Introduction
to
Power Electronics

THYRISTOR

Thyristor

- Is a solid-state semiconductor device with **four layers** of alternating N and P-type material.
- They act as a switch, conducts when their gate receives a current, and will continue to conduct for as long as they are forward-biased.
- Thyristors include the **4-layer diode**, the **silicon-controlled rectifier** (SCR), the **diac**, the **triac**, and the **silicon-controlled switch** (SCS).

Thyristor

- They act as open circuits capable of withstanding a certain rated voltage until they are triggered.
- When *triggered*, they **turn on** and become **low-resistance** current paths and remain so, even after the trigger is removed, until the current is reduced to a certain level or until they are triggered off (latch circuit), depending on the type of device.
- Latch Circuit is a circuit which locks its output, when a momentarily input trigger signal is applied, and retains that state, even after the input signal is removed. This State will remain indefinitely until the power is reset or some external signal is applied.

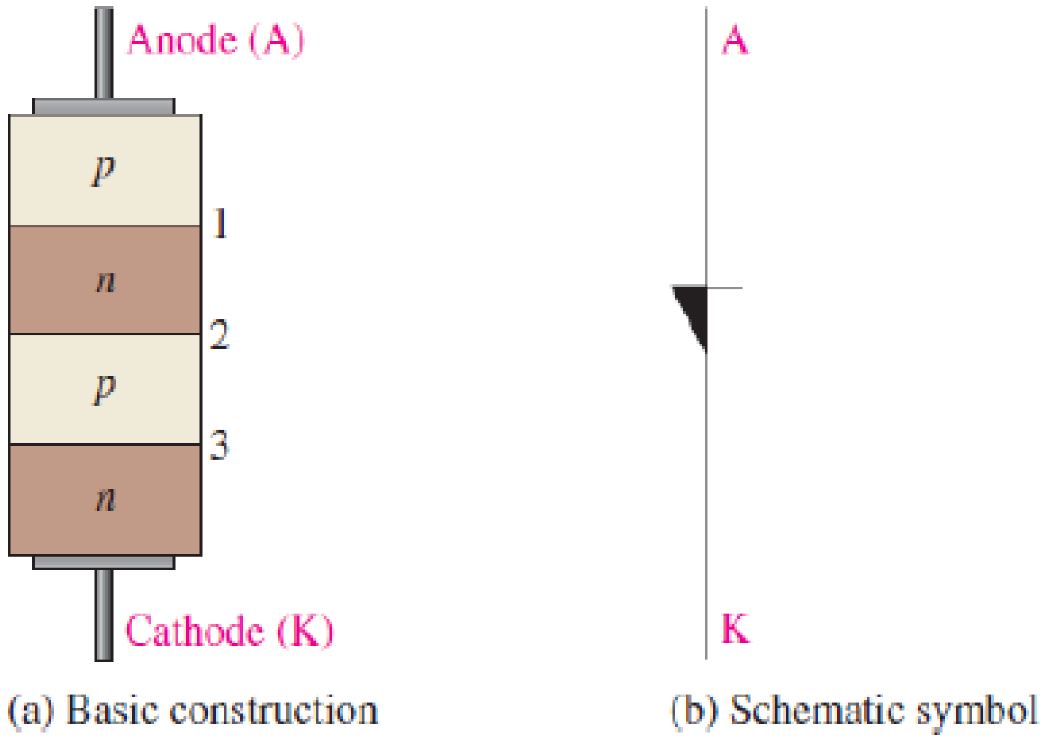
The Four-Layer Diode

- The basic thyristor is a 4-layer device with two terminals, the anode and the cathode.
- It is constructed of four semiconductor layers that form a pnpn structure.
- The device acts as a switch and remains off until the forward voltage reaches a certain value; then it turns on and conducts.
- Conduction continues until the current is reduced below a specified value.
- Although the 4-layer diode is seldom used in new designs, it is still the basis of the other thyristors.

Shockley Diode

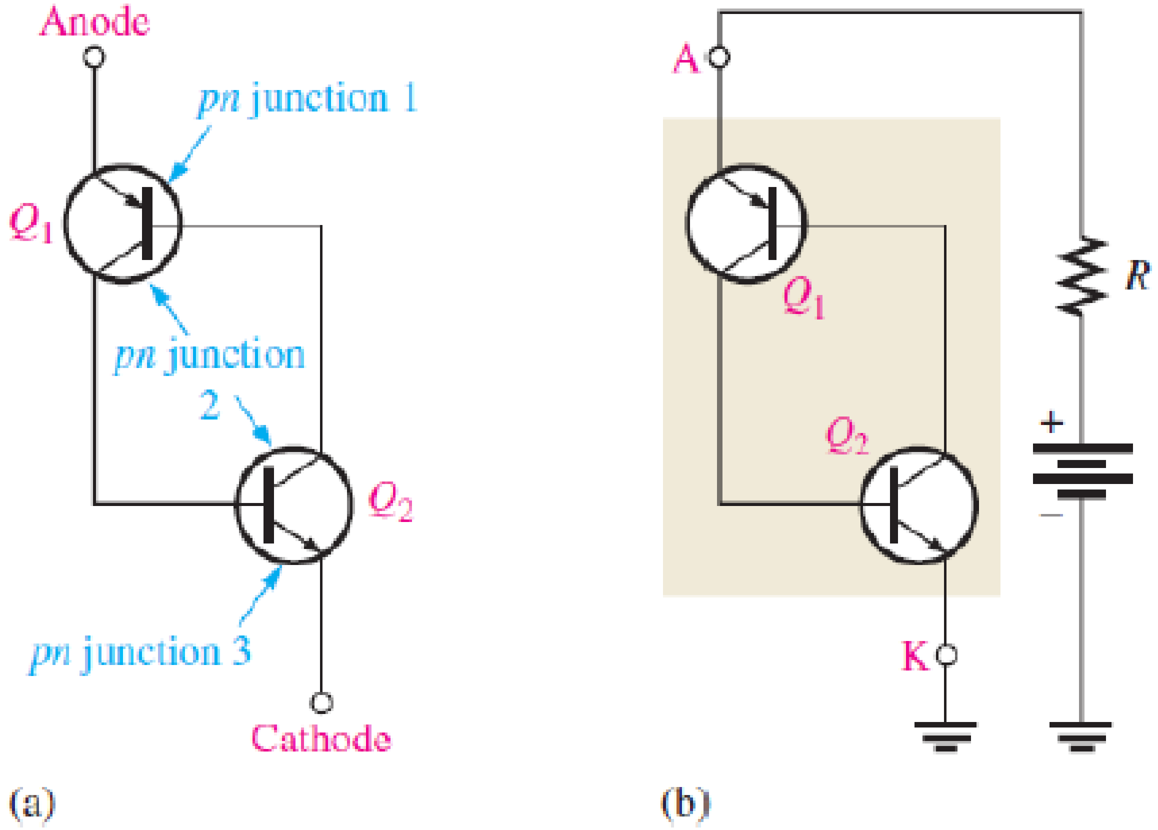
- Other term used for a **4-layer diode** or also known as “Silicon Unilateral Switch” (SUS).

The basic construction of a 4-layer diode and its schematic symbol



▲ FIGURE 1–1

The 4-layer diode.



▲ FIGURE 1–2

A 4-layer diode equivalent circuit.

Forward-Breakover Voltage

- The operation of the 4-layer diode may seem unusual because when it is forward-biased, it can act essentially as an open switch.
- There is a region of forward bias, called the **forward-blocking region**, in which the device has a very high forward resistance (ideally an open) and is in the off state.
- The forward-blocking region exists from VAK = 0 V up to a value of called the forward-breakover voltage, VBR(F).

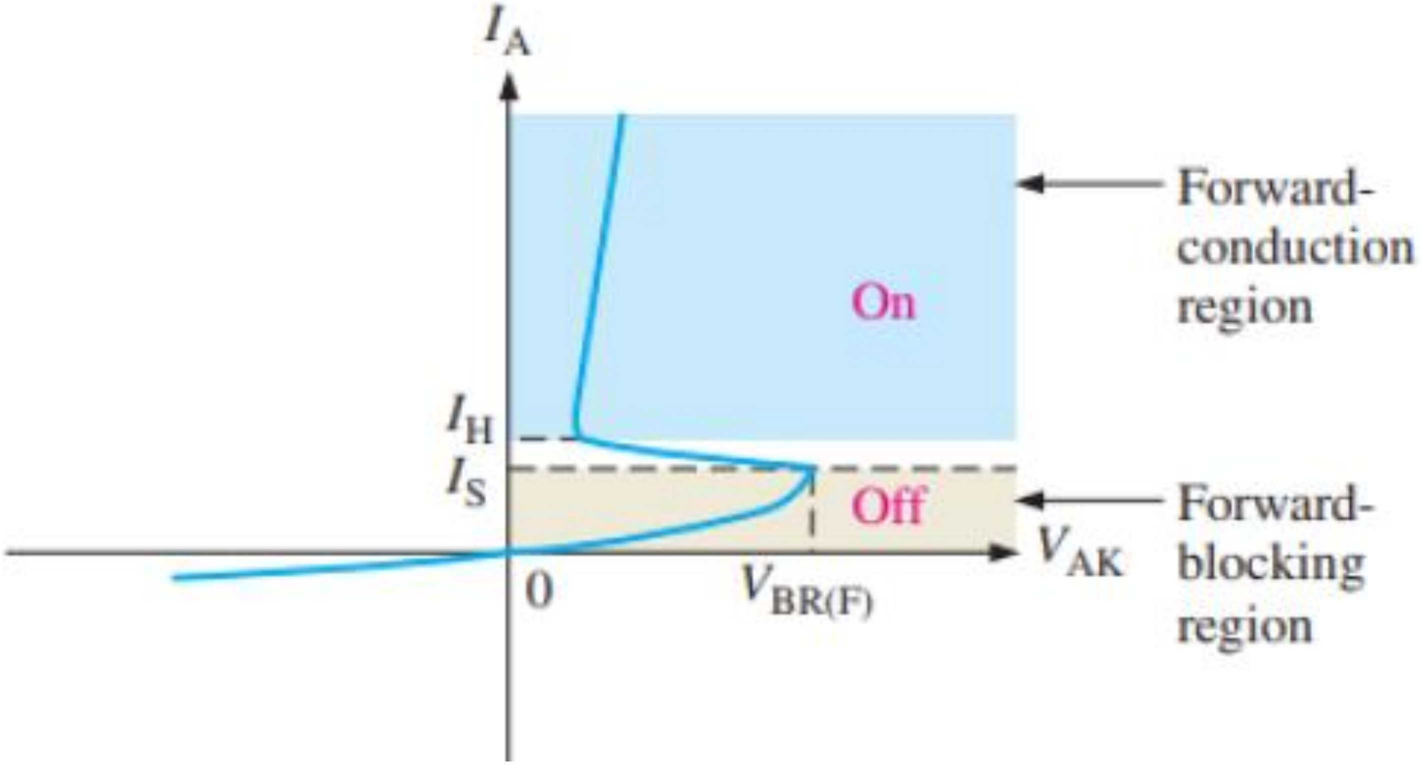
Forward-Breakover Voltage

- As V_{AK} is increased from 0, the anode current, I_A gradually increases, as shown on the graph.
- As I_A increases, a point is reached where I_A = I_S the **switching current**. At this point, V_{AK} =$V_{BR(F)}$, and the internal transistor structures become saturated. When this happens, the forward voltage drop, V_{AK}, suddenly decreases to a low value, and the 4-layer diode enters the *forward-conduction region* as indicated in Figure 1–3.
- Now, the device is in the *on* state and acts as a closed switch. When the anode current drops back below the holding value, $\mathrm{I_H}$, the device turns off.

4-Layer Diode Characteristic Curve

FIGURE 1–3

A 4-layer diode characteristic curve.



Switching Current

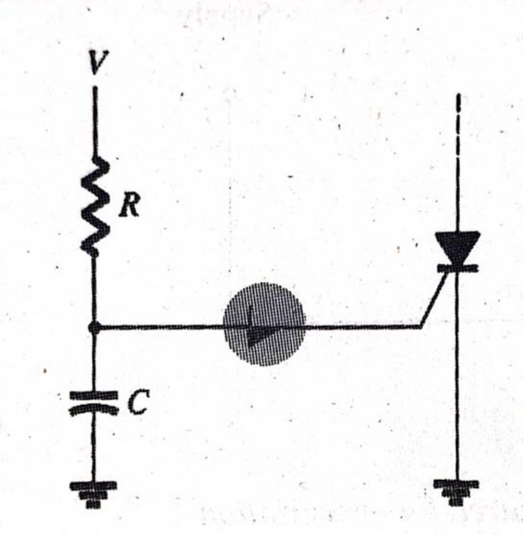
- The value of the anode current at the point where the device switches from the forward-blocking region (off) to the forward-conduction region (on) is called the switching current, IS.
- This value of current is always less than the holding current, IH.

Holding Current

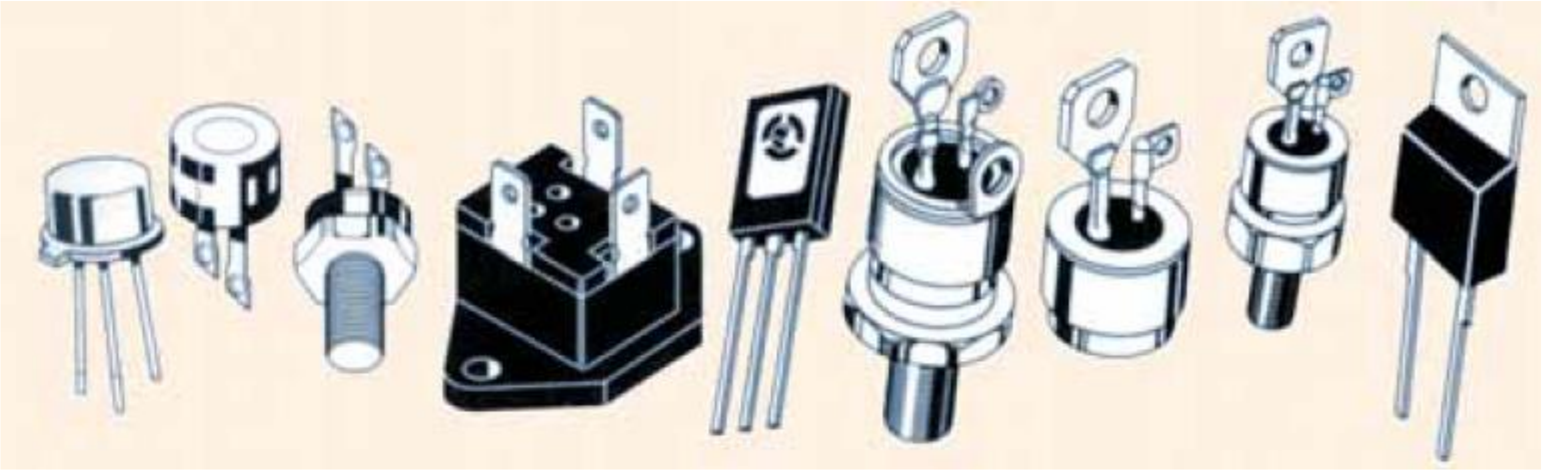
- Once the 4-layer diode is conducting (in the on state), it will continue to conduct until the anode current is reduced below a specified level, called the holding current, $\mathrm{I_H}$.
- This parameter is also indicated on the characteristic curve in Figure 1–3. When I_A falls below I_H, the device rapidly switches back to the off state and enters the forward-blocking region.

Trigger Switch

- One common applications of the Shockley diode is 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.



SILICON-CONTROLLED RECTIFIER (SCR)



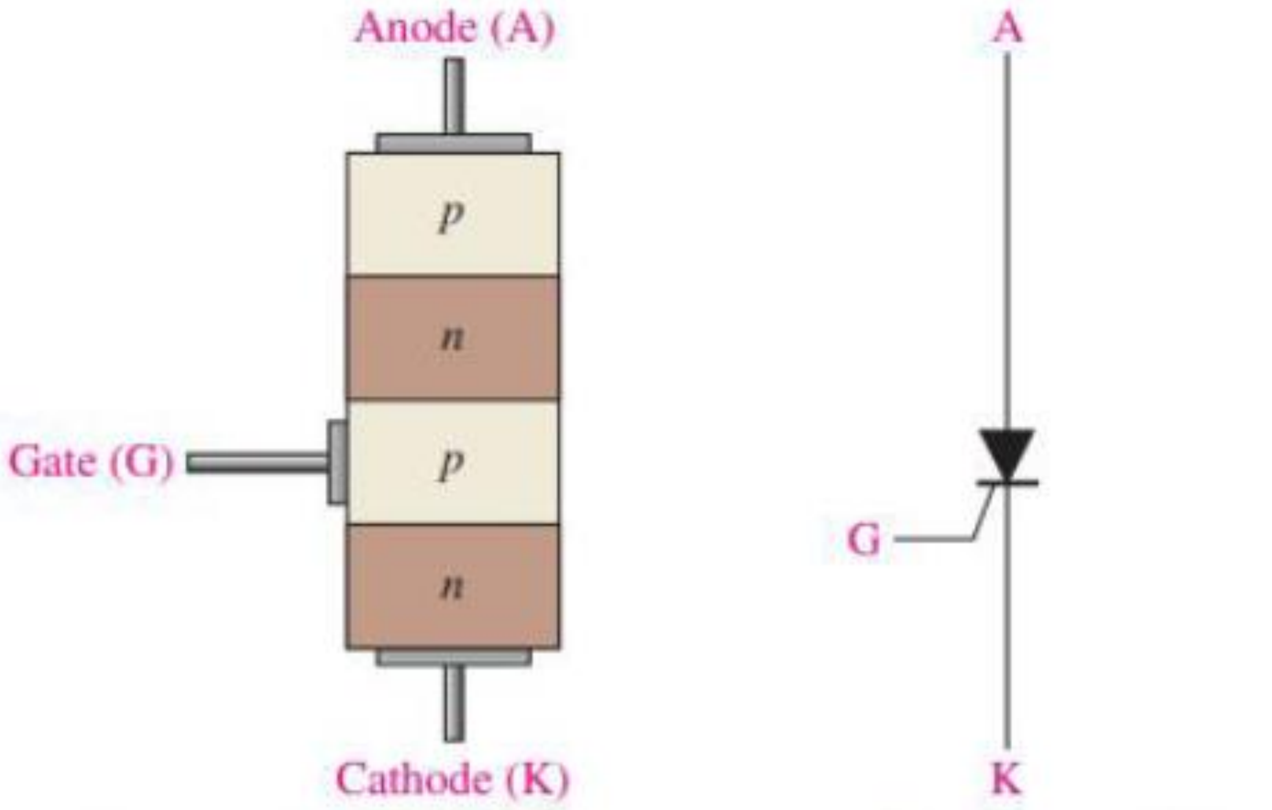
SILICON-CONTROLLED RECTIFIER (SCR)

- Within the family of pnpn devices, the SCR is of the 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 application such as induction heating and ultrasonic cleaning.

SILICON-CONTROLLED RECTIFIER (SCR)

- As the terminology indicates, 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 “gate” determines when the rectifier switches from the off-state to on-state.
- In the **off state**, it acts ideally as an open circuit between the anode and the cathode; actually, rather than an open, there is a very high resistance (typically 100 $\mathrm{k}\Omega$ or more).
- In the **on state**, the SCR acts ideally as a short from the anode to the cathode; actually, there is a small on (forward) resistance (0.01 to 0.1 Ω).

The basic construction of a SCR and its schematic symbol



(a) Basic construction (b) Schematic symbol

FIGURE 1-4

The silicon-controlled rectifier (SCR).

The basic construction of a SCR and its schematic symbol

- As shown on the Figure1-4, 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 by I_{GT}.
- A more detailed examination of the basic operation of an SCR is best effected by splitting the four-layer pnpn structure into two three-layer transistor structures as shown in the equivalent circuit.

SCR EQUIVALENT CIRCUIT

- Like the 4-layer diode operation, the SCR operation can best be understood by thinking of its internal pnpn structure as a two-transistor arrangement, as shown in Figure 1–5.
- This structure is like that of the 4-layer diode except for the gate connection. The upper pnp layers act as a transistor, Q1, and the lower npn layers act as a transistor, Q2. Again, notice that the two middle layers are "shared."

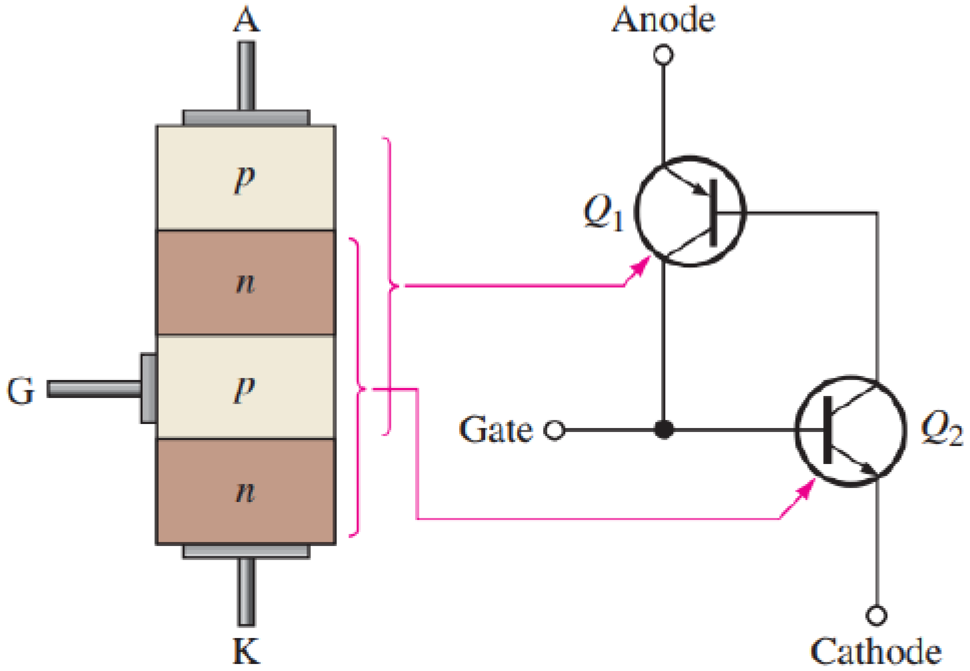


FIGURE 1-5

SCR equivalent circuit.

Turning the SCR ON and OFF

- An SCR has only two distinct states of operation: **on or off**.
- When the forward voltage is below the value of VBRF, the SCR acts like an open switch.
- When the forward voltage exceeds the breakover voltage, VBRF, the SCR conducts and acts like a closed switch.
- As a reminder, note that the SCR remains in the on state as long as the anode current is greater than the holding current, IH.

Turning the SCR ON and OFF

- Figure 1-6(b) shows how the level of the gate current, I_G, can control the forward breakover voltage, V_{BRF}. The maximum forward breakover voltage, V_{BRF}, occurs when the gate current, I_G, equals zero.
- When the gate-cathode junction is forward-biased, the SCR will fire at a lower anode-cathode voltage. Notice in Figure 1– 6*(b)* that as the gate current, I_G, is increased, the value of V_{BRF} is decreased. As the value of gate current, I_G, is increased, the SCR functions much like an ordinary rectifier diode.
- An important characteristic of an SCR is that once it is turned on by gate current, the gate loses all control. The only way to turn off the SCR is to reduce the anode current below the level of holding current, I_H. Not even a negative gate voltage will turn the SCR off in this case. In most cases, the anode supply voltage is an alternating voltage. This means that the SCR will automatically turn off when the anode voltage drops to zero or goes negative. Of course, when the anode voltage is negative, the SCR is reverse-biased. The process of turning off an SCR is called **commutation**.

SCR Characteristic Curves

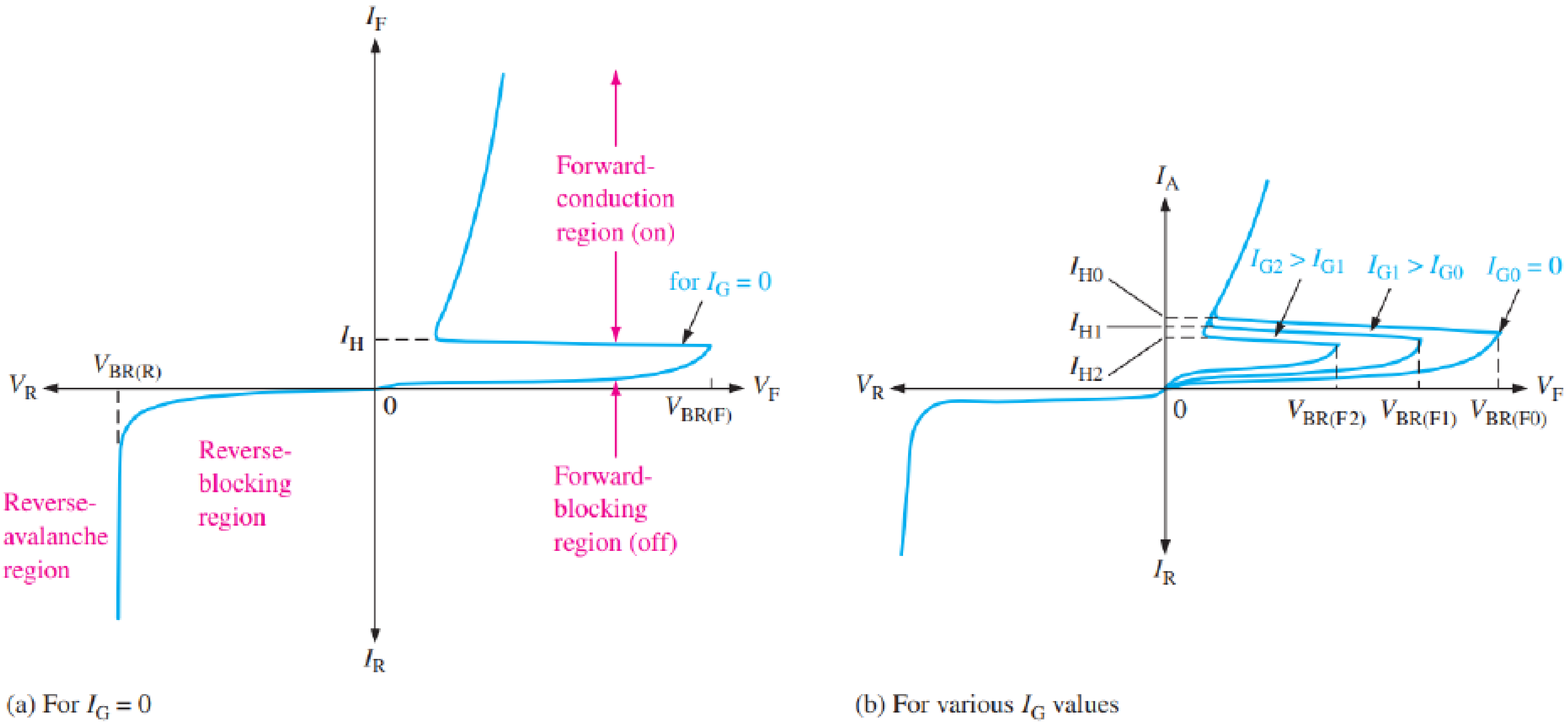


FIGURE 1-6

SCR characteristic curves.

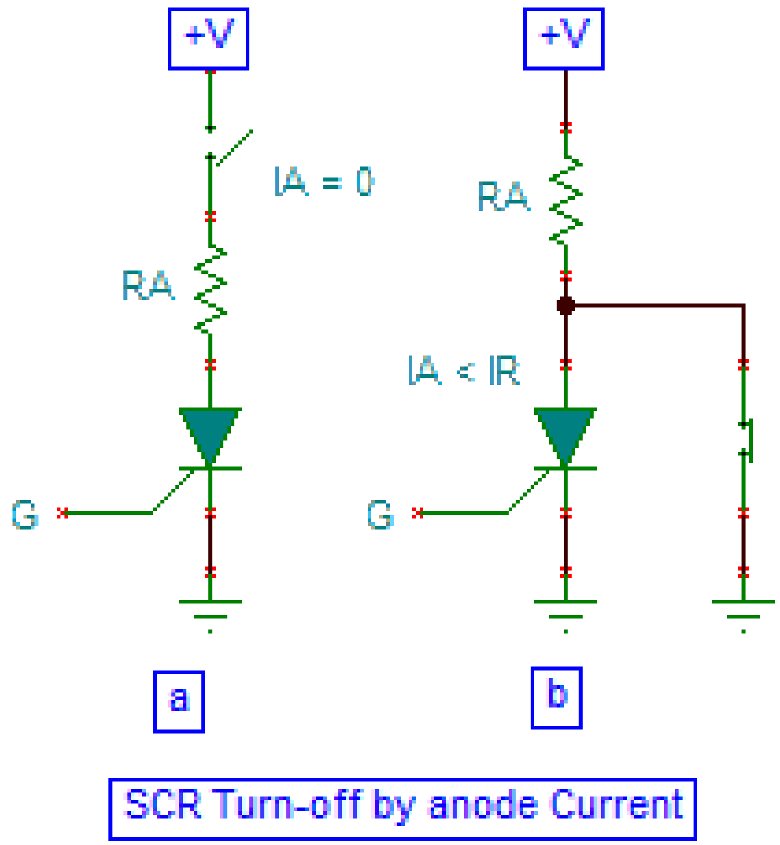
2 Basic Methods for Turning off an SCR

1) Anode Current Interruption
   - ➢In this method a parallel or a series switch is used to turn OFF the Silicon Control Rectifier (SCR electronics) by turning OFF the switch.
   - ➢Breaking the anode current path or providing a path around the SCR→ dropping the anode voltage to the point that IA < IH

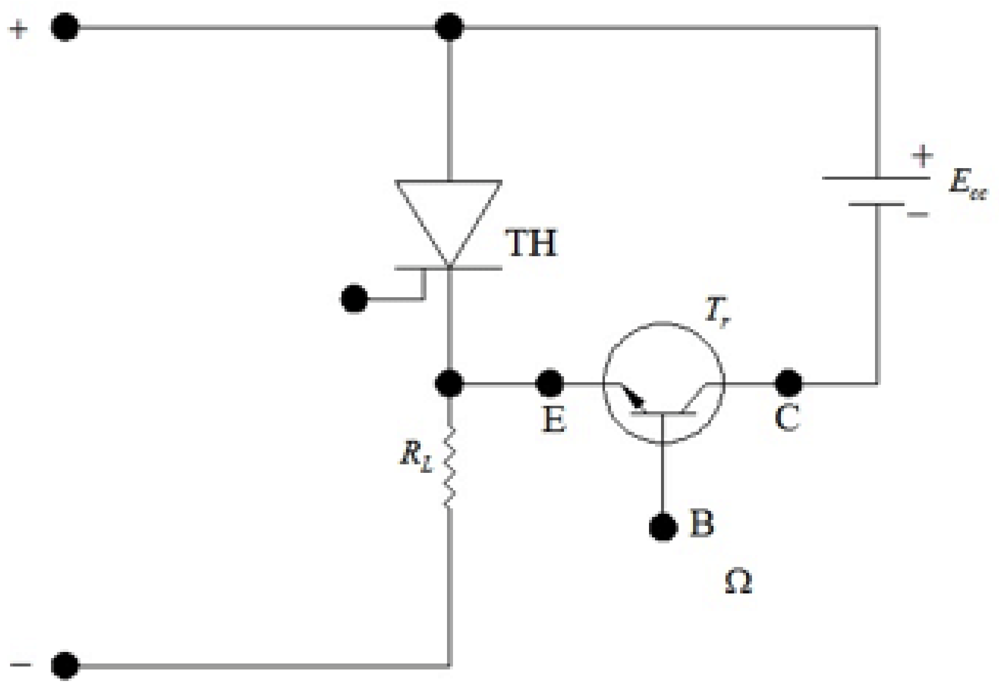
2) Force Commutation
   - ➢The thyristor can be turned off by reverse biasing the SCR or by using active or passive components. Thyristor current can be reduced to a value below the value of holding current. Since the thyristor is turned off forcibly it is termed as a forced commutation process.
   - ➢In such circuits, forward current must be forced to zero with an external circuit (known as **Commutating Circuit**) to commutate the SCR. Hence the name, Forced Commutation.

2 Basic Methods for Turning off an SCR

Anode Current Interruption

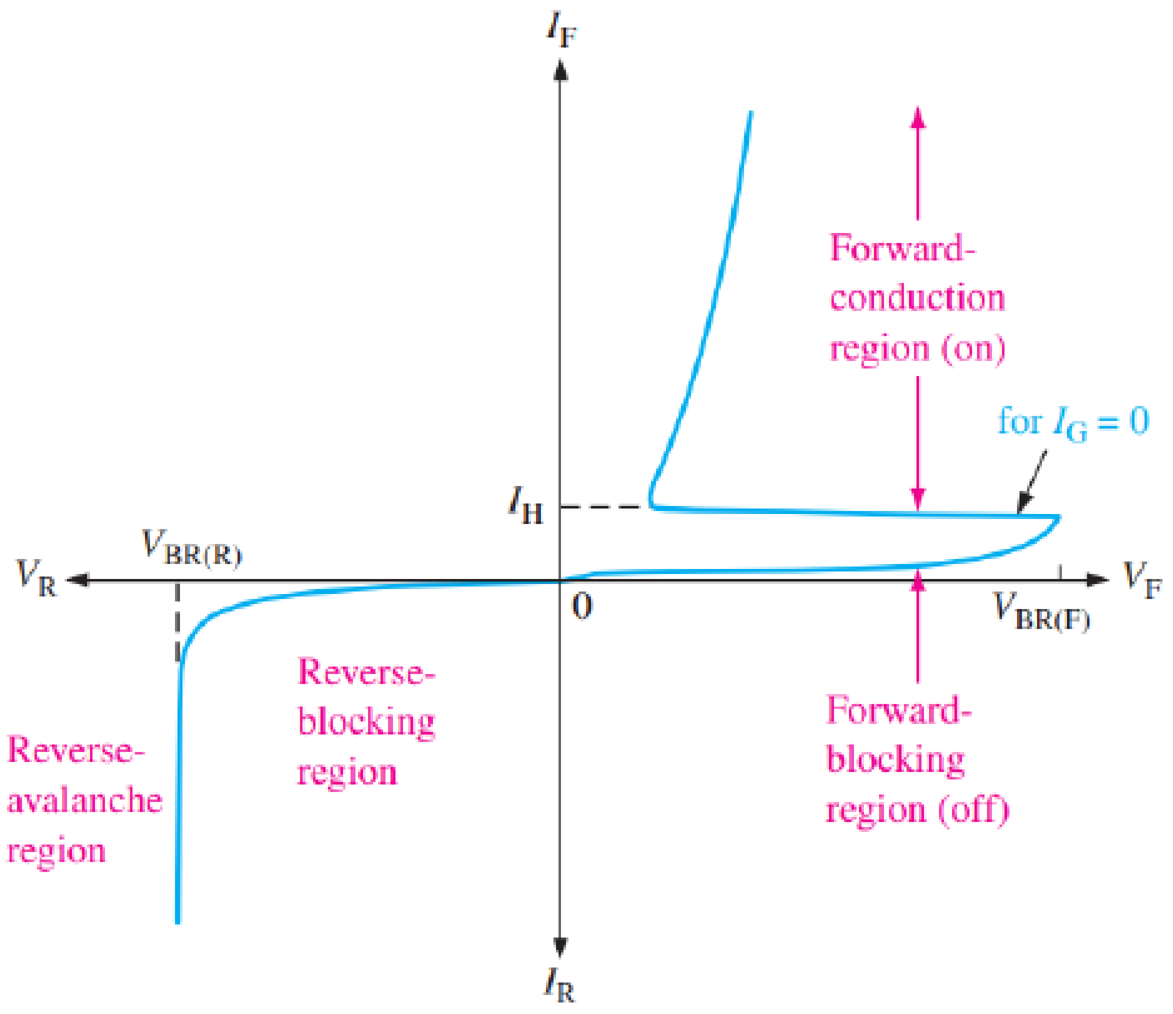


Force Commutation

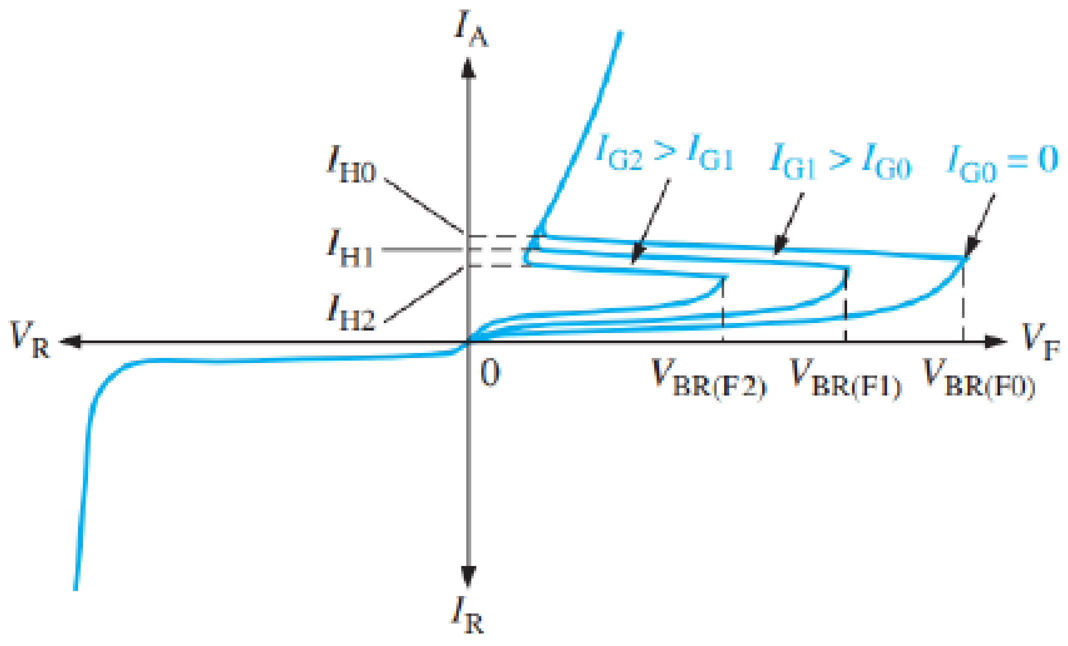


SCR Characteristics and Ratings

- Several of the most important SCR characteristics and ratings are defined as follows.



(a) For $I_G = 0$



(b) For various I_G values

▲ FIGURE 1-6

SCR characteristic curves.

Forward-breakover voltage, VBR(F)

- This is the voltage at which the SCR enters the forward-conduction region. The value of *VBR(F)* is maximum when *IG = 0* and is designated *VBR(F0)*.
- When the gate current in increased, *VBR(F)* decreases and is designated *VBR(F1)*, *VBR(F2)* and so on, for increasing steps in gate current (*IG1*, *IG2*, and so on).

Holding current, IH

- This is the value of anode current below which the SCR switches from the forward-conduction region to the forward-blocking region.
- The value increases with decreasing values of I_G and is maximum for $I_G = 0$

Gate trigger current, IGT

- This is the value of gate current necessary to switch the SCR from the forward-blocking region to the forward-conduction region under specified conditions.

Average forward current, IF(AVG)

- This is the maximum continuous anode current (dc) that the device can withstand in the conduction state under specified conditions.
- Overheat!

Forward-conduction region

- This region corresponds to the *on* condition of the SCR where there is forward current from anode to cathode through the very low resistance (approximate short) of the SCR.

Forward-blocking and reverse-blocking regions

- These regions correspond to the off condition of the SCR where the forward current from anode to cathode is blocked by the effective open circuit of the SCR.

Reverse-breakdown voltage, VBR(R)

- This parameter specifies the value of reverse voltage from cathode to anode at which the device breaks into the avalanche region and begins to conduct heavily (the same as in a *pn* junction diode).

SCR Applications

On-Off Control of Current

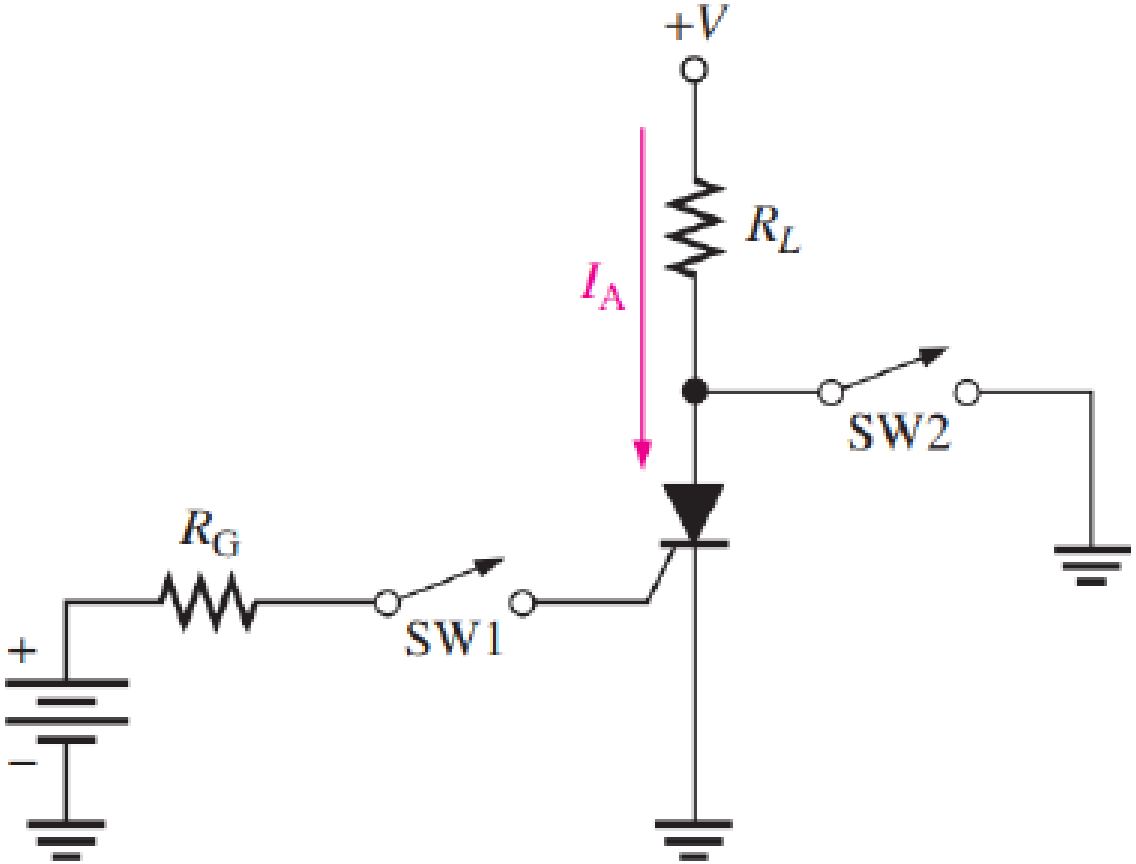


FIGURE 1-7

On-Off SCR control circuit.

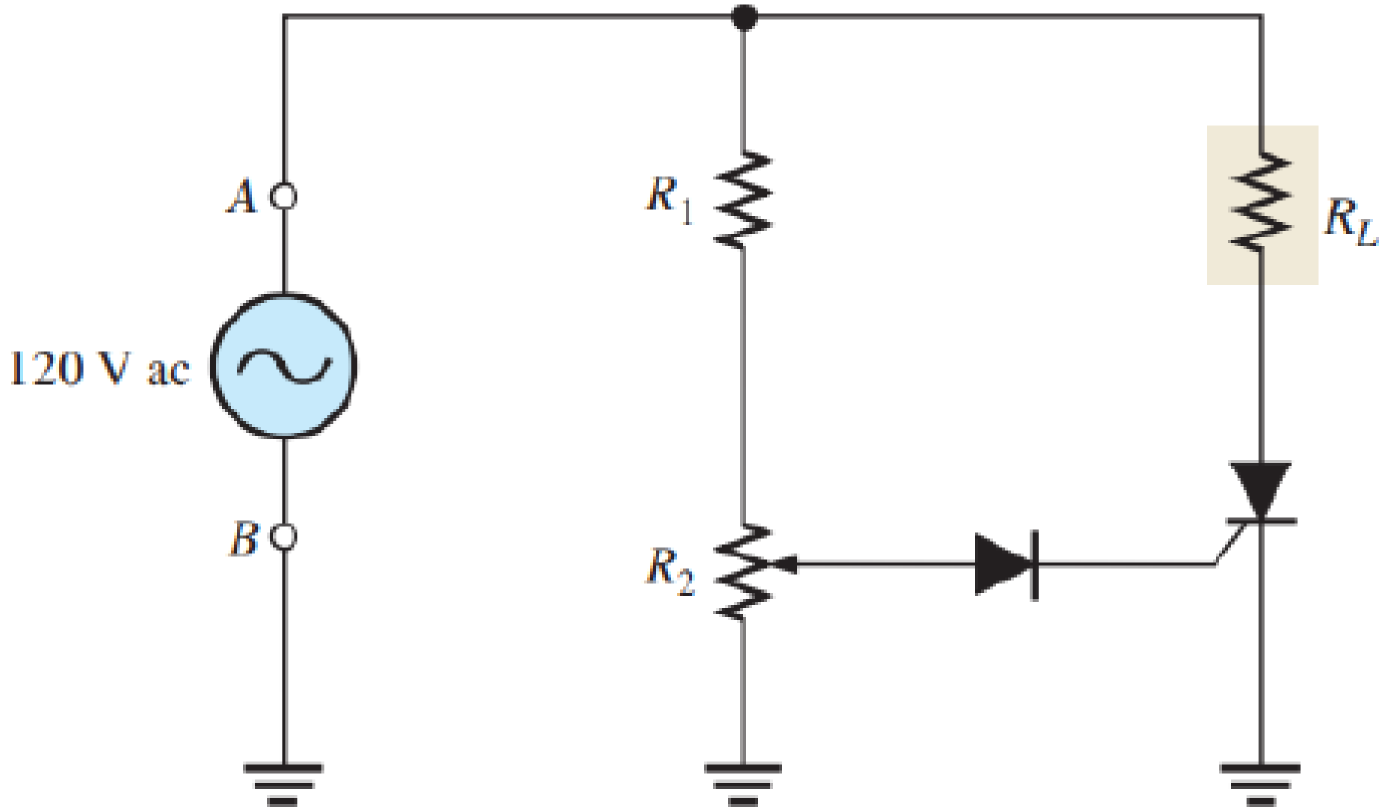
On-Off Control of Current

- Figure 1–7 shows an SCR circuit that permits current to be switched to a load by the momentary closure of switch SW1 and removed from the load by the momentary closure of switch SW2.
- Assuming the SCR is initially off, momentary closure of SW1 provides a pulse of current into the gate, thus triggering the SCR on so that it conducts current through RL.
- The SCR remains in conduction even after the momentary contact of SW1 is removed if the anode current is equal to or greater than the holding current, IH.
- When SW2 is momentarily closed, current is shunted around the SCR, thus reducing its anode current below the holding value, IH. This turns the SCR off and reduces the load current to zero.

Half-Wave Power Control

▶ FIGURE 1-8

Half-wave, variable-resistance, phase-control circuit.



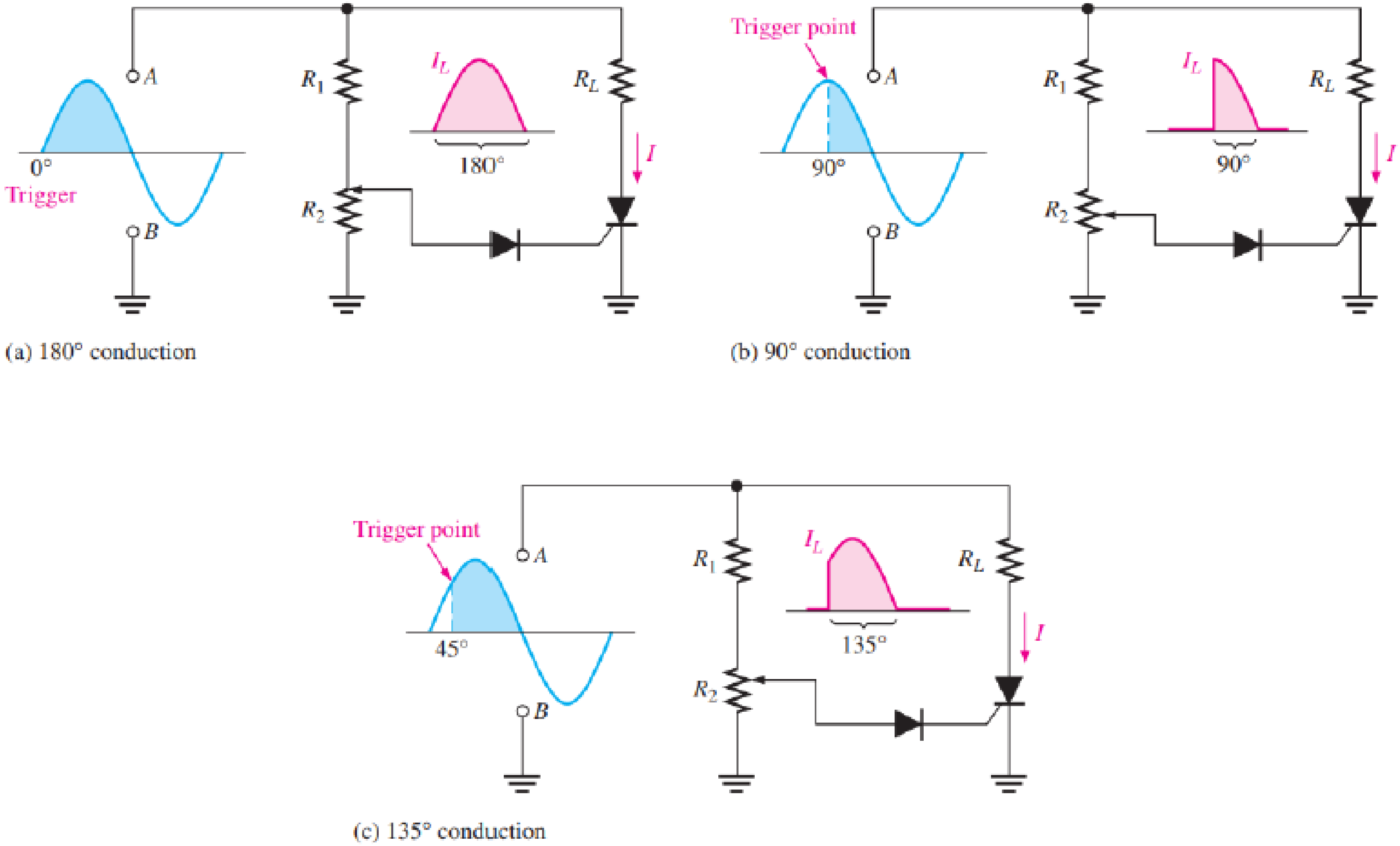
Half-Wave Power Control

- A half-wave, variable-resistance, phase-control circuit is shown in Figure 1–8; 120 V ac are applied across terminals A and B; RL represents the resistance of the load (for example, a heating element or lamp filament).
- Resistor R1 limits the current, and potentiometer R2 sets the trigger level for the SCR
- By adjusting *R2*, the SCR can be made to trigger at any point on the positive half-cycle of the ac waveform between 0° and 90°, as shown in Figure 1–9.
- When the SCR triggers near the beginning of the cycle (approximately 0°), as in Figure 1–9(a), it conducts for approximately 180° and maximum power is delivered to the load.

Half-Wave Power Control

- When it triggers near the peak of the positive half-cycle (90°), as in Figure 1–9(b), the SCR conducts for approximately 90° and less power is delivered to the load. By adjusting R2, triggering can be made to occur anywhere between these two extremes, and therefore, a variable amount of power can be delivered to the load.
- Figure 1–9(c) shows triggering at the 45° point as an example. When the ac input goes negative, the SCR turns off and does not conduct again until the trigger point on the next positive half-cycle. The diode prevents the negative ac voltage from being applied to the gate of the SCR.

Half-Wave Power Control



▲ FIGURE 1-9

Operation of the phase-control circuit.

Backup Lighting for Power Interruptions

- Figure 1–10 shows a center-tapped full-wave rectifier used for providing ac power to a low-voltage lamp. As long as the ac power is available, the battery charges through diode D3 and R1.

Backup Lighting for Power Interruptions

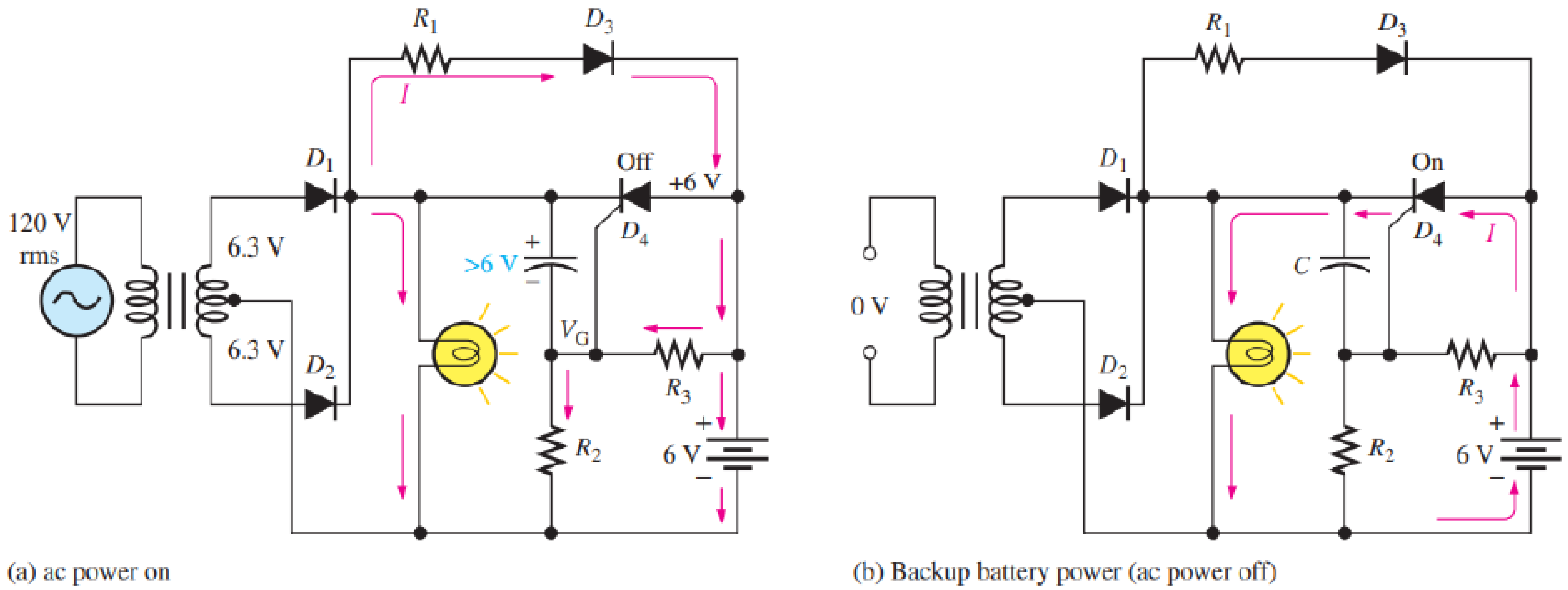


FIGURE 1-10

Automatic backup lighting circuit.

Backup Lighting for Power Interruptions

- The SCR's cathode voltage is established when the capacitor charges to the peak value of the full-wave rectified ac (6.3 V rms less the drops across R2 and D1).
- The anode is at the 6 V battery voltage, making it less positive than the cathode, thus preventing conduction.
- The SCR's gate is at a voltage established by the voltage divider made up of R2 and R3. Under these conditions the lamp is illuminated by the ac input power and the SCR is off, as shown in Figure 1–10(a).
- When there is an interruption of ac power, the capacitor discharges through the closed path R1, D3, and R3 making the cathode less positive than the anode or the gate. This action establishes a triggering condition, and the SCR begins to conduct. Current from the battery is through the SCR and the lamp, thus maintaining illumination, as shown in Figure 1–10(b). When ac power is restored, the capacitor recharges and the SCR turns off. The battery begins recharging.

Backup Lighting for Power Interruptions

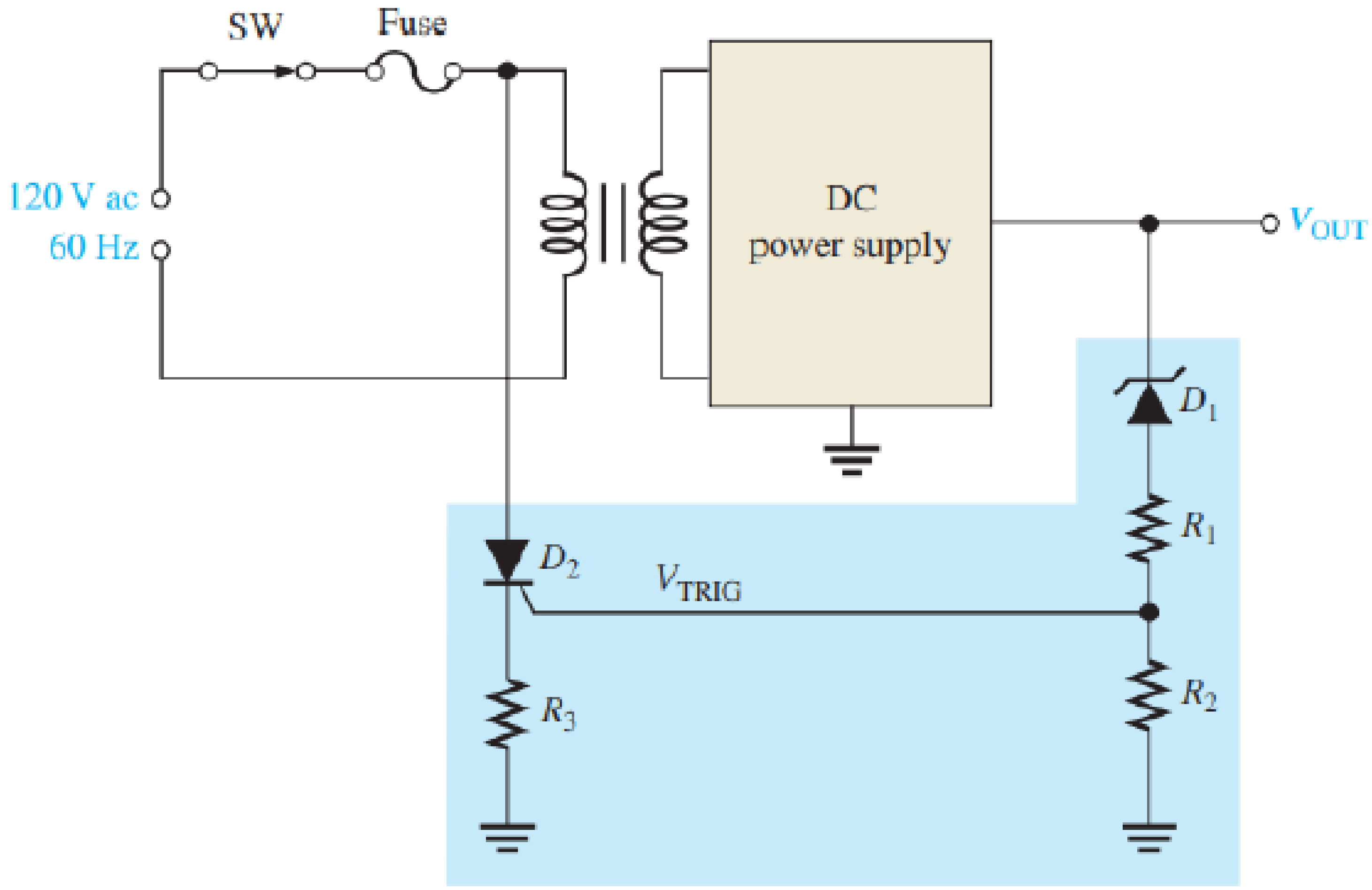


FIGURE 1-11

A basic SCR over-voltage protection circuit (shown in blue).

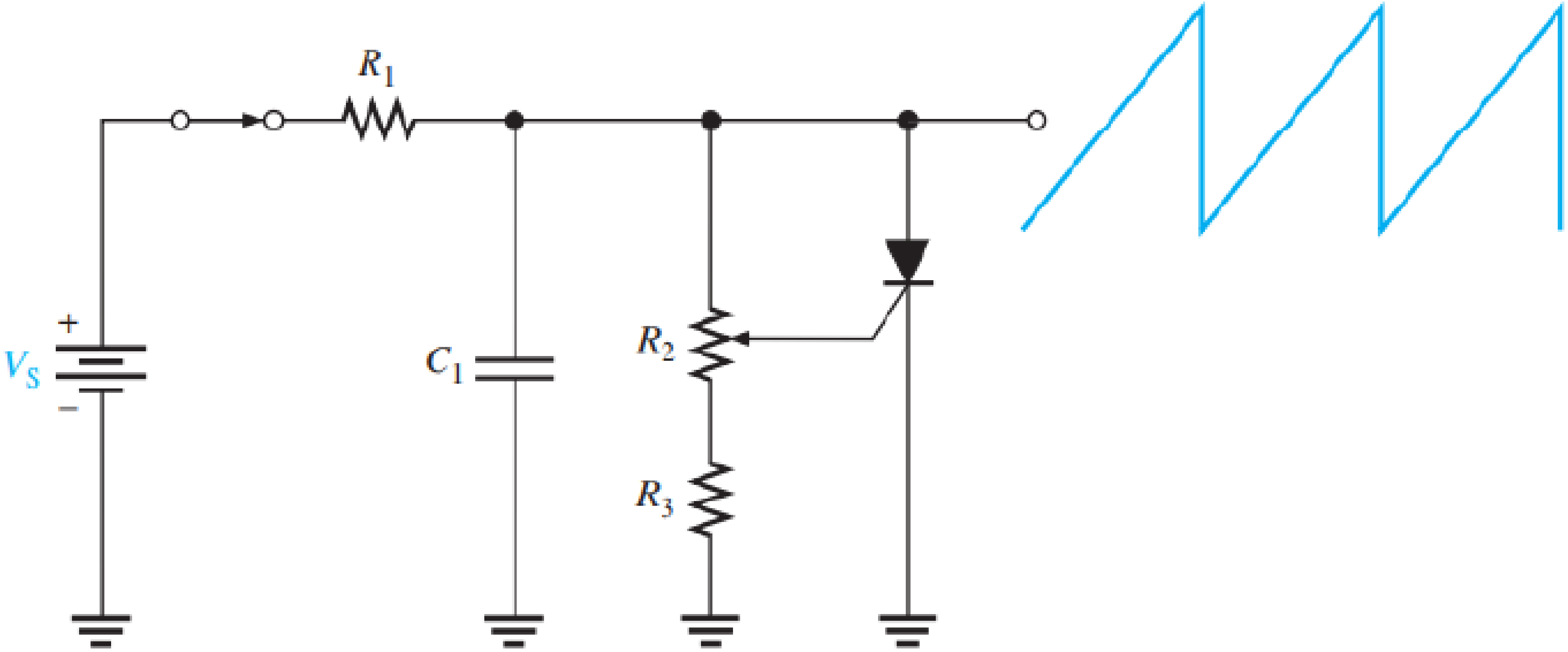
Backup Lighting for Power Interruptions

- Figure 1–11 shows a simple over-voltage protection circuit, sometimes called a “crow-bar” circuit, in a dc power supply.
- The dc output voltage from the regulator is monitored by the Zener diode D1 and the resistive voltage divider (R1 and R2). The upper limit of the output voltage is set by the Zener voltage.
- If this voltage is exceeded, the Zener conducts and the voltage divider produces an SCR trigger voltage. The trigger voltage turns on the SCR, which is connected across the line voltage. The SCR current causes the fuse to blow, thus disconnecting the line voltage from the power supply.

Sawtooth Generator

- The SCR can be used in conjunction with an RC circuit to produce a repetitive sawtooth waveform.
- The circuit is shown in Figure 1–12. The time constant is set by R1 and C1, and the voltage at which the SCR triggers on is determined by the variable voltage-divider formed by R2 and R3.
- When the switch is closed, the capacitor begins charging and turns on the SCR. When the SCR turns on, the capacitor quickly discharges through it; the anode current then decreases below the holding value, causing the SCR to turn off.
- As soon as the SCR is off, the capacitor starts charging again and the cycle is repeated. By adjusting the potentiometer, the frequency of the sawtooth waveform can be changed.

Sawtooth Generator



Sample Problems

Problem #1

- A certain 4-layer diode is biased in the forward-blocking region with an anode-to-cathode voltage of 20 V. Under this bias condition, the anode current is 1 μA. Determine the resistance of the diode in the forward-blocking region.

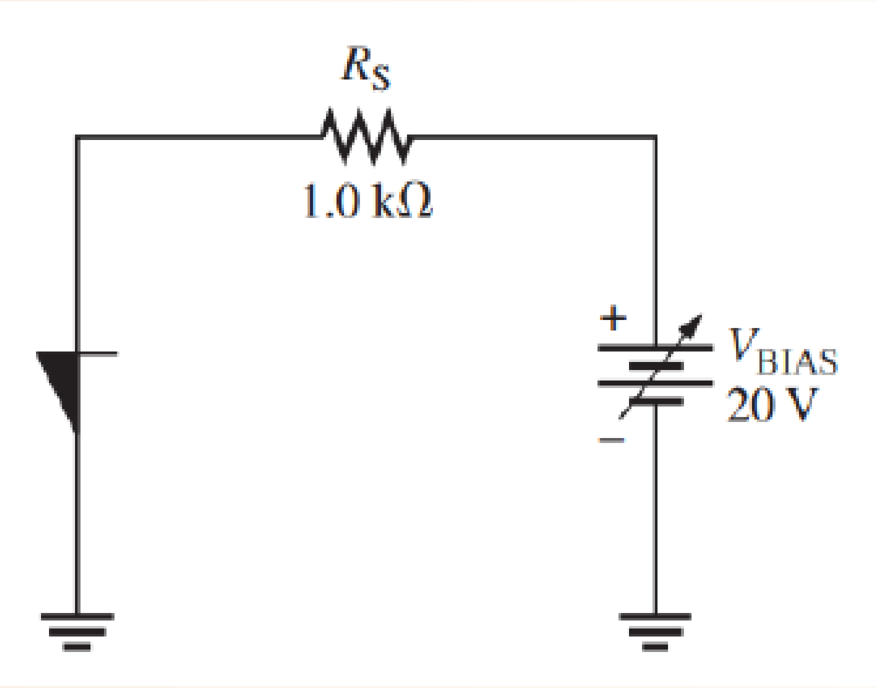
Ans.

$$R_{AK} = 20\ M\Omega$$

Problem #2

- Determine the value of anode current in Figure 1-13 when the device is on. *VBR(F)* = 10 V. Assume the forward voltage drop is 0.9 V.

FIGURE 1-13



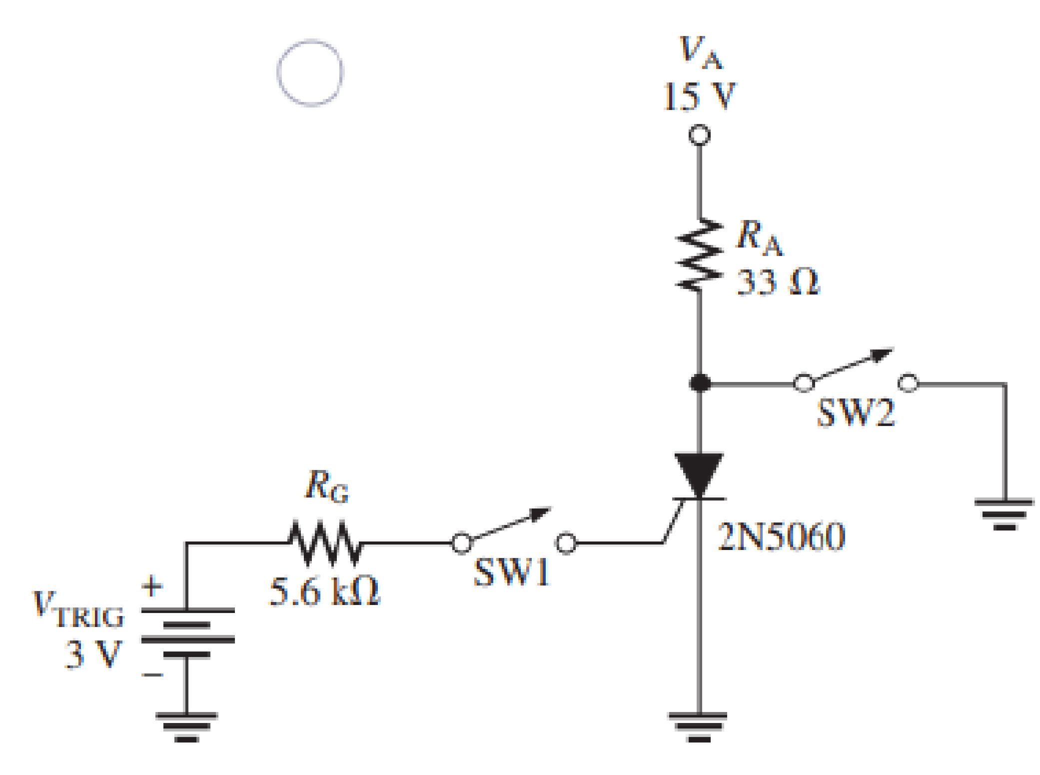
Ans.

$V_{RS} = 19.1$ V $\quad$ $I_A = 19.1$ mA

Problem #3

- Determine the gate trigger current and the anode current when the switch, SW1, is momentarily closed in Figure 1-14. Assume *VAK* = 0.2 V, *VGK* = 0.7 V, and *IH* = 5mA.

FIGURE 1-14



Ans.

$I_G = 410\ \mu A$

Problem #4

- An SCR in a circuit is subjected to a 50 A surge that lasts for 12 ms. Determine whether or not this surge will destroy the device. Given that circuit fusing rating is 90 $\mathrm{A^2s}$.

Ans.

No. (90 $\mathrm{A^2s}$ > 30 $\mathrm{A^2s}$)

Problem #5

- An SCR has a circuit fusing rating of 50 A^2s. The device is being used in a circuit where it could be subjected to a 100 A surge. Determine the maximum allowable duration of such a surge.

Ans.

t =5 ms

Problem #6

- A 220Ω resistor is connected in series with the gate of an SCR as shown in Fig. 20.6. The gate current required to fire the SCR is 7mA. What is the input voltage (Vin) required to fire the SCR ?

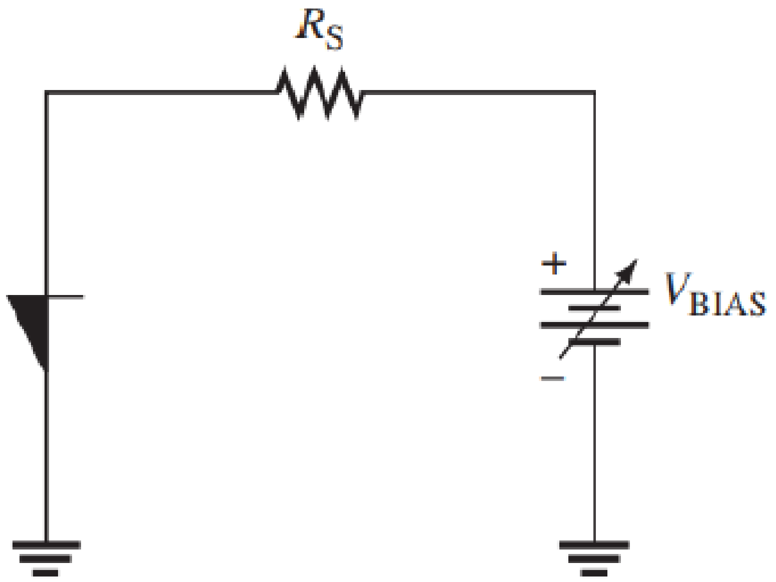
Ans.

$$V_{in} = 2.24\ V$$

Problem #7

- Determinet the value of anode current on the given circuit when the device is on.

Givens: $V_{BR(F)} = 100\text{ V}, V_{BE} = 0.7\text{ V}, V_{CE(sat)} = 0.1\text{ V}, V_{BIAS} = 110\text{ V}, R_S = 1\text{k}\Omega$



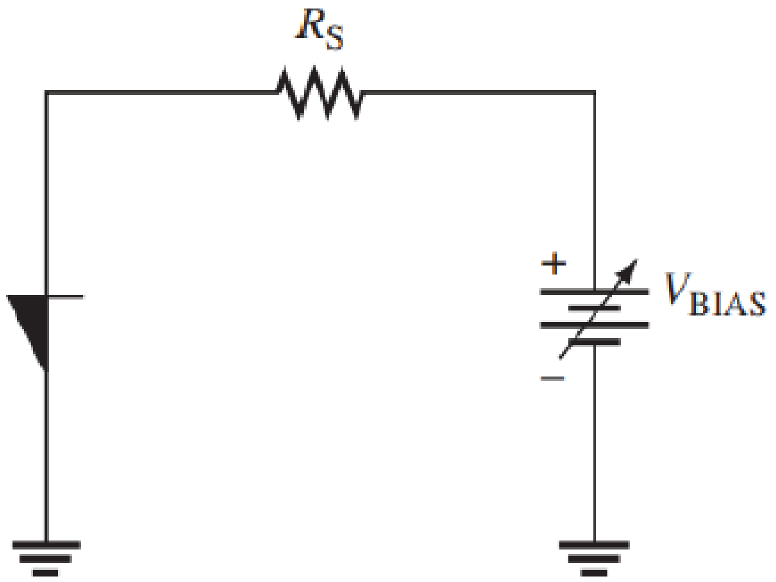
Ans.

$$I = 109.2\text{ mA}$$

Problem #8

- Determinet the value of anode current on the given circuit when the device is on.

Givens: $V_{BR(F)} = 20\text{ V}$, $V_{BE} = 0.7\text{ V}$, $V_{CE(sat)} = 0.2\text{ V}$, $V_{BIAS} = 25\text{ V}$, $R_S = 1\text{k}\Omega$



Ans.

$I = 24.1\text{ mA}$

Problem #9

- An a.c. voltage $v = 240 \sin 314t$ is applied to an SCR half-wave rectifier. If the SCR has a forward breakdown voltage of 180 V, find the time during which SCR remains off.

Ans.

2.7 ms

Problem #10

- In an SCR half-wave rectifier circuit, what peak-load current will occur if we measure an average (d.c.) load current of 1A at a firing angle of 30° ?

Ans.

3.36 A

Problem #11

- A load operation is to be varied by controlling the firing angle of an SCR in a half-wave rectifier circuit supplied with 90 V a.c. What r.m.s. voltage and current are developed in the load at firing angle $\alpha = 20°$ if the load resistance is 120 ohms?

Ans.

$$\mathrm{Vrms} = 63.36\mathrm{V}$$

$$\mathrm{Irms} = 0.528\ \mathrm{A}$$

Problem #12

- An SCR full-wave rectifier supplies to a load of 100 Ω. If the peak a.c. voltage between centre tap and one end of secondary is 200V, find (i) d.c. output voltage and (ii) load current for a firing angle of 60°.

Ans.

i) 95.5 V

ii) 0.955 A