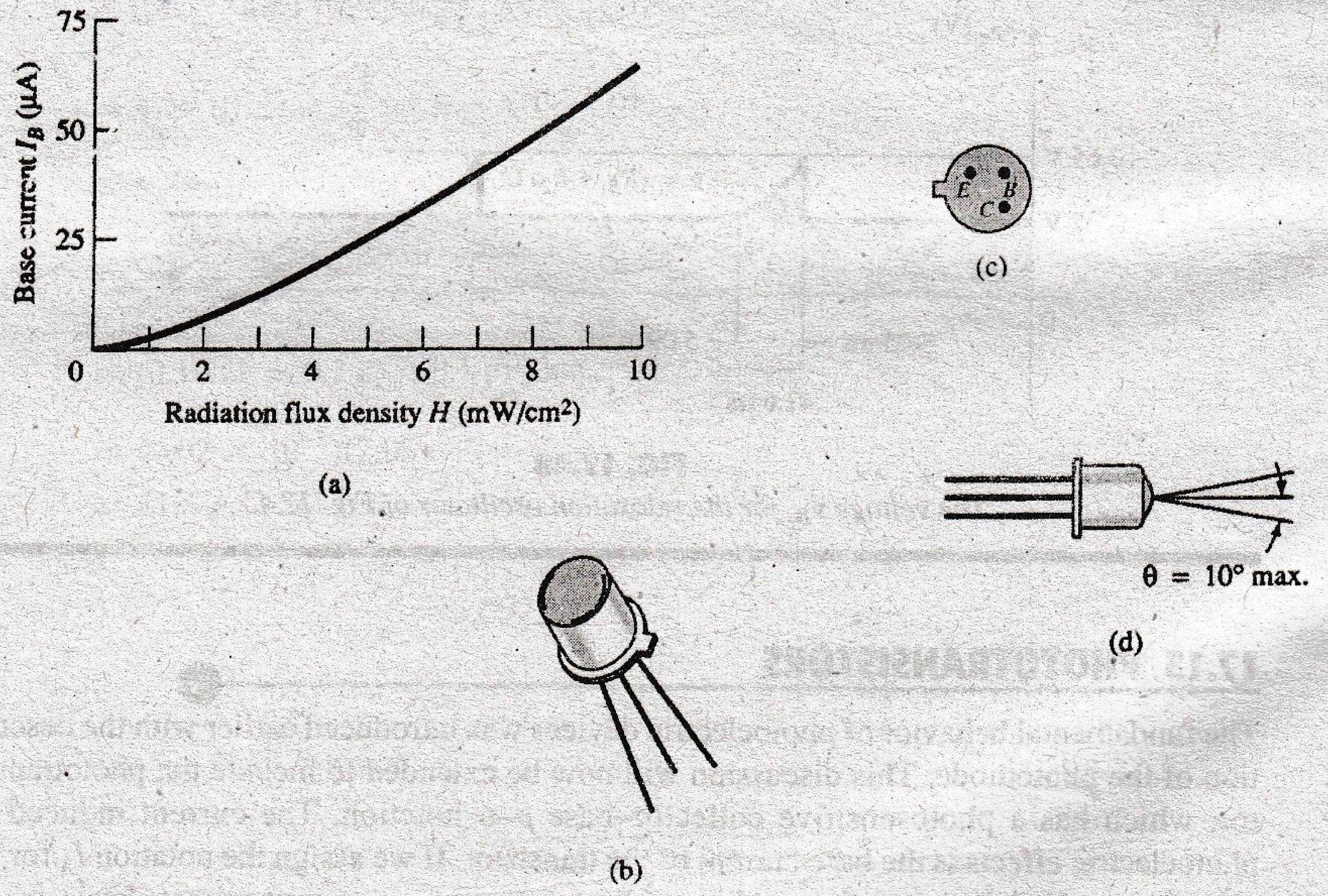


FIG. 17.50
Phototransistor: (a) base current versus flux density; (b) device; (c) terminal identification; (d) angular alignment.

High-Isolation AND Gate

A high-isolation AND gate is shown in Fig. 17.51 using three phototransistors and three LEDs (light-emitting diodes). The LEDs are semiconductor devices that emit light at an intensity determined by the forward current through the device. With the aid of discussions in Chapter 1, the circuit behavior should be relatively easy to understand. The terminology *high isolation* simply refers to the lack of an electrical connection between the input and output circuits.

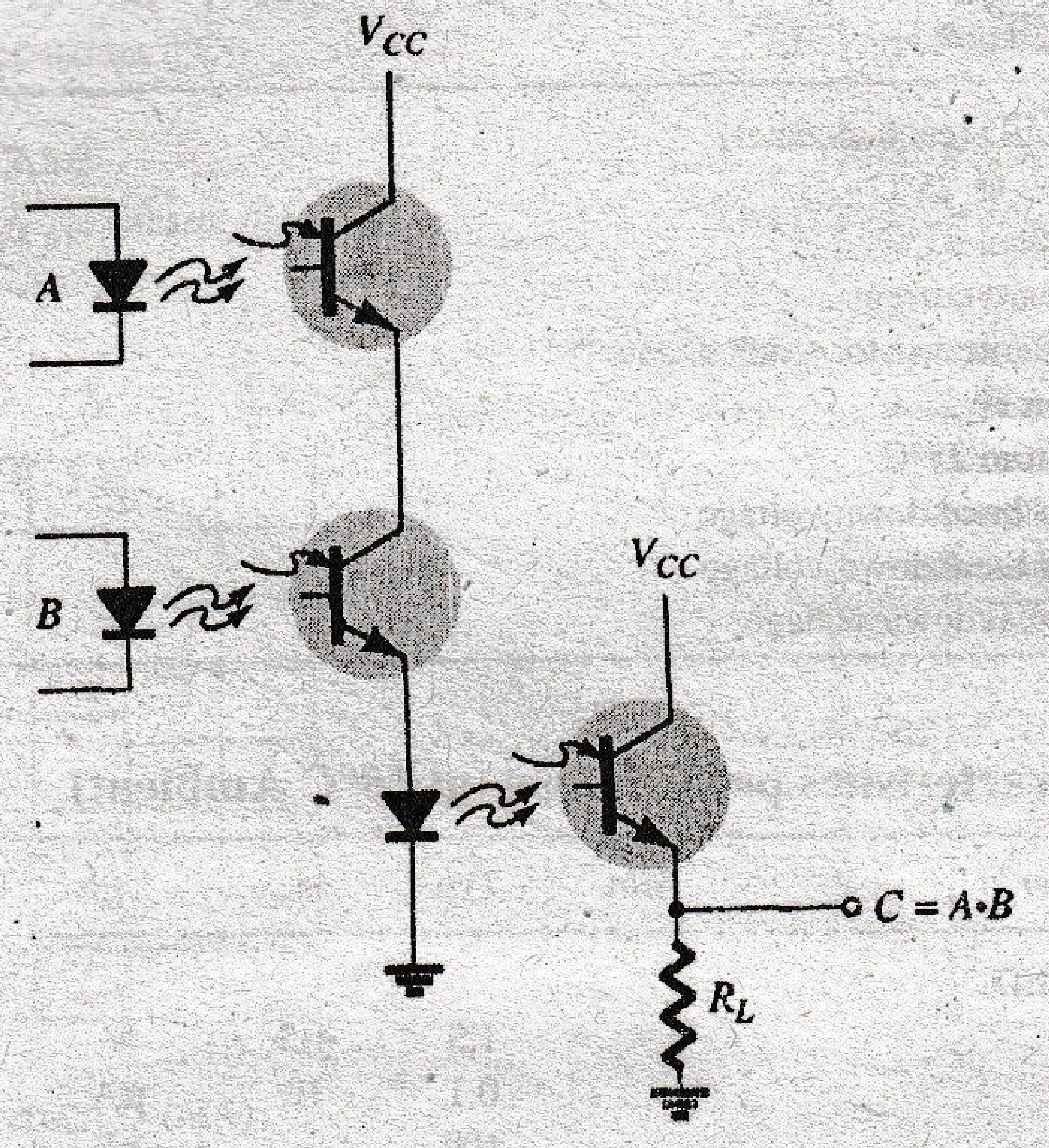
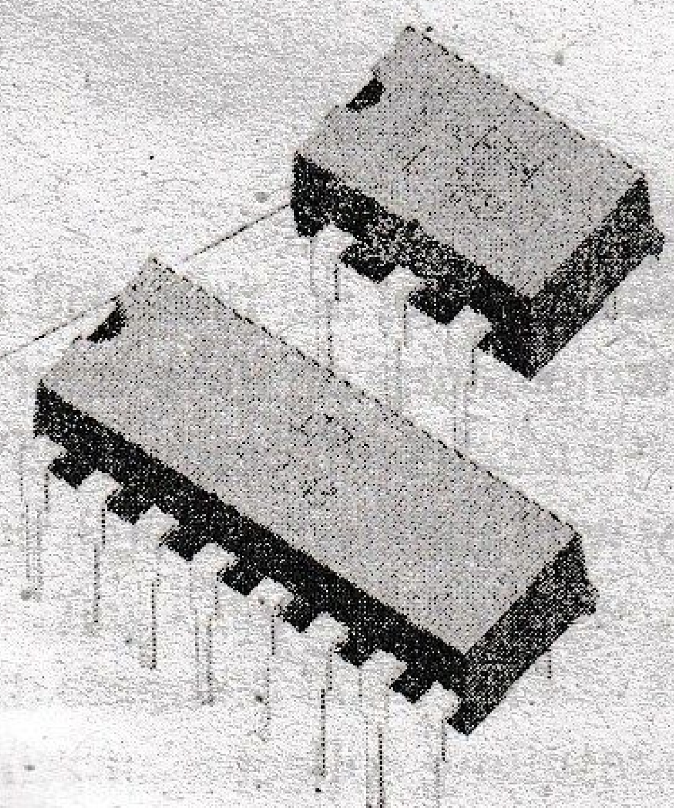
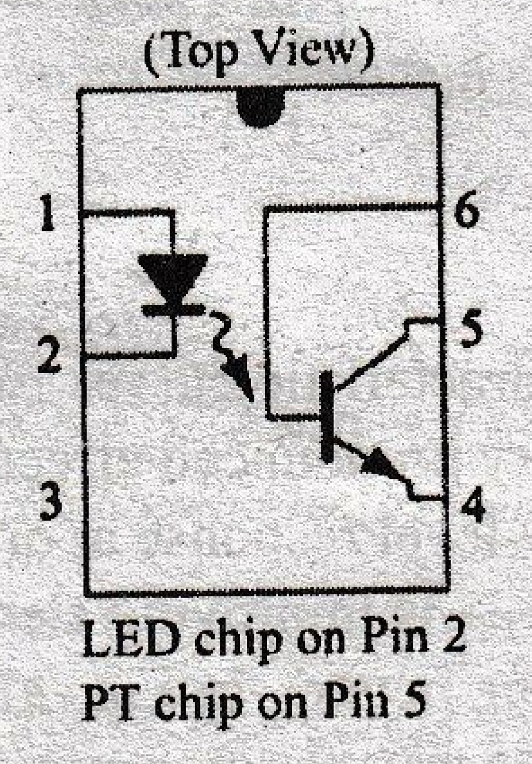


FIG. 17.51
High-isolation AND gate employing phototransistors and light-emitting diodes (LEDs).

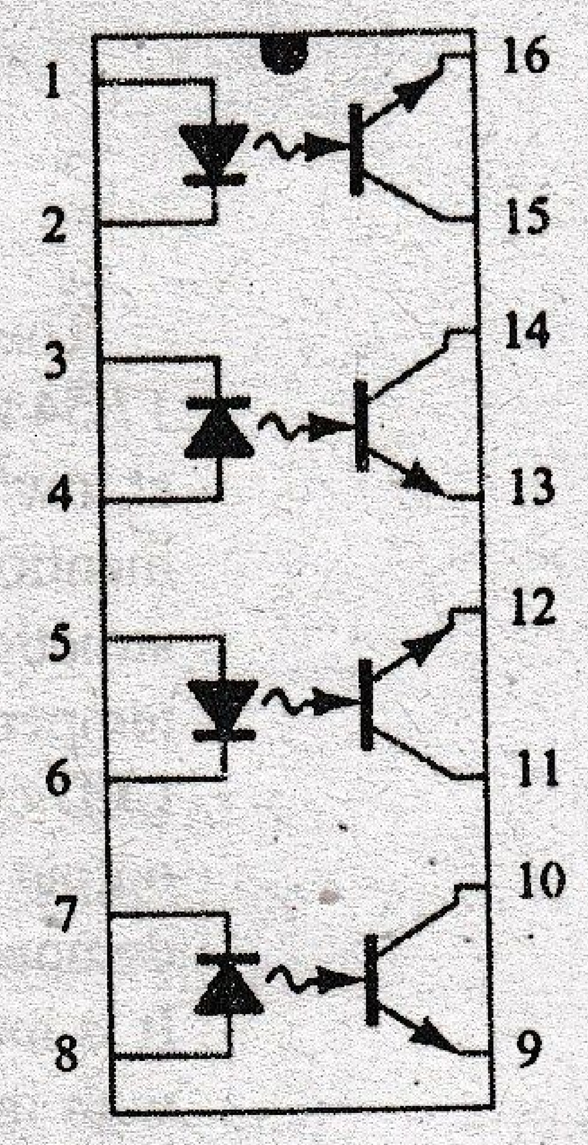
17.14 OPTO-ISOLATORS

The *opto-isolator* is a device that incorporates many of the characteristics described in the preceding section. It is simply a package that contains both an infrared LED and a photodetector such as a silicon diode, transistor Darlington pair, or SCR. The wavelength response of each device is tailored to be as identical as possible to permit the highest measure of coupling possible. In Fig. 17.52, two possible chip configurations are provided,





Pin No.	*Function*
1	anode
2	cathode
3	nc
4	emitter
5	collector
6	base



Pin No.	*Function*
1	anode
2	cathode
3	cathode
4	anode
5	anode
6	cathode
7	cathode
8	anode
9	emitter
10	collector
11	collector
12	enitter
13	emitter
14	collector
15	collector
16	emitter

FIG. 17.52
Two Litronix opto-isolators.

with a drawing of each. There is a transparent insulating cap between each set of elements embedded in the structure (not visible) to permit the passage of light. They are designed with response times so small that they can be used to transmit data in the megahertz range.

The maximum ratings and electrical characteristics for the 6-pin model are provided in Fig. 17.53. Note that I_{CEO} is measured in nanoamperes and that the power dissipation of the LED and transistor are about the same.

Maximum Ratings

Gallium arsenide LED (each channel)	
Power dissipation @ 25°C	200 mW
Derate linearly from 25°C	2.6 mW/°C
Continuous forward current	150 mA
Detector silicon phototransistor (each channel)	
Power dissipation @ 25°C	200 mW
Derate linearly from 25°C	2.6 mW/°C
Collector-emitter breakdown voltage	30 V
Emitter-collector breakdown voltage	7 V
Collector-base breakdown voltage	70 V

Electrical Characteristics per Channel (at 25°C Ambient)

Parameter	*Min.*	*Typ.*	*Max.*	*Unit*	*Test Conditions*
Gallium arsenide LED					
Forward voltage		1.3	1.5	V	$I_F = 60$ mA
Reverse current		0.1	10	μA	$V_R = 3.0$ V
Capacitance		100		pF	$V_R = 0$ V
Phototransistor detector					
BV_{CEO}	30			V	$I_C = 1$ mA
I_{CEO}		5.0	50	nA	$V_{CE} = 10$ V, $I_F = 0$ A
Collector-emitter capacitance		2.0		pF	$V_{CE} = 0$ V
BV_{ECO}	7			V	$I_E = 100$ μA
Coupled characteristics					
dc current transfer ratio	0.2	0.35			$I_F = 10$ mA, $V_{CE} = 10$ V
Capacitance, input to output		0.5		pF	
Breakdown voltage	2500			V	DC
Resistance, input to output		100		GΩ	
V_{sat}			0.5	V	$I_C = 1.6$ mA, $I_F = 16$ mA
Propagation delay					
$t_{D\ on}$		6.0		μs	$R_L = 2.4$ kΩ, $V_{CE} = 5$ V
$t_{D\ off}$		25		μs	$I_F = 16$ mA

FIG. 17.53
Opto-isolator characteristics.

The typical optoelectronic characteristic curves for each channel are provided in Figs. 17.54 through 17.58. Note the very pronounced effect of temperature on the output current at low temperatures but the fairly level response at or above room temperature (25°C). As mentioned earlier, the level of I_{CEO} is improving steadily with improved design and construction techniques (the lower the better). In Fig. 17.54, we do not reach 1 μA until the temperature rises above 75°C. The transfer characteristics of Fig. 17.55 compare the input LED current (which establishes the luminous flux) to the resulting collector current of the output transistor (whose base current is determined by the incident flux). In fact, Fig. 17.56 demonstrates that the V_{CE} voltage affects the resulting collector current only very slightly. It is interesting to note in Fig. 17.57 that the switching time of an opto-isolator decreases with increased current, whereas for many devices it is exactly the reverse. Consider that it is only 2 μs for a collector current of 6 mA and a load R_L of 100 Ω. The relative output versus temperature appears in Fig. 17.58.

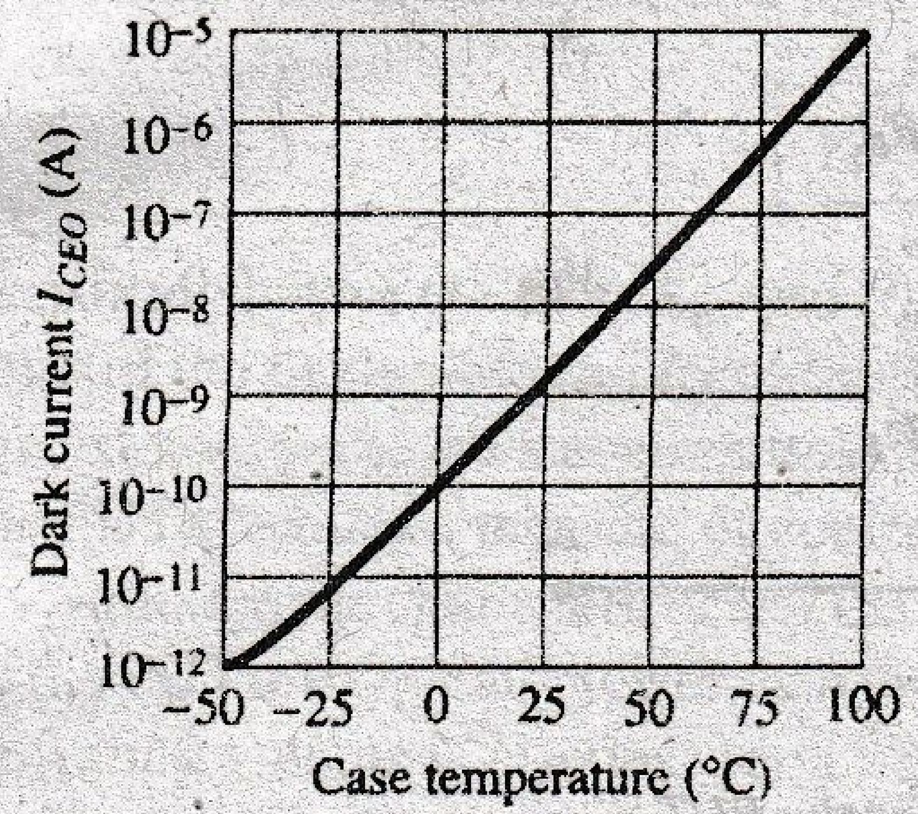


FIG. 17.54
Dark current I_{CEO} versus temperature.

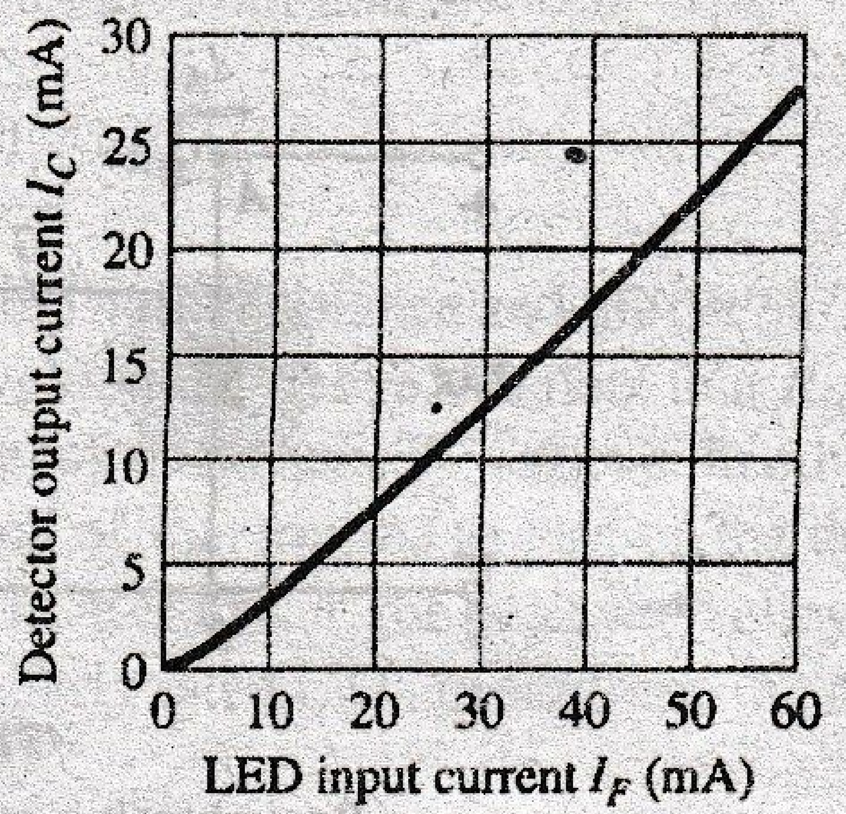


FIG. 17.55
Transfer characteristics.

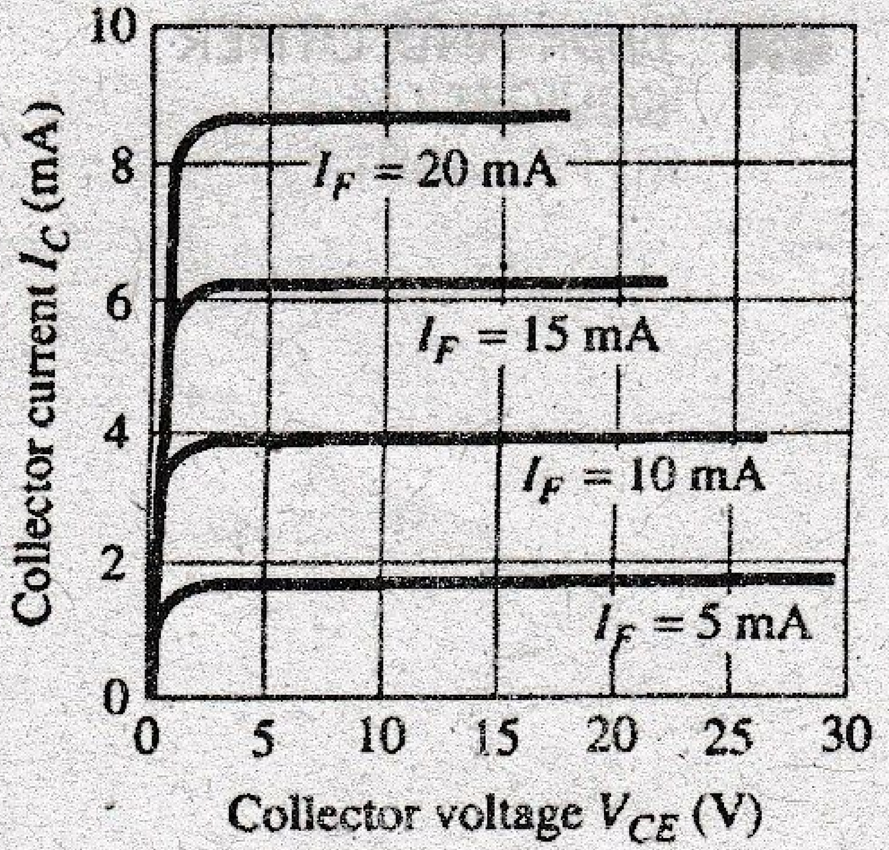


FIG. 17.56
Detector output characteristics.

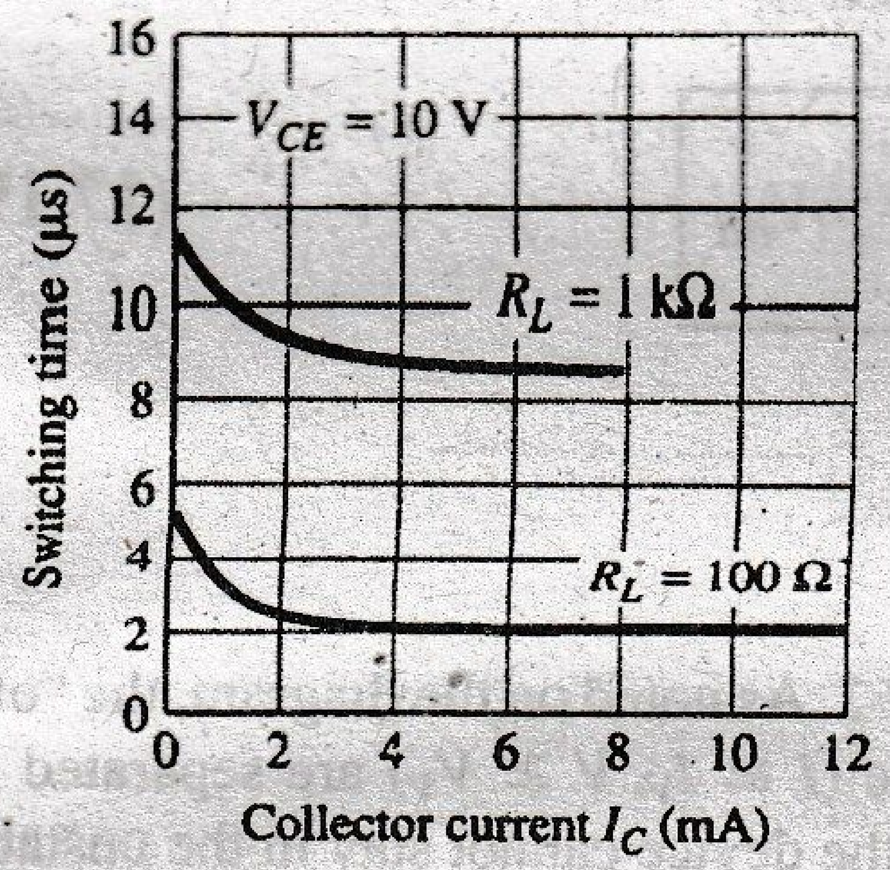


FIG. 17.57
Switching time versus collector current.

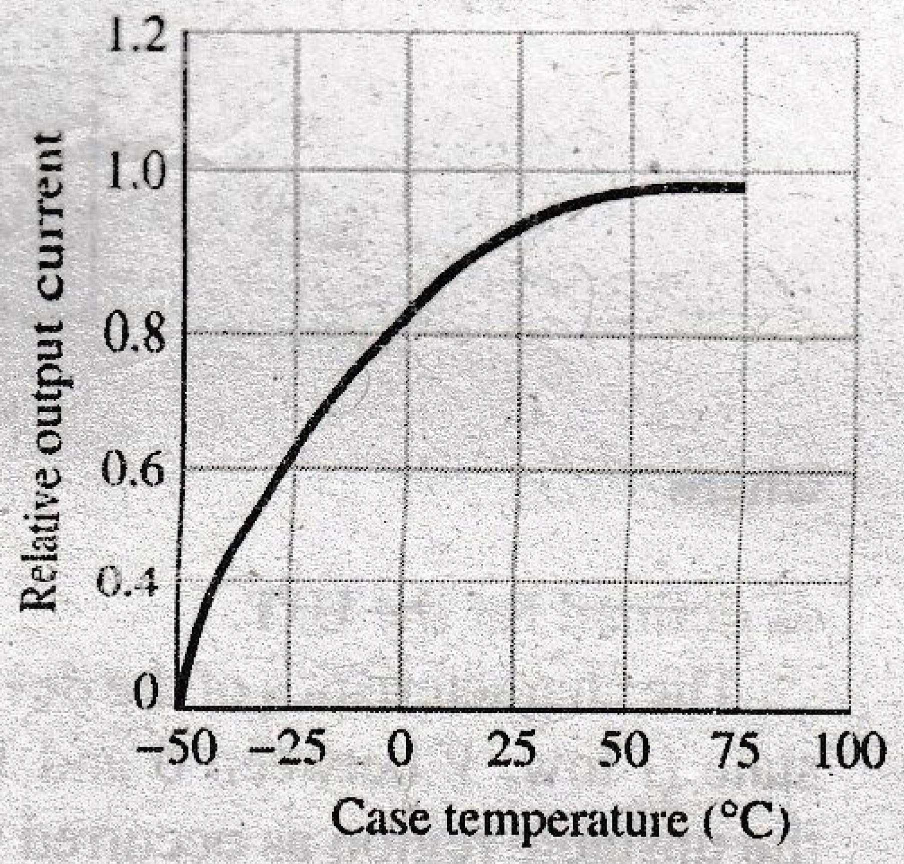


FIG. 17.58
Relative output versus temperature.

The schematic representation for a transistor coupler appears in Fig. 17.52. The schematic representations for a photodiode, a photo-Darlington, and a photo-SCR opto-isolator appear in Fig. 17.59.

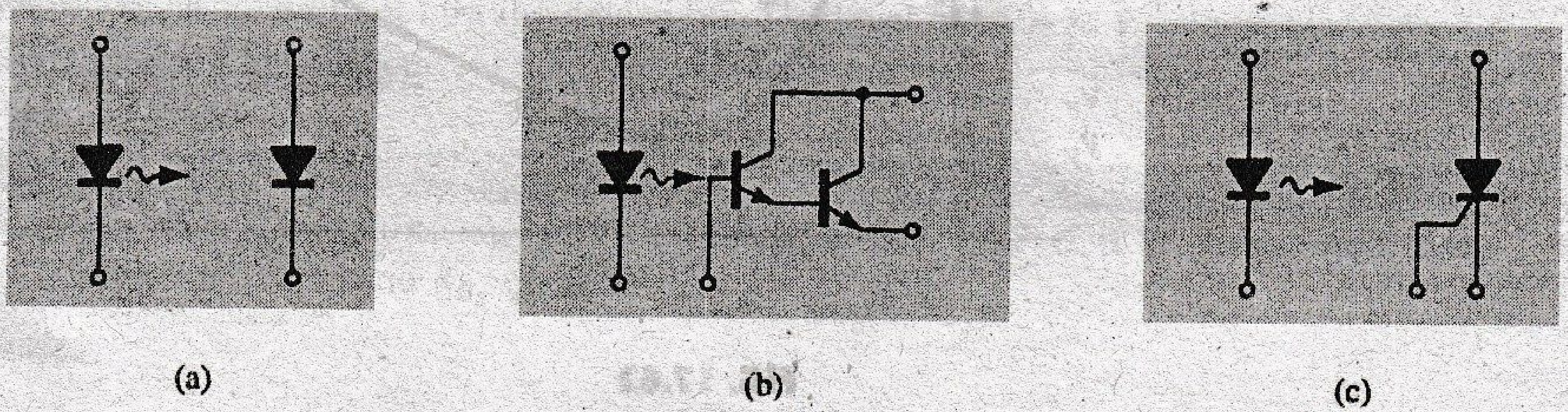


FIG. 17.59
Opto-isolators: (a) photodiode; (b) photo-Darlington; (c) photo-SCR.

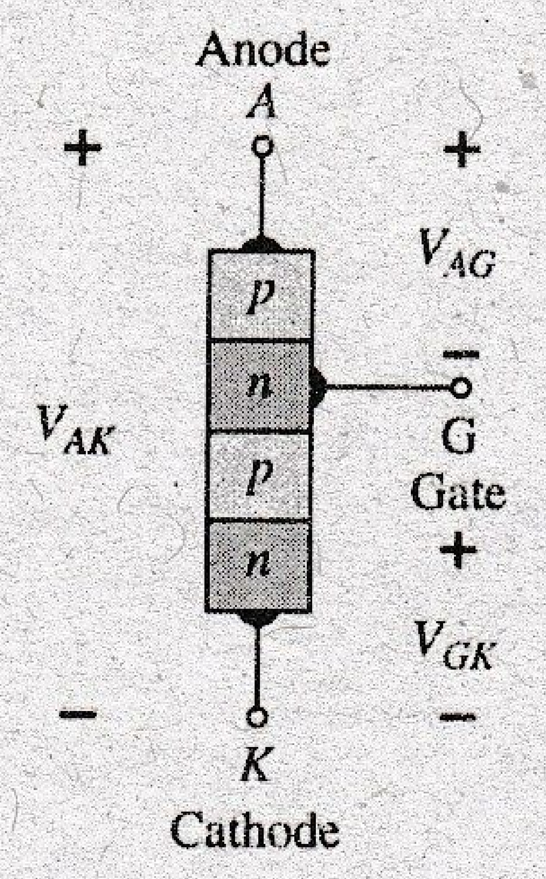


FIG. 17.60
Programmable UJT (PUT).

17.15 PROGRAMMABLE UNIJUNCTION TRANSISTOR

Although there is a similarity in name, the actual construction and mode of operation of the programmable unijunction transistor (PUT) are quite different from those of the unijunction transistor. The fact that the *I–V* characteristics and applications of each are similar prompted the choice of labels.

As indicated in Fig. 17.60, the PUT is a four-layer *pnpn* device with a gate connected directly to the sandwiched *n*-type layer. The symbol for the device and the basic biasing arrangement appear in Fig. 17.61. As the symbol suggests, it is essentially an SCR with

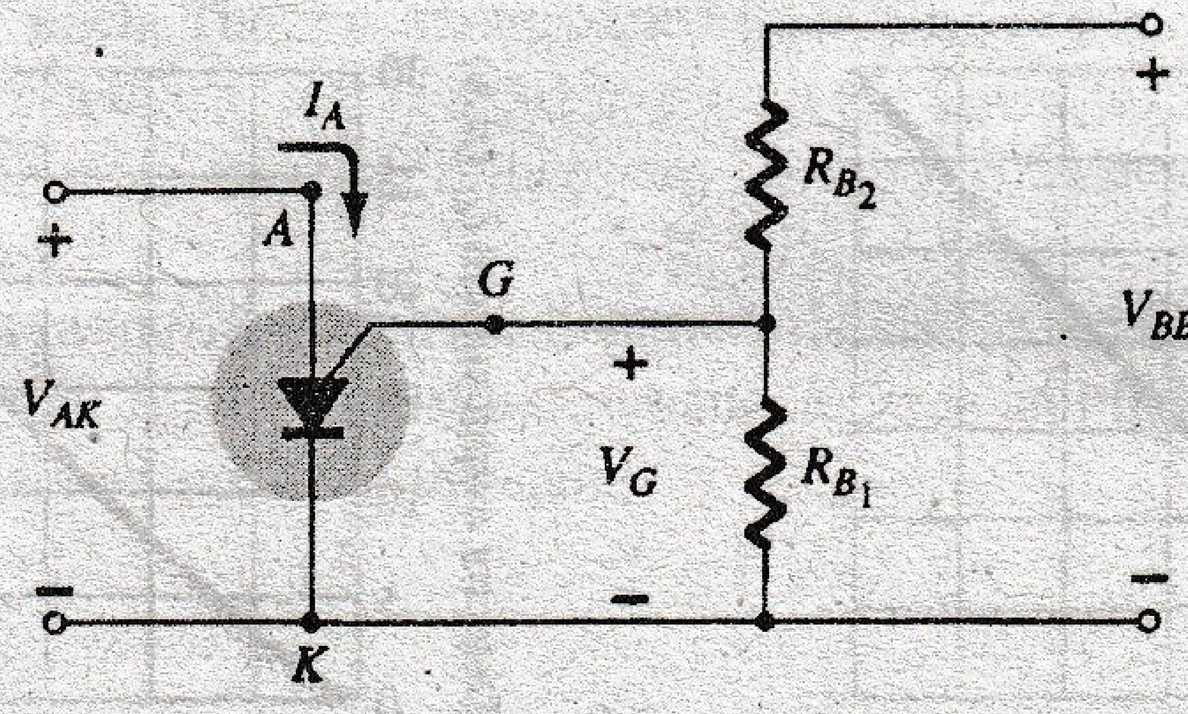


FIG. 17.61
Basic biasing arrangement for the PUT.

a control mechanism that permits a duplication of the characteristics of the typical SCR. The term *programmable* is applied because R_{BB}, η, and V_P as defined for the UJT can be controlled through the resistors R_{B_1}, R_{B_2}, and the supply voltage V_{BB}. Note in Fig. 17.61 that through an application of the voltage-divider rule, when $I_G = 0$,

$$\boxed{V_G = \frac{R_{B_1}}{R_{B_1} + R_{B_2}} V_{BB} = \eta V_{BB}} \tag{17.19}$$

where
$$\eta = \frac{R_{B_1}}{R_{B_1} + R_{B_2}}$$

as defined for the UJT.

The characteristics of the device appear in Fig. 17.62. As noted on the diagram, the "off" state (I low, V between 0 and V_P) and the "on" state ($I \geq I_V$, $V \geq V_V$) are separated by the unstable region as occurred for the UJT. That is, the device cannot stay in the unstable state—it will simply shift to either the "off" or the "on" stable state.

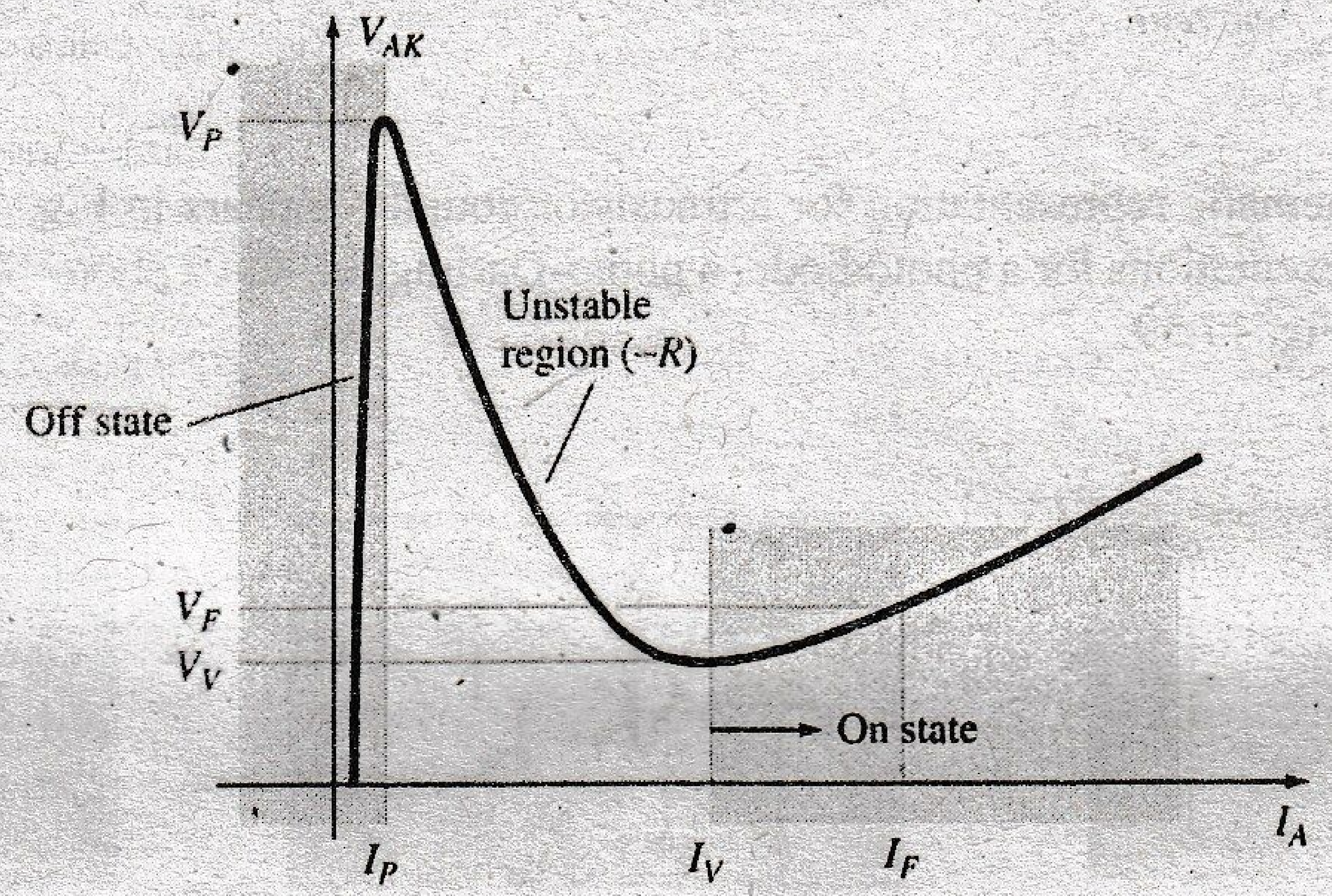


FIG. 17.62
PUT characteristics.

The firing potential V_P, or voltage necessary to "fire" the device, is given by

$$\boxed{V_P = \eta V_{BB} + V_D} \tag{17.20}$$

as defined for the UJT. However, V_P represents the voltage drop V_{AK} in Fig. 17.60 (the forward voltage drop across the conducting diode). For silicon, V_D is typically 0.7 V. Therefore,

$$V_{AK} = V_{AG} + V_{GK}$$
$$V_P = V_D + V_G$$

and
$$\boxed{V_P = \eta V_{BB} + 0.7\text{ V}} \quad \text{silicon} \tag{17.21}$$

We noted above, however, that $V_G = \eta V_{BB}$, with the result that

$$\boxed{V_P = V_G + 0.7} \quad \text{silicon} \tag{17.22}$$

Recall that for the UJT, R_{B_1} and R_{B_2} represent the bulk resistance and the ohmic base contacts of the device—both inaccessible. In the development above, we note that R_{B_1} and R_{B_2} are external to the device, permitting an adjustment of η and hence V_G above. In other words, the PUT provides a measure of control on the level of V_P required to turn on the device.

Although the characteristics of the PUT and UJT are similar, the peak and valley currents of the PUT are typically lower than those of a similarly rated UJT. In addition, the minimum operating voltage is also less for a PUT.

If we take a Thévenin equivalent of the network to the right of the gate terminal in Fig. 17.61, the network of Fig. 17.63 results. The resulting resistance R_S is important because it is often included in specification sheets since it affects the level of I_V.

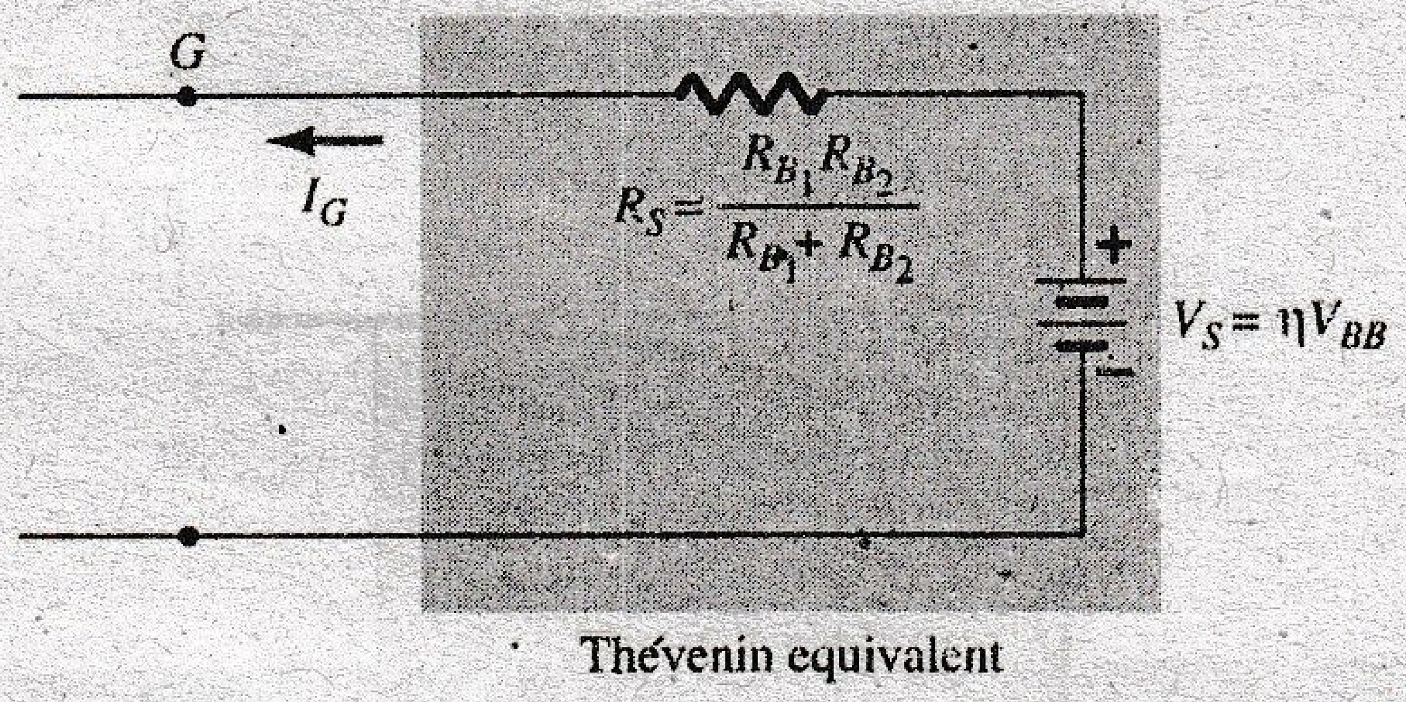


FIG. 17.63
Thévenin equivalent for the network to the right of the gate terminal in Fig. 17.61.

The basic operation of the device can be reviewed through reference to Fig. 17.62. A device in the "off" state will not change state until the voltage V_P as defined by V_G and V_D is reached. The level of current until I_P is reached is very low, resulting in an open-circuit equivalent since $R = V(\text{high})/I(\text{low})$ will result in a high resistance level. When V_P is reached, the device will switch through the unstable region to the "on" state, where the voltage is lower but the current higher, resulting in a terminal resistance $R = V(\text{low})/I(\text{high})$, which is quite small, representing a short-circuit equivalent on an approximate basis. The device has therefore switched from essentially an open-circuit to a short-circuit state at a point determined by the choice of R_{B_1}, R_{B_2}, and V_{BB}. Once the device is in the "on" state, the removal of V_G will not turn the device off. The level of voltage V_{AK} must be dropped sufficiently to reduce the current below a holding level.

EXAMPLE 17.2 Determine R_{B_1} and V_{BB} for a silicon PUT if it is determined that $\eta = 0.8$, $V_P = 10.3$ V, and $R_{B_2} = 5\text{ k}\Omega$.

Solution:

$$\text{Eq. (17.4):}\quad \eta = \frac{R_{B_2}}{R_{B_1} + R_{B_2}} = 0.8$$

$$R_{B_1} = 0.8(R_{B_1} + R_{B_2})$$

$$0.2R_{B_1} = 0.8R_{B_2}$$

$$R_{B_1} = 4R_{B_2}$$

$$R_{B_1} = 4(5\text{ k}\Omega) = \mathbf{20\text{ k}\Omega}$$

$$\text{Eq. (17.20):}\quad V_P = \eta V_{BB} + V_D$$

$$10.3\text{ V} = (0.8)(V_{BB}) + 0.7\text{ V}$$

$$9.6\text{ V} = 0.8V_{BB}$$

$$V_{BB} = \mathbf{12\text{ V}}$$

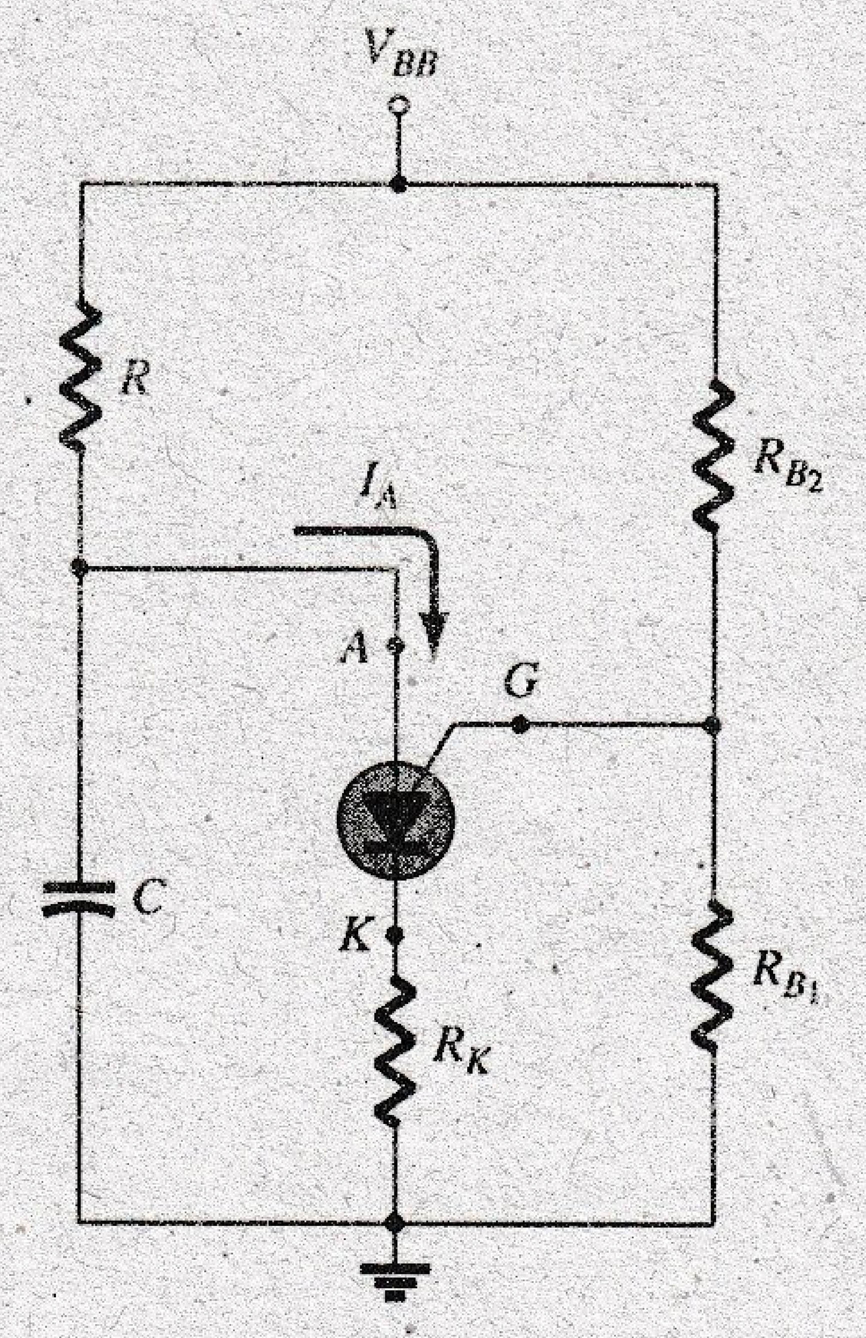


FIG. 17.64
PUT relaxation oscillator.

Relaxation Oscillator

One popular application of the PUT is in the relaxation oscillator of Fig. 17.64. The instant the supply is connected, the capacitor will begin to charge toward V_{BB} volts since there is no anode current at this point. The charging curve appears in Fig. 17.65. The period T required to reach the firing potential V_P is given approximately by

$$T \cong RC \log_e \frac{V_{BB}}{V_{BB} - V_P} \tag{17.23}$$

or, when $V_P \cong \eta V_{BB}$,

$$T \cong RC \log_e \left(1 + \frac{R_{B_1}}{R_{B_2}}\right) \tag{17.24}$$

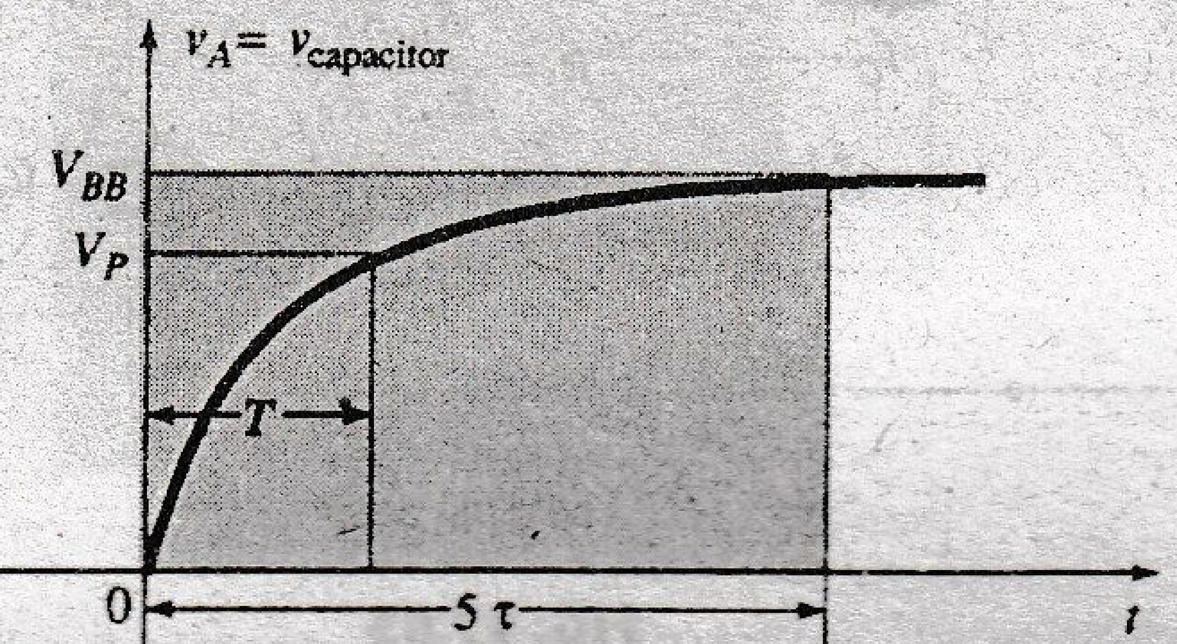


FIG. 17.65
Charging wave for the capacitor C of Fig. 17.64.

The instant the voltage across the capacitor equals V_P, the device will fire and a current $I_A = I_P$ will be established through the PUT. If R is too large, the current I_P cannot be established and the device will not fire. At the point of transition,

$$I_P R = V_{BB} - V_P$$

and

$$R_{max} = \frac{V_{BB} - V_P}{I_P} \tag{17.25}$$

The subscript is included to indicate that any R greater than R_{max} will result in a current less than I_P. The level of R must also be such as to ensure it is less than I_V if oscillations are to occur. In other words, we want the device to enter the unstable region and then return to the "off" state. From reasoning similar to that above, we obtain

$$R_{min} = \frac{V_{BB} - V_V}{I_V} \tag{17.26}$$

The discussion above requires that R be limited to the following for an oscillatory system:

$$R_{min} < R < R_{max}$$

The waveforms of v_A, v_G, and v_K appear in Fig. 17.66. Note that T determines the maximum voltage that v_A can charge to. Once the device fires, the capacitor will rapidly discharge through the PUT and R_K, producing the drop shown. Of course, v_K will peak at the same time due to the brief but heavy current. The voltage v_G will rapidly drop from V_G to a level just greater than 0 V. When the capacitor voltage drops to a low level, the PUT will once again turn off and the charging cycle will be repeated. The effect on V_G and V_K is shown in Fig. 17.66.

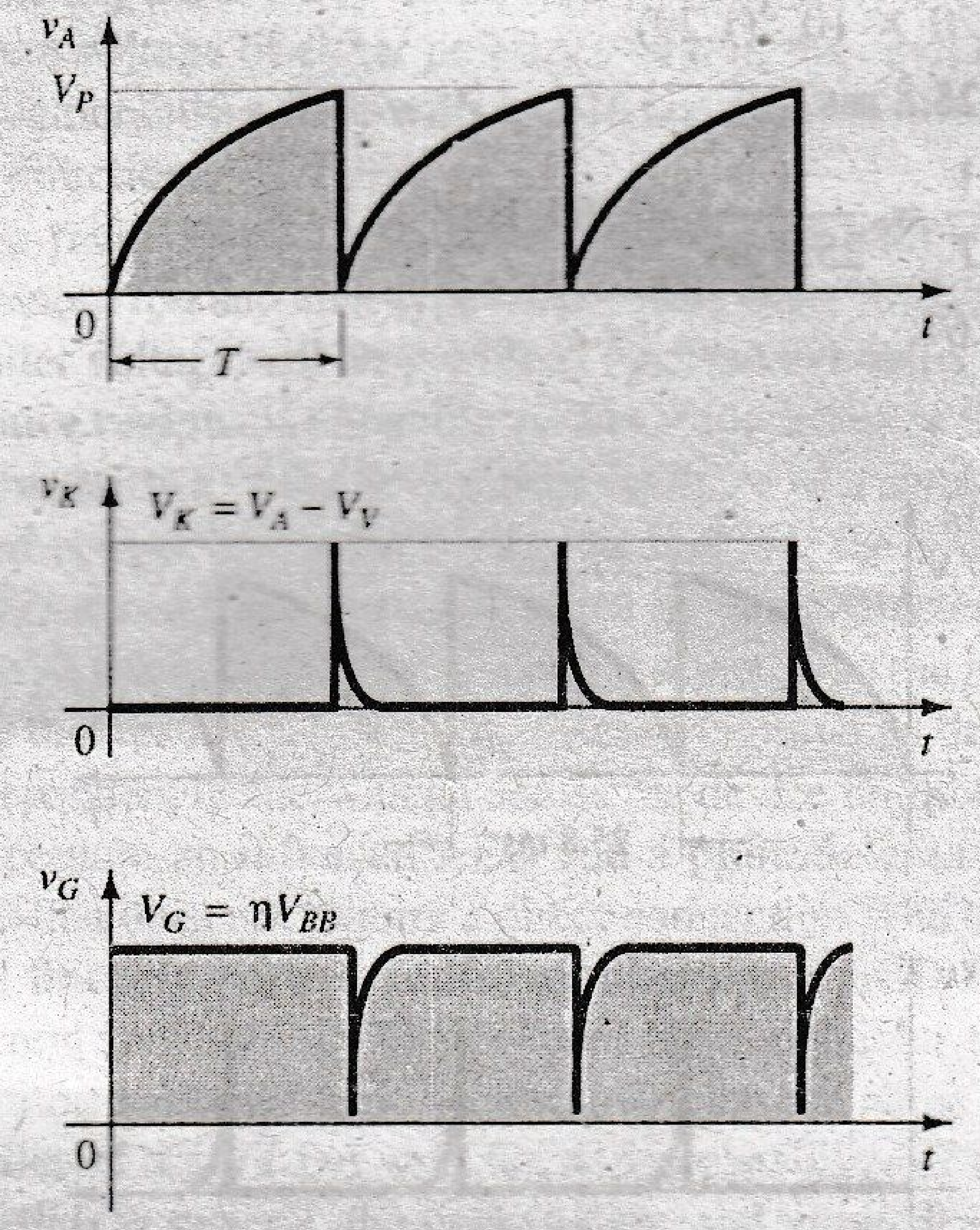


FIG. 17.66
Waveforms for PUT oscillator of Fig. 17.64.

EXAMPLE 17.3 For the network of Fig. 17.64, if $V_{BB} = 12$ V, $R = 20$ kΩ, $C = 1$ μF, $R_K = 100$ Ω, $R_{B_1} = 10$ kΩ, $R_{B_2} = 5$ kΩ, $I_P = 100$ μA, $V_V = 1$ V, and $I_V = 5.5$ mA, determine:

a. V_P.
b. R_{max} and R_{min}.
c. T and frequency of oscillation.
d. The waveforms of v_A, v_G, and v_K.

Solution:

a. Eq. (17.20):
$$V_P = \eta V_{BB} + V_D$$
$$= \frac{R_{B_1}}{R_{B_1} + R_{B_2}} V_{BB} + 0.7\text{ V}$$
$$= \frac{10\text{ k}\Omega}{10\text{ k}\Omega + 5\text{ k}\Omega}(12\text{ V}) + 0.7\text{ V}$$
$$= (0.67)(12\text{ V}) + 0.7\text{ V} = \mathbf{8.7\text{ V}}$$

b. From Eq. (17.25):
$$R_{max} = \frac{V_{BB} - V_P}{I_P}$$
$$= \frac{12\text{ V} - 8.7\text{ V}}{100\ \mu\text{A}} = \mathbf{33\text{ k}\Omega}$$

From Eq. (17.26):
$$R_{min} = \frac{V_{BB} - V_V}{I_V}$$
$$= \frac{12\text{ V} - 1\text{ V}}{5.5\text{ mA}} = \mathbf{2\text{ k}\Omega}$$
$$R:\ 2\text{ k}\Omega < 20\text{ k}\Omega < 33\text{ k}\Omega$$

c. Eq. (17.23):
$$T = RC \log_e \frac{V_{BB}}{V_{BB} - V_P}$$
$$= (20\text{ k}\Omega)(1\ \mu\text{F}) \log_e \frac{12\text{ V}}{12\text{ V} - 8.7\text{ V}}$$
$$= 20 \times 10^{-3} \log_e (3.64)$$

$$= 20 \times 10^{-3}(1.29)$$
$$= \mathbf{25.8\ ms}$$
$$f = \frac{1}{T} = \frac{1}{25.8\ \text{ms}} = \mathbf{38.8\ Hz}$$

d. Indicated in Fig. 17.67.

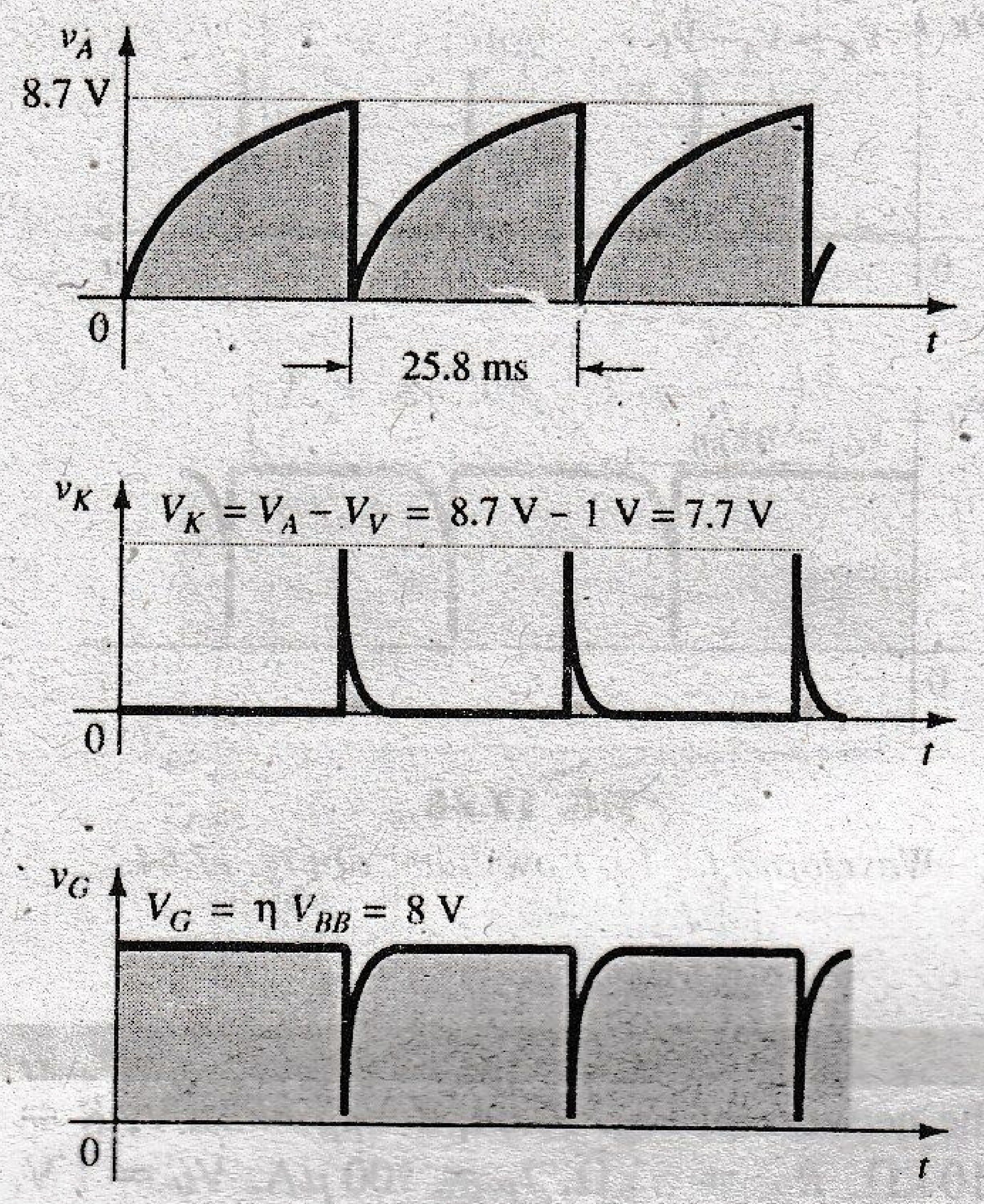


FIG. 17.67
Waveforms for the oscillator of Example 17.3.

17.16 SUMMARY

Important Conclusions and Concepts

1. The **silicon-controlled rectifier** (SCR) is a rectifier whose state **is controlled by the magnitude of the gate current**. The forward-bias voltage across the device will determine the level of gate current required to "fire" (turn on) the device. The **higher** the level of biasing voltage, the **less** is the required gate current.
2. In addition to gate triggering, an SCR can be **turned on with zero gate current** simply by applying **sufficient voltage** across the device. The higher the gate current, however, the less is the required biasing voltage to turn the SCR on.
3. The **silicon-controlled switch** has both **an anode gate and a cathode gate** for controlling the state of the device, although the anode gate is now connected to an *n*-type layer and the cathode gate to a *p*-type layer. The result is that **a negative pulse at the anode gate will turn the device on, whereas a positive pulse will turn it off**. The reverse is true for the cathode gate.
4. A **gate turn-off switch** (GTO) looks similar in construction to the SCR with only **one gate connection**, but the GTO has the added advantage of being able to turn the device **off and on** at the gate terminal. However, this added option of being able to turn the device off at the gate results in a much **higher gate current** to turn the device on.
5. The **LASCR** is a light-activated SCR whose state can be controlled by **light falling on a semiconductor layer** of the device **or by triggering the gate terminal** in a manner described for SCRs. The higher the junction temperature of the device, the less is the required incident light to turn the device on.
6. The **Shockley diode** has essentially the **same characteristics as an SCR with zero gate current**. It is turned on by simply increasing the forward-bias voltage across the device beyond the breakover level.

7. The **diac** is essentially a **Shockley diode that can fire in either direction**. The application of sufficient voltage of either polarity will turn the device on.
8. The **triac** is fundamentally a **diac with a gate terminal to control the action of the device** in either direction.
9. The **unijunction transistor** is a three-terminal device with a p–n junction formed between an aluminum rod and an n-type silicon slab. Once the emitter firing potential is reached, the emitter voltage will drop with an increase in emitter current, establishing a **negative-resistance region** excellent for oscillator applications. Once the valley point is reached, the characteristics of the device **take on those of a semiconductor diode**. The higher the applied voltage across the device, the higher is the emitter firing potential.
10. The **phototransistor** is a three-terminal device having characteristics **very similar to those of a BJT** with a base and collector current sensitive to the incident light intensity. The base current that results is essentially **linearly related to the applied light** with a level almost independent of the voltage across the device until breakdown results.
11. **Opto-isolators** contain an **infrared LED** and a **photodetector** to provide a linkage between systems that does not require a direct connection. The output detector current **is less than but linearly related to the applied input LED current**. Furthermore, the collector current is essentially independent of the collector-to-emitter voltage.
12. The **PUT** (programmable unijunction transistor) is, as the name implies, a device with the **characteristics of a UJT** but with the added capability of **being able to control the firing potential**. In general, the peak, valley, and minimum operating voltages of PUTs are less than those of UJTs.

Equations

Diac:

$$V_{BR_1} = V_{BR_2} \pm 0.1V_{BR_2}$$

UJT:

$$R_{BB} = (R_{B_1} + R_{B_2})\big|_{I_E=0}$$

$$V_{R_{B_1}} = \frac{R_{B_1}}{R_{B_1} + R_{B_2}} \cdot V_{BB} = \eta V_{BB}\Big|_{I_E=0}$$

$$\eta = \frac{R_{B_1}}{R_{BB}}$$

$$V_P = \eta V_{BB} + V_D$$

Phototransistor:

$$I_C \cong h_{fe} I_\lambda$$

PUT:

$$V_G = \frac{R_{B_1}}{R_{B_1} + R_{B_2}} \cdot V_{BB} = \eta V_{BB}$$

$$V_P = \eta V_{BB} + V_D$$

PROBLEMS

**Note:* Asterisks indicate more difficult problems.

17.3 Basic Silicon-Controlled Rectifier Operation

1. Describe in your own words the basic behavior of the SCR using the two-transistor equivalent circuit.
2. Describe two techniques for turning an SCR off.
3. Consult a manufacturer's manual or specification sheet and obtain a turn-off network. If possible, describe the turn-off action of the design.

17.4 SCR Characteristics and Ratings

*4. a. At high levels of gate current, the characteristics of an SCR approach those of what two-terminal device?

b. At a fixed anode-to-cathode voltage less than $V_{(BR)F^*}$, what is the effect on the firing of the SCR as the gate current is reduced from its maximum value to the zero level?
c. At a fixed gate current greater than $I_G = 0$, what is the effect on the firing of the SCR as the gate voltage is reduced from $V_{(BR)F^*}$?
d. For increasing levels of I_G, what is the effect on the holding current?

5. **a.** Based on Fig. 17.8, will a gate current of 50 mA fire the device at room temperature (25°C)?
b. Repeat part (a) for a gate current of 10 mA.
c. Will a gate voltage of 2.6 V trigger the device at room temperature?
d. Is $V_G = 6$ V, $I_G = 800$ mA a good choice for firing conditions? Would $V_G = 4$ V, $I_G = 1.6$ A be preferred? Explain.

17.5 SCR Applications

6. In Fig. 17.10b, why is there very little loss in potential across the SCR during conduction?

7. Fully explain why reduced values of R_1 in Fig. 17.11 will result in an increased angle of conduction.

***8.** Refer to the charging network of Fig. 17.12.
a. Determine the dc level of the full-wave rectified signal if a 1:1 transformer is employed.
b. If the battery in its uncharged state is sitting at 11 V, what is the anode-to-cathode voltage drop across SCR_1?
c. What is the maximum possible value of V_R ($V_{GK} \cong 0.7$ V)?
d. At the maximum value of part (c), what is the gate potential of SCR_2?
e. Once SCR_2 has entered the short-circuit state, what is the level of V_2?

9. Refer to the temperature controller of Fig. 17.13.
a. Sketch the waveform of the full-wave rectified waveform across the SCR.
b. What is the peak current through the heater when the SCR is "on" and has a short-circuit equivalent between anode and cathode? Assume each diode has a drop of 0.7 V when conducting.
c. When the SCR is on, what is the maximum current through the thermostat?
d. What is the total time for the rise time of the positive pulse of the applied ac voltage from 0 V to the maximum voltage of the rectified signal?
e. What is the time constant of the capacitor that is charging during the same period of part (d)? How do they compare? Why is this a concern?
f. What is the state of the SCR during this charging period? Why?
g. If the gate-firing potential is 40 V, what is the time period between successive triggering of the SCR?
h. Once the thermostat reaches its set temperature and assumes the short-circuit state, how will the SCR react?
i. What method was used to turn the SCR off: anode current interruption or forced commutation?

10. Refer to the emergency-lighting system of Fig. 17.14.
a. Sketch the waveform of the full-wave rectified signal across the bulb using a drop of 0.7 V during conduction of each diode.
b. Determine the peak voltage across the capacitor C_1 when the SCR_1 is off.
c. What is the peak voltage across R_1 during the charging phase if the battery voltage drops to 5 V?
d. What is the voltage across the lamp when the SCR turns on and the battery is fully charged at 6 V?
e. What is the current drawn from the battery if the lamp is dissipating 2 W of power?

17.6 Silicon-Controlled Switch

11. Fully describe in your own words the behavior of the networks of Fig. 17.16.

12. What is the suggested turn-off procedure for the network of Fig. 17.18?

13. For the network of Fig. 17.19
a. Write an equation for the voltage from gate to ground for the SCR.
b. What is the voltage V_{GK} when $R_S = R'$?
c. Find R_S to establish a turn-on voltage of 2 V if $R' = 10$ kΩ.
d. When the alarm turns on, what is the current through the relay?
e. At $V_A = 0$ V, the maximum dc current through the rate-effect resistor will be established. What is its value?
f. When the reset button is activated, is there any reason for concern about spikes in voltage anywhere in the network? How could they be suppressed?

17.7 Gate Turn-Off Switch

14. **a.** In Fig. 17.22, if $V_Z = 50$ V, determine the maximum possible value the capacitor C_1 can charge to ($V_{GK} \cong 0.7$ V).

b. Determine the approximate discharge time (5τ) for $R_3 = 20\,k\Omega$.
c. Determine the internal resistance of the GTO if the rise time is one-half the decay period determined in part (b).

17.8 Light-Activated SCR

15. a. Using Fig. 17.24b, determine the minimum irradiance required to fire the device at room temperature (25°C).
b. What percentage reduction in irradiance is allowable if the junction temperature is increased from 0°C (32°F) to 100°C (212°F)?

17.9 Shockley Diode

16. For the network of Fig. 17.28, if $V_{BR} = 6\,V$, $V = 40\,V$, $R = 10\,k\Omega$, $C = 0.2\,\mu F$, and V_{GK} (firing potential) $= 3\,V$, determine the time period between energizing the network and the turning on of the SCR.

17.10 Diac

17. Using whatever reference you require, find an application of a diac and explain the network behavior.
18. If V_{BR_2} is 6.4 V, determine the range for V_{BR_1} using Eq. (17.1).
19. Find the level of human body capacitance C_b that would result in a 45-degree phase shift between v_i and v_G for the network of Fig. 17.30.

17.11 Triac

20. For the network of Fig. 17.33, if $C = 1\,\mu F$, find the level of R that will result in a 50% conduction period for the load in either direction if the turn-on voltage for the diac in either direction is 12 V and the applied sinusoidal signal has a peak value of 170 V ($= 1.414 \times 120$ V) at 60 Hz.

17.12 Unijunction Transistor

21. For the network of Fig. 17.40, in which $V = 40\,V$, $\eta = 0.6$, $V_V = 1\,V$, $I_V = 8\,mA$, and $I_P = 10\,\mu A$, determine the range of R_1 for the triggering network.
22. For a unijunction transistor with $V_{BB} = 20\,V$, $\eta = 0.65$, $R_{B_1} = 2\,k\Omega$ ($I_E = 0$), and $V_D = 0.7\,V$, determine:
a. R_{B_2}.
b. R_{BB}.
c. $V_{R_{B_1}}$.
d. V_P.

*23. Given the relaxation oscillator of Fig. 17.68:
a. Find R_{B_1} and R_{B_2} at $I_E = 0\,A$.
b. Determine V_P, the voltage necessary to turn on the UJT.
c. Determine whether R_1 is within the permissible range of values defined by Eq. (17.8).
d. Determine the frequency of oscillation if $R_{B_1} = 200\,\Omega$ during the discharge phase.
e. Sketch the waveform of v_C for two full cycles.
f. Sketch the waveform of v_{R_2} for two full cycles.
g. Determine the frequency using Eq. (17.17) and compare to the value determined in part (d). Account for any major differences.

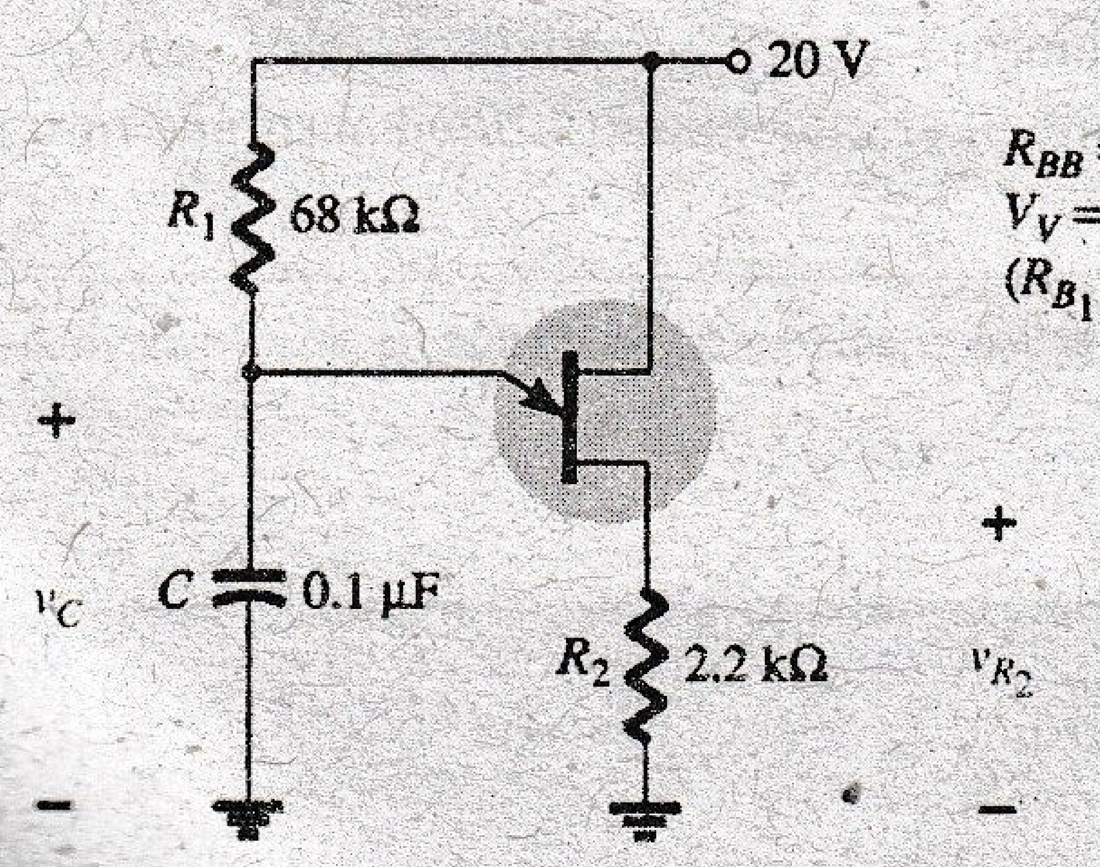


FIG. 17.68
Problem 23.

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17.13 Phototransistors

24. For a phototransistor having the characteristics of Fig. 17.50, determine the photoinduced base current for a radiant flux density of 5 mW/cm^2. If $h_{fe} = 40$, find I_C.

*25. Design a high-isolation OR-gate employing phototransistors and LEDs.

17.14 Opto-Isolators

26. a. Determine an average derating factor from the curve of Fig. 17.58 for the region defined by temperatures between $-25°C$ and $+50°C$.
 b. Is it fair to say that for temperatures greater than room temperature (up to 100°C), the output current is somewhat unaffected by temperature?

27. a. Determine from Fig. 17.54 the average change in I_{CEO} per degree change in temperature for the range 25°C to 50°C.
 b. Can the results of part (a) be used to determine the level of I_{CEO} at 35°C? Test your theory.

28. Determine from Fig. 17.55 the ratio of LED output current to detector input current for an output current of 20 mA. Would you consider the device to be relatively efficient in its purpose?

*29. a. Sketch the maximum-power curve of $P_D = 200$ mW on the graph of Fig. 17.56. List any noteworthy conclusions.
 b. Determine β_{dc} (defined by I_C/I_F) for the system at $V_{CE} = 15$ V, $I_F = 10$ mA.
 c. Compare the results of part (b) with those obtained from Fig. 17.55 at $I_F = 10$ mA. Do they compare? Should they? Why?

*30. a. Referring to Fig. 17.57, determine the collector current above which the switching time does not change appreciably for $R_L = 1\ \text{k}\Omega$ and $R_L = 100\ \Omega$.
 b. At $I_C = 6$ mA, how does the ratio of switching times for $R_L = 1\ \text{k}\Omega$ and $R_L = 100\ \Omega$ compare to the ratio of resistance levels?

17.15 Programmable Unijunction Transistor

31. Determine η and V_G for a PUT with $V_{BB} = 20$ V and $R_{B_1} = 3R_{B_2}$.

32. Using the data provided in Example 17.3, determine the impedance of the PUT at the firing and valley points. Are the approximate open- and short-circuit states verified?

33. Can Eq. (17.24) be derived exactly as shown from Eq. (17.23)? If not, what element is missing in Eq. (17.24)?

*34. a. Will the network of Example 17.3 oscillate if V_{BB} is changed to 10 V? What minimum value of V_{BB} is required (V_V a constant)?
 b. Referring to the same example, what value of R would place the network in the stable "on" state and remove the oscillatory response of the system?
 c. What value of R would make the network a 2-ms time-delay network? That is, would provide a pulse v_K at 2 ms after the supply is turned on and then stay in the "on" state.

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