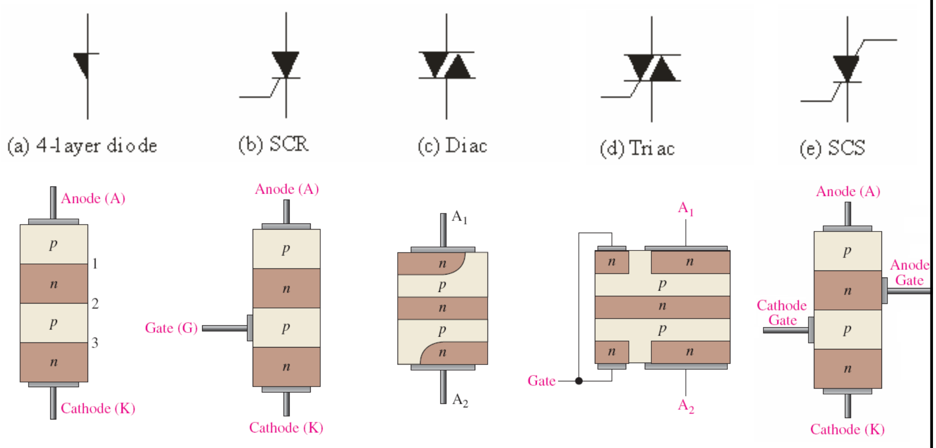
Chapter 11: Thyristors

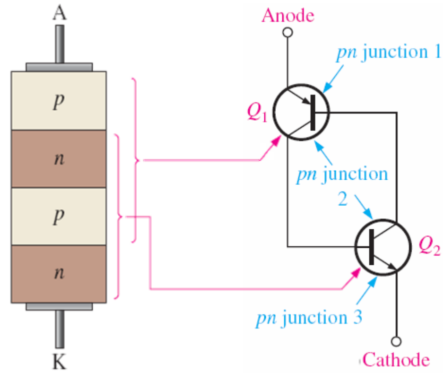
11. Thyristors

- **Thyristors** are semiconductor devices characterized by 4-layers of alternating *p*- and *n*-material. Four-layer devices act as either open or closed switches; for this reason, they are mostly used in control applications.
- Some thyristors and their symbols are



11. Thyristors

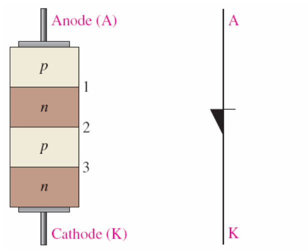
■ The concept of 4-layer devices is usually shown as an equivalent circuit of a *pnp* and an *npn* transistor. Ideally, these devices would not conduct, but when forward biased, if there is sufficient leakage current in the upper *pnp* device, it can act as base current to the lower *npn* device causing it to conduct and bringing both transistors into saturation.



Four layer device equivalent circuit

11-1: The Four-Layer Diode

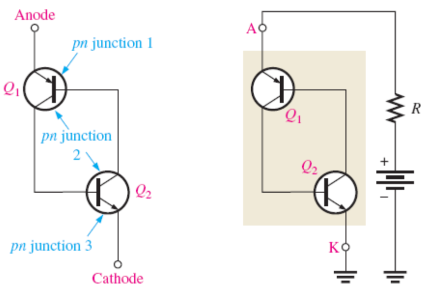
■ The **4-layer diode** (or Shockley diode) is a type of thyristor that acts like an ordinary diode but conducts in the forward direction only after a certain anode to cathode voltage (V_{AK}) called the forward-breakover voltage, $V_{BR(F)}$, is reached.



(a) Basic construction (b) Schematic symbol

■ The 4-layer diode has two leads, labeled the anode (A) and the cathode (K). The symbol reminds you that it acts like a diode.

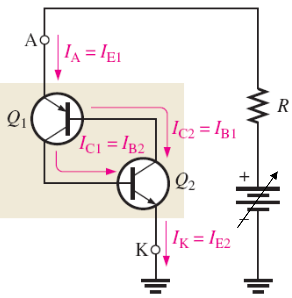
■ When a positive bias voltage is applied, the base-emitter junctions of and (*pn* junctions 1 and 3) are forward-biased, and the common base-collector junction (*pn* junction 2) is reverse-biased → *at low level bias voltage* → very little current (I_A) pass from A to K (can be neglected) → the diode is in off state (it has very high resistance)

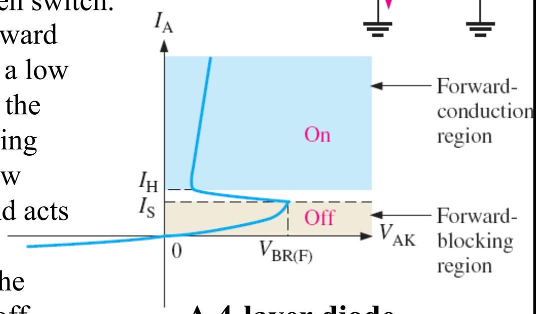


(a) (b)

11-1: The Four-Layer Diode: characteristic curve

- As bias voltage increases → V_{AK} increases → leakage current ($I_{C1} = I_{B2}$) increases and hence anode current, I_A, increases very little until reaching the switching current I_S at $V_{AK} = V_{BR(F)}$.
- the region at which the current I_A is very little (can be neglected) is called the forward blocking region → the device has very high resistance → it is in its *off* state and act as an open switch.
- When current reaches I_S, the forward voltage V_{AK} suddenly decreases to a low value, and the 4-layer diode enters the *forward-conduction region* at holding current I_H → the device has very low resistance → it is in the *on* state and acts as a closed switch.
- When the I_A drops back below the holding value I_H, the device turns off and enters the forward blocking region. This is the only way to stop conduction.





A 4-layer diode characteristic curve.

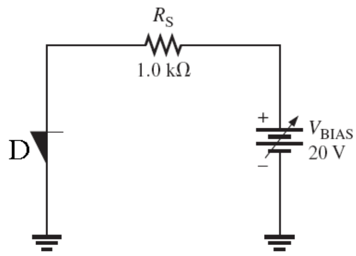
11-1: The Four-Layer Diode: Examples

Example: A 4-layer diode is biased in the forward-blocking region with V_{AK} = 20 V. If the anode current is 1 μA. Determine the resistance of the diode in the forward-blocking region.

$$R_{AK} = \frac{V_{AK}}{I_A} = \frac{20\text{ V}}{1\ \mu\text{A}} = \mathbf{20\ M\Omega}$$

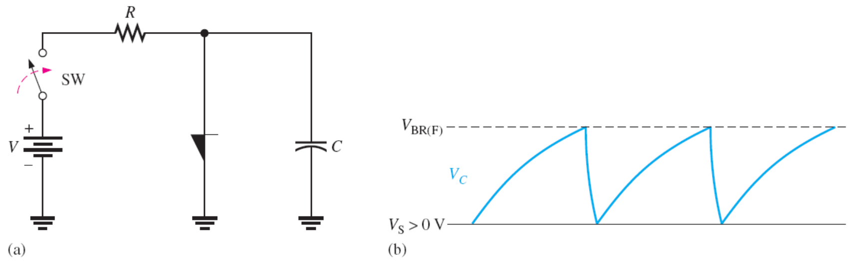
Example: Determine the value of anode current in the diode D shown below when the device is on. $V_{BR(F)}$ = 10 V. Assume the forward voltage drop of D is 0.9 V.

$$I_A = \frac{V_{bias} - V_D}{R_S} = \frac{20 - 0.9}{1k\Omega} = 19.1mA$$



11-1: The Four-Layer Diode: Application

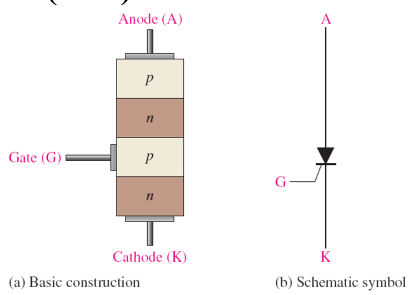
■ An application for the 4-layer diode is **relaxation oscillator**, shown in the circuit below



■ When the switch is closed→ C charges through *R* → capacitor voltage and hence V_{AK} increases until its voltage reaches the $V_{BR(F)}$ of the 4-layer diode → Diode switches on, and the capacitor rapidly discharges through the diode → V_{AK} decrease → Discharging continues until the current through the diode falls below the holding value I_H. At this point, the diode switches back to the *off* state, and the capacitor begins to charge again. The result of this action is a voltage waveform across *C* like that shown above.

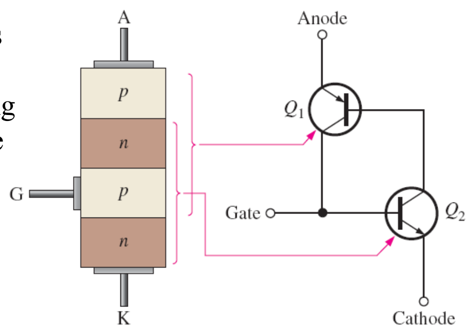
11-2: The Silicon-Controlled Rectifier (SCR)

■ The **SCR** had its roots in the 4-layer diode. By adding a gate connection, the SCR could be triggered into conduction. This improvement made a much more useful device than the 4-layer diode.



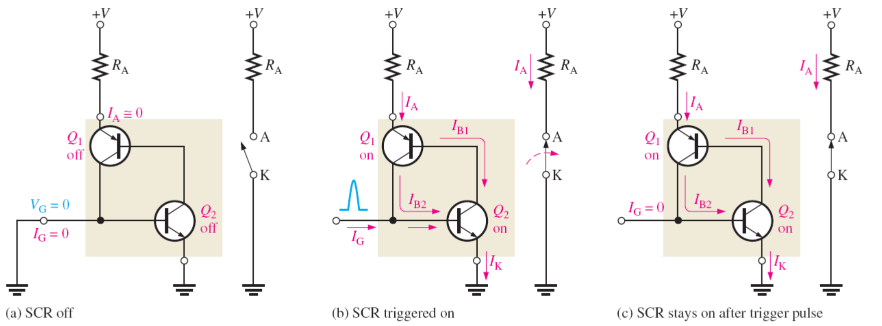
■ The SCR equivalent circuit shows that the gate current is applied to the third p-region of the device providing a current pulse (a trigger) to the base of Q_2.

→ SCR can be turned on by exceeding the forward breakover voltage or by gate current.



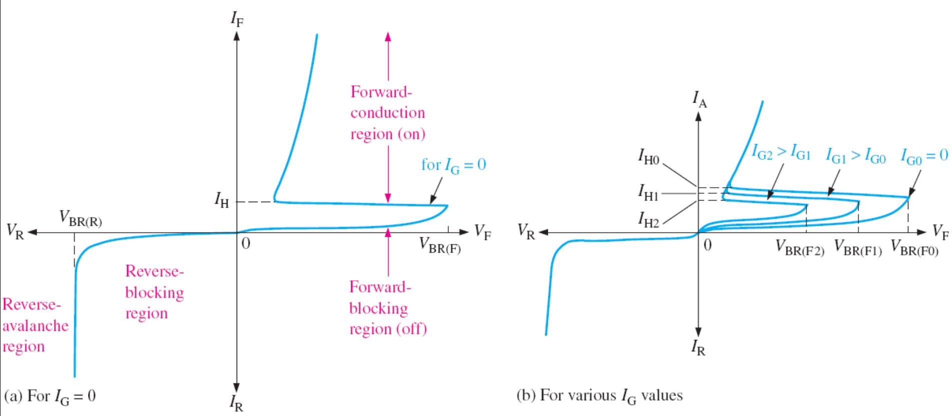
11-2: The Silicon-Controlled Rectifier (SCR)

- At low level V_{AK} when $I_G = 0$ → the SCR is off and no forward current will pass.
- When a positive pulse of current (**trigger**) is applied to the gate, both transistors turn on (there must $V_A > V_K$) → I_{B2} turns on Q_2, providing a path for I_{B1} into the Q_2 collector, thus turning on Q_1. The collector current of Q_1 provides additional base current I_{B2} for Q_2 so that Q_2 stays in conduction after the trigger pulse is removed from the gate



11-2: The Silicon-Controlled Rectifier (SCR): Characteristic Curve

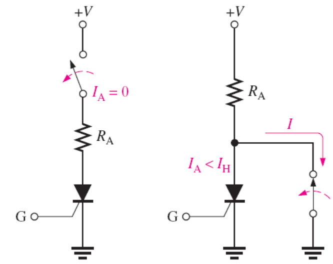
- At $I_G = 0$, the characteristic curve it typically like the four-layer Diode.
- as I_G is increased above 0 V → $V_{BF(F)}$ decreases → we can have the SCR turns on at a very low V_{AK} as I_G is is increased to suitable value→ the I_G controlled the value $V_{BR(F)}$ required for turn-on.



11-2: The Silicon-Controlled Rectifier (SCR): Turning the SCR Off

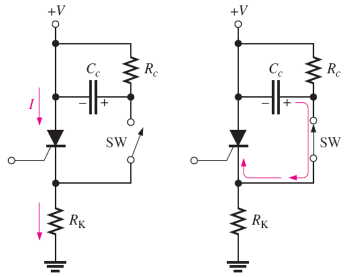
- Like the 4-layer diode, the SCR will conduct as long as forward current exceeds I_H. There are two ways to drop the SCR out of conduction: **anode current interruption** and **forced commutation**.

1) Anode current can be interrupted by breaking the anode current path (shown here) or providing a path around the SCR→ dropping the anode voltage to the point that $I_A < I_H$.



(a) (b)

2) Force commutation uses an external circuit (like the shown) to momentarily forcing current through the SCR in direction opposite to the direction of forward conduction current I_F



(a) On (b) Off

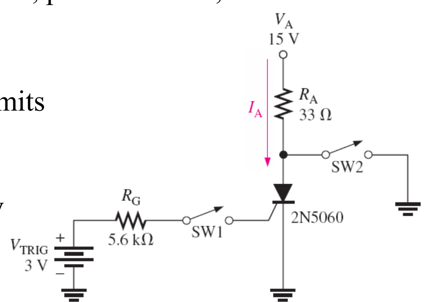
- SCRs are commonly used in ac circuits, which forces the SCR out of conduction when the ac reverses.

11-3: SCR Applications

The SCR is used in many applications, including motor controls, time-delay circuits, heater controls, phase controls, relay controls, and sawtooth generators.

- On-Off Control of Current

The figure shows an SCR circuit that permits current to be switched to a load by the momentary closure of switch SW_1 and removed from the load by the momentary closure of switch SW_2.



Example:

Determine the gate trigger current and the anode current when the switch, SW1, is momentarily closed in Figure 11–16. Assume $V_{AK} = 0.2$ V, $V_{GK} = 0.7$ V, and $I_H = 5$ mA.

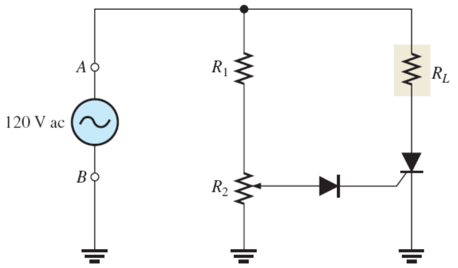
$$I_G = \frac{V_{TRIG} - V_{GK}}{R_G} = \frac{3\text{ V} - 0.7\text{ V}}{5.6\text{ k}\Omega} = \mathbf{410\ \mu A}$$

$$I_A = \frac{V_A - V_{AK}}{R_A} = \frac{15\text{ V} - 0.2\text{ V}}{33\ \Omega} = \mathbf{448\ mA}$$

11-3: SCR Applications

-Half-Wave Power Control

- A common application of SCRs is in the control of ac power for different applications like lamp dimmer, electric heaters, and electric motors



- A half-wave, variable-resistance, phase-control circuit is shown in figure above; R_L represents the resistance of the load. Resistor R_1 limits the current, and potentiometer R_2 sets the trigger level for the SCR.

- The SCR conduct at positive half cycle (because $V_A > V_K$). At negative half cycle → The SCR does not conduct (because $V_A < V_K$).

- By adjusting R_2, the SCR can be made to trigger at any point on the positive half-cycle of the ac waveform between 0° and 90°

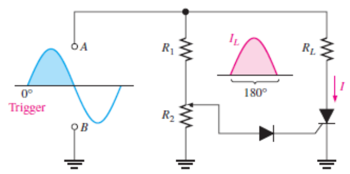
11-3: SCR Applications

-Half-Wave Power Control

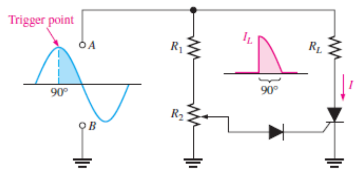
- In figure (a) R_2 is adjusted at highest V_{GK} → I_G is max. → the SCR is conduct near the beginning of the cycle → RL is conducting for approximately 180° → max power delivered to R_L.

- In figure (b) R_2 is adjusted at intermediate V_{GK} → I_G is less than in (a) → the SCR is conduct near the peak of the cycle → R_L is conducting for approximately 90° → less power delivered to R_L.

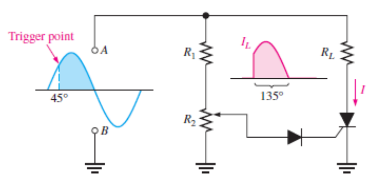
- In figure (c) R_2 is adjusted at V_{GK} between that in (a) and (b)→ I_G is between that in (a) and (b) → the SCR is conduct midway between (a) and (b) → R_L is conducting for approximately 45°.



(a) 180° conduction



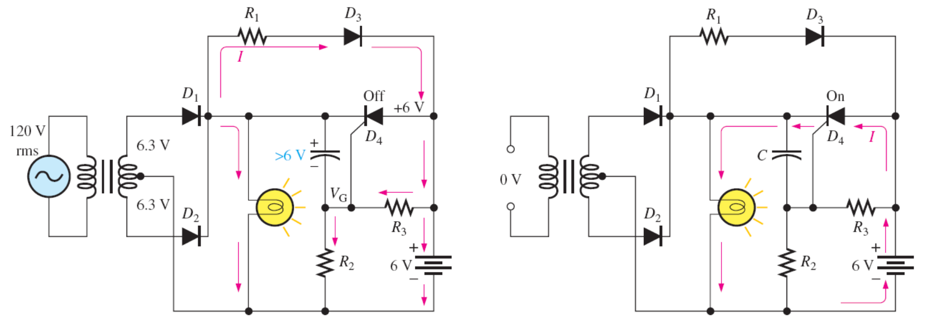
(b) 90° conduction



(c) 135° conduction

11-3: SCR Applications

- Backup Lighting for Power Interruptions



(a) ac power on (b) Backup battery power (ac power off)

■ The figure shows a full-wave rectifier used for providing power to a low-voltage lamp. As long as the ac power is available, the battery charges through diode R_1 and D_3. Also C is charged to voltage higher than anode → $V_K > (V_A =$ +6V of the battery)

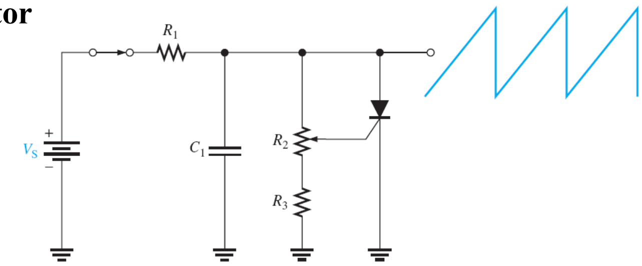
■ When there is an interruption of ac power, the capacitor discharges through R_1, D_3, and R_3 → $V_K < V_A$ or gate →SCR begins to conduct → Current from the battery is through the SCR and lamp→ lamp maintaining illumination,

11-3: SCR Applications

- Sawtooth generator

Sawtooth wave

■ The circuit is shown is used to produce the sawtooth wave



■ The time constant is set by R_1 and C_1, and the voltage at which the SCR triggers on is determined by the variable voltage-divider formed by R_2 and R_3

■ When the switch is closed, the capacitor begins charging increasing the V_{AK} → at $V_{BR(F)}$, the SCR turns on. When the SCR turns on, the capacitor quickly discharges through it→ V_{AK} decrease → 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.

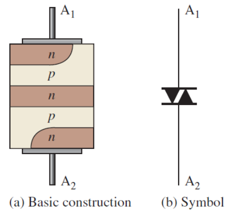
■ By adjusting the potentiometer, the frequency of the sawtooth waveform can be changed.

11-4: The Diac and Triac

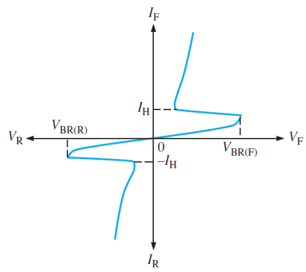
- The diac and the triac are types of thyristors that can conduct current in both directions (bilateral). The difference between the two devices is that a diac has two terminals, while a triac has a third terminal, which is the gate for triggering

The Diac

- The **diac** acts like two back-to-back 4-layer diodes. It can conduct current in either direction. It is constructed of two back to back *pnpn* as shown. Because it is bidirectional, the terminals are equivalent and labeled A_1 and A_2.



- The diac conducts current after the breakdown voltage is reached with either polarity across the two terminals, as shown in the characteristic curve. At break points, the diac goes into avalanche conduction, creating a forward (I_F) or reverse (I_R)current . The diac remains in conduction as long as the current is above the holding current, I_H.

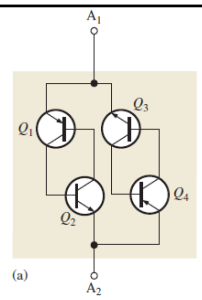


Diac characteristic curve.

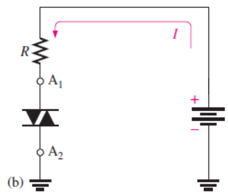
11-4: The Diac and Triac

The Diac

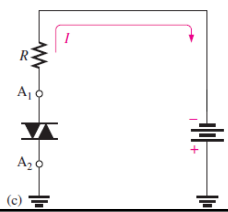
- The equivalent circuit of a diac consists of four transistors arranged as shown in Figure (a)



- When the diac is biased as in Figure (b), the *pnpn* structure from A_1 to A_2 provides the same operation as was described for the 4-layer diode. In the equivalent circuit, Q_1 and Q_2 are forward-biased, and Q_3 and Q_4 are reverse-biased → device work in upper portion of the characteristic curve



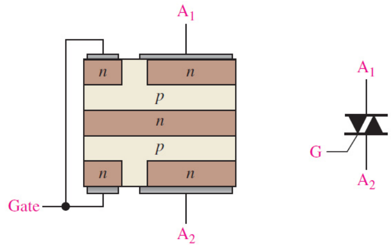
- When the diac is biased as in Figure (b), the *pnpn* structure from A_2 to A_1 → Q_3 and Q_4 are forward-biased, and Q_1 and Q_1 are reverse-biased → device work in lower portion of the characteristic curve



11-4: The Diac and Triac

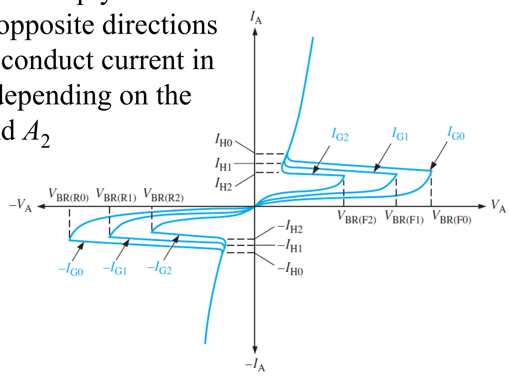
The Triac

- The **Triac** acts like a diac with a gate terminal used to trigger the device on so that it conducts at lower break voltage than in the diac



(a) Basic construction (b) Symbol

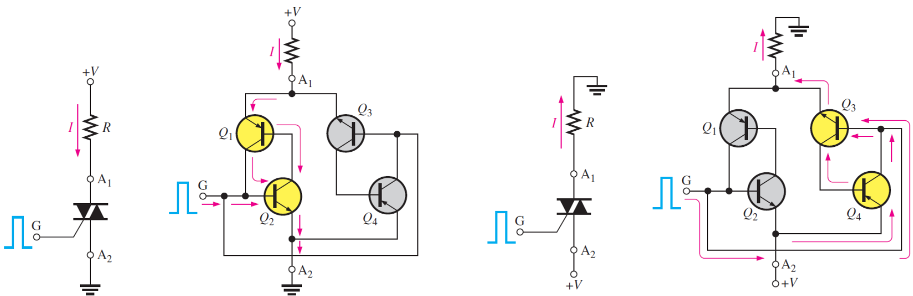
- Basically, a triac can be thought of simply as two SCRs connected in parallel and in opposite directions with a common gate terminal → it conduct current in both direction when triggered on, depending on the polarity of the voltage across A_1 and A_2
- The characteristic curve is shows that the breakover potential decreases as the gate current increases (like the SCR). The triac turns off when the anode current drops below I_H



11-4: The Diac and Triac

The Triac

- The mechanism of conduction for a triac in both direction is shown on equivalent circuit for two shown voltage polarities



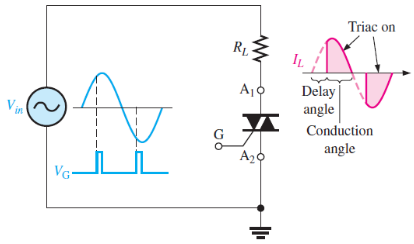
(a) (b) Q_1 and Q_2 on (c) (d) Q_3 and Q_4 on

The conduction of current in both direction for the diac is very similar to the conduction of current in the SCR

11-4: The Diac and Triac

The Triac: An application

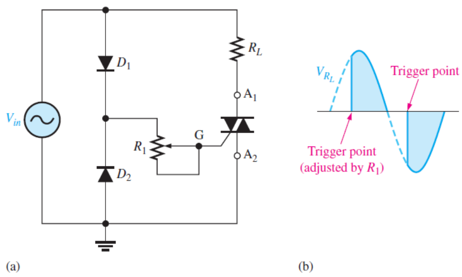
- Triacs are used for control of ac power by the method of phase control as shown. It is used in applications like electric range heating controls, light dimmers, and small motors.



Basic triac phase-control.

- phase control using a triac is illustrated in Figure (a).
- During the positive half-cycle, D_1 conducts → G and A_1 are +ve with respect to A_2 The value of R_1 sets the point on the positive half-cycle at which the triac triggers.

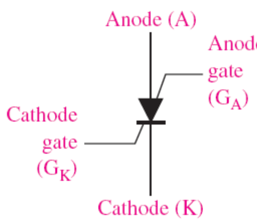
During –ve half cycle, D_2 conducts → G and A_2 are +ve with respect to A_1→ triac conducts during –ve cycle at a trigger point set by R_1



Triac phase-control circuit

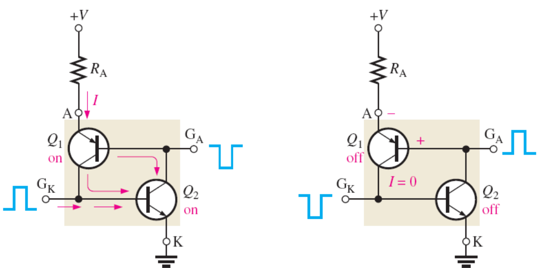
11-5: The Silicon controlled switch (SCS)

- The **SCS** is similar to an SCR but with two gate: (cathod gate, G_K, and Anode gate, G_A) that are us(trigger the device on and off. SCS is also used in similar application for SCR, but with faster turn of
- Turning on SCS; +ve pulse on G_K drive Q_2 into conduction → it provide path for Q_1 to switch on (like SCR). Also, -ve pulse on G_A drive Q_1 into conduction→ provide current for Q_2 base → Q_2 switch on.



- Turning off SCS; +ve pulse on G_A makes EB junction of Q_1 reverse biase → Q_1turns off → Q_2 also cut off

Also, -ve pulse on G_K makes BE of $Q2$ reverse biase → Q_2 turns off and hence Q1 will become off.



(a) *Turn-on*: Positive pulse on G_K *or* negative pulse on G_A

(b) *Turn-off*: Positive pulse on G_A *or* negative pulse on G_K