Leakage current is independent of reverse bias voltage until breakdown region.
Shorter drift region of punch-through diode allows lower on-state voltage compared with nonpunch-through diode.

Diode is reverse biased in its blocking state.
Diode is forward biased in its conducting state.

In circuits with a large leakage inductance, an Rs-Cs snubber is sometimes needed to protect diodes against overvoltages. An optimum value of Rs can be found which minimizes overvoltages. Cs normally has a capacitance near:

\[ C_{\text{base}} = L_\sigma \left[ \frac{I_r}{V_d} \right]^2 \]

**Schottky Diode characteristics:**
1. Lower on-state voltage (0.3 V to 0.4 V)
2. Higher reverse leakage current
3. Lower breakdown voltage (100 V)
4. Quicker (shorter) \( t_{\text{off}} \) and \( t_{\text{on}} \) for switching
5. Majority carrier device
Thickness of the drift region determines breakdown voltage.

**Gate Drive Requirements:**
1. Base currents are large.
2. Negative base current needed when turning off the device.
3. Drive current for parallel devices must function at the same time.

Auxiliary power supplies should be referred to emitter reference and supplied by isolation transformers. Overcurrent protection (which turns BJT off) must be provided.

Length of conductor that connects base drive circuit to emitter of power transistors must be as short as possible. Separate gate drives on same printed circuit board (PCB) must be separated by at least 1 cm. No intermixing of drive signals can occur on PCB.

To achieve electrical isolation between logic level components and base drive circuits:
1. fiber optics
2. optocoupler
   a. LED
   b. Output transistor
   c. Built-in Schmitt trigger
3. transformer

Blanking time is needed in bridge circuits (single phase or three phase) to avoid cross conduction (short circuit).

Snubber circuits for BJTs:
1. turn-off snubber – to provide zero voltage across BJT at initial
2. turn-off snubber – only used to reduce losses at high switching frequency
3. overvoltage snubber – because of stray inductance

BJT is a normally off device. Turned on by a sufficiently large base current.
Trade-off in BJTs are between lower on-state losses and shorter switching times. (Can have either not both.) By controlling the rate of change of base current at turn-off to the BJT allows shorter turn-off times.
MOSFETs are intrinsically faster than BJTs because they have no excess minority carriers. Switching losses in a MOSFET are independent of junction temperature because MOSFET capacitances do not vary with temperature. Conduction loss does vary with junction temperature because on-state resistance varies with temperature. MOSFETs can be easily paralleled because of positive temperature coefficient for on-state resistance.

Safe Operating Area (SOA) is constrained by three factors:
1. Maximum drain current
2. Maximum junction temperature
3. Breakdown voltage

Faster switching yields:
1. higher EMI
2. higher diode reverse recovery current
3. overvoltage because of stray inductance
4. lower switching losses

MOSFET switching times can be controlled by gate current. Sometimes a gate current of 1 A is needed. MOSFETs also need electrical isolation and gate drivers like BJTs.

MOSFET snubbers:
1. Need for snubbers in MOSFETs is much less than that in BJTs.
2. Turn-off snubber increases with faster switching speeds.
3. Turn-on snubber is not needed for most applications because switching speed can be controlled by gate current.
Thyristors (SCRs – Semiconductor Controlled Rectifier)

Figure 23-1 Structural details of a generic thyristor: (a) vertical cross section; (b) gate and cathode layouts; (c) circuit symbol.

Figure from *Power Electronics: Converters, Applications, and Design*, Mohan, Undeland, Robbins, 2nd Edition.

Thyristor is a minority carrier device.
Thyristor can be turned on by gate signal – cannot be turned off by gate signal.
Thyristor has the highest voltage and current handling capability of power electronic devices.
Thyristor is the slowest switching device and is used only at lower switching frequency.

A minimum holding current is required to flow through thyristor to keep it in its conducting state.
A pulse of gate current with a positive voltage across the thyristor allows it to turn on and conduct.
To turn off, current must fall below the holding current for a specified time duration.

Forward blocking voltage and reverse blocking voltage decrease rapidly for junction temperatures greater than 150 deg. Celsius

Rate of rise of anode current must be limited or device damage or failure occurs.

Turn-on time of thyristor is much shorter than turn-off time.

To prevent accidental turn-on:
1. The thyristor has a minimum turn-off time where it should be reverse biased (negative voltage) before a forward voltage is applied.
2. Rate of change of forward voltage should be limited to less than max value (100V/usec to 1000V/usec)

GATT – gate assisted turn-off thyristor
Has turn off time as short as 10 microseconds

Turn-off snubbers may be needed because thyristors have a reverse recovery current like power diodes that may produce large overvoltages due to series inductance.
GTO – Gate Turn-Off Thyristor


Differences between a GTO and a thyristor:
1. Gate and cathode structures are interdigitated in a GTO.
2. Cathode is formed by etching away silicon so that they appear as mesas connected to a metal heat sink.
3. N+ regions penetrate the p+ region to short anode to n-region. This speeds up turn-off of device.
4. GTO has no blocking capability because of this anode short.
5. GTO has higher on-state voltage drop than thyristor.
6. GTO has shorter turn-off and forward recovery time.

RCT – reverse conducting thyristor
Has shorted anode which leads to short turn-off and forward recovery times like GTO but cannot be turned off with negative gate current like GTO can.

GTOs require snubber circuits.
Inductive turn-on snubbers are required because GTOs have slow free-wheeling anti-parallel diodes and fast current rise times.
A pulse of gate current (at least 10 usec in length) triggers GTO to turn on. A minimum amount of gate current must flow to prevent unwanted turn-off.
Negative turn-off gate current must be large (approximately 1/5 to 1/3 the anode current being turned off). GTOs must be on and off for a minimum time duration so that current sharing among the cathode islands is evenly distributed.
Limiting the negative gate-cathode voltage limits the maximum gate current, which in turn limits the maximum controllable anode current.

GTOs can turn off a much large anode current than its RMS rating. The maximum controllable anode current depends on Cs (snubber capacitance). The larger Cs – the larger controllable anode current – the larger the switching loss.
Always put snubber as close as possible to GTO to limit stray inductance.

Overcurrent protection requires a crowbar technique – thyristor in parallel with GTO turns on to shunt current until fuse blows OR in a three-phase inverter, all 6 GTOs turn on and short until a fuse blows.

If anode current is higher than maximum controllable, then it cannot be turned off.
IGBT (Insulated Gate Bipolar Transistors)

Most IGBTs are n-channel type.
Asymmetric IGBTs have n+ buffer layer
Symmetric IGBTs have no n+ layer.

Buffer layer:
1. Improves on-state voltage drop (advantage)
2. Shortens turn-off time (advantage)
3. Reduces reverse blocking capability (drawback)

Symmetric == nonpunch through == no buffer layer
Asymmetric == punch through == buffer layer

On-state voltage drop usually between 0.7V and 1.0V.

Tradeoff between faster turn-off and on-state losses.
On-state voltage Vds(on) varies little with temperature of junction.
In power MOSFET, Vds(on) increases significantly as junction temperature increases.

Generally, the same gate drive circuits for power MOSFETs can also be used with IGBTs.

Snubbers are not usually needed because gate series resistance can be controlled to change ton and toff to desired values.

IGBT is faster than BJT but slower than MOSFET.
On-state loss is lower than MOSFET but higher than BJT.

Power JFET

JFET is a normally-on device – when gate is shorted to source, device is in the on-state. All other devices are normally-off devices. Normally-on is difficult at startup. JFET has higher blocking voltage than BJT, MOSFET. On state losses are larger than MOSFET. Normally-on JFET is a majority carrier device. Normally-off JFET is a minority carrier device.

Normally off JFET is called BSIT (bipolar static induction transistor). JFET requires $V_{gs} > 0$ for turn on and $V_{gs} < 0$ for turn off. MOSFET is the opposite.

FCT – Field Controlled Thyristor

FCT has smaller on-state voltage than JFET. Switching speed is much slower for FCT than JFET. Turn-off of FCT requires a large negative gate pulse like GTO.

MCT – (MOS Controlled Thyristor)

Thyristor with two MOSFET built into the gate structure – one to turn on the thyristor and one to turn it off.

Alternative Materials:

1. Gallium Arsenide (GaAs) – can be used at higher temperature than Si. On state voltage drop is less in GaAs.
2. Silicon Carbide (SiC)
3. Diamond

Likely that silicon carbide devices will be available in near future.

<table>
<thead>
<tr>
<th>Property</th>
<th>Si</th>
<th>GaAs</th>
<th>3C–SiC</th>
<th>6H–SiC</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandgap at 300 K (eV)</td>
<td>1.12</td>
<td>1.43</td>
<td>2.2</td>
<td>2.9</td>
<td>5.5</td>
</tr>
<tr>
<td>Relative dielectric constant</td>
<td>11.8</td>
<td>12.8</td>
<td>9.7</td>
<td>10</td>
<td>5.5</td>
</tr>
<tr>
<td>Saturated drift velocity (cm/s)</td>
<td>$1 \times 10^7$</td>
<td>$2 \times 10^7$</td>
<td>$2.5 \times 10^7$</td>
<td>$2.5 \times 10^7$</td>
<td>$2.7 \times 10^7$</td>
</tr>
<tr>
<td>Thermal conductivity (W/cm²K)</td>
<td>1.5</td>
<td>0.5</td>
<td>5.0</td>
<td>5.0</td>
<td>20</td>
</tr>
<tr>
<td>Maximum operating temperature (K)</td>
<td>300</td>
<td>460</td>
<td>873</td>
<td>1240</td>
<td>1100</td>
</tr>
<tr>
<td>Melting temperature (°C)</td>
<td>1415</td>
<td>1238</td>
<td>Sublime</td>
<td>Sublime</td>
<td>Phases</td>
</tr>
<tr>
<td>Electron mobility at 300 K (cm²/V.s)</td>
<td>1400</td>
<td>8500</td>
<td>1000</td>
<td>600</td>
<td>2200</td>
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<tr>
<td>Breakdown electric field (V/cm)</td>
<td>$3 \times 10^5$</td>
<td>$4 \times 10^5$</td>
<td>$4 \times 10^6$</td>
<td>$4 \times 10^6$</td>
<td>$1 \times 10^7$</td>
</tr>
</tbody>
</table>

Table 26-1 Properties of Semiconductor Materials with Potential for Power Devices

IGBTs can be found with ratings of 4500 V and 2000 A.
MOSFETs can be found with ratings up to 1000V, 33A or 200V, 146A.

Minority (holes) carrier devices (like BJTs, IGBTs) have lower power dissipation capability
Majority (electrons) carrier devices (like MOSFETs) have higher power dissipation capability

Trade-offs in power electronic devices:
Reduced on-state losses requires a large stored charge – this requires a longer switching time.
High breakdown (blocking) voltage causes large voltage drop during conduction.