

## Lecture 22

### Switch Protective Snubber Circuits and Emerging Thyristor Solid State Switches

#### A.. Snubber Circuits to Save Both Switches and Energy

1. Bipolar Snubber
2. Unidirectional Snubbers
  - a. R-C-diode Snubber
  - b. L-R-diode Snubber
  - c. L-R-C-diode Snubber

#### B. Emerging Thyristor Solid State Switches

1. Overview of SCR Operation
2. Device Construction and Operation
- 3. Optically Switched Thyristor**
4. Protective SCR Circuits
5. Control Circuit Programmable Thyristor Switches Independent of Circuit Conditions
  - a. Overview of controlled SCR Operation
  - b. Gate Turn-off Controlled Thyristor(GTO)
  - c. MOS controlled thyristor (MCT)
6. Summary/Comparison

## A. Snubbers to save switches

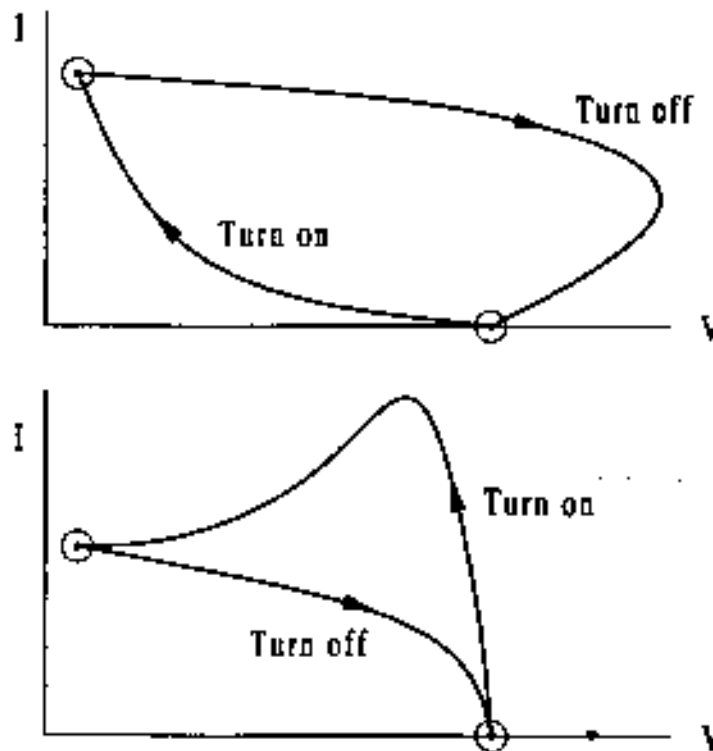
### 1. General Philosophy of Snubber Circuits

Neglecting the control electronics power required:

Total switch power loss is:

$$P(\text{total}) = P(\text{static}) + P(\text{switching})$$

Static losses in switches are fixed by average circuit voltages and currents as well as by the on/off duty cycles but switch losses depend on the switching trajectories as shown below for both turn-on and turn-off.



Trajectory comparison with and without snubber.

We can tailor one trajectory say the turn-off by adding extra components to the inverter circuit to reduce switch stress but we often end up increasing the switch stress during turn-on cycle. For inductive commutation we saw before that switch loss is

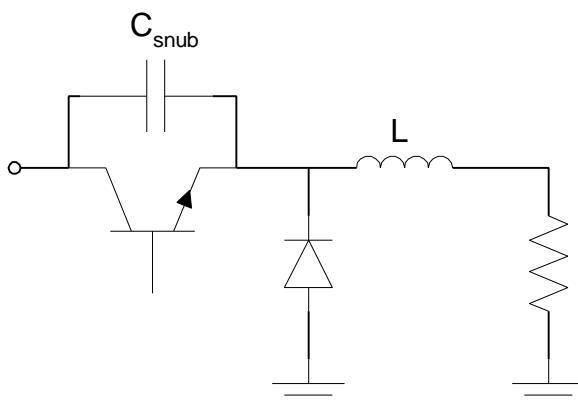
$$V_{\text{off}} I_L(\text{on}) \frac{t_{\text{off}}}{2} * f_{\text{sw}}$$

Can we beat this upper limit?

Snubber circuits are employed in locations around power switches to alter switching trajectories so that switches are less stressed moving losses to passive and cheap components like resistors away from active and expensive switches. Get it? Snubbers act to reduce power loss in the switch only. Usually snubbers consume 1-5 % of the switched power. A cheap price to pay for switch reliability.

## 2. Bi-directional Snubber

A simple bi-directional snubber is the capacitor placed across the switch below to reduce  $dv/dt$  across the switch during turn-off. It works well, but, because C is bi-directional at turn-on the stored C charge gives an additional  $di/dt$  current stress.

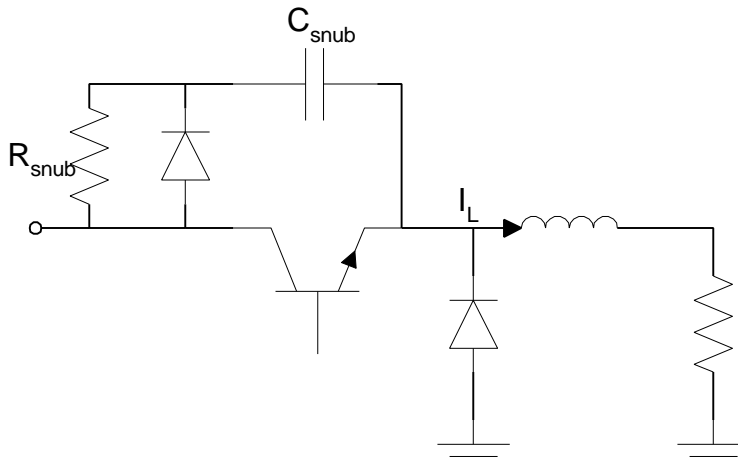


Inductive load switching with bi-directional snubber capacitor.

## 3. Unidirectional Snubbers

### a. Unidirectional R-C-diode snubbers

By use of a simple diode in the snubber circuit we can get the benefit of low  $dv/dt$  turn-off and no high  $di/dt$  through the switch during turn-on. Rather the high  $di/dt$  flows through the snubber resistor which also insures lower  $di/dt$ . We trade off resistor loss for lower device loss in the circuit below:



Turn-off unidirectional R-C-diode.

Proper R and C values are chosen as follows:

1. During the switch turn-off the C must be big enough that during di/dt decline it slows the dv/dt rise on the switch. This keeps the V-I product minimum.
2. R must be small enough that the stored energy is released during switch turn-on.

For an inductive load assume di/dt decline is linear during the fall time  $t_f$  while the capacitor current has linear di/dt rise

$$i(\text{switch}) = \frac{I_L}{C} (1 - t/t_f) \text{ and the capacitor current ramp-up is } i_c = I_L -$$

$$i(\text{switch}) = I_L(t/t_f). \quad V_c = \left( \frac{1}{C} \right) \int i_c dt \text{ and will vary as } t^2 \text{ for } i_c \sim t. \text{ For}$$

$$\begin{aligned} \text{large } C, \quad V_c &= \left( \frac{I_L}{C} \right) \frac{t^2}{2t_f} \text{ and } W(\text{switch}) = \int_0^{t_f} \left( \frac{I_L}{C} \right) \frac{t^2}{2t_f} I_L \left( 1 - \frac{t}{t_f} \right) dt \\ &= \left( \frac{I_L^2}{24C} \right) t_f^2 \end{aligned}$$

Employing a snubber switch loss will decline as C increases! We beat the inductive switching loss without a snubber by a long shot:

$$W(\text{no snubber}) = V_{\text{off}} I_L(\text{on}) \frac{t_{\text{off}}}{2} * f_{\text{sw}}$$

however, the energy in the capacitor  $\frac{1}{2} C V_{\text{off}}^2$  is lost in the resistor with a required power rating of  $\frac{1}{2} C V_{\text{off}}^2 f_{\text{sw}}$ . The total energy lost

$$\text{is: } P(\text{total}) = \left[ \left( \frac{I_L^2}{24C} \right) t_f^2 + \frac{1}{2} C V_{\text{off}}^2 \right] f_{\text{sw}}$$

Compared to the switch without a snubber we desire:

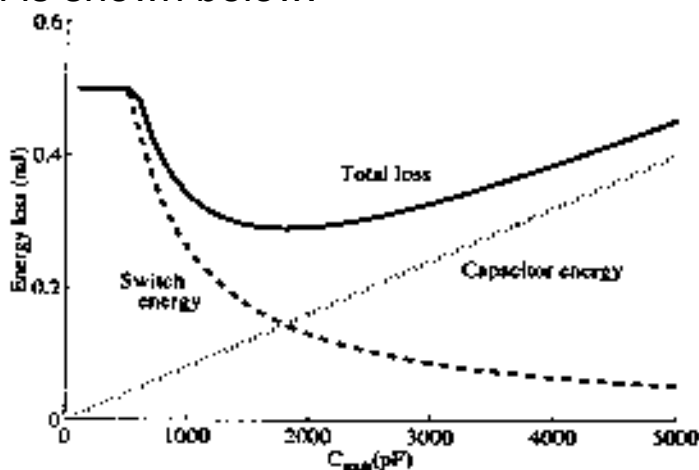
$$\left[ \left( \frac{I_L^2}{24C} \right) t_f^2 + \frac{1}{2} C V_{\text{off}}^2 \right] < I_L(\text{on}) V_{\text{off}} t_f$$

The capacitor reduces switch loss but adds to resistive loss. Is there an optimum C value to reduce total loss?

The partial derivative of the left-hand side equation with respect to

$$C \text{ leads to: } C_{\text{opt}} = \left( \frac{I_L(\text{on})}{\sqrt{12} V_{\text{off}}} \right) t_f = \left( \frac{I_L(\text{on})}{3.5 V_{\text{off}}} \right) t_f$$

The optimum is shown below:



Switching power loss as a function of snubber capacitor value after Krein. If we are “saving the switches” not the whales or trees clearly a capacitor chosen higher than  $C_{\text{opt}}$  is best because it reduces switch stress increasing switch reliability while causing only a higher power rated resistor to be used (cheap). The savings in the lower cost switch can be 10-100 times the added R and C component costs.

In summary C(snubber) avoids during switch turn-off voltage overshoot and keeps the switch within the 50 A, safe operating area. It stores energy as the switch enters its off state. For turn-on snubbers the dual of this behavior is needed a series inductance that limits di/dt rise during turn-on.

### b. Unidirectional R-L-diode snubbers

The buck converter during turn-on can benefit from a L-R-diode snubber which limits di/dt during turn-on. The snubber energy stored,  $\frac{1}{2} L(\text{snubber}) \cdot i^2$ , is dissipated in the resistor during switch turn-off.

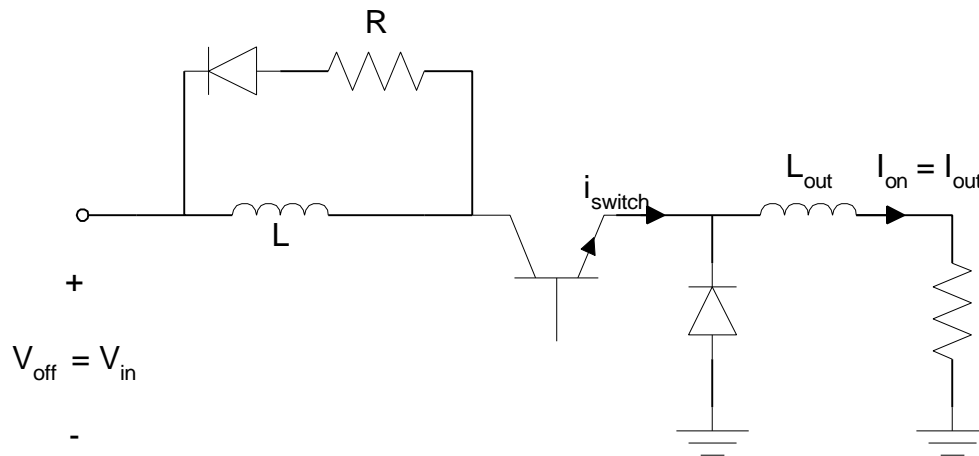


Figure 13.57 Unidirectional L-R-diode turn-on snubber.

During turn-on the diode remains on so  $V_{\text{off}} = V_L + V(\text{switch})$ . Assume  $V(\text{switch})$  falls linearly during the turn-on time,  $t_{fv}$ , the voltage fall time. We also assume the current rise time  $t_{ir} = t_{vf}$ .  $L = L(\text{snubber})$  below:

$$V(\text{switch}) = V_{\text{off}}(1 - t/t_{fv})$$

$$V_L = V_{\text{off}} = V(\text{switch}) = V_{\text{off}}t/t_{fv}$$

$$i_L = \left(\frac{1}{L}\right) \int v_L dt = V_{\text{off}} \frac{t^2}{2t_{fv}} = i(\text{switch})$$

$$W(\text{switch}) = \int_0^{t_{fv}} V_{\text{off}} \left(1 - \frac{t}{t_{fv}}\right) V_{\text{off}} \frac{t^2}{2t_{fv}} dt = V_{\text{off}}^2 \frac{t_{fv}^2}{24L}$$

As L(snubber) increase W(switch) decreases as the energy is removed from the switch and dissipated in the resistor. As with C(snubber) one can show:  $L_{\text{opt}}(\text{snubber}) = \left(\frac{V_{\text{off}}}{\sqrt{12} * I_{\text{on}}}\right) t_{fv}$

### 3. Combined L-C-R-diode Snubbers

in this snubber configuration L avoids  $i(\text{peak})$ , C prevents  $v(\text{peak})$ , and R dissipates the snubber power,  $(\frac{1}{2} CV_{\text{off}}^2 + \frac{1}{2} LI_{\text{on}}^2)f_{\text{sw}}$ . This unified snubber circuit is shown below:

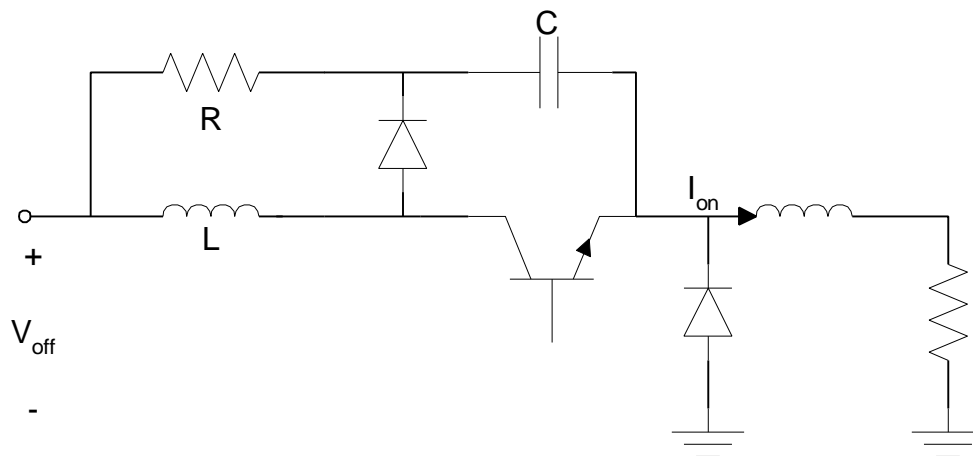


Figure 13.59 unidirectional R-L-C-diode snubber for inductive load.

Finally we note that in high power converters the snubber power of 1-5% of the switched power is large enough to be recovered to provide the raw pump circuits power for the electronic control circuits.

## Problems of hard switching

- device stress
- switching losses
- EMI due to high  $di/dt$  and  $dv/dt$
- in motor drives winding insulation and bearing failures due to high  $dv/dt$

## Possible solutions (combination)

- snubbers to reduce  $di/dt$  and  $dv/dt$ 
  - ➔ usually no change in losses (unless loss recovery)
- circuit layout to reduce stray inductances
- gate drive
  - ➔ circuit layout
  - ➔ turn on / off speeds
- soft switching to achieve ZVS and/or ZCS

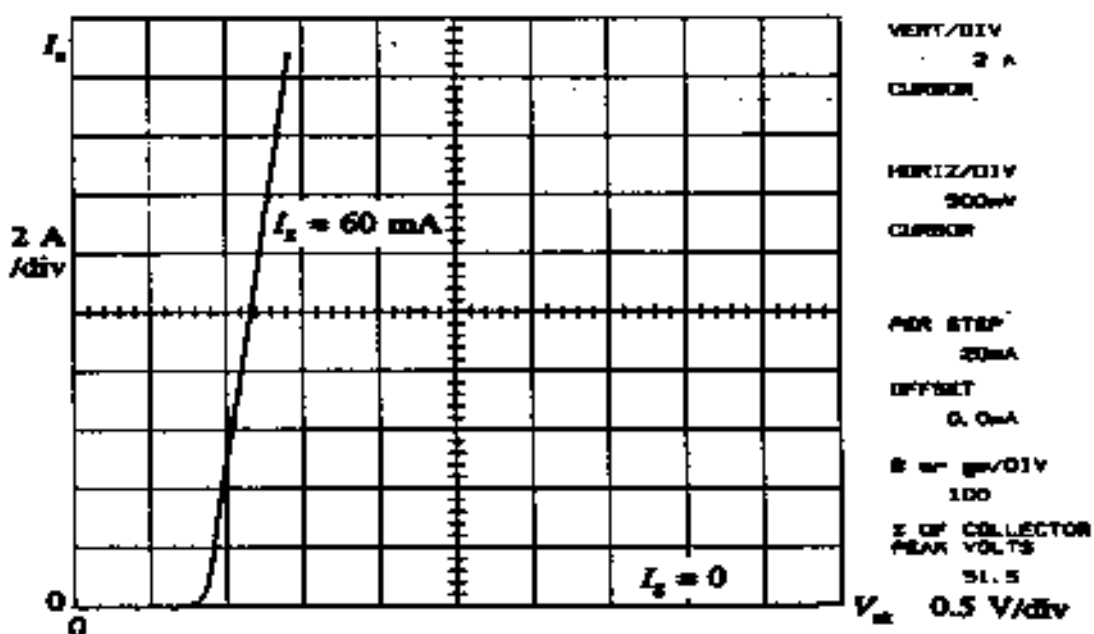
Clearly, we have just given a brief introduction to snubber issues and some possible circuits. PLEASE FEEL FREE TO CHOOSE A TERM PAPER ON SNUBBER ISSUES.



## B. Thyristor Evolution:

### 1. Overview

The SCR or thyristor is a latching diode-like switch that is triggered on only by an external gate signal. The thyristor goes off only by experiencing circuit conditions that try to reverse current flow. The I-V characteristics of a 2N6508 SCR are shown below with and without gate signal. We repeat that there is no way to turn it off by a gate signal alone once the SCR is switched on. Rather, we have to wait till the current through the device tries to go negative for turn-off to be initiated.



Forward behavior of 2N6508 SCR with and without gate signal.

In the on state the SCR or thyristor looks like two series pn junctions. The two-transistor model for the SCR before being latched on evolves from the four-layer pnpn junction device as shown below. That is the gate signal on the silicon controlled rectifier (SCR) is placed on the p layer as shown. This corresponds to the base of a NPN transistor. Without any base current the PNP stack will not conduct current due to the BACK-BIASED NP junction in the middle of the stack. This back biased junction can be removed when the lower NPN transistor on the stack is turned on by the active gate drive as shown on page 9.

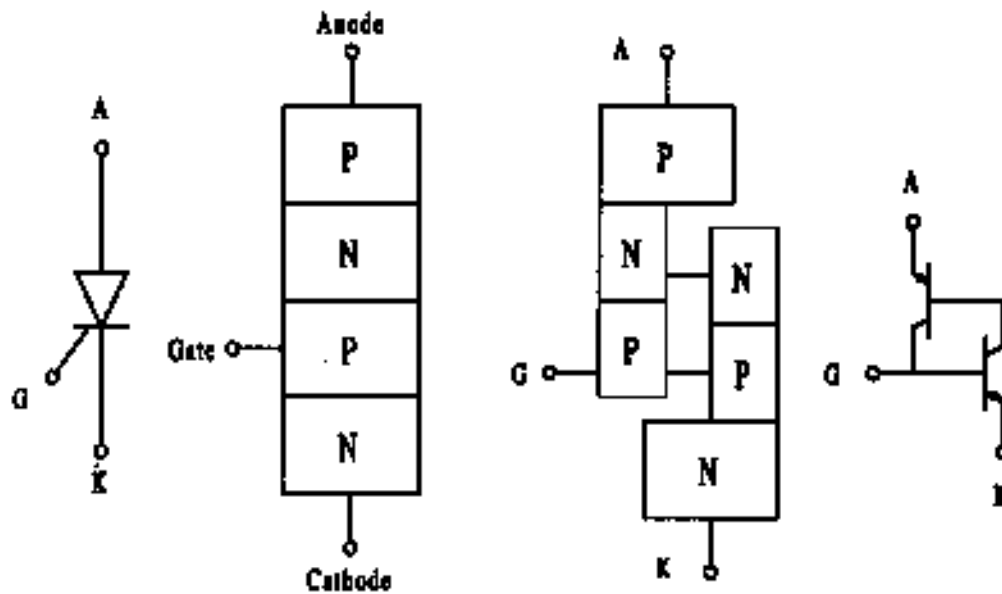
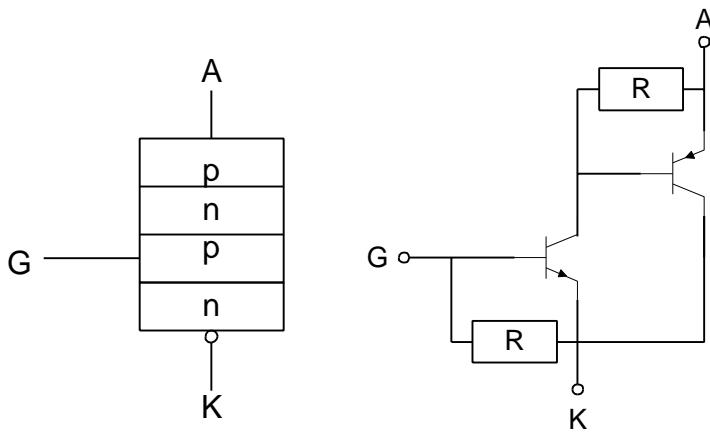


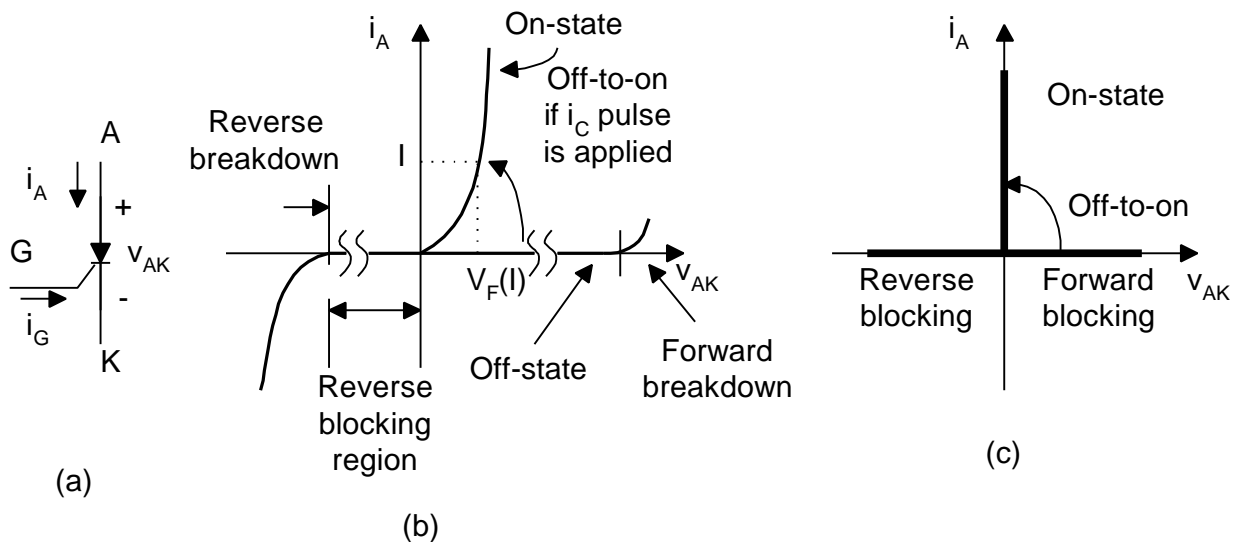
Fig. 13.33 Evolution of Two-transistor current loop model of the SCR

## 2. DEVICE OPERATION

The stacked and overlapped pnp and npn transistors are in a current loop with loop current gain  $\beta(\text{nnp}) * \beta(\text{pnp})$ . With no gate current applied both devices are off blocking either forward or reverse flow of current through the stack. With a small,  $> 10\text{mA}$ , gate current trigger applied for at least several  $\mu\text{s}$  and the current loop gain,  $\beta(\text{nnp}) * \beta(\text{pnp}) > 1$ , we find the pnp collector current can replace the gate current and **latch the device on to current levels of  $\geq 10\text{-}100\text{ A}$** . We do not want any less gate threshold current or noise may turn on the SCR so we purposely set the gate drive high to avoid inadvertent turn-on. The SCR will stay on until the current through it goes below a minimum holding current or in some cases try to reverse polarity. In an actual SCR there are some bulk semiconductor resistances that are in the bulk silicon, which act to split currents entering various nodes as shown below on page 10. The block labeled R is actually controllable by the choice of doping in the various levels of the stacked device. By proper choice of R values we can tweek the loop current gain to vary the switch on and switch off conditions of the SCR.



SCR device is triggered on by transient pulse but once on you have no active means to shut it off. Turn off occurs when the current crosses zero provided  $t_{off}$  is long enough.



Thyristor: (a) symbol, (b)  $i$ - $v$  characteristics (c), idealized characteristics.

The on voltage of a power thyristor is similar to that of a power diode. A 15A SCR takes about 1 microsecond to turn on but turn-off time,  $t_r$ (ms), is much slower due to the diode stored charge. The Dc on voltage for a SCR is typically,  $V_{on}$ : 1.2-2.2 V. The diode operates, with high efficiency, for  $f_{sw}$  up to 10-15 kHz. The stand-off voltage,  $V_{off}$ , is similar to other bipolar diodes or transistors being about 4-5 kV for lower power SCR's. With proper choices of the bulk resistance's, R, the SCR goes off only if the circuit it is employed in lets  $i \rightarrow 0$  or negative as shown below.

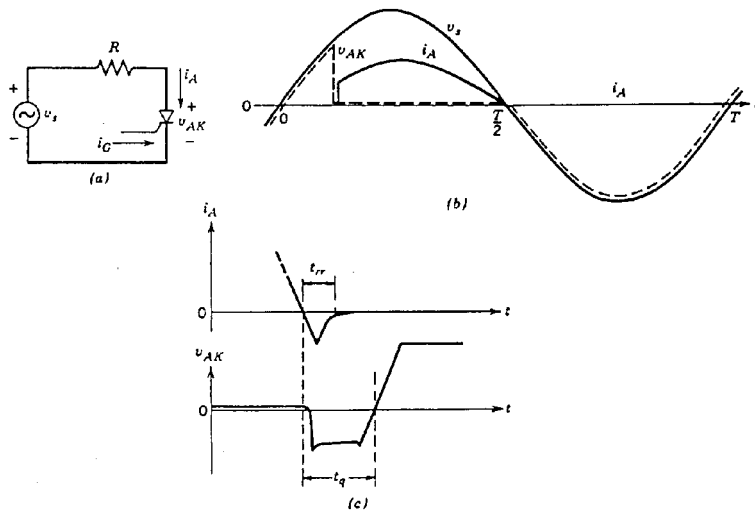


Figure 2-4 Thyristor: (a) circuit. (b) waveforms. (c) turn-off time interval  $t_q$ .

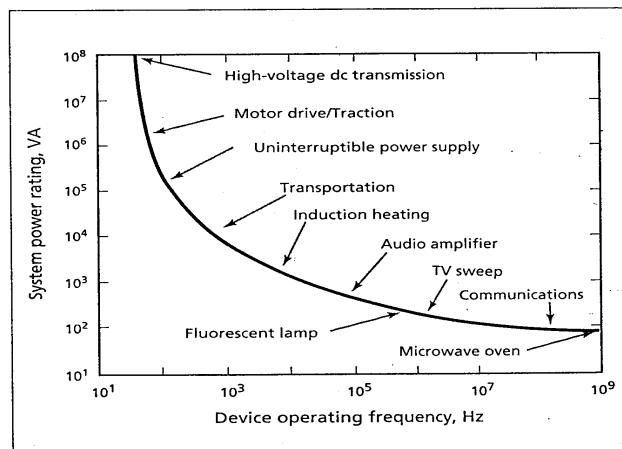
Again SCR's like diodes have a reverse stored charge current and  $t_q$  is the circuit commutated recovery time for this charge:  
 $1 \mu\text{s} \leq t_q \leq 200 \mu\text{s}$   
 Base charge must be recovered before the SCR can block forward voltage.

For today's heavy duty thyristors we find:

$I_{\text{max}}(\text{on})$ : 5 to 10 kVA  $\Rightarrow$  **Highest current ratings of all switches we will employ**

$V_{\text{block}}(\text{off})$ : 7 kV  $\Rightarrow$  This value is moving upwards yearly  
 $f(\text{operation})$  up to kHz, but  $t_{rr}$  is still milliseconds

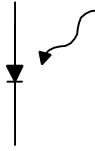
**Which part of the curve below do thyristors operate best?**



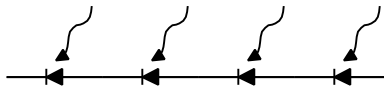
▲ Because of component limitations, the higher a system's operating frequency, the lower its operating power level. Power electronics systems for microwave ovens, for example, operate at about 1 GHz and have a rating of under 200 VA.

### 3. Optically Switched Thyristor

We can also trigger the thyristor turn-on optically rather than by a gate current. This can be a big advantage for some applications.



Photon activated gate for turn-on. Requires 5 mW light beam. Which is now easily available from a variety of LED's (GaAlAs at 800nm or InGaN at 420nm).

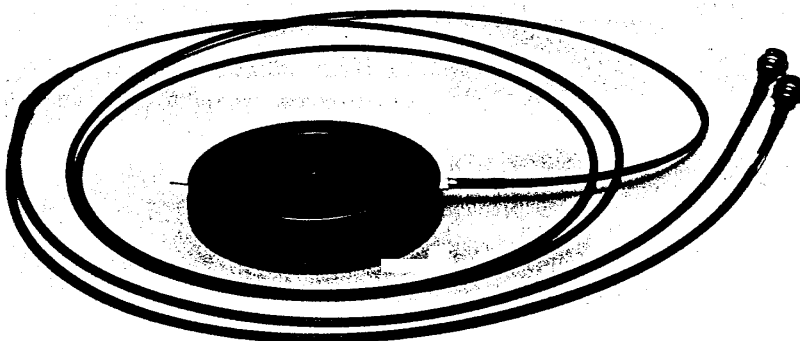


A series stack of thyristors employed to reach the desired blocking voltage is sometimes harder to trigger electrically than optically, especially if the SCR is placed on a MV dc transmission line. Below we illustrate a “hockey puck” LED driven thyristor

Hitachi Light-Triggered Thyristor Cells for HVDC

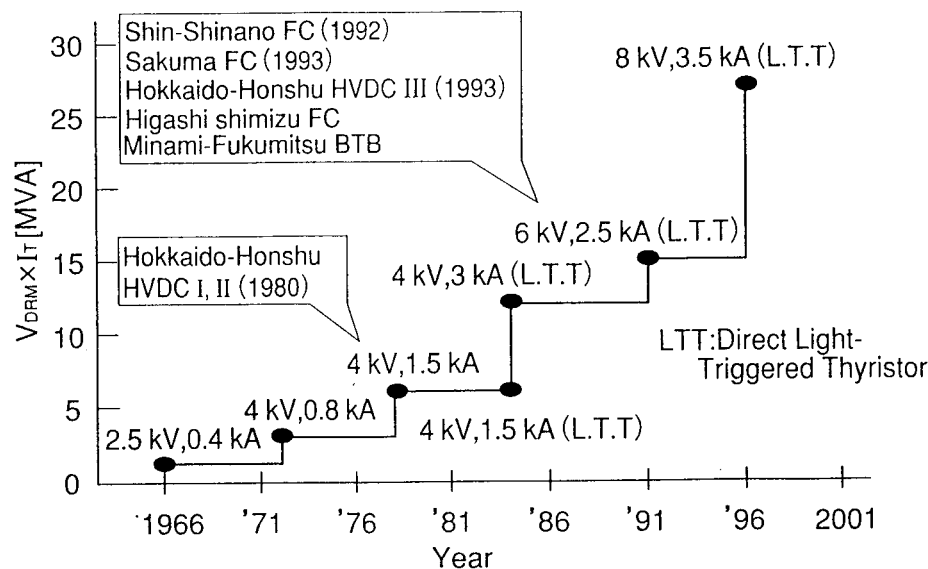
Item No.	Thyristor Diameter	Repetitive Peak Off-State Voltage VDRM (volts)	Average On-State Current *1 IT (A) ave.	Device Power Handling Capacity (MVA)
1	4" (100mm)	6 kV	1.2 kA	7.2 MVA
2	5" (125mm)	6 kV	2.5 kA	15 MVA
3	6" (150mm)	8 kV	3.5 kA	27 MVA

\*1 : Single -phase half sine wave 180° conduction



8 kV-3.5 kA Direct Light-Triggered Thyristor Cell with Duplicated Light Guide

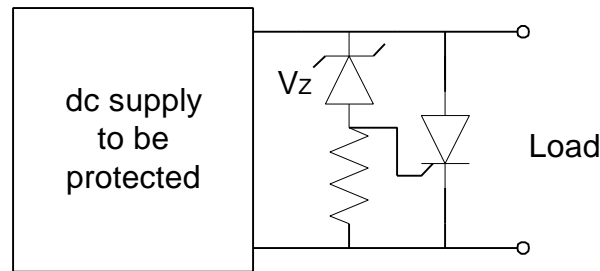
Below we list the time line of the power handling capability of this type of thyristor in the power transmission application area. Note that today it is routinely switching MVA of power. As electric power deregulation becomes more widespread the need for such devices will increase.



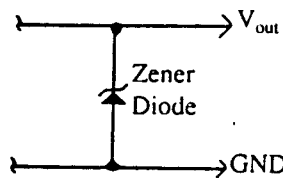
Trend of Device Power Handling Capacity

#### 4. SCR for Protective Circuitry

Can you understand how the SCR in the circuits below act to crowbar the output voltage to less than  $V(zener)$  and protect the output circuit of the dc supply from transient over voltages occurring at the load? This same approach is employed on the bond pads of integrated circuits to protect the IC from electrical damage originating outside the chip.

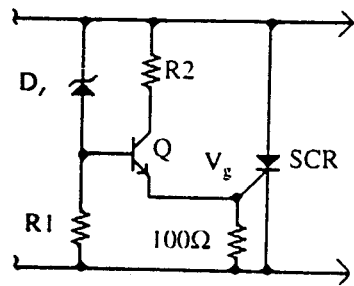


SCR with Zener diode gate control for Power supply protection



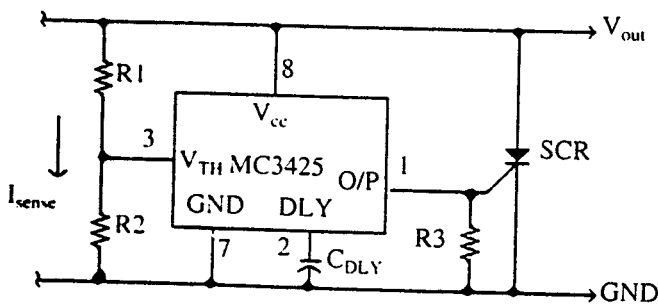
(a)

$V_z \approx 1.4 V_{out(rated)}$   
 $P_D > 1 W$   
 Tolerance  $\leq 5\%$



(b)

$R1 \approx 270 \Omega$   
 $V_{Dz} \approx V_{trip} - V_{BE} - V_{g(th)}$   
 $R2 \approx \frac{V_{trip} - 2V}{I_{g(min)}}$



(c)

$$V_{trip} = 2.5V \left(1 + \frac{R1}{R2}\right)$$

$$I_{sense} \approx 1 \text{ mA}$$

$$R2 = \frac{2.5 \text{ V}}{I_{sense}}$$

$$R1 = \frac{V_{trip} - 2.5 \text{ V}}{I_{sense}}$$

$$C_{DLY} = \frac{V_{DLY}}{12,500}$$

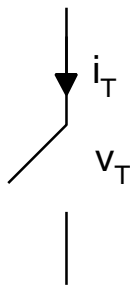
Fig. Overvoltage protection schemes: (a) Zener diode clamp; (b) overvoltage crowbar; (c) integrated overvoltage crowbar.

Above we show the evolution from simple to more complex protection schemes. All employ a SCR to short out or crowbar the output in attempt to protect the load from a voltage overshoot.

The same type of circuitry is placed on an IC bond pad to protect from electrostatic discharge(ESD).

5. Control Circuit Programmable Thyristor Switches Independent of Circuit Conditions a. Overview

You can turn some devices on/off by a control v or i regardless of circuit conditions. The device, however, stays on/off only if the control v or i is continuously present. When on control is absent even momentarily for example the device is off. Why not try to achieve this condition with thyristors??



Ideally we have:

- stand off voltage  $\pm V_T$  with  $i_T = 0$
- on state  $V_T = 0$  unipolar i usually in one direction
- $t_{switch} \rightarrow "0"$  (i.e. 10-100 nsec)
- required switch trigger energy E(small)  $\mu J \rightarrow mJ$

b. **Gate turn-off Thyristor**

As a first step in this direction researchers invented the GTO, Gate turn off thyristor: Active turn off on this new type of thyristor is possible for the first time. How was this achieved??

In the npn - pnp transistor current loop model of an off state SCR if  $\beta(npn) = 8$  and  $\beta(pnp) = 1/5$  then  $\beta(npn)*\beta(pnp) > 1$ . But to turn the pnp off we would need only  $1/5 I_{out}$ . This controlled reduction of the pnp transistor  $\beta$  value is the basis of the gate turn off thyristor. In this case LARGE base current turns off the device as well. But only a small base current turns it on as shown below.

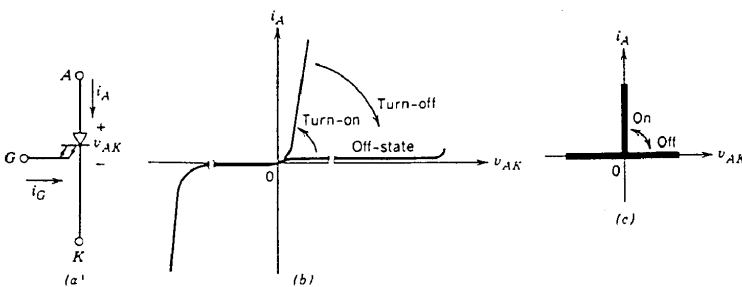


Figure 2-10 A GTO: (a) symbol. (b)  $i-v$  characteristics. (c) idealized characteristics.

ON: by low i (10mA) gate pulse  
OFF: by high i gate pulse  $\approx 1/5$  to  $1/3 I_{on}$



Typical operating specifications of today's available GTO's are:

$V_{on}$ : 1.8-2.3 V

$V_{block(off)}$ : 5 kV

$I_{max(on)}$ : 2 kA

**But  $f_{sw}$  is limited!**

**$0.1 < f_{sw} < 10$  kHz**

The turn-off capability is unique but it takes a big drive current to do it - nearly 1/3 to 1/5 of the pass current.

In case we see a high  $dv/dt$  across the thyristor this can cause inadvertent and undesired SCR firing via parasitic currents in junction capacitance's. For 10pF coupling to the gate and  $dv/dt$  only 100V/ $\mu$ s to 1000V/ $\mu$ s across the anode-cathode terminals. We obtain  $i(\text{gate}) = 1$  to 10 mA respectively. Hence,  $dv/dt$  limits on off state SCR's exist. Often snubber circuits are employed to limit  $dv/dt$ .  $f_{sw}$  limits are usually due to limited ability of GTO to withstand gate drive transients. Most applications of GTO's require snubber circuits across the output of the SCR as shown on the following page.

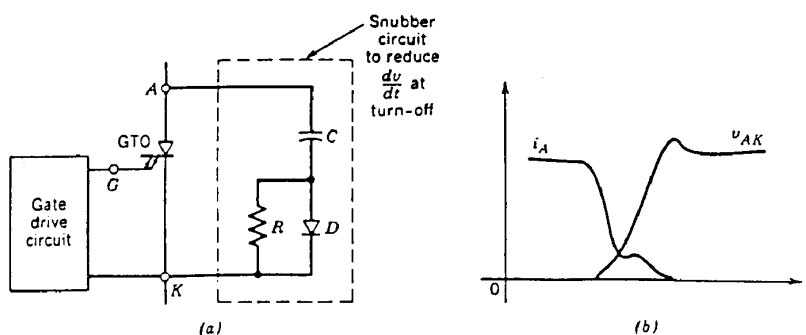


Figure 2-11 Gate turn-off transient characteristics: (a) snubber circuit. (b) GTO turn-off characteristic.

Snubber circuits limit  $dv/dt$  across the SCR &  $di/dt$  to the gate via parasitic C coupling.

- Turn-on snubber: Minimize overcurrents through the costly GTO device.
- Turn-off snubber: Minimize overvoltages across the costly GTO device which could trigger the SCR on
- Stress reduction snubber: Restricts simultaneous high V & I

The trade off is:

Snubber circuit  
total costs

vs.

Better GTO device that  
takes more stress but  
costs more money

**c. MCT: MOS controlled thyristor -- newest power switch contender**

The newest generation of thyristors are MOS controlled GTO's, with a MOSFET at the input rather than a bipolar transistor. The MOS assisted turn off thyristor, is a GTO which has the same four layer construction pnpn with input contacts modified as shown below by the addition of a MOS and bipolar cascade at TWO SEPARATE LOCATIONS.

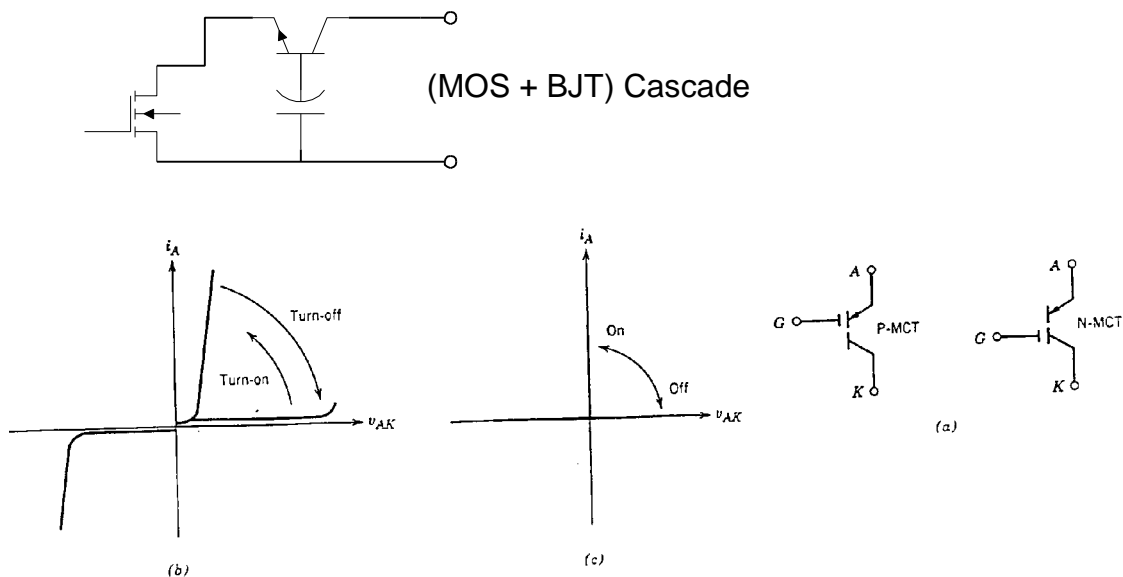
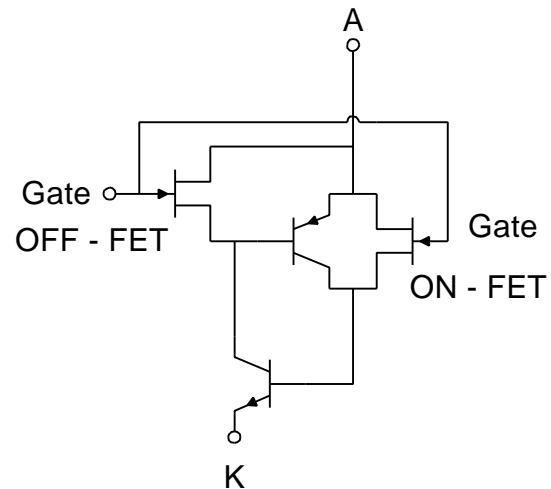


Figure 2-13 An MCT: (a) circuit symbols. (b)  $i_A$ - $v_{AK}$  characteristic. (c) idealized characteristics.

The three terminal equivalent circuit for an MCT is shown here,

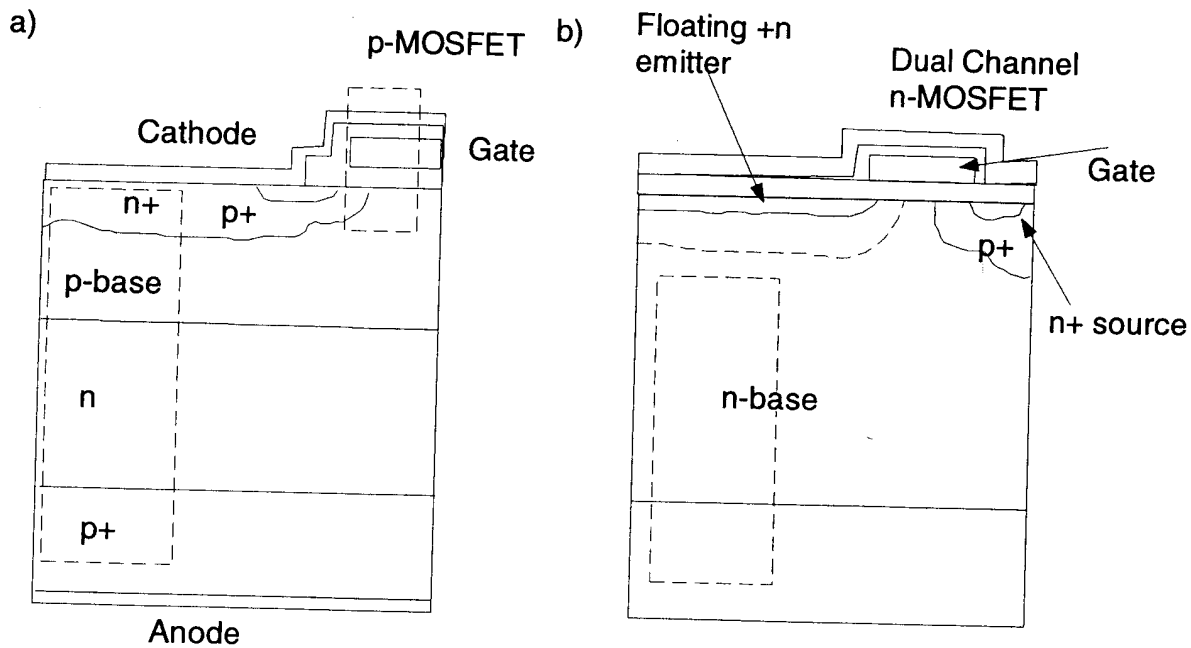


This device is turned on by gate voltage  $V$  but will stay on when gate voltage is removed. It is a voltage controlled device. However, no large negative gate current is required to turn it off due to the second MOS/bipolar cascade.

Today's available MCT specifications are:

- **$t_{\text{on}}$ (switch) is faster** (1-3  $\mu\text{sec}$ ) than other diodes/thyristors
  - $V_{\text{block}}(\text{off})$ : 3 kV;  $I_{\text{max}}(\text{on})$ : **100A, which is lower compared to other thyristors**
- turn off delay  $\approx 350 - 250 \text{ ns}$  } P-MCT Half-bridge rectifier is  
 turn off fall time  $\approx 300 \text{ ns}$  } the newest design from Harris.

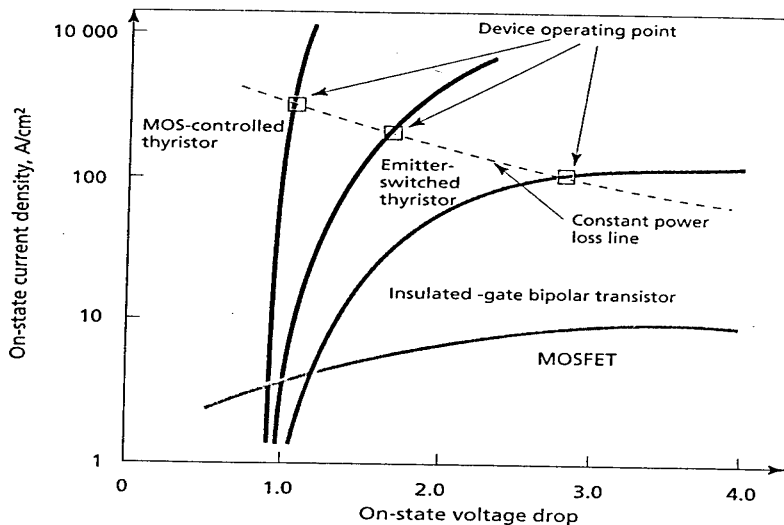
Below we show device cross-sections for both MOS and Emitter switched thyristors.



MOS-controlled thyristor

Emitter-switched thyristor

It is beyond the intent of this chapter to go into great detail in



comparing the emitter and MOS controlled thyristors to IGBT's and MOSFET's. The above chart serves this purpose adequately. As time evolves and new designs arise these curves may change. Now it's a horse race for the highest performance device.

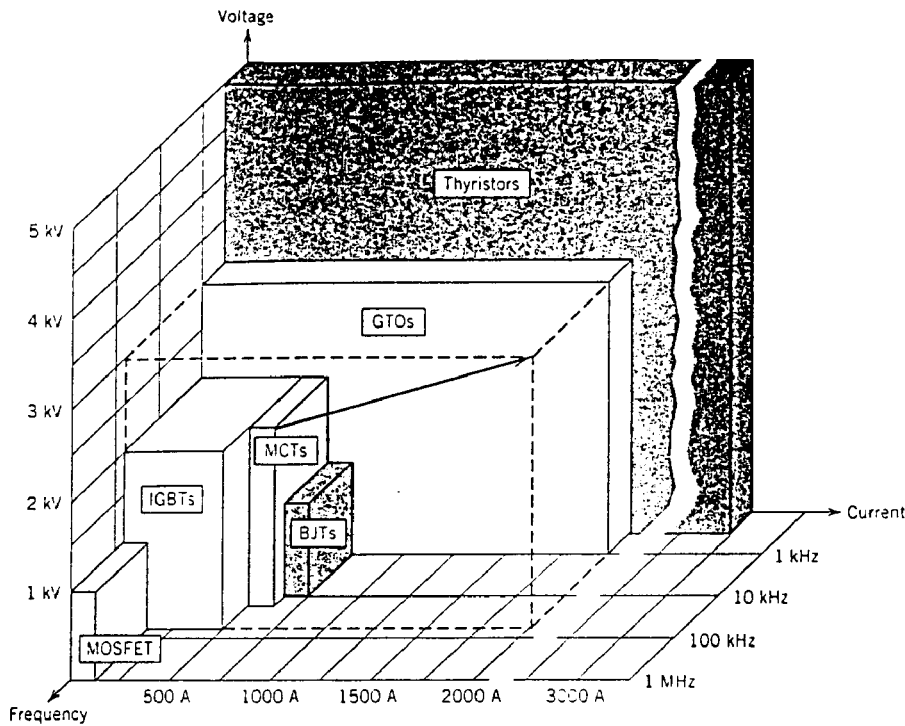
## 6. Summary/Comparison

Table 2-1 Relative Properties of Controllable Switches

<i>Device</i>	<i>Power Capability</i>	<i>Switching Speed</i>
BJT/MD	Medium	Medium
MOSFET	Low	Fast
GTO	High	Slow
IGBT	Medium/High	Medium
MCT	Medium	Medium

**MCT devices combine the thyristors power handling ability with the flexibility of on/off switching via MOSFET devices. When the ability to limit current briefly or to slow down the  $dV/dt$  rates across the device a IGFET may be a better choice.**

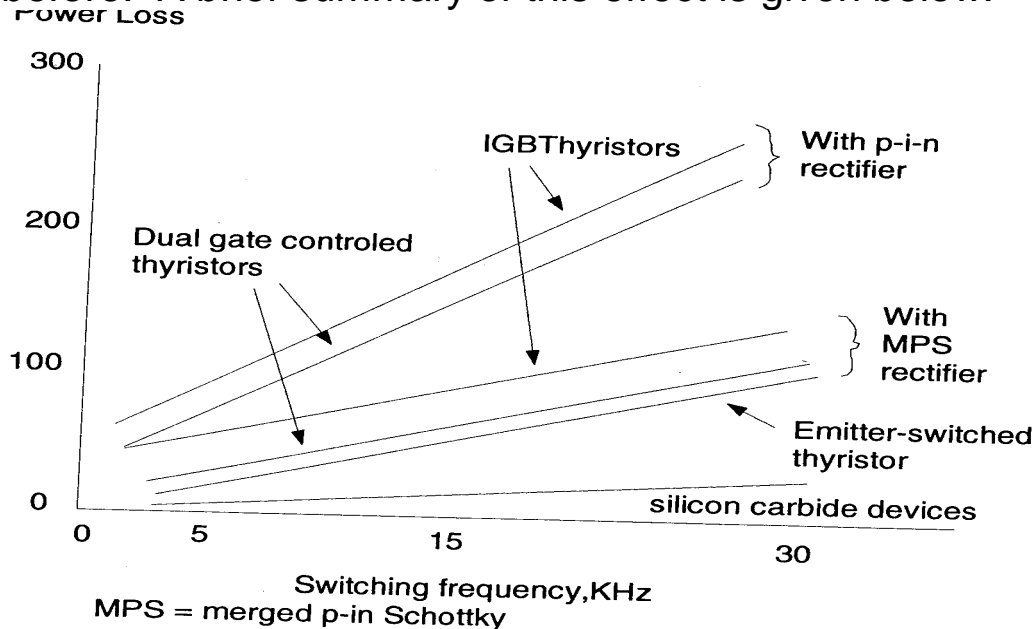
Remember that the high power devices are really composed of millions of small cells connected in parallel to achieve the device spec's. High power devices require large areas of silicon, which in turn means a higher probability of one or more defective devices. To achieve reasonable yield on such wafers redundant devices and wafer repair via fusible links are employed. V-I plots of modern power switch capability shown on the next page with operating frequency as a third axis. The trends are more clear when we peruse such a plot. Again, we have to realize that the MCT plot is the one experiencing the greatest changes in recent days.

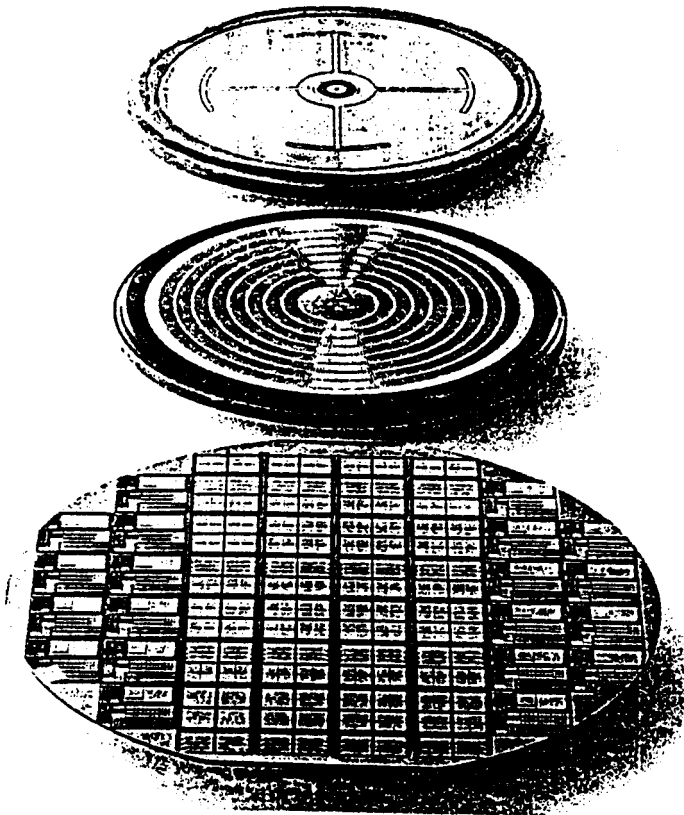


It is expected that MCT specs will soon equal other thyristors

Figure 2-14 Summary of power semiconductor device capabilities. All devices except the MCT have a relatively mature technology, and only evolutionary improvements in the device capabilities are anticipated in the next few years. However, MCT technology is in a state of rapid expansion, and significant improvements in the device capabilities are possible, as indicated by the expansion arrow in the diagram.

The Power loss in a switched device is also dependent on the type of diode employed, as the stored charge varies widely as we saw before. A brief summary of this effect is given below.





**THREE GENERATIONS** of thyristors show how these devices have increased in complexity and capability. The first-generation silicon-controlled rectifier (*top*) can switch power off only at the beginning of an AC cycle. Gate turn-off devices (*middle*) can switch at any point in the cycle, and MOS-controlled thyristors (*bottom*) switch more quickly while consuming significantly less power.

For a project worth 30 % of the course grade do a detailed comparison of available modern power devices. You may focus entirely on one type of switch if you wish. Use manufacturers spec sheets to guide your work.

**Finally, For HW#4 Due in 1 week:**

1. Answer any Questions asked throughout the lectures 18-22.
2. Erickson Chapter 4 Problems 2, 4, 5, and 6.