Lecture 23

Review of Emerging and Traditional Solid State Switches

A. Solid State Switches
  1. Circuit conditions and circuit controlled switches
    A. Silicon Diode
    B. Silicon Carbide Diodes
  2. Control circuit programmable switches are Independent of circuit conditions
    a. Bipolar Junction Transistor BJT devices
    b. IGBT: Insulated gate bipolar transistor
    c. Summary

    C. Brief Review of Switch Properties

1. Nine Switch Properties
  1. Off conditions
  2. On status
  3. Switch time
  4. Paralleling switches
  5. Switch power
  6-9. Issues that drive higher I, higher V, and higher P specifications

2. Summary and Comparison

A. Available Solid State Switches: A Second Look

1. Circuit condition controlled switches

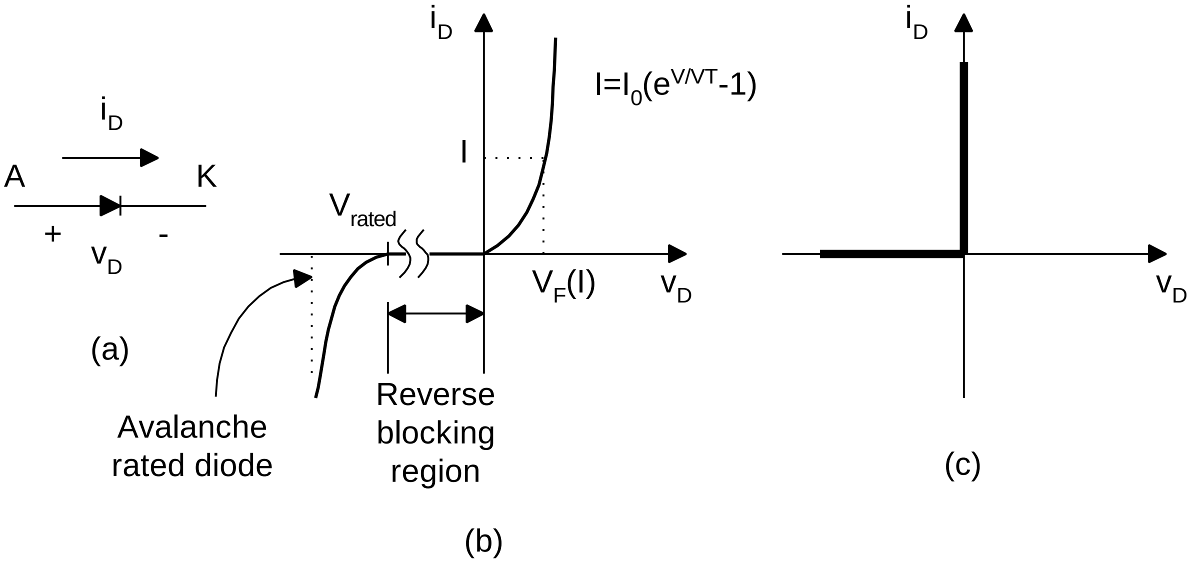
Power circuit current flow determines on/off state of the switch automatically.

a) Silicon Diode

1. Line-frequency or mains diodes have normal doping: $V_{on} \approx 0$ but t(off) = t_{rr} requires ≈ 10-1000µs for I_{on}: 1-10A. This long turn off time is adequate for SLOW mains frequencies with half cycle times of 8-10 milliSeconds. V(blocking) for mains diodes: 2 kV; the maximum through current is I_{max}: kA

Slow recovery diodes (line-frequency diodes) have very small forward voltage drop compared to fast recovery diodes because they are designed purposefully that way.

2. **Fast recovery diodes, to be used at high switch frequencies,** usually have a higher transient forward voltage drop along with a higher on-state voltage as seen in lecture 19. These diodes often contain gold doping to speed the charge neutralization via extra recombination sites, thereby reducing t_{rr}. Another recombination enhancing method involves MV electron irradiation of the bulk silicon.



(a) (b) (c)

Diode: a) symbol b) *i-v* characteristics c) idealized characteristics.
fastest power diode t(off) ≈ 1 msec

t(on) for a high frequency switching diode is very fast w.r.t. f_{sw}, typically 10-100 nsec, faster than $1/f_{sw}$ or T_s.
t(off) for a switching diode is 1000 times slower, typically 10-100 μsec, slower than f_{sw} but faster than line or mains diodes for which, t_{off} = ms.

Dynamic switching properties of gold doped fast recovery diodes must be compared to power diodes. For either diode:

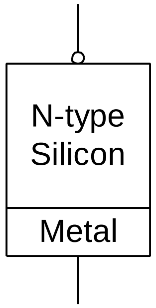
Recovery loss = Reverse Voltage*Recovery Charge*Frequency.

There is another type of diode besides bipolar diodes.

3. Schottky Diodes

The device cross-section is shown on page 4 for you perusal.

3. Schottky diode:



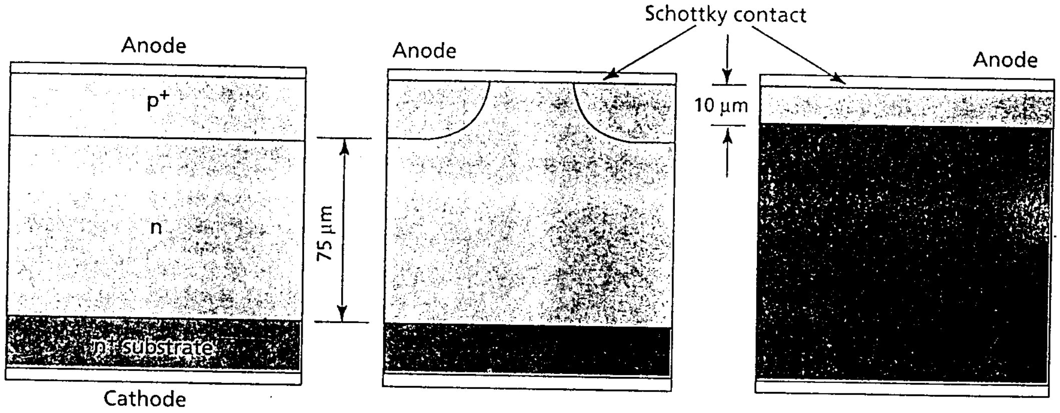
V_{on} = 0.3 to 0.5V
V(blocking) $\leq$ 100V
$\leq$ 300 V for GaAs

t(off) ≈ 10-20nsec for silicon diodes diodes

Usually n-type Si contacts metal rather than p-Si to form a diode. The recovery charge for low voltage Schottky's is smaller due to the lack of a diffusive capacitive junction. This junction is normally formed in a bipolar diode due to the pn-junction. **The use of Metal instead of the n-type Si eliminates the capacitance in the junction which stores charge Q_{rr}. Now, Q_{rec} has a different I-t nature than bipolar diodes with unique Q_{rr}, t_{rr} and i_{rr}.** The Schottky reverse current is large, 10mA, compared to a bipolar diode, 10µA, primarily because V_{on} is so small. Low V_{on} and low V_{off} means Schottky diodes are best for low voltage converters, eg. Power supplies with V_{out} of 1.5V, 3V etc.

4. Silicon Carbide Diodes

The power rectifier, at high switch frequency, is often the dominant source of loss. Hence, there has been considerable effort to make batter diodes as shown below on page 5 by the evolution from Silicon P-I-N diode structures to Merged Schottky and then to Silicon Carbide replacing silicon for the reasons we will outline.



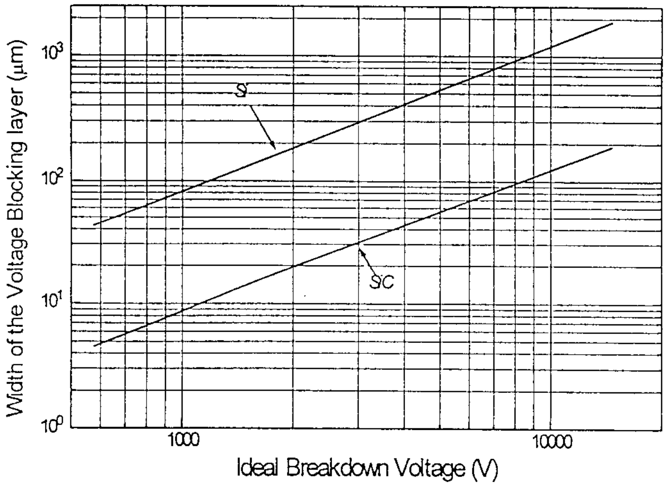
Silicon p-i-n structure

Silicon merged p-i-n Schottky structure

Silicon carbide Schottky barrier diode structure

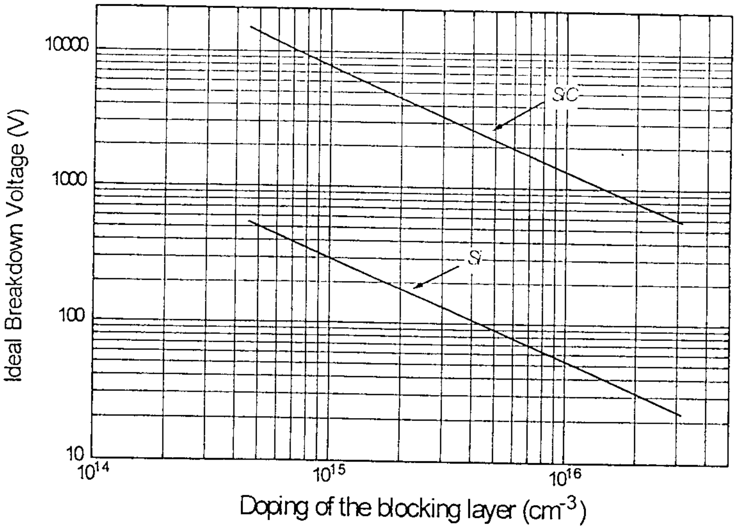
▲ The performance of power rectifiers could seriously limit the increase in operating frequency of power electronics systems. Although th try now relies on p-i-n rectifiers [left], the merged p-i-n Schottky (MPS) structure [center] could provide an eightfold reduction in power loss future. Over the longer term, the silicon carbide Schottky barrier diode (SBD) will provide another order of magnitude reduction in powe The thickness of the n-drift layer required for obtaining a reverse blocking voltage of 1000 V is different for each device—only 10 μm for th carbide Schottky barrier diode [right], much smaller than for the silicon devices. Silicon carbide's higher breakdown field strength reduces tl resistance of the drift region, enabling forward current conduction with a low on-state voltage drop.

Silicon carbide has several advantages that we note below



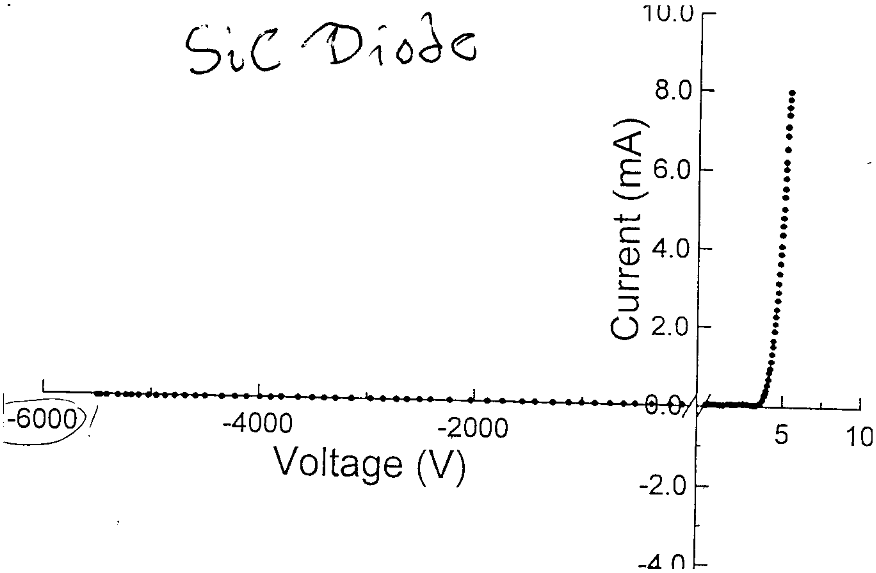
- *10X thinner voltage blocking layers required in SiC than Si for same voltage*
- *Leads to much faster minority carrier devices like thyristors, GTOs etc.*
- *SiC has 3X higher thermal conductivity enabling it to carry 3X higher current density for identical heating and thermal design of Si device*

. The width of the voltage blocking layer in SiC is so much smaller allowing for more compact devices. This also allows us to better trade off the layer thickness in devices with doping levels as shown on the next page.



- *20-25X higher breakdown voltage devices for equivalent doping levels can be made in SiC than Si*
- *Leads to much lower On-resistance majority carrier devices like Schottky Diodes, Power MOSFETs etc.*

In short, SiC allows us to simultaneously improve BOTH R_{ON} and the maximum stand-off voltage as compared to silicon. A SiC diode characteristic is shown below. Nearly 6000 Volts can be blocked using a SiC diode.



This capability will allow a new class of diode switches to arise. Moreover, we can also make SiC Schottky diodes with new characteristics not possible when employing silicon.

Silicon Carbide Schottky Barrier Diodes

- *Near zero reverse recovery charge during turn-off*
- *Reduce thermal load on power module in half*
- *Substantially increases safe operating area margin of power switch during inductive switching*

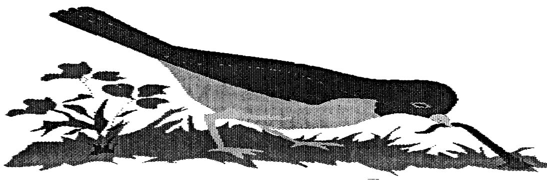
Specifications of SiC Schottkys

- *> 600 Volts, 5 and 10 Amps*
- *Forward Voltage drop < 1 V*
- *Leakage Current Density < 5 X 10^{-4} A/cm^2 at 600 V*
- *> 250°C operation*

- *> 1200 Volts, 5 and 10 Amps*
- *Forward Voltage drop < 1.2 V*
- *Leakage Current Density < 1 X 10^{-3} A/cm^2 at 1200 V*
- *> 250°C operation*

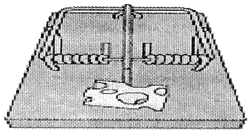
These I-V characteristics are simply not possible using silicon Schottky diodes. There are problems however, as SiC devices do not behave as reliably as silicon devices with time and use especially at high stress levels. Remember the old saw……

The early bird gets the worm



but

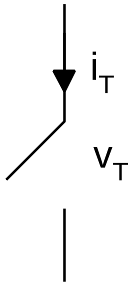
The second mouse gets the cheese.



Still SiC provides nearly 200 fold improvement in preformance from old reliable silicon.

2. Control Circuit Programmable Switches Independent of Circuit Conditions

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 turned off.



Ideally we have:

- stand off voltage ± V_T with $i_T = 0$
- on state $V_T = 0$ unipolar i <u>usually</u> in one direction
- $t_{switch} \rightarrow$ “0" (i.e. 10-100 nsec)
- required switch trigger energy E(small) µJ → mJ

a) Power BJT Devices

Power BJT’s are a dying breed being replaced by power MOSFET’s. Typical power BJT device characteristics are:

V_{on}: 1-2 V
β: 5-10
$I_c = 30$ A

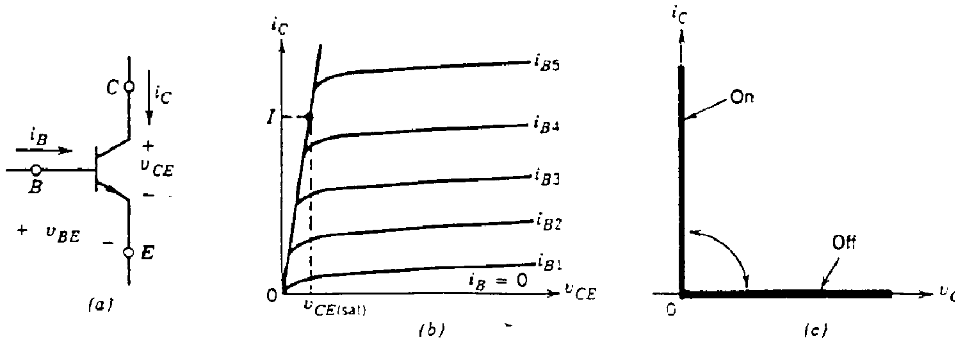
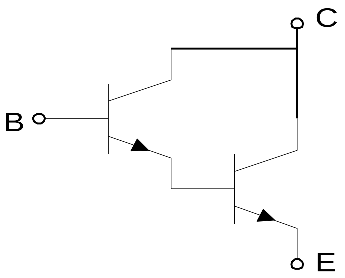


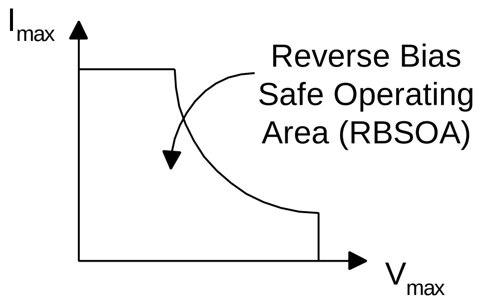
Figure 2-7 A BJT: (a) symbol. (b) i–v characteristics. (c) idealized characteristics.

The power BJT is a current controlled device and it requires a BIG base current drive of $I_c/10$. This can be 1-10 amperes for devices passing and controlling 10 - 100 A. To lower required I_β one uses Darlington configurations. For a 30 A transistor turn-on delays of 200ns are common while rise times of 500ns are typical. Turn off delays are typically 2µs for 30 A devices if we avoid saturation. To lower required I_β one uses Darlington configurations.



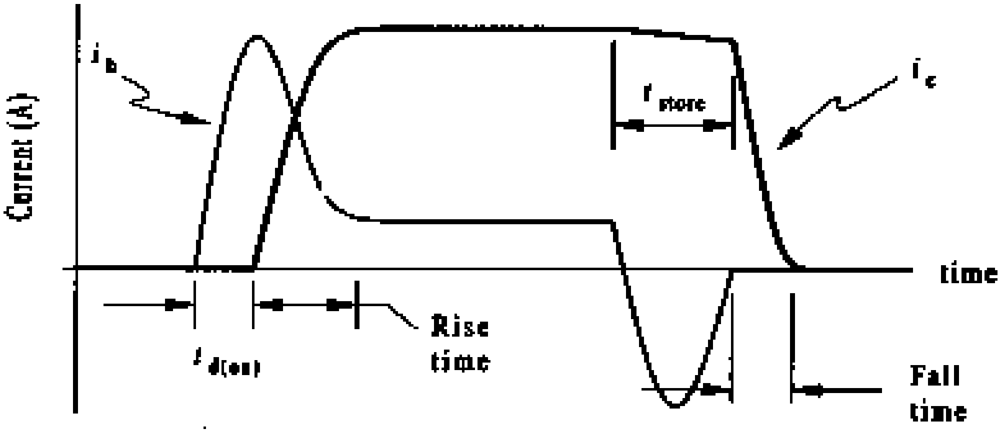
Darlington connection for high gain BJT switching

With today’s technology we expect blocking voltages and on currents as follows:



V_{block}(off): 1500 V
I_{max}(on): 100 A

Each device has a manufacturers spec. for RBSOA.
The figure below shows base current, I_B, and collector current, I_C versus time for a fast BJT switch. Note that we need a DC level of base current to keep the BJT on and we need LARGER base currents to accomplish both turn-on and turn-off as shown below.

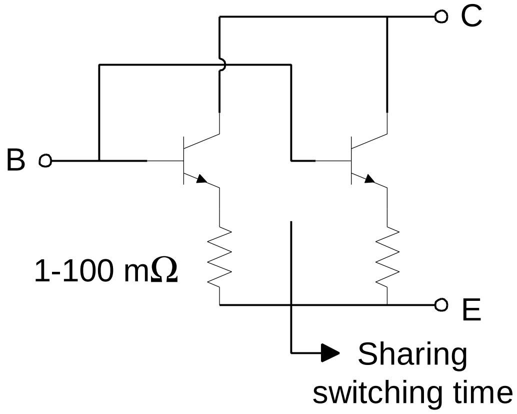


I_B and I_c currents for fast BJT switching.

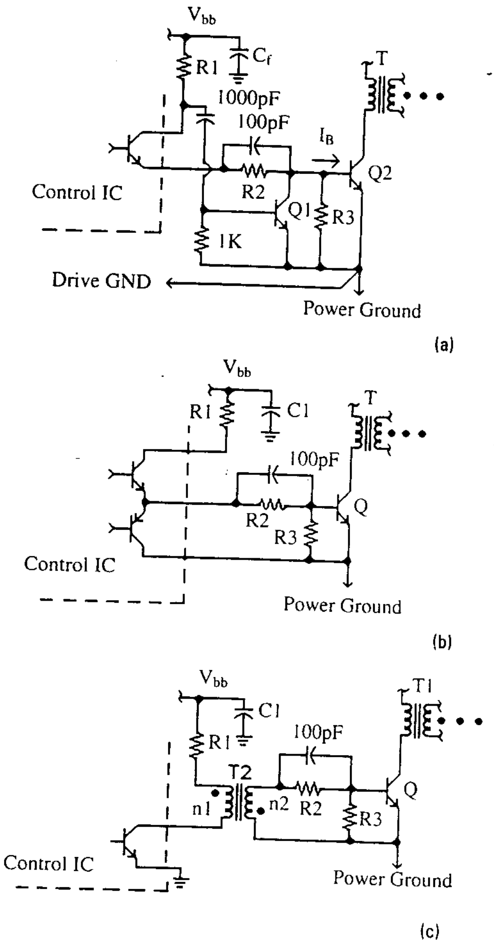
High I_B overdrive minimizes the turn-on delay while for fast turn-off a negative I_B is employed to speed up stored charge removal.

Unlike diodes or thyristors, BJT's have an undesired active state between cutoff and saturation that occurs if $I_{in}<I_B$(saturation). Then we obtain I_c with high V_{CE} causing power dissipation problems in switching circuits and often switch failure.

For paralleled BJT devices one big problem is - T coefficient of R_{on} varies such that the hotter the device the lower R_{on} hence it is hard to parallel devices. Use of emitter resistors helps equalize current sharing.



Fixed base drive drives the transistor into saturation at all times by overdriving the base current and achieving deep saturation. However, this causes large storage charge and a delay between the base drive going off and the collector current turning off. This requires a shortening of the allowable duty cycle. In fixed base drive we employ a low voltage source and a resistor is series between the supply and the base to limit the DC base current. We also place a bypass capacitor of 100pF, around this resistor to speed up the transient turn-on and turn-off by providing more rapid positive and negative surges and thereby reducing the time required for transitions. In turn-off the base voltage goes negative but not above the base-emitter breakdown voltage Finally, the collector resistance also limits the on-state base current. Three fixed base drive circuits are shown on page 11.



Q1 - 2N3904 or equivalent NPN

$R3 \approx 62\ \Omega$, 1/4 W

$R2 \approx 100\ \Omega$, $P_D \approx I_B^2 \cdot R2$

$$R1 \approx \frac{V_{CC} - 1.0\ V}{I_B} - R2$$

$P_{D(R1)} \approx I_B^2 \cdot R1$

$R3 \approx 64\ \Omega$, 1/4 W

R1 & R2 see above

$R3 \approx 62\ \Omega$, 1/4 W

$$R1 \approx \frac{V_{CC}}{(N2/N1) \cdot I_B}$$

$$P_{D(R1)} \approx \frac{V_{CC}^2}{R_1}$$

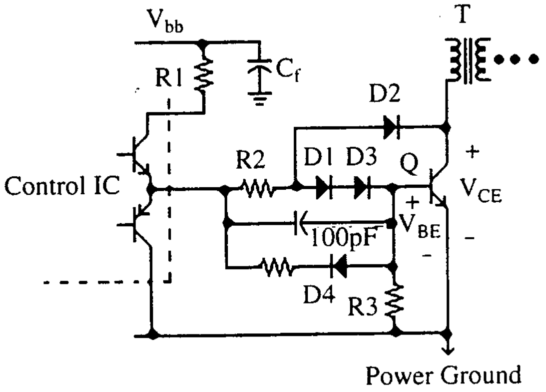
R2 - see above

Fixed base drive circuits: (a) quasi-totem-pole drive; (b) totem-pole drive; (c) transformer-coupled drive.

As an alternative to fixed base drive one may employ proportional base drive as shown on page 12. The transistor driven by proportional base drive, **always stays out of saturation eliminating storage charge effects.** To achieve this we employ an ultra-fast diode for the collector to base connection that prevents saturation from occurring. D_1 andD_3 are used to increase the required turn-on voltage while D_4 protects from excessive reverse voltage on the base during turn-off.

D1, D3, D4 - 1N4148

D2 UltraFast Recovery Diodes
$I_F \approx I_B$, $V_{R(D2)} > V_{CE}$



$R3 \approx 62\ \Omega$, 1/4W

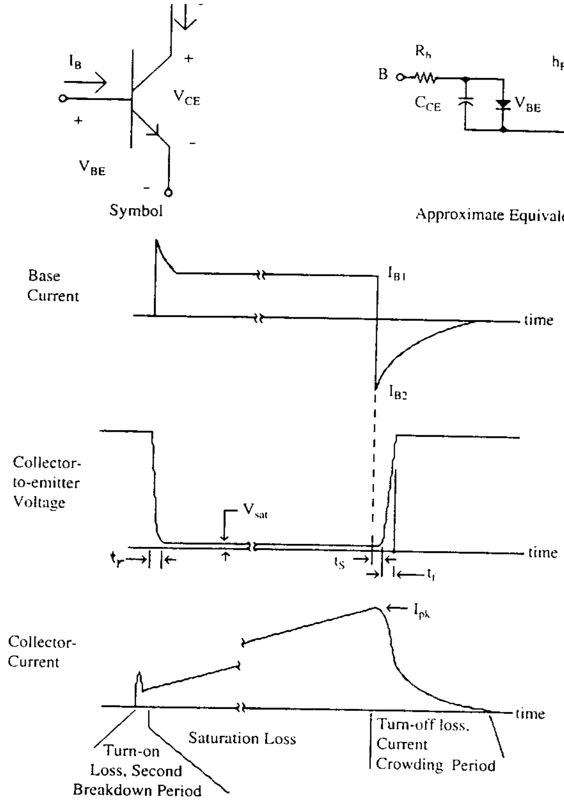
$R2 \approx 100\ \Omega$, $P_D \approx I_B^2 \cdot R2$

$$R1 \approx \frac{V_{CC} - 1.0\ V}{I_B} - R2$$

$P_{D(R1)} \approx I_B^2 \cdot R1$

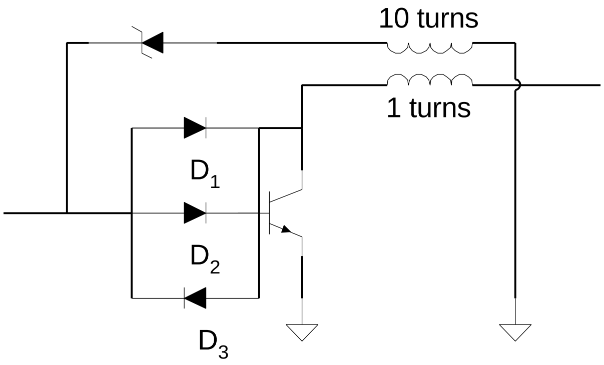
(a)

A full set of BJT waveforms for the general case is given below.



Waveforms for a bipolar power transistor within a PWM switching power supply.

The anti-saturation circuit on the top of page 12 is sometimes termed **a Baker clamp anti-saturation circuit. It also** is used to turn off the transistor faster improving RBSOA.



Transformer reduces drive power.

D_1, D_2, and D_3 are a Baker clamp anti-saturation circuit. Important to turn off fast within RBSOA.

For all the problems with BJT's their use is on the decline in power electronics while the IGBT below is rapidly replacing it.

b.Power Insulated gate bipolar transistor: IGBT

In lecture 20 we outlined the basic properties of the IGBT as a switch to achieve higher switch I, lower gate drive current and the ability to block both polarity voltages.

For this capability we pay a price in slow turn-off as shown below.

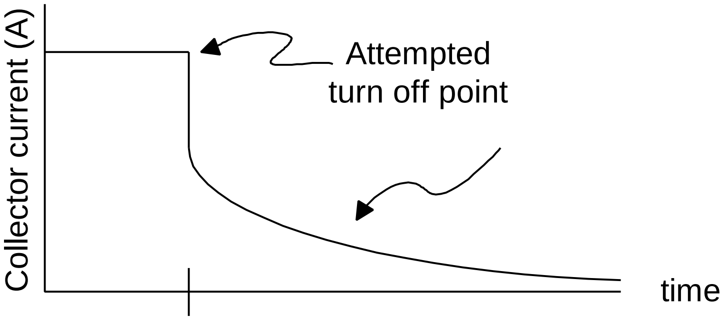


Fig. 13.47 IGBT long tail turn-off current.

The static model for the IGBT is a diode in series with a power MOSFET to better explain: forward voltage behavior, low gate current and reverse blocking ability as shown below.

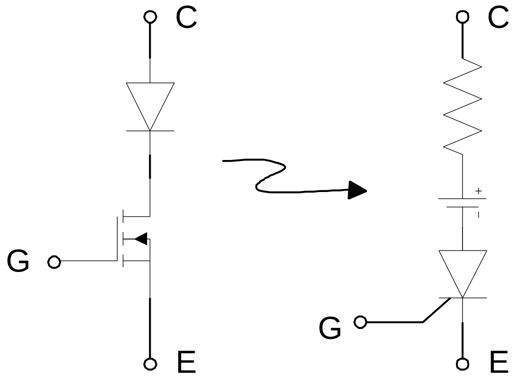


Fig. 13.48 Static model for IGBT

Tradeoffs are made in IGBT manufacture between the static model V_{on} and the turn-off speed. You can get both small. Consider two IGBT specs.

Fast IGBT	**Slow IGBT**
V_{on} = 2.7 V @ 100 A	**V_{on} = 1.5 V @ 100 A**
W(switch) = 4mJ/switch	**W(switch) = 12mJ/switch**

The total losses for each in a converter with duty cycle D are:

P(fast)=D(2.7)(100)+f_{sw}(4mJ) vs. P(slow)=D(1.5)(100)+f_{sw}(12mJ)

The losses match when D = 1 and fsw = 15 kHz or for D = ½ when f_{sw} = 7.5 kHz.

Fast IGBT is a better choice	**Slow IGBT is a better choice**
for f_{sw} > 10 kHz	**for f_{sw} < 5 kHz**

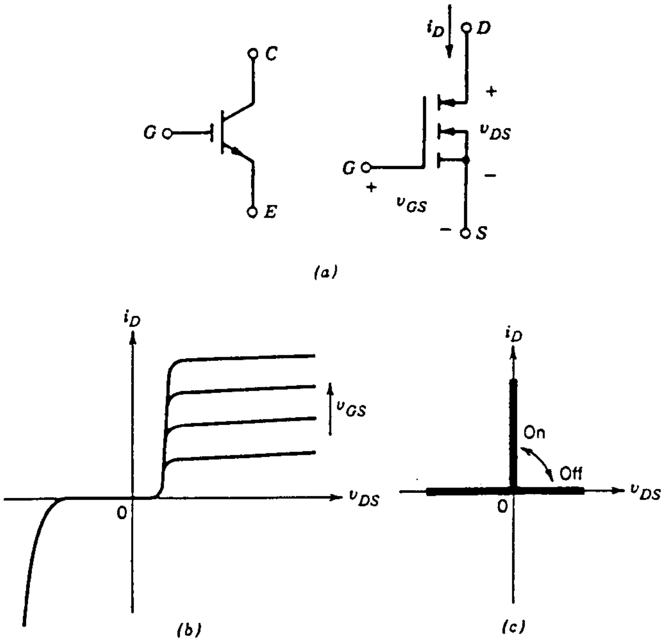
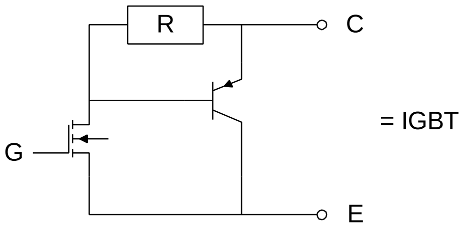


Figure 2-12 An IGBT: (*a*) symbol, (*b*) *i–v* characteristics, (*c*) idealized characteristics.

Typical specifications of today's IGBT's:

V_{on}: 2-3 V
V_{block}(off): 3 kV
I_{max}(on): 1 kA



- The IGBT is a voltage controlled device with a high impedance gate. The pnp BJT usually is designed with low β and has a small t_{on} delay but t_{off} delay is large
400-1μs.
- Its advantage is that only a small energy is required to switch the device either on or off. t_{rise} is 100 - 400 ns
t_{fall} is 50 - 400 ns

International Rectifier announced in Jan. 98 a 1200 V stand off and 500 A on current IGBT for use in uninterupted power supplies (UPS), welders and induction heaters. That's hefty power control.

B. Brief Review of Switch Properties

1. Nine Properties of switches

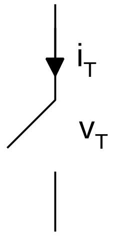
Switch losses include: $P_T(\text{loss}) = P(\text{static}) + P(\text{switch}) + P(\text{control})$

1. In on state:

$V_{block}(\text{off}) = \pm V$ and $I_{off} = 0$

$\Rightarrow$ No static power loss

$I_{off} \neq 0 \Rightarrow$ DC power loss occurs



2. $V_{on} = 0$ and $R_{on} = 0 \Rightarrow$ no power loss occurs for all currents
Static power loss occurs if V_{on} or R_{on} exist for any switch.

3. Switch on-off/off-on transients want to occur very fast
$\Delta t \rightarrow 0$ means less switching loss
If switching time Δt is not zero then for linear switch commutation $E_{sw} = ½ * V_{off} * I_{on}(\Delta t)$
$P_{sw} = 1/2 * V_{off} * I_{on} * \Delta t * f_{sw}$
Clearly we desire $\Delta t << T_s$ (switch cycle) as $\Delta t \downarrow$ then f_{sw} may increase.

4. For paralleling switches we need +T coefficient for R_{on} for ease of current sharing (sharing of on losses and switching losses).

5. Small control power required to drive the switches means ease of switching and less total switching loss.

Issues that drive the need for higher I, V, and P specifications on solid state switches:

6. Higher $V_{block}(\text{off})$ for one device means no need to use a series of devices in tandem. Series switches are hard to control because of timing differences compared to one series

switch of greater capability.

7. Higher I_{max}(on) capability of one big switch means no need to use parallel shunts to handle I_{max}. Avoids current sharing problems which arise because of different device on-resistances and negative temperature coefficients for R_{on}.

8. Higher stress handling switch that handles I_{max}(on) and V_{block}(off) simultaneously eliminates need for surrounding snubber circuits protecting the switch. Contrariwise a good snubber allows a lower power rating switch to be employed.

9. Cost of switch versus what extra capabilities bring is always a tradeoff. Similar cost arguments hold for snubber and control circuits.

2. SUMMARY and Comparision of Switches

Relative Properties of Controllable Switches

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

In a V-I plot of modern power switch capability shown on the next page, the above trends are more clear.

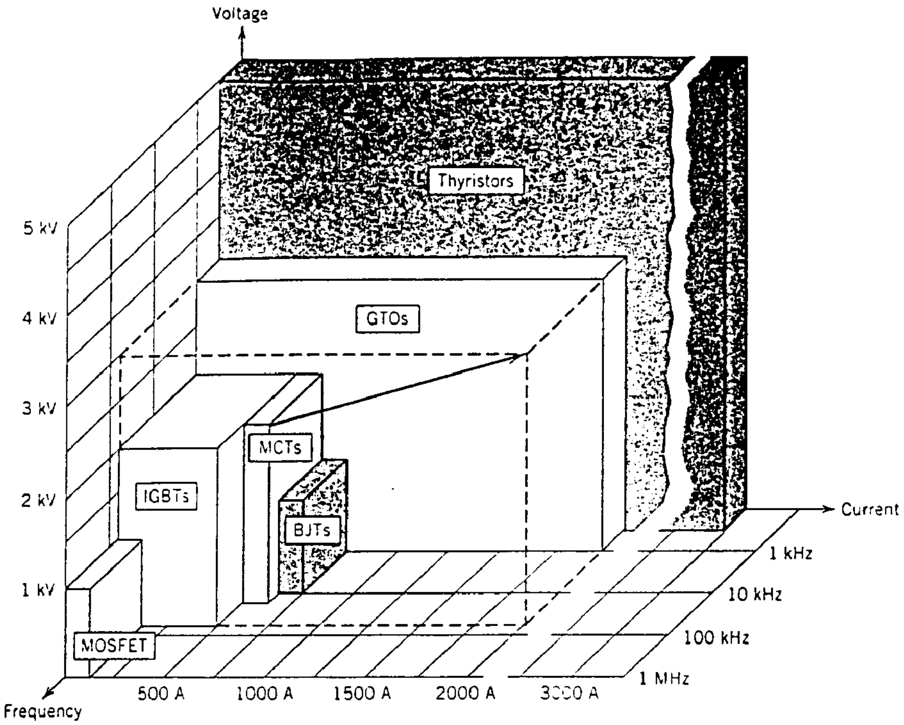
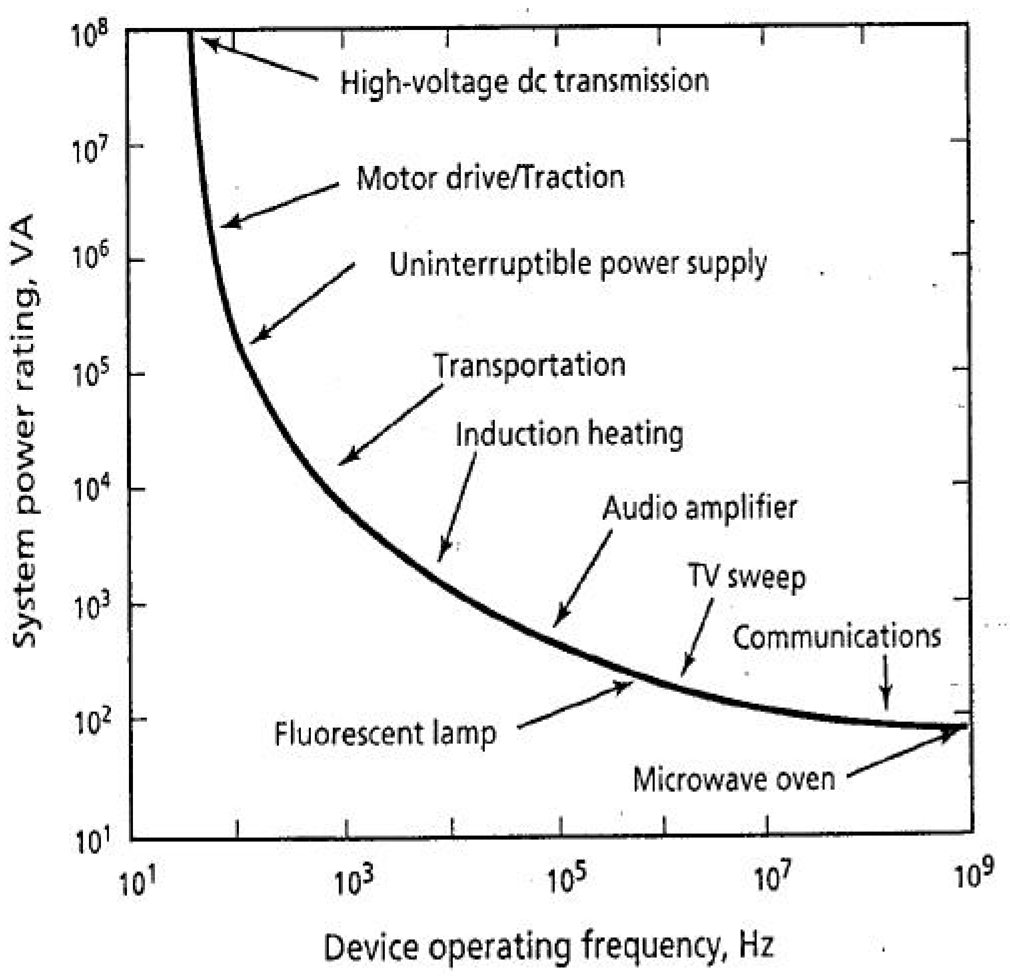


Figure 2-14 Summary of power semiconductor device capabilities. All devices except the MCT have a relatively mature technology, and only evolutionary improvements in the device capabilities are anticipated in the next few years. However, MCT technology is in a state of rapid expansion, and significant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

It is expected that MCT specs will soon equal other thyristors

For a term paper in the course grade do a detailed comparison of available modern power devices with the tradeoffs detailed. Keep in mind that different devices are suitable for different applications as shown on page 19.



▲ **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.**