ĐHBK Tp HCM-Khoa Đ-ĐT
BMĐT
GVPT: Hồ Trung Mỹ
Môn học: Dụng cụ bán dẫn

Chương 5

BJT

1

5.10 Thyristor và các dụng cụ liên quan

2

Giới thiệu

- Thyristor là 1 dụng cụ công suất quan trọng mà được thiết kế để xử lý ***điện áp cao và dòng điện lớn***. Thyristor được sử dụng chính cho các ứng dụng chuyển mạch mà cần dụng cụ đổi từ trạng thái tắt hay chặn sang trạng thái mở hay dẫn, hoặc ngược lại. Cơ chế chuyển mạch trong thyristor khác với BJT.

- Do cấu trúc của dụng cụ thyristor có dải trị số làm việc của dòng và áp rộng hơn nhiều so với BJT. Hiện nay có các thyristor có định mức dòng điện từ vài mA đến hơn 5000A và định mức điện áp trên 10KV.

- Thyristor là dụng cụ 3 cực và có 4 lớp bán dẫn, tên thương mại của thyristor là SCR (Silicon Controlled Rectifier) do hãng GE đặt.

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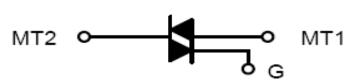
Các ký hiệu sơ đồ mạch của Thyristor

Tên dụng cụ — **Ký hiệu**

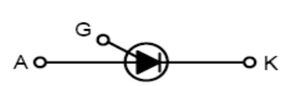
Silicon Controlled Rectifier (SCR)

Triac



Thyristor Surge Protective Devices & Sidac

Programmable Unijunction Transistor (PUT)



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5.10.1 Đặc tính cơ bản

- Hình kế (a) cho thấy mặt cắt ngang của cấu trúc thyristor, nó là dụng cụ 4 lớp p-n-p-n với 3 chuyển tiếp mắc nối tiếp: J1, J2, và J3. Điện cực tiếp xúc với lớp p bên ngoài là được gọi là anode(A) và với lớp n bên ngoại được gọi là cathode(K). Cấu trúc này (không có thêm điện cực nào) là dụng cụ 2 cực và được gọi là diode p-n-p-n. Nếu có thêm điện cực, được gọi là điện cực cổng G (gate), được nối vào lớp p bên trong (p2), kết quả là ta có dụng cụ 3 cực là SCR (semiconductor controlled rectifier) hay thyristor.

- Hình kế (b) cho thấy nồng độ tạp chất tại các lớp của SCR, hình(c) cho thấy giản đồ năng lượng của SCR ở điều kiện cân bằng. Chú ý là mỗi chuyển tiếp có miền nghèo với điện thế nội được xác định bởi các nồng độ tạp chất pha trong SCR.

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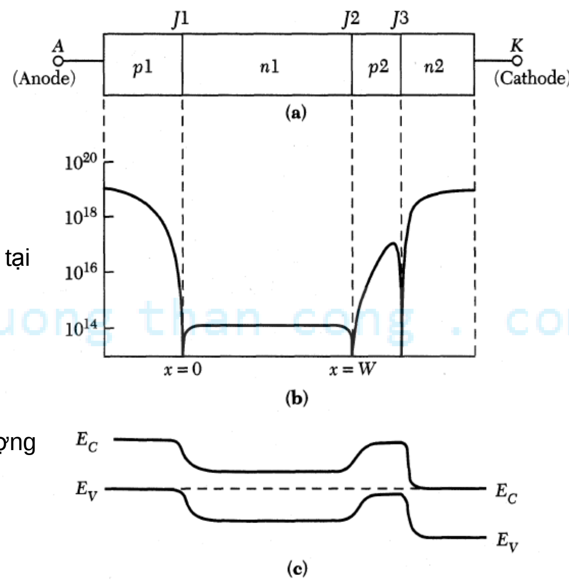
Diode 4 lớp p-n-p-n

a) Cấu trúc của diode 4 lớp p-n-p-n

b) Nồng độ tạp chất tại các lớp của SCR

c) Giản đồ năng lượng



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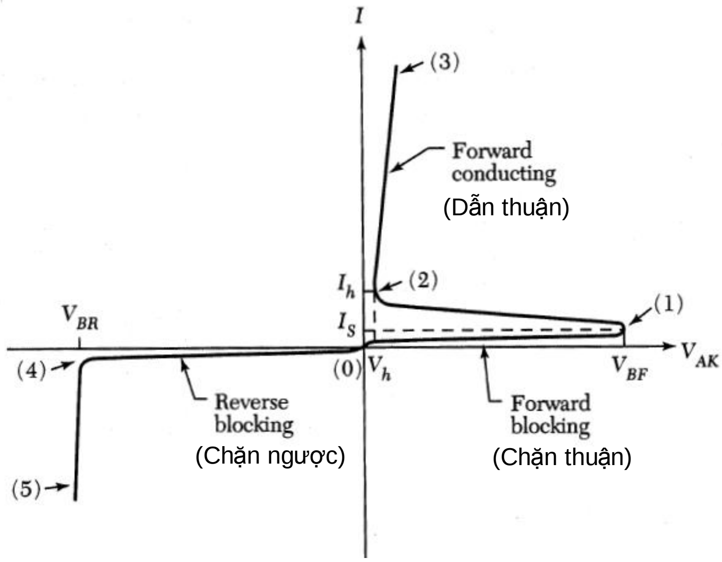
Đặc tuyến dòng-áp của diode p-n-p-n



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Đặc tuyến dòng-áp của diode p-n-p-n (..)

Có 5 miền trong đặc tuyến I-V:

- **0-1:** Dụng cụ ở ***trạng thái tắt*** (off) hay chặn thuận và có tổng trở tất cao. Chuyển trạng thái (hay chuyển mạch) xảy ra ở chỗ *dV/dI* = 0; và ở điểm **1** ta định nghĩa điện áp V_{BF} (hay V_{FB}-FB=forward-breakover), và dòng chuyển mạch I_S.
- **1-2:** Dụng cụ ở trong ***miền điện trở âm***, nghĩa là khi dòng tăng thì áp giảm.
- **2-3:** Dụng cụ ở ***trạng thái dẫn*** (on) hay dẫn thuận và có tổng trở thấp. Ở điểm **2,** với *dV/dI = 0,* ta định nghĩa dòng giữ (holding current) I_h (hay I_H) và điện áp giữ V_h (*hay* V_H).
- **0-4:** Dụng cụ ở ***trạng thái chặn ngược***.
- **4-5:** Dụng cụ ở miền ***đánh thủng ngược***.

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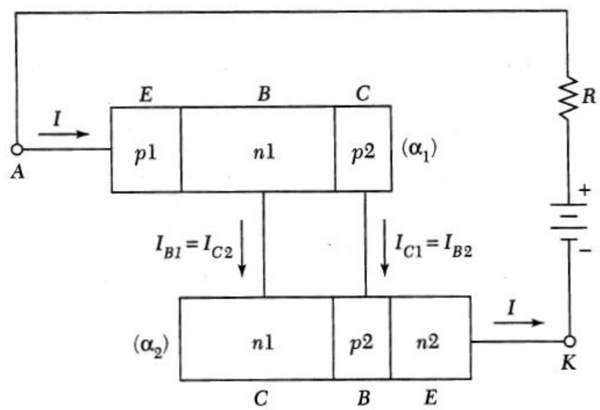
Biểu diễn SCR bằng 2 BJT

- Như vậy diode p-n-p-n làm việc ở miền thuận là dụng cụ lưỡng ổn (bistable device) mà có thể chuyển từ trạng thái tắt (off) dòng thấp, tổng trở cao sang trạng thái dẫn (on) dòng cao, tổng trở thấp, hoặc ngược lại.
- Để hiểu đặc tính chặn thuận, ta xét dụng cụ như 2 BJT nối theo cách sau:



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- Dòng nền của BJT PNP (BJT 1 có $\alpha=\alpha_1$)

$$
\begin{aligned}
I_{B1} &= I_{E1} - I_{C1} \\
&= (1 - \alpha_1)I_{E1} - I_1 \\
&= (1-\alpha_1)I - I_1,
\end{aligned}
$$

  với I_1 là dòng rĩ I_{CBO} của BJT 1.
- Dòng thu của BJT NPN (BJT 2 có $\alpha=\alpha_2$)

$$I_{C2} = \alpha_2 I_{E2} + I_2 = \alpha_2 I + I_2,$$

  với I_2 là dòng rĩ I_{CBO} của BJT 2.
- Vì $I_{B1} = I_{C2}$, ta suy ra được

$$\boxed{I = \frac{I_1 + I_2}{1 - (\alpha_1 + \alpha_2)}}.$$

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EXAMPLE 5

Consider a thyristor in which the leakage currents I_1 and I_2 are 0.4 and 0.6 mA, respectively. Explain the forward-blocking characteristics when $(\alpha_1 + \alpha_2)$ is 0.01 and 0.9999.

SOLUTION The current gains are functions of the current I and generally increase with increasing current. At low currents both α_1 and α_2 are much less than 1, and we have

$$I = \frac{0.4\times10^{-3} + 0.6\times10^{-3}}{1-0.01} = 1.01 \text{ mA}$$

In this case, the current flowing through the device is the sum of the leakage currents I_1 and I_2 ($\cong$ 1 mA).

As the applied voltage increases, the current I also increases, as do α_1 and α_2. This in turn causes I to increase further—a regenerative behavior. When $\alpha_1 + \alpha_2 = 0.9999$,

$$I = \frac{0.4\times10^{-3} + 0.6\times10^{-3}}{1-0.9999} = 10 \text{ A} .$$

This value is 10,000 times larger than $I_1 + I_2$. Therefore, as $(\alpha_1 + \alpha_2)$ approaches 1, the current I increases without limit, that is, the device is at forward breakover. ◀

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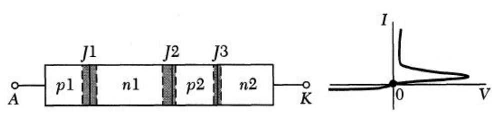
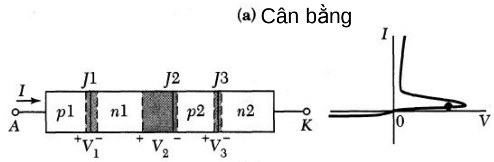
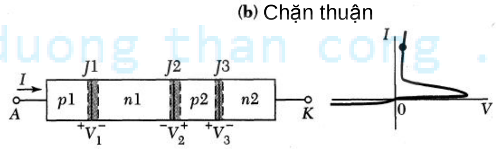
Bề rộng miền nghèo và sụt áp trên thyristor ở các điểm làm việc khác nhau



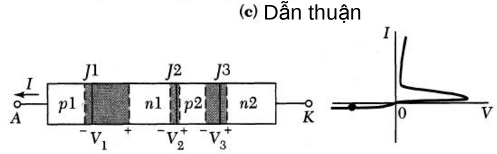
(a) Cân bằng



(b) Chặn thuận



(c) Dẫn thuận



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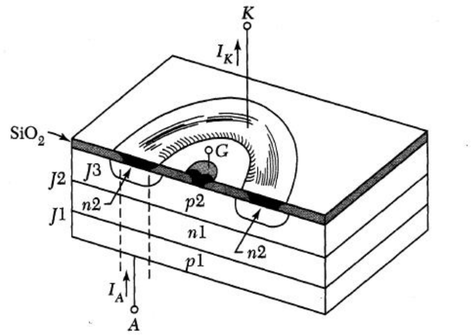
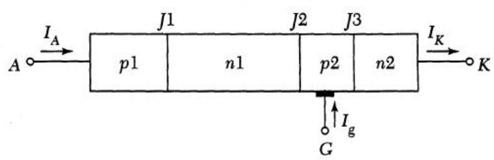
(d) Dẫn ngược

Cấu tạo của SCR



(a) Cấu tạo của SCR 3 cực planar



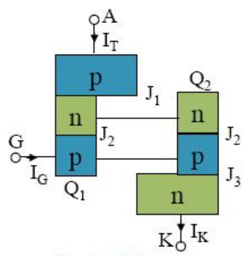
(b) Mặt cắt ngang 1 chiều của SCR planar

Two-Transistor Model of Thyristors

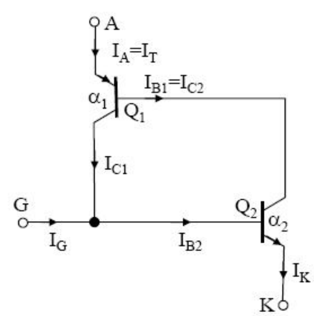
Collector-base junction leakage current

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

Collector current — Collector Emitter current gain — Emitter current



Basic Structure



Equivalent Circuit

$Q_1 \rightarrow$ $$I_{C1} = \alpha_1 I_A + I_{CBO1}$$

$Q_2 \rightarrow$ $$I_{C2} = \alpha_2 I_K + I_{CBO2}$$

$$I_A = I_{C1} + I_{C2} = \alpha_1 I_A + I_{CBO1} + \alpha_2 I_K + I_{CBO2}$$

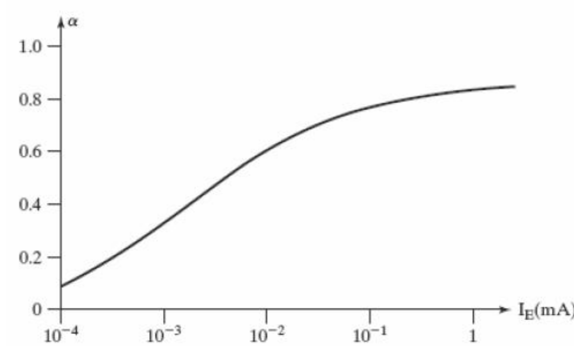
$$I_K = I_A + I_G \Rightarrow I_A = \frac{\alpha_2 I_G + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)}$$

Current Gain with Emitter Current

$\alpha \uparrow$ when $I_E \uparrow$

If I_G is suddenly increased, the anode current I_A will immediately increase.

$\alpha_1, \alpha_2 \uparrow \Rightarrow I_A \uparrow\uparrow$



$$\alpha_1 + \alpha_2 \rightarrow 1 \Rightarrow 1 - (\alpha_1 + \alpha_2) \rightarrow 0 \Rightarrow I_A \uparrow\uparrow\uparrow$$

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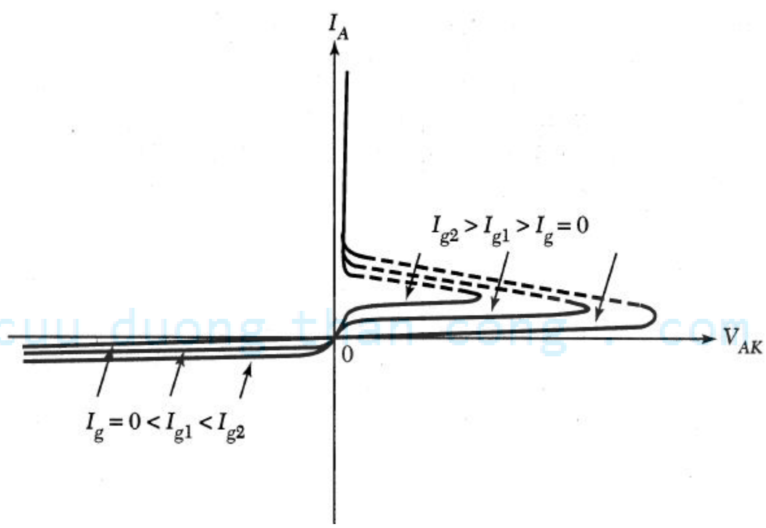
Ảnh hưởng của dòng cổng I_G



Khi dòng cổng I_G tăng thì điện áp chuyển V_{BF} giảm

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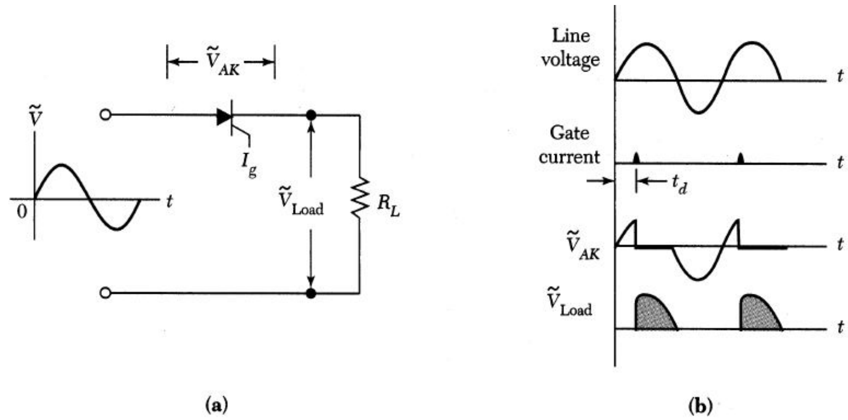
TD: Ứng dụng SCR để điều khiển công suất ra tải



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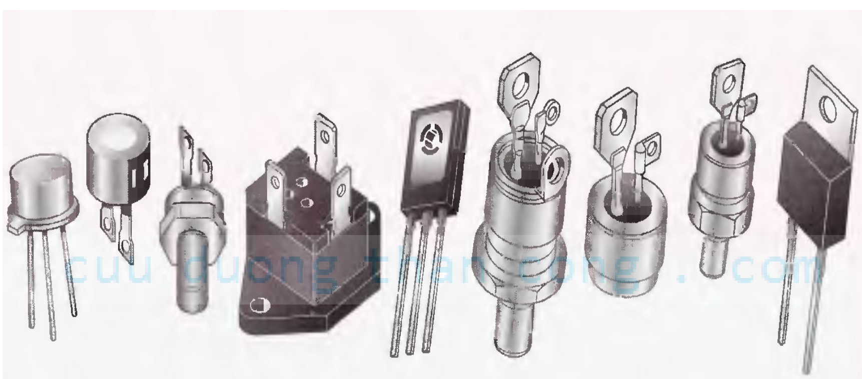
Hình dạng thực tế của Thyristor



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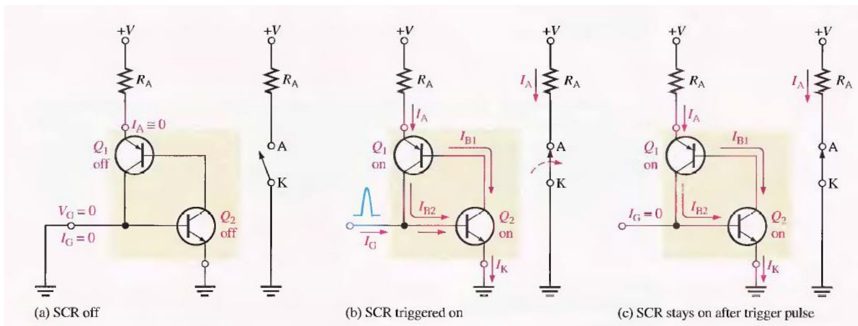

(a) SCR off (b) SCR triggered on (c) SCR stays on after trigger pulse

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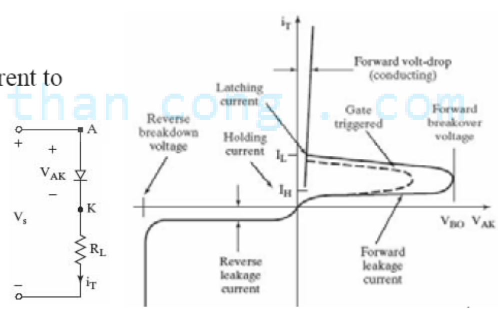
Characteristics of thyristors

- Forward breakdown voltage V_{BO}
  - The voltage of avalanche breakdown
- Latching current I_L
  - The minimum anode current required to maintain the thyristor in the on-state immediately after it is turned on and the gate signal has been removed
- Holding current I_H
  - The minimum anode current to maintain the thyristor in the on-state
- $I_L > I_H$



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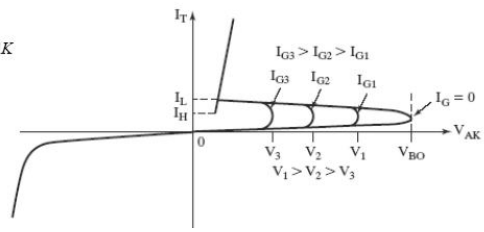
Ways to turn-on thyristors

- Thermals
  - Thermal ionization increasing leakage currents
- Light
  - Photo-ionization increasing leakage currents
- High voltage
  - Voltage V_{AK} higher than V_{BO}
- *dv/dt*
  - Too high rising rate of V_{AK}
- Gate current
  - Normal operation



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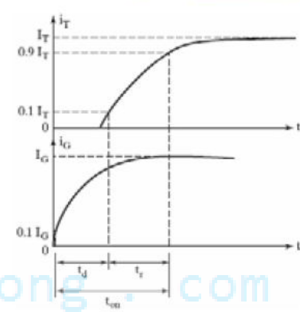
Considerations on gating signals

- The gate signal should be removed after the thyristor is turned on ⇒ To prevent power loss in gate junction
- Even if the thyristor is reverse biased, there should be no gate signal ⇒ To prevent increased leakage current failure
- The width of gate pulse t_G should be longer than the time required for the anode current to rise to the holding current I_H



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Thyristor turn-off characteristics

- A thyristor can be turned off by reducing the forward current to a level below the holding current I_H
- A reverse voltage across the thyristor will accelerate the turn-off process
- Similar to a diode, there is reverse recovery time t_{rr} for a thyristor
- Reverse recovered charge Q_{RR} is the amount of charge that has to be recovered during the turn-off process
- The inner *pn*-junction J_2 requires a recombination time t_{rc} to recombine the excess carriers
- A negative reverse voltage would reduce the recombination time
- The turn-off time t_q is the sum of t_{rr} and t_{rc} , and is the minimum time interval required for a thyristor to withstand forward voltage

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Thyristor Turn Off

$i_T < I_H$ ➡ Thyristor turns off

- ❑ If anode current is maintained below the holding current during a sufficient long time for all excess carriers in the four layers to be swept out or recombined, then the thyristor turns off completely.
- ❑ There are two main types of techniques to turn off a thyristor:
  - ❖ Line commutation
  - ❖ Forced commutation

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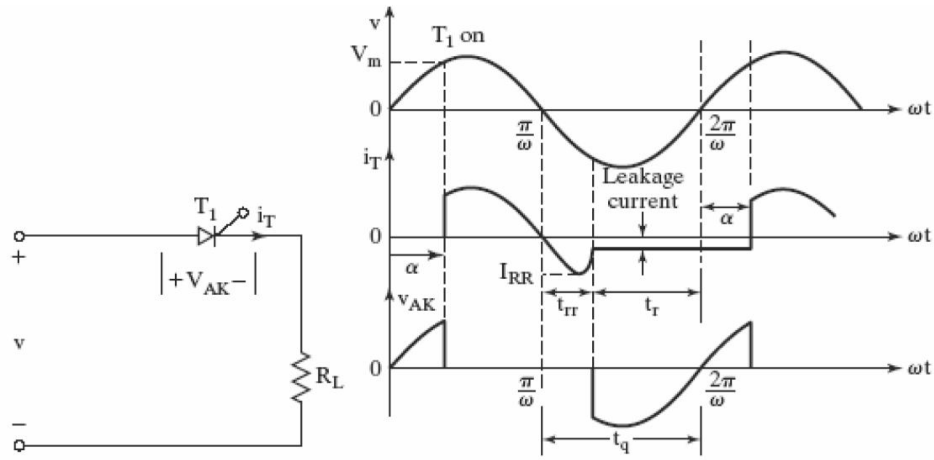
Thyristor Turn-Off: Line-Commutated Thyristor Circuit



(a) Line-commutated thyristor circuit

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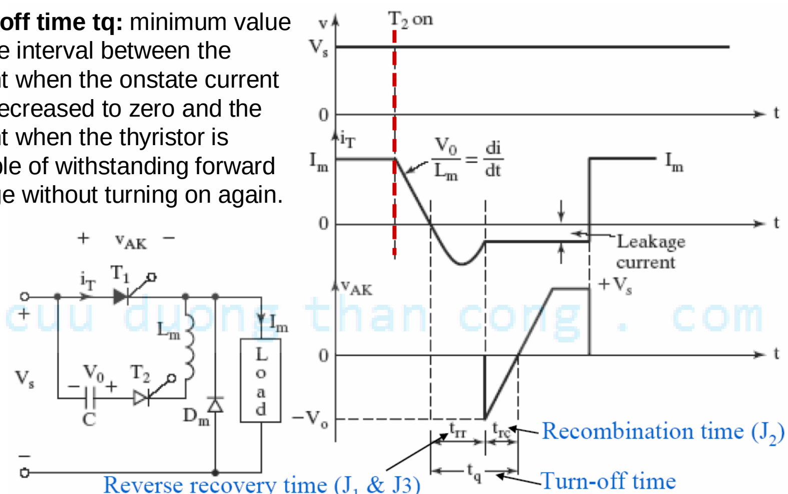
Thyristor Turn-Off: Forced-Commutated Thyristor Circuit

Turn-off time tq: minimum value of time interval between the instant when the onstate current has decreased to zero and the instant when the thyristor is capable of withstanding forward voltage without turning on again.



(b) Forced-commutated thyristor circuit

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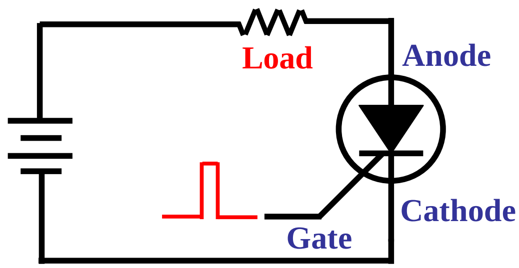
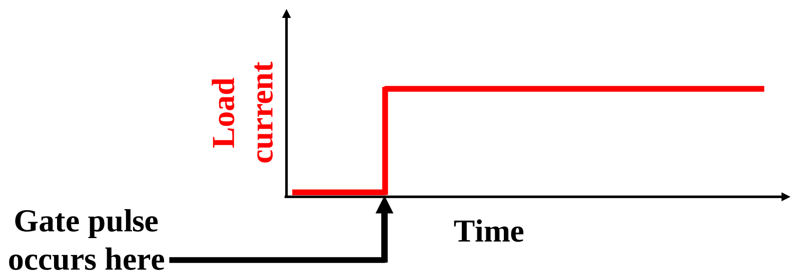
The SCR can be turned on at its gate terminal.

With a dc source, the SCR stays on after it is gated.





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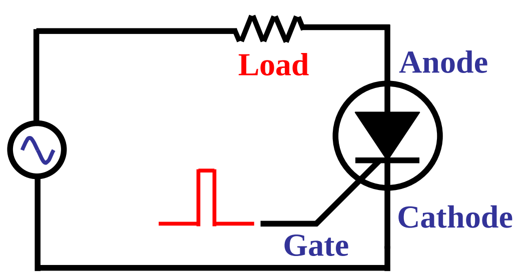
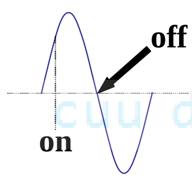
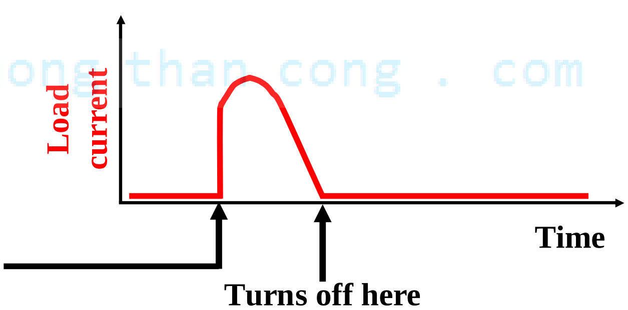
With an ac source, the SCR turns off at the zero-crossing.







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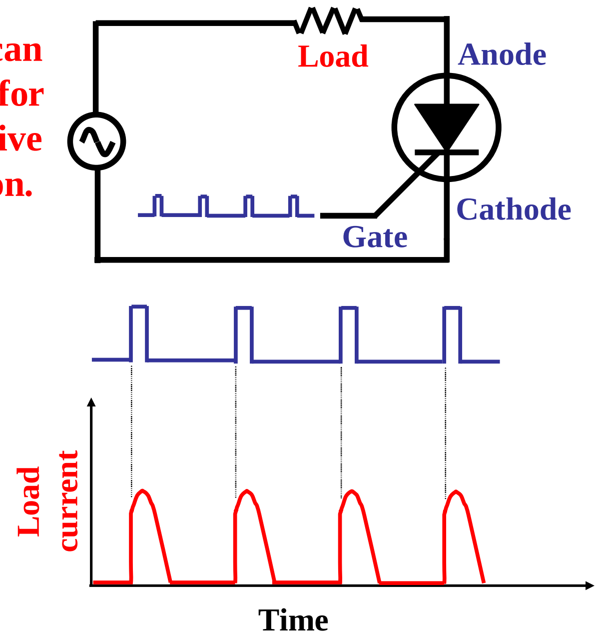
The gate can be pulsed for each positive alternation.



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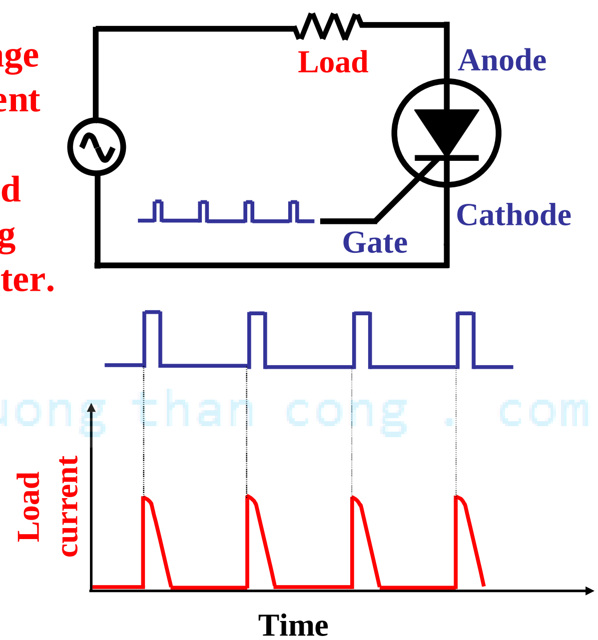
The average load current can be decreased by gating the SCR later.



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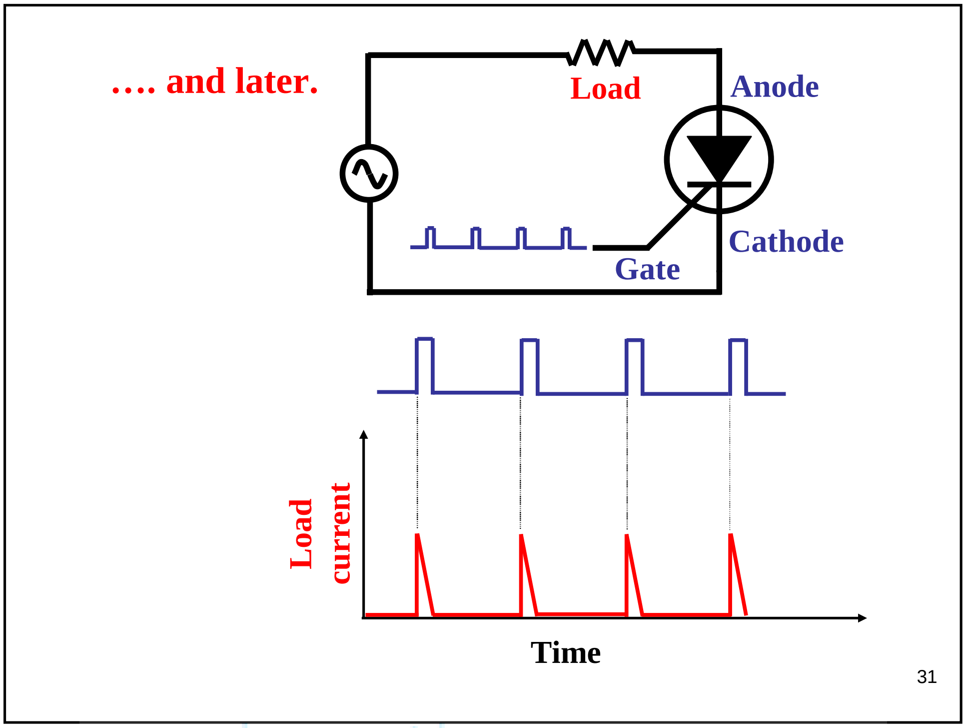
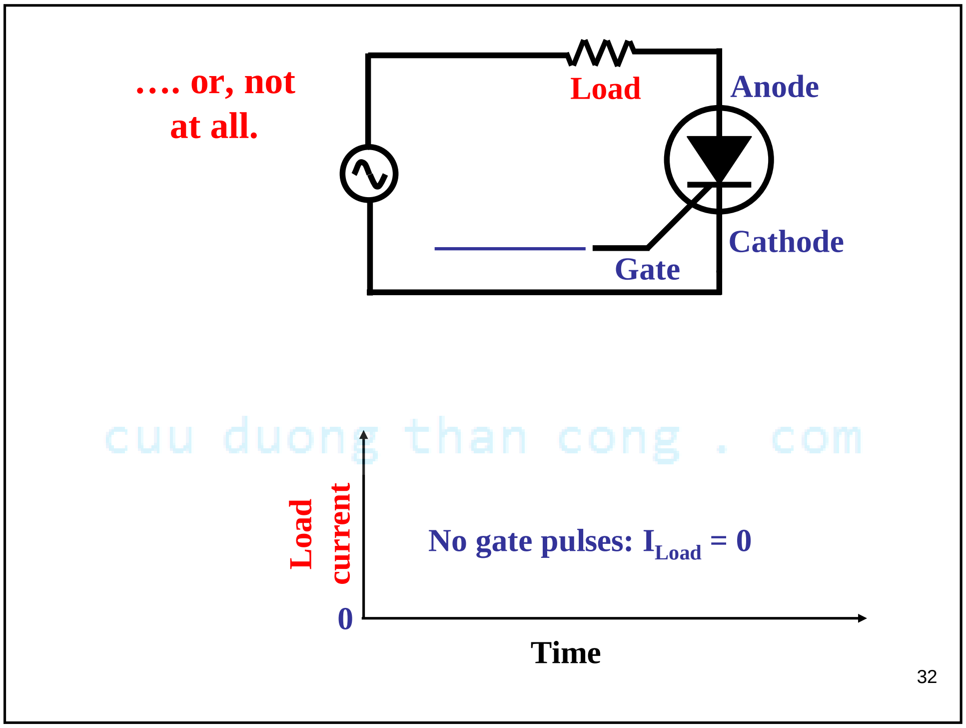
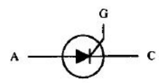
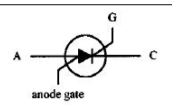
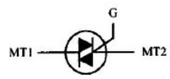
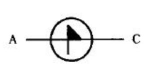
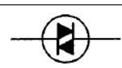


…. and later.
Load
Anode
Cathode
Gate
Load current
Time
31



…. or, not at all.
Load
Anode
Cathode
Gate
No gate pulses: $I_{Load} = 0$
Load current
0
Time
32

Major Kinds of Thyristors

TYPE	SYMBOL	MODE OF OPERATION
Silicon-controlled rectifier (SCR)		Normally off, but when a small current enters its gate (*G*), it turns on. Even when the gate current is removed, the SCR remains on. To turn it off, the anode-to-cathode current flow must be removed, or the anode must be set to a more negative voltage than the cathode. Current flows in only one direction, from anode (*A*) to cathode (*C*).
Silicon-controlled switch (SCS)		Similar to an SCR, but it can be made to turn off by applying a positive voltage pulse to a four-lead, called the *anode gate*. This device also can be made to trigger on when a negative voltage is applied to the anode-gate lead. Current flows in one direction, from anode (*A*) to cathode (*C*).
Triac		Similar to a SCR, but it can switch in both directions, meaning it can switch ac as well as dc currents. A triac remains on only when the gate is receiving current, and it turns off when the gate current is removed. Current flows in both directions, through *MT*1 and *MT*2.
Four-layer diode		It has only two leads. When placed between two points in a circuit, it acts as a voltage-sensitive switch. As long as the voltage difference across its leads is below a specific breakdown voltage, it remains off. However, when the voltage difference exceeds the breakdown point, it turns on. Conducts in one direction, from anode (*A*) to cathode (*C*).
Diac		Similar to the four-layer diode but can conduct in both directions. Designed to switch either ac or dc.

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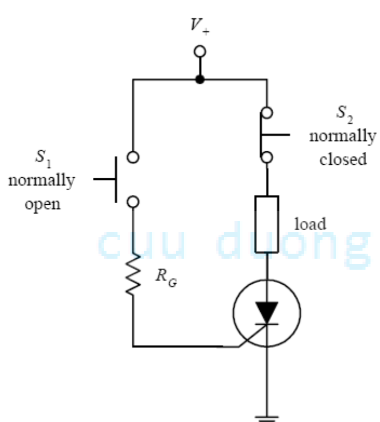
Các ứng dụng cơ bản của SCR

BASIC LATCHING SWITCH



Here, an SCR is used to construct a simple latching circuit. S_1 is a momentary contact, normally open pushbutton switch, while S_2 is a momentary contact, normally closed pushbutton switch. When S_1 is pushed in and released, a small pulse of current enters the gate of the SCR, thus turning it on. Current will then flow through the load. The load will continue to receive current until the moment S_2 is pushed, at which time the SCR turns off. The gate resistor acts to set the SCR's triggering voltage/current. We'll take a closer look at the triggering specifications in a second.

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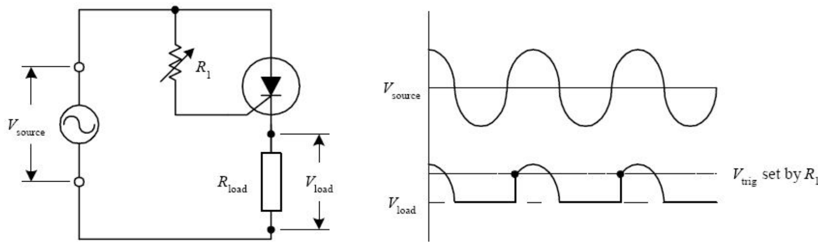
ADJUSTABLE RECTIFIER



Here, an SCR is used to rectify a sinusoidal signal that is to be used to power a load. When a sinusoidal waveform is applied to the gate, the SCR turns on when the anode and gate receive the positive going portion of the waveform (provided the triggering voltage is exceeded). Once the SCR is on, the waveform passes through the anode and cathode, powering the load in the process. During the negative going portion of the waveform, the SCR acts like a reverse-biased diode; the SCR turns off. Increasing R_1 has the effect of lowering the current/voltage supplied to the SCR's gate. This in turn causes a lag in anode-to-cathode conduction time. As a result, the fraction of the cycle over which the device conducts can be controlled (see graph), which means that the average power dissipated by R_{load} can be adjusted. The advantage of using an SCR over a simple series variable resistor to control current flow is that essentially no power is lost to resistive heating.

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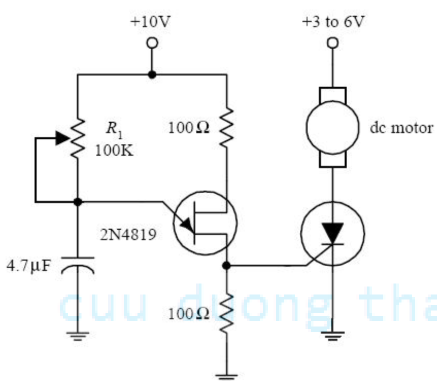
DC MOTOR SPEED CONTROLLER



An SCR along with a few resistors, a capacitor, and a UJT can be connected together to make a variable-speed control circuit used to run a dc motor. The UJT, the capacitor, and the resistors make up an oscillator that supplies an ac voltage to the SCR's gate. When the voltage at the gate exceeds the SCR's triggering voltage, the SCR turns on, thus allowing current to flow through the motor. Changing the resistance of R_1 changes the frequency of the oscillator and hence determines the number of times the SCR's gate is triggered over time, which in turn controls the speed of the motor. (The motor appears to turn continuously, even though it is receiving a series of on/off pulses. The number of on cycles averaged over time determines the speed of the motor.) Using such a circuit over a simple series variable resistor to control the speed of the motor wastes less energy.

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