Physics of Semiconductor Devices – Chapter 4: ***Thyristors***

- 4.1: Introduction
- 4.2: Basic characteristics
- 4.3: Shockley diode and three-terminal thyristor
- 4.4: Related power thyristors
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- 4.6: Unijunction transistor and trigger thyristor
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Student presentations

4.1: Introduction

- The word “thyristor” comes from the word “gas thyratron”, which was an old-fashioned gas-based device having roughly the same electrical characteristics as the semiconductor-based thyristor.
- Basically, a thyristor is a switch which has a forward high impedance low current OFF state and a forward low impedance high current ON state.
- In general terms a thyristor is a semiconductor device of the type pnpn or npnp, i.e., a four-layer device. A two-terminal thyristor is often called a Shockley diode.
- A theoretical description of how a thyrisor works was developed by Moll et al. (J.L. Moll, M. Tanenbaum, J.M. ‘Goldley and N. Holonyak, “p-n-p-n Transistor Switches”, Proc. IRE 44, 1174 (1956)).
- It is typically used in the high voltage, high current regime (typically 10 kV, 5kA)

4.2: Basic characteristics

Shockley diode

Thyristor

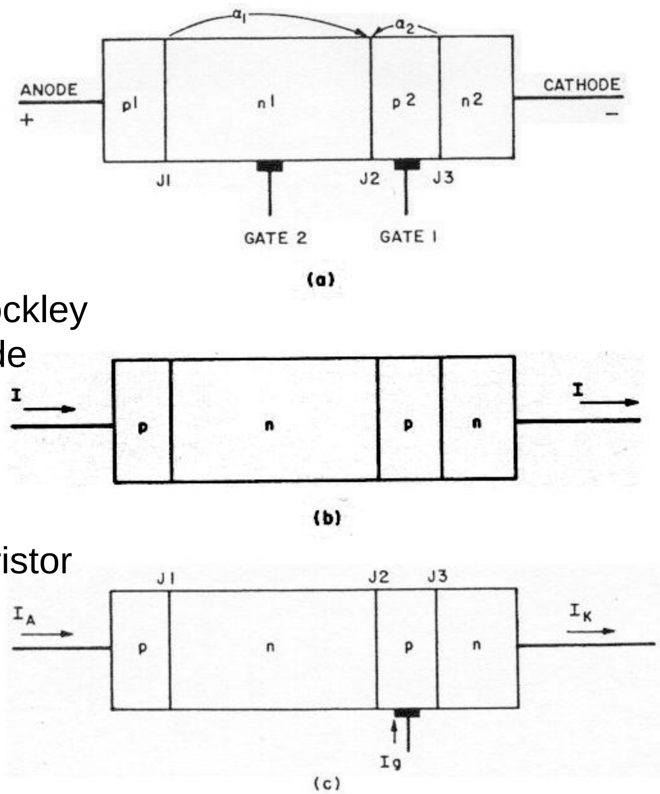


Fig. 1 (a) General thyristor with anode, cathode, and two gate electrodes. There are three *p-n* junctions in series J1, J2, and J3. Current gain α_1 is for the *p-n-p* transistor and α_2 for the *n-p-n*. Under forward blocking condition, as shown, the center junction J2 is reverse-biased and serves as a common collector for the *p-n-p* and *n-p-n* transistors. (b) Two-terminal *p-n-p-n* diode (Shockley diode). (c) Three-terminal thyristor.

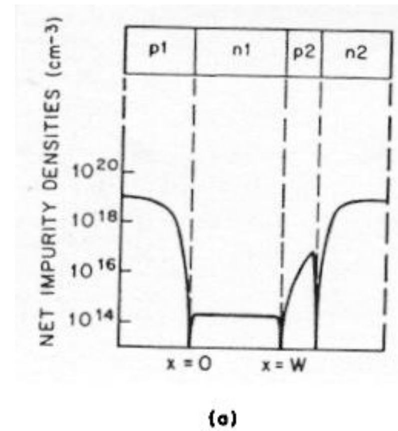


Fig.2a: Typical doping profiles in a thyristor

In these lectures I use the term ‘thyristor’ to denote also the ‘Shockley diode’

4.2: Basic characteristics

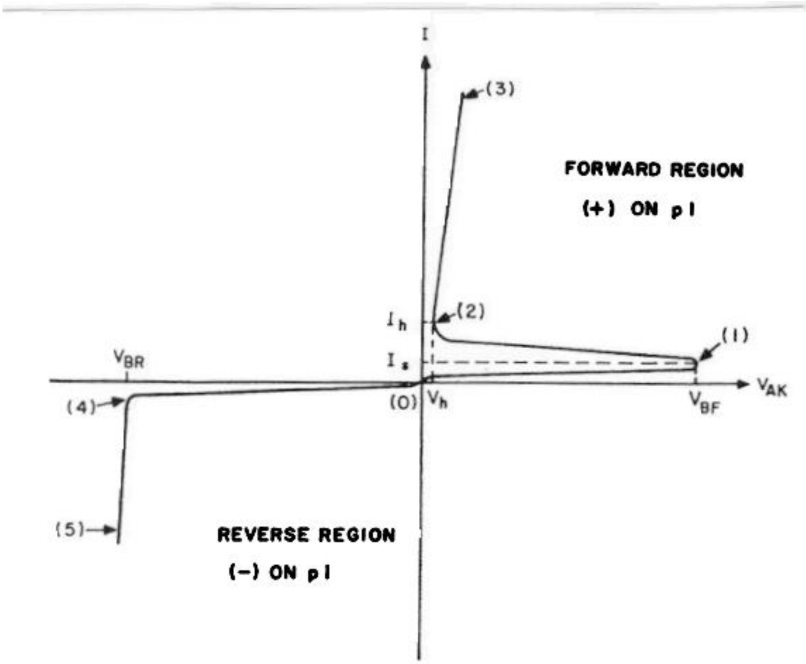


Fig. 3 Current–voltage characteristics of a thyristor.

- (0)-(1): Forward blocking (or OFF) state
- (1): Forward breakover (at breakover voltage V_{BF} and switching current I_s)
- (1)-(2): Negative resistance region
- (2): Holding state (at holding voltage V_h and holding current I_h)
- (2)-(3): Forward conducting (or ON) state
- (0)-(4): Reverse blocking state
- (4)-(5): Reverse breakdown state

Forward OFF, breakover and ON

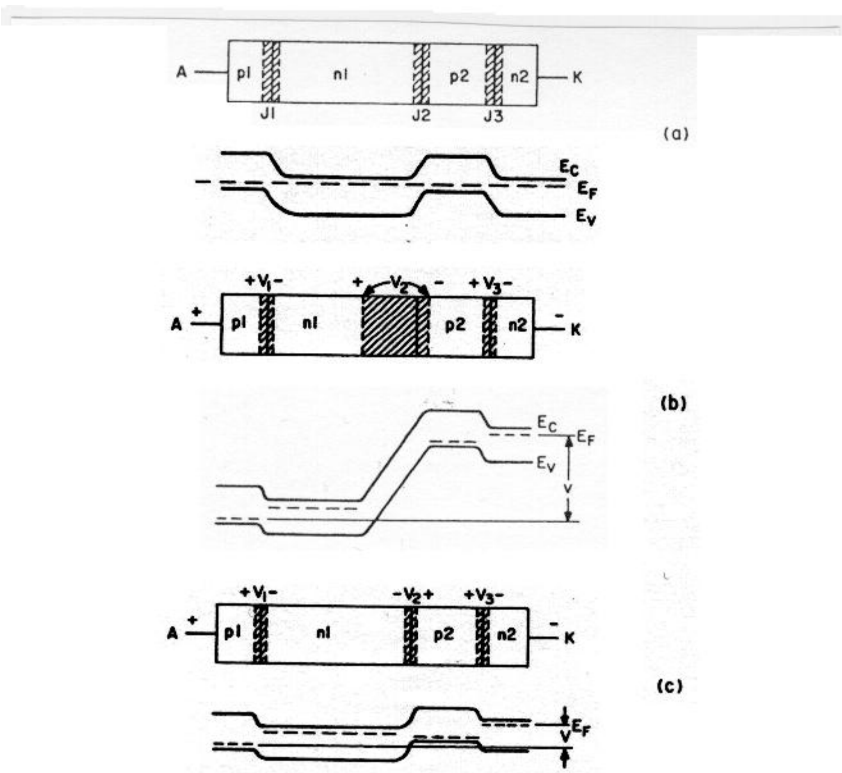


Fig. 10 Energy-band diagram for forward regions. (*a*) Equilibrium condition. (*b*) Forward OFF state, where most of the voltage drops across the center junction J2. (*c*) Forward ON state, where all three junctions are forward-biased.

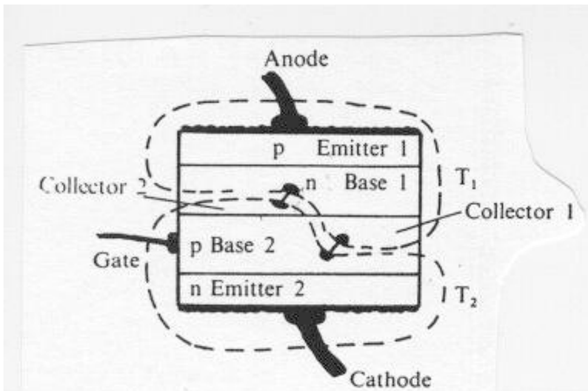
(a) In equilibrium

(b) In the forward OFF-state: J1 and J3 are forward biased, J2 is reverse biased

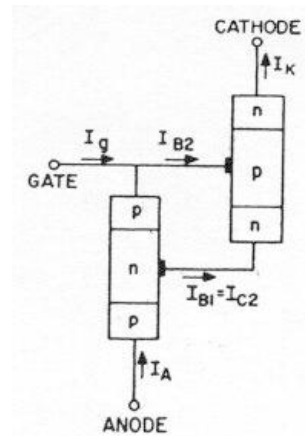
(c) In the forward ON state: All junctions are forward biased

Between forward OFF state and forward ON state, there is a breakover point (besides the negative resistance region and holding state), which will be investigated next.

Analysis of forward OFF and forward breakover (a model borrowed from transistors)

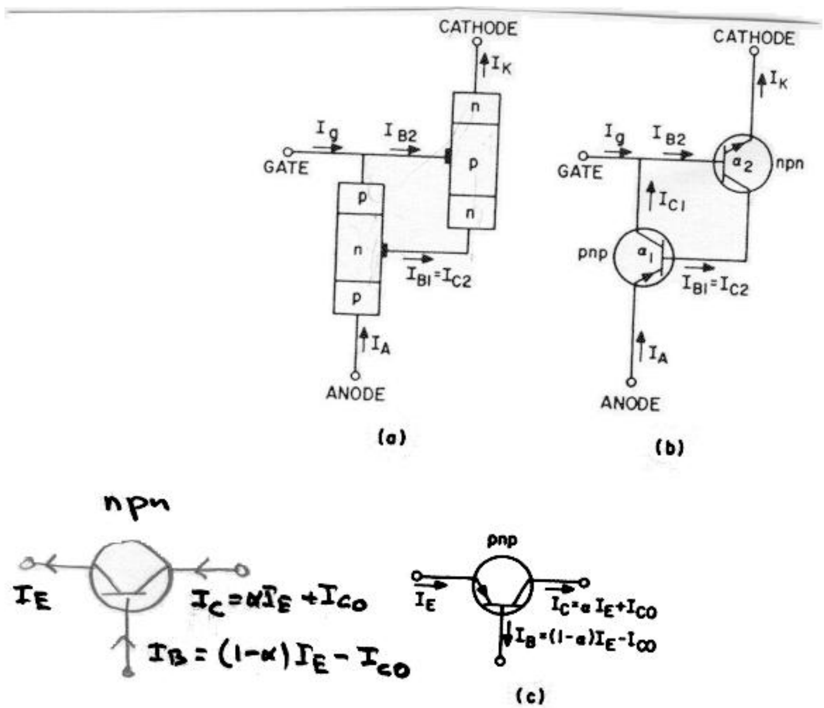


A thyristor can be partitioned into two closely coupled transistors, one npn and one pnp



Resulting transistor equivalent

Analysis of forward OFF and forward breakover



This model describes the forward OFF state up to forward breakover. It results in a regenerative behaviour (amplification in the constituent transistors).

From the transistor model we get

$$I_{B1}=(1-\alpha_1)I_A-I_{CO1}$$

$$I_{C2}=\alpha_2 I_K+I_{CO2}$$

Leakage currents

Since $I_{B1}=I_{C2}$ (see fig)

$$(1-\alpha_1)I_A-I_{CO1}=\alpha_2 I_K+I_{CO2}$$

Furthermore, since

$I_A+I_g=I_K$ we get

$$I_A=\frac{\alpha_2 I_g+I_{CO1}+I_{CO2}}{1-(\alpha_1+\alpha_2)}$$

α_1 and α_2 are increasing functions of I_A, such that they are small for small I_A and $(\alpha_1+\alpha_2)$ approaches unity for larger currents. Thus I_A grows, giving rise to **forward breakover**.

Analysis of forward OFF and forward breakover

From the expression just derived,

$$I_A = \frac{\alpha_2 I_g + I_{CO1} + I_{CO2}}{1-(\alpha_1+\alpha_2)}$$

we find that

$$\frac{dI_A}{dI_g} = \frac{\alpha_2}{1-(\alpha_1+\alpha_2)}$$

This instability at breakover may result in a large anode current not only caused by a small gate current (as in this derivation), but also by a slight increase in tempera-ture.

The forward breakover point can also be obtained by assuming that the junction J2 starts to go into ava-lanche (see the book, p.205-206). There an expression is derived for the forwared breakover voltage V_{BF}:

$$V_{BF} = V_B(1-\alpha_1-\alpha_2)^{1/n}$$

where *n* is a constant (approx. 4-6) and V_B is the breakdown voltage at the junction J1.
Again, the importance of the expression $(1-\alpha_1-\alpha_2)$ and its role in describing the **instability** at forward breakover is evident.

Analysis of forward ON state

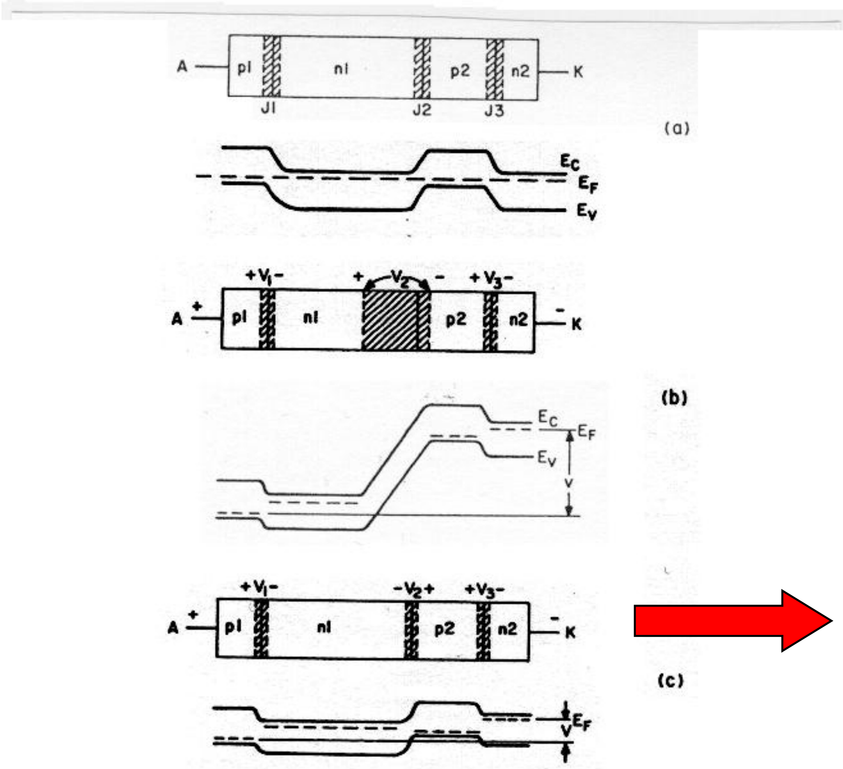
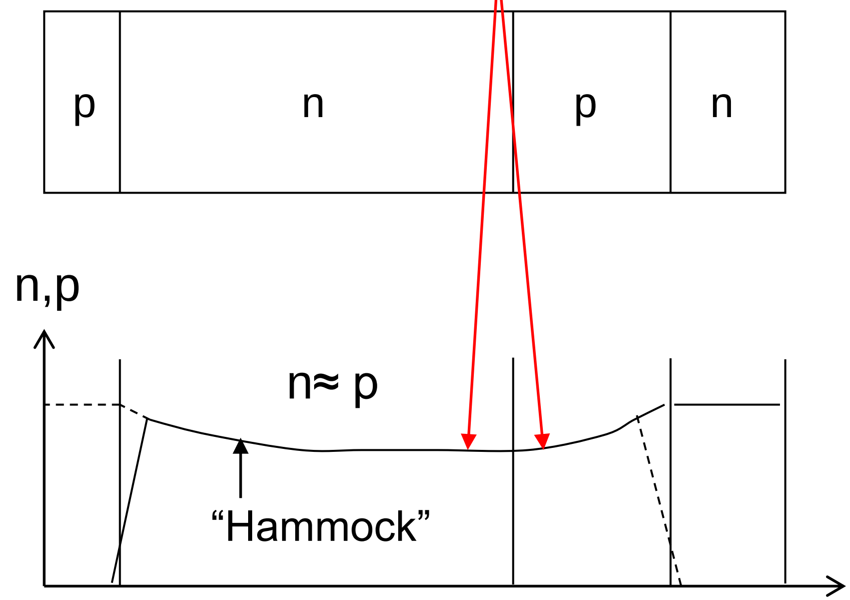


Fig. 10 Energy-band diagram for forward regions. (*a*) Equilibrium condition. (*b*) Forward OFF state, where most of the voltage drops across the center junction J2. (*c*) Forward ON state, where all three junctions are forward-biased.

The high electron-hole concentration floods J2, screening out the electric field from the ionized dopants, thereby reducing the reverse bias.



n

p

Analogous to a pin diode

Analysis of forward ON state

• The effects of lifetime

- Let τ denote the electron/hole lifetime when $n \approx p$: $R = n/\tau$.
- For large life times, a high density electron-hole plasma can be built up and the large concentration of charge carriers gives a high current for a given potential drop across the thyristor.
- For small lifetimes, only a low density electron-hole plasma can be built up, resulting in a relatively low current for a given potential drop across the thyristor.

Reverse blocking and breakdown voltage

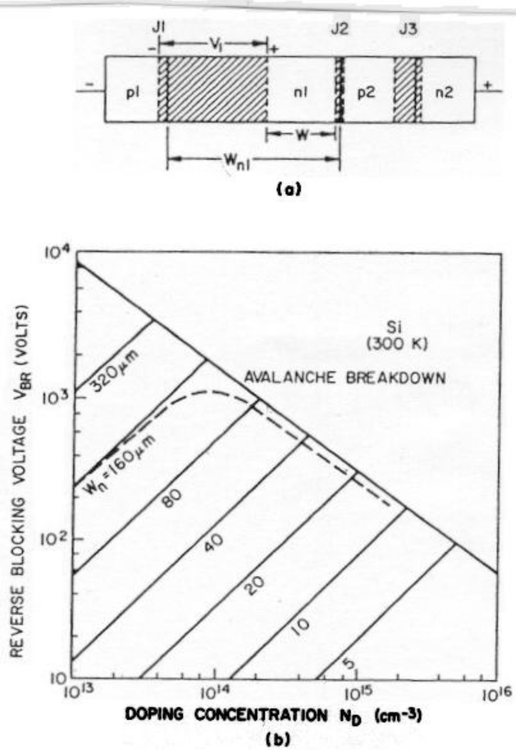


Fig. 4 Reverse blocking capability of a thyristor. The avalanche breakdown line indicates the maximum voltage attainable in the *n*1 layer with doping concentration as a parameter. The parallel lines indicate the punch-through of the *n*1 layer for various layer widths. (After Herlet, Ref. 9.)

- Under reverse blocking, junctions J1 and J3 are reverse biased.
- Breakdown (i.e., large reverse current) happens **either if** J1 goes into avalanche **or** if the depletion region reaches the junction J2 (punch through)
- In the latter case holes in the p2 region diffuse to J2 and is accelerated by the strong electric field in the depletion region. When they reach the p1 region, electrons are pulled in from the contact. In this way a large current is set up in the reverse direction.

Reaching for high breakdown voltages: Beveled structures

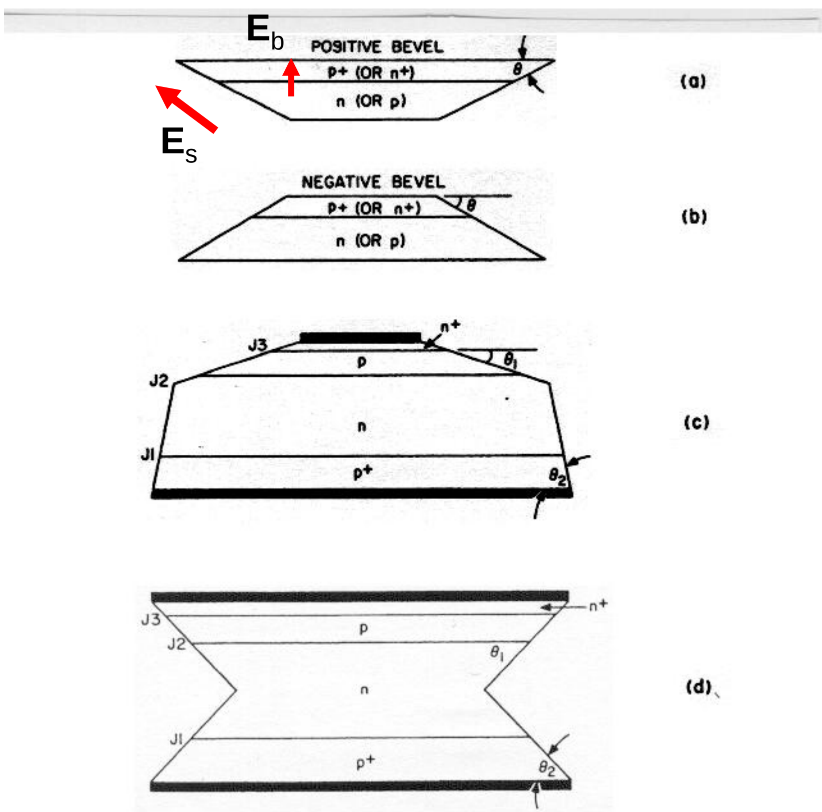


Fig. 6 (a) Positive bevel angle. (*b*) Negative bevel angle. (*c*) Thyristor with one negative bevel angle and one positive bevel angle. (*d*) Thyristor with two positive bevel angles.

- Typical high-voltage high-current (=power) thyristors look like CD-discs (without the hole in the middle).
- By choosing appropriate doping and n1-layer thickness, high breakdown voltages **inside** the thyristor can be achieved.
- On the (circular) edge, however, breakdown in the air can take place at much lower voltages.
- To avoid this, different types of edge profiles can be used (beveled edges).
- By using beveled structures, the surface field $\mathbf{E}_s$ can be lowered significantly compared to the bulk field $\mathbf{E}_b$, ensuring that the breakdown will occur uniformly in the bulk.

4.3.1: Thyristor Turn-On

Ways to turn on a thyristor are

- Voltage triggering
  - Slowly increasing the anode current to pass the holding current (see figure on the right)
  - High dV/dt
- Gate current triggering
- Light triggering

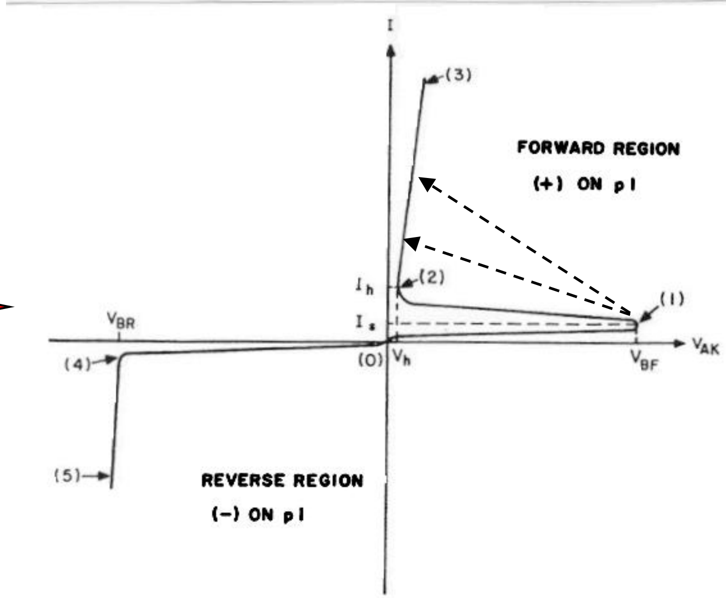
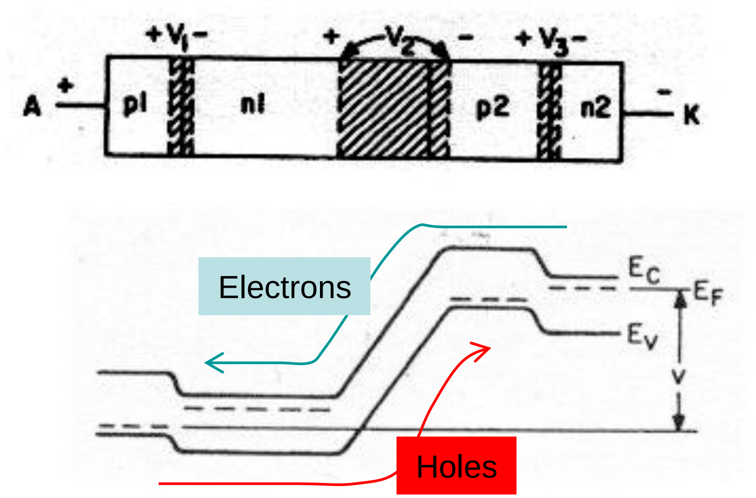


Fig. 3 Current–voltage characteristics of a thyristor.

Thyristor Turn-On

- ***High dV/dt,*** i.e., rapid increase of the voltage across the thyristor
- When the voltage is suddenly increased, so that almost no recombination has time to take place, ‘all’ holes injected from A and ‘all’ electrons from K diffuse to the reverse-biased junction J2, flooding this junction and thereby reducing the reverse bias, starting a forward ON current.
- Alternatively, the large current associ-ated with the rapid motion of charge makes the sum of the alphas approach unity, thereby turning on the thyristor.
- This may reduce the breakover voltage to half or less of its static value.



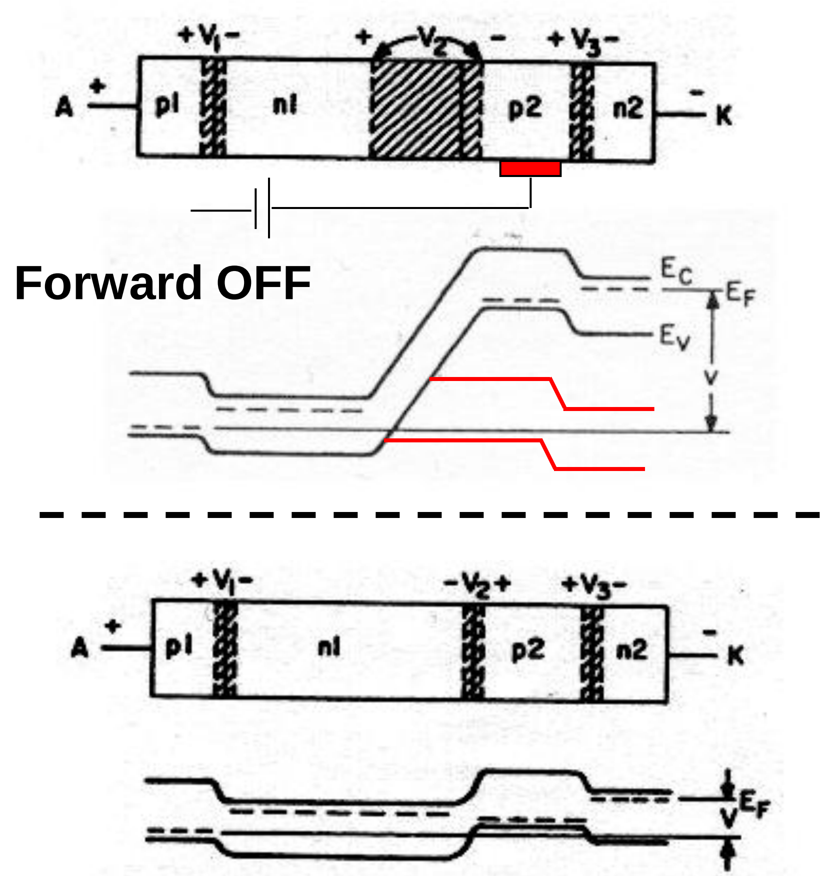
Forward OFF

Thyristor Turn-On

- ***Gate current triggering***
- With a positive gate voltage on the p2 layer for a thyristor in the forward OFF state, the reverse bias in the junction J2 can be reduced considerably, increasing the thyristor current considerably.
- In addition, this increase in thyristor current makes the sum of the alphas approach unity:

$$I_A = \frac{\alpha_2 I_g + I_{CO1} + I_{CO2}}{1-(\alpha_1+\alpha_2)}$$

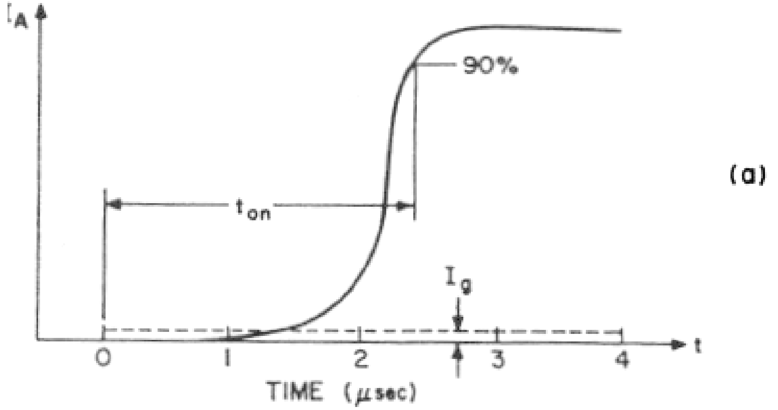
- The thyristor is turned ON.
- The GTO (Gate Turn Off Thyristor) works in this way.



Forward ON

Thyristor Turn-On

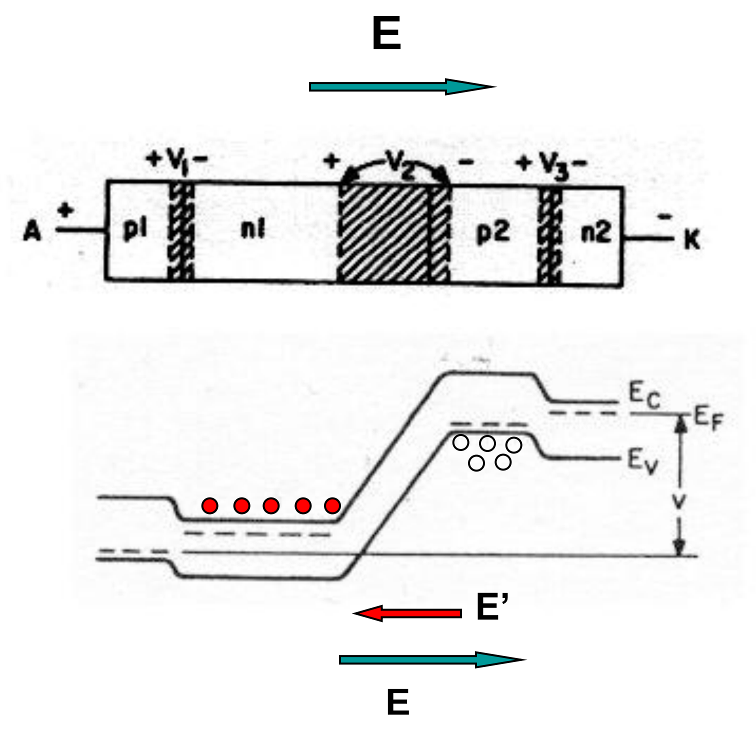
- Turn-on characteristics when a gate current I_g is applied at time zero
- The figure shows the delay in time before the thyristor is fully turned ON.



Thyristor Turn-On

- ***Light triggering***

- If light of appropriate energy hits the reverse biased junction J2, the generated electrons will move to the n1 side and the generated holes will move to the p2 side.
- This creates an electric field which <u>counteracts</u> the forward OFF state reverse bias (at J2), and a current will begin to flow.
- For the same reason as for a gate current triggered thyristor, the thyristor goes into its forward ON state.

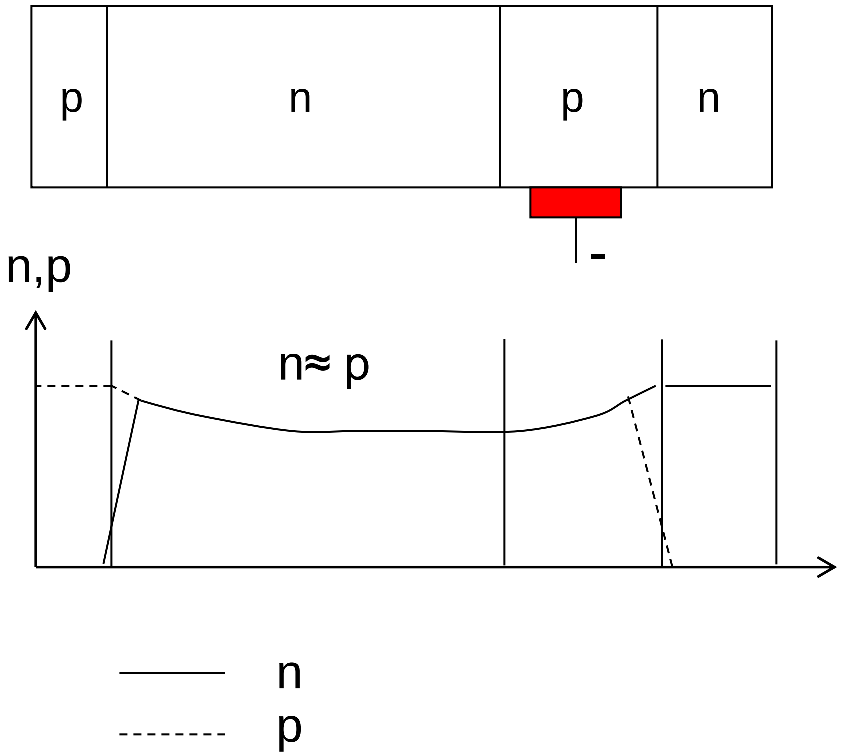


Thyristor Turn-Off

- To turn off the thyristor, the electron-hole plasma in it must either be made to disappear through recombination or be pulled out from the device (through the contacts).

<u>Ways to turn off a thyristor are</u>:

- Reducing the current below the holding current
- Reversing the anode current below zero (current controlled turn off)
  - Charge pulled out through the anode-cathode contacts + recombination
- Changing the polarity of the voltage (voltage controlled turn off)
  - Charge pull out + recombination
- Applying a negative gate voltage
  - Charge pulled out through the gate + recombination
  - The junction J3 is forced to become reverse biased, thus opposing injection of electrons into the device.

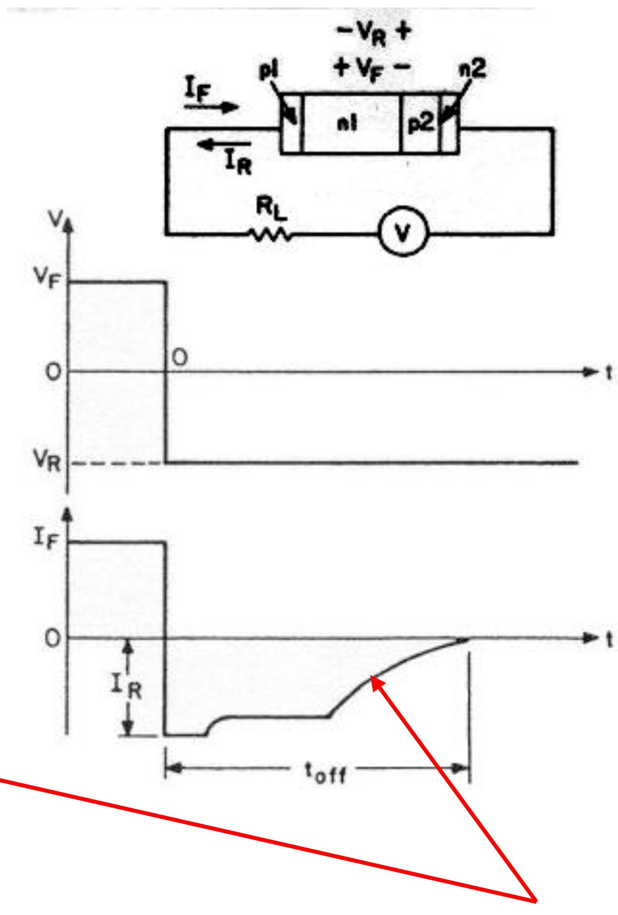


A GTO (Gate Turn-off) thyristor can be both turned on <u>and</u> turned off with a gate electrode.

Thyristor Turn-Off

Voltage-controlled turn off of a thyristor

- Turn-off characteristics where the voltage suddenly changes polarity.
- The tail during the later part of the switch-off mode is mainly due to recombination inside the device.



Thyristor Turn-Off

Current-controlled turn-off of a thyristor

- In many applications an external circuit turns off the thyristor by reducing the current through it.
- After the current has gone through zero, a (negative) voltage builds up at the same time as there is a reverse current (pulled-out charge from the device).
- The simultaneous occurrence of current and voltage represents a power loss (P=U·I).
- This power loss has important consequences on the design of thyristors and leads to expensive cooling equipment!!!

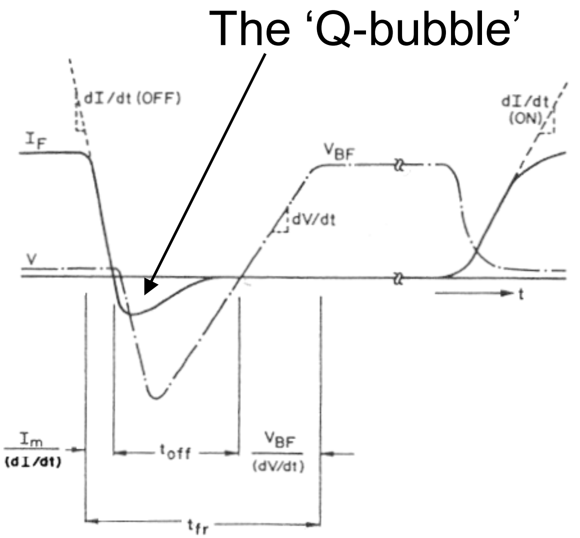


Fig. 23 Terminal voltage and current variations in a thyristor during switching. (After Roberts and Wilkinson, Ref. 33.)

A common application of thyristors

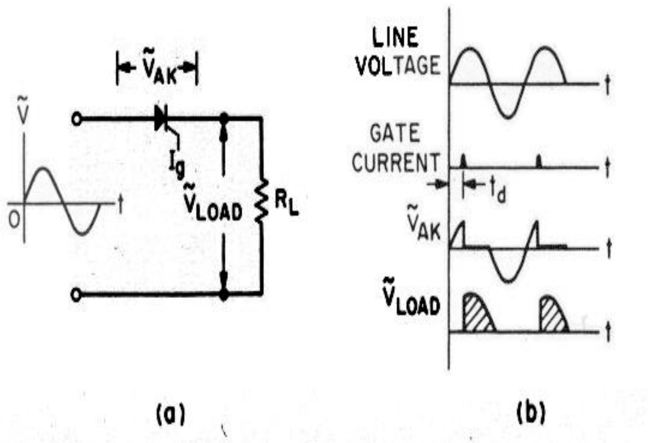


Fig. 33 (*a*) Schematic circuit for a thyristor application. (*b*) Wave forms of voltages and gate current.

- The load may for instance be a light bulb or a heater
- If the turn-on gate current pulses are delivered near the beginning of each cycle, more power is delivered to the load.
- If the gate current pulses are delayed, the thyristor will not turn on until later in the cycle, and less power will be delivered to the load.
- One common aplication of thyristors is as ‘dimmers’.

4.4: Related power thyristors

Some common power thyristors:

- GTO (Gate Turn-Off) thyristor
- Light-activated thyristors
- RCT (Reverse Conducting Thyristors)

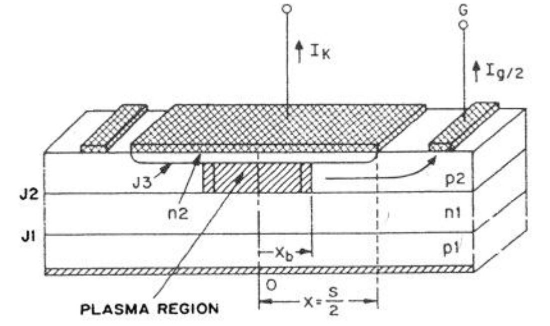


Fig. 32 Plasma focusing in the *p* base of a gate turn-off thyristor. (After Wolley, Ref. 36.)

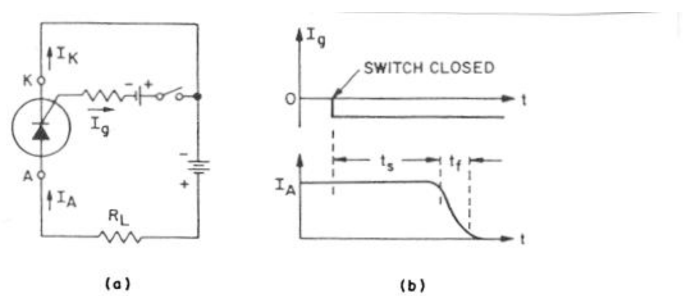


Fig. 31 (*a*) Circuit diagram for gate turn-off thyristor, GTO. (*b*) Turn-off characteristics of a GTO. (After Wolley, Ref. 36.)

4.4: Related power thyristors

- Light-triggered (or light activated) thyristor

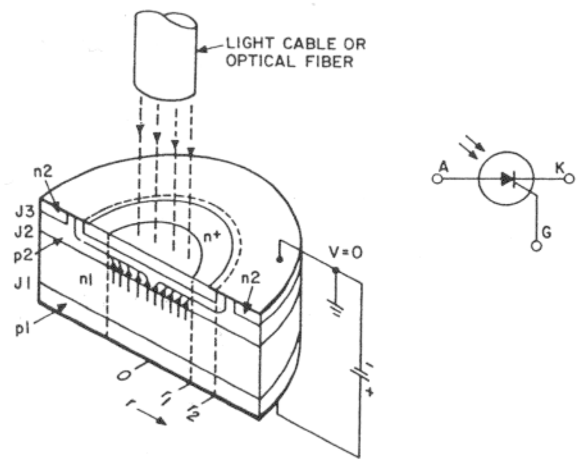


Fig. 28 Schematic diagram and symbol of a light-activated thyristor having a shorted cathode. (After Gerlach, Ref. 35.)

4.4: Related power thyristors

Reverse Conducting Thyristor (RCT)

- Both the anode and cathode are shorted.
- When the RCT is in the reverse bias, the electrons (holes) on the anode (cathode) side enter the device through the n^+ (p) region between the p- (n-) type islands.
- Hence, no reverse biased junction stops the current, and the RCT can conduct in both directions.

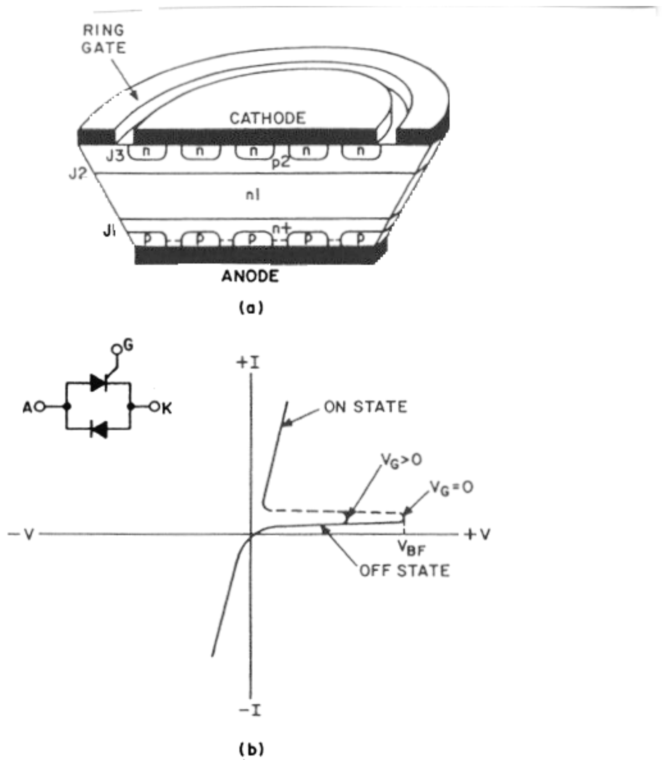


Fig. 26 (a) Cross section of a high-voltage, high-temperature reverse-conducting thyristor (RCT). (b) Current–voltage characteristics and device symbol of a RCT. (After Kokosa and Tuft, Ref. 34.)

Student Tasks

Make a lecture presentation for your fellow students on one of the following topics:

1. The diac (**di**ode **ac** switch)
2. The triac (**tri**ode **ac** switch)
3. The UJT (**u**ni**j**unction **t**ransistor)
4. The PUT (**p**rogrammable **u**nijunction **t**ransistor), SUS (**s**ilicon unilateral **s**witch), and SBS (**s**ilicon **b**ilateral **s**witch)
5. The FCT (**f**ield-**c**ontrolled **t**hyristor)

Try to <u>explain</u> the physics behind the functioning of the devices!