Chapter 1
Power Electronic Devices
(Part I)
Outline

1.1 An introductory overview of power electronic devices
1.2 Uncontrolled device — power diode
1.3 Half-controlled device — thyristor
1.4 Typical fully-controlled devices
1.5 Other new power electronic devices
1.6 Drive circuit for power electronic devices
1.7 Protection of power electronic devices
1.8 Series and parallel connections of power electronic devices
1.1 An introductory overview of power electronic devices

- The concept and features
- Configuration of systems using power electronic devices
- Classifications
- Major topics
The concept of power electronic devices

- **Power electronic devices:**
  - are the electronic devices that can be directly used in the power processing circuits to convert or control electric power.

- **In broad sense**
  - Vacuum devices: Mercury arc rectifier thyratron, etc. – seldom in use today
  - Semiconductor devices: major power electronic devices

- **Very often:** Power electronic devices = Power semiconductor devices

- **Major material used in power semiconductor devices**
  - Silicon
Features of power electronic devices

- The electric power that power electronic device deals with is usually much larger than that the information electronic device does.

- Usually working in switching states to reduce power losses

  On-state ➔ Voltage across the device is 0 ➔ \( p=vi=0 \)  
  \( v=0 \)  

  Off-state ➔ Current through the device is 0 ➔ \( p=vi=0 \)  
  \( i=0 \)
Features of power electronic devices

- Need to be controlled by information electronic circuits. Very often, drive circuits are necessary to interface between information circuits and power circuits.

- Dissipated power loss usually larger than information electronic devices — special packaging and heat sink are necessary.
Power losses on power semiconductor devices

\[
\text{Total power loss on power semiconductor} = \text{conduction loss} + \text{turn-off loss} + \text{off-state loss} + \text{turn-on loss (on-state loss)}
\]
Configuration of systems using power electronic devices

Power electronic system:

- Control circuit (in a broad sense)
- Detection circuit
- Drive circuit
- Power circuit (power stage, main circuit)

Electric isolation: optical, magnetic

Protection circuit is also very often used in power electronic system especially for the expensive power semiconductors.
A power electronic device usually has a third terminal — control terminal to control the states of the device.

Control signal from drive circuit must be connected between the control terminal and a fixed power circuit terminal (therefore called common terminal).
A classification of power electronic devices

- **Uncontrolled device: diode**
  (Uncontrollable device)

  has only two terminals and cannot be controlled by control signal. The on and off states of the device are determined by the power circuit.

- **Half-controlled device: thyristor**
  (Half-controllable device)

  is turned-on by a control signal and turned-off by the power circuit.

- **Fully-controlled device: Power MOSFET, IGBT, GTO, IGCT**
  (Fully-controllable device)

  The on and off states of the device are controlled by control signals.
Other classifications

- Power electronic devices
  - Current-driven (current-controlled) devices
  - Voltage-driven (voltage-controlled) devices
    - (Field-controlled devices)
  - Pulse-triggered devices
  - Level-sensitive (level-triggered) devices
  - Unipolar devices (Majority carrier devices)
  - Bipolar devices (Minority carrier devices)
  - Composite devices
Major topics for each device

- Appearance, structure, and symbol
- Physics of operation
- Characteristics
  - Static characteristics
  - Switching characteristics
- Specification
- Special issues
- Devices of the same family
Passive components in power electronic circuit

- Transformer, inductor, capacitor and resistor: these are passive components in a power electronic circuit since they cannot be controlled by control signal and their characteristics are usually constant and linear.

- The requirements for these passive components by power electronic circuits could be very different from those by ordinary circuits.
1.2 Uncontrolled device Power diode

Appearance

Structure

Symbol
PN junction

- **Semiconductor (Column IV element, Si)**
- **Electrons and holes.**
- **Pure semiconductor (intrinsic semiconductor)**
- **Doping, p-type semiconductor. N-type semiconductor**
- **PN junction**
- **Equilibrium of diffusion and drift**
PN junction with voltage applied in the forward direction
PN junction with voltage applied in the reverse direction

Effective direction of electronic field
Construction of a practical power diode

- Larger size
- Vertically oriented structure
- \( n^- \) drift region (p-i-n diode)
- Conductivity modulation

Features different from low-power (information electronic) diodes

- Breakdown voltage dependent
- 10 \( \mu \) m
- 250 \( \mu \) m

\[ \begin{align*}
&\text{Anode} \\
&\text{Cathode} \\
&\text{p}^+ \\
&\text{n}^- \text{ epi} \\
&\text{n}^+ \text{ substrate}
\end{align*} \]
Forward-biased power diode

conductivity modulation

minority carrier injection
Reverse-biased power diode

Breakdown
- Avalanche breakdown
- Thermal breakdown
Junction capacitor

- The positive and negative charge in the depletion region is variable with the changing of external voltage. — Junction capacitor $C_J$.

- Junction capacitor $C_J$ —
  - Potential barrier capacitor $C_B$
  - Diffusion capacitor $C_D$

- Junction capacitor influences the switching characteristics of power diode.
Static characteristics of power diode

The I-V characteristic of power diode

The I-V characteristic of power diode
Switching (dynamic) characteristics of power diode

Turn-off transient

Reverse-recovery process:
Reverse-recovery time, reverse-recovery charge, reverse-recovery peak current.
Switching (dynamic) characteristics of power diode

Turn-on transient

Forward recovery process:
forward-recovery time
### Specifications of power diode

- Average rectified forward current $I_{F(AV)}$
- Forward voltage $U_F$
- Peak repetitive reverse voltage $U_{RRM}$
- Maximum junction temperature $T_{JM}$
- Reverse-recovery time $t_{rr}$
Types of power diodes

- **General purpose diode (rectifier diode):**
  - standard recovery

- **Fast recovery diode**
  - Reverse recovery time and charge specified. \( t_{rr} \) is usually less than 1 \( \mu \)s, for many less than 100 ns —— ultra-fast recovery diode.

- **Schottky diode (Schottky barrier diode-SBD)**
  - A majority carrier device
  - Essentially no recovered charge, and lower forward voltage.
  - Restricted to low voltage (less than 200V)
Examples of commercial power diodes

<table>
<thead>
<tr>
<th>Part number</th>
<th>Rated max voltage</th>
<th>Rated avg current</th>
<th>$V_F$ (typical)</th>
<th>$t_r$ (max)</th>
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<tr>
<td><strong>Fast recovery rectifiers</strong></td>
<td></td>
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<tr>
<td>1N3913</td>
<td>400V</td>
<td>30A</td>
<td>1.1V</td>
<td>400ns</td>
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<td>SD453N25S20PC</td>
<td>2500V</td>
<td>400A</td>
<td>2.2V</td>
<td>2μs</td>
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<td><strong>Ultra-fast recovery rectifiers</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUR815</td>
<td>150V</td>
<td>8A</td>
<td>0.975V</td>
<td>35ns</td>
</tr>
<tr>
<td>MUR1560</td>
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<td>15A</td>
<td>1.2V</td>
<td>60ns</td>
</tr>
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<td>RHHRU100120</td>
<td>1200V</td>
<td>100A</td>
<td>2.6V</td>
<td>60ns</td>
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<td><strong>Schottky rectifiers</strong></td>
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<td></td>
</tr>
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<td>MBR6030L</td>
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<td>60A</td>
<td>0.48V</td>
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<tr>
<td>444CNQ045</td>
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<td>440A</td>
<td>0.69V</td>
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<tr>
<td>30CPQ150</td>
<td>150V</td>
<td>30A</td>
<td>1.19V</td>
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</tbody>
</table>
History and applications of power diode

- Applied in industries starting 1950s
- Still in-use today. Usually working with controlled devices as necessary components
- In many circumstances fast recovery diodes or schottky diodes have to be used instead of general purpose diodes.
1.3 Half-controlled device—Thyristor

History

✦ Another name: SCR—silicon controlled rectifier

✦ Thyristor Opened the power electronics era
  – 1956, invention, Bell Laboratories
  – 1957, development of the 1st product, GE
  – 1958, 1st commercialized product, GE
  – Thyristor replaced vacuum devices in almost every power processing area.

✦ Still in use in high power situation. Thyristor till has the highest power-handling capability.
Appearance and symbol of thyristor

Appearance

Symbol

K

G

A

Cathode

Gate

Anode
Structure and equivalent circuit of thyristor

- Structure

- Equivalent circuit

(a) Structure diagram

(b) Equivalent circuit diagram
Physics of thyristor operation

- Equivalent circuit: A pnp transistor and an npn transistor interconnected together
- Positive feedback
- Trigger
- Can not be turned off by control signal
- Half-controllable
Quantitative description of thyristor operation

\[ I_{c1} = \alpha_1 I_A + I_{CBO1} \]  \hspace{1cm} (1-1)

\[ I_{c2} = \alpha_2 I_K + I_{CBO2} \]  \hspace{1cm} (1-2)

\[ I_K = I_A + I_G \]  \hspace{1cm} (1-3)

\[ I_A = I_{c1} + I_{c2} \]  \hspace{1cm} (1-4)

\[ I_A = \frac{\alpha_2 I_G + I_{CBO1} + I_{CBO2}}{1 - (\alpha_1 + \alpha_2)} \]  \hspace{1cm} (1-5)

When \( I_G = 0 \), \( \alpha_1 + \alpha_2 \) is small.
When \( I_G > 0 \), \( \alpha_1 + \alpha_2 \) will approach 1, \( I_A \) will be very large.
Other methods to trigger thyristor on

- High voltage across anode and cathode—avalanche breakdown
- High rising rate of anode voltage — du/dt too high
- High junction temperature
- Light activation
Static characteristics of thyristor

- Blocking when reverse biased, no matter if there is gate current applied
- Conducting only when forward biased and there is triggering current applied to the gate
- Once triggered on, will be latched on conducting even when the gate current is no longer applied
- Turning off: decreasing current to be near zero with the effect of external power circuit
- Gate I-V characteristics

\[ U_{RSM} \quad U_{RRM} \quad I_H \quad U_{DSM} \quad U_{bo} \quad U_{Ak} \]

- Increasing \( I_G \)
- Forward conducting
- Reverse blocking
- Avalanche breakdown

\[ I_{G2} \quad I_{G1} \quad I_G = 0 \]
Switching characteristics of thyristor

- Turn-on transient
  - Delay time $t_d$
  - Rise time $t_r$
  - Turn-on time $t_{gt}$

- Turn-off transient
  - Reverse recovery time $t_{rr}$
  - Forward recovery time $t_{gr}$
  - Turn-off time $t_q$
## Specifications of thyristor

- Peak repetitive forward blocking voltage $U_{DRM}$
- Peak repetitive reverse blocking voltage $U_{RRM}$
- Peak on-state voltage $U_{TM}$
- Average on-state current $I_{T(AV)}$
- Holding current $I_H$
- Latching up current $I_L$
- Peak forward surge current $I_{TSM}$
- $du/dt$
- $di/dt$
The family of thyristors

- Fast switching thyristor—FST
- Triode AC switch—TRIAC
  (Bi-directional triode thyristor)

- Reverse-conducting thyristor—RCT
- Light-triggered (activated) thyristor—LTT
1.4 Typical fully-controlled devices

1.4.1 Gate-turn-off thyristor — GTO
1.4.2 Giant transistor — GTR
1.4.3 Power metal-oxide-semiconductor field effect transistor — Power MOSFET
1.4.4 Insulated-gate bipolar transistor — IGBT

Features

- IC fabrication technology, fully-controllable, high frequency

Applications

- Begin to be used in large amount in 1980s
- GTR is obsolete and GTO is also seldom used today.
- IGBT and power MOSFET are the two major power semiconductor devices nowadays.
1.4.1 Gate-turn-off thyristor—GTO

Major difference from conventional thyristor:
The gate and cathode structures are highly interdigitated, with various types of geometric forms being used to layout the gates and cathodes.
Physics of GTO operation

- The basic operation of GTO is the same as that of the conventional thyristor.

- The principal differences lie in the modifications in the structure to achieve gate turn-off capability.
  - Large $\alpha_2$
  - $\alpha_1 + \alpha_2$ is just a little larger than the critical value 1.
  - Short distance from gate to cathode makes it possible to drive current out of gate.
Characteristics of GTO

- **Static characteristic**
  - Identical to conventional thyristor in the forward direction
  - Rather low reverse breakdown voltage (20-30V)

- **Switching characteristic**
Specifications of GTO

Most GTO specifications have the same meanings as those of conventional thyristor.

Specifications different from thyristor’s

- Maximum controllable anode current $I_{ATO}$
- Current turn-off gain $\beta_{off}$
- Turn-on time $t_{on}$
- Turn-off time $t_{off}$
1.4.2 Giant Transistor—GTR

- GTR is actually the bipolar junction transistor that can handle high voltage and large current.
- So GTR is also called power BJT, or just BJT.
Structures of GTR different from its information-processing counterpart

Multiple-emitter structure

Darlington configuration

Emitter
Base

Collector

$Q_1$

$D_1$

$Q_2$
Physics of GTR operation

- Same as information BJT device

\[ i_c = \beta i_b \]

\[ i_c = (1 + \beta) i_b \]

- Electrons
- Holes
Static characteristics of GTR

- **Saturation region**
- **Amplifying (active) region**
- **Cut-off region**

$I$ and $U_{ce}$ are the axes of the graph. The lines $i_{b1}$, $i_{b2}$, and $i_{b3}$ represent different bias currents in the device.
Switching characteristics of GTR

- **Turn-on transient**
  - Turn-on delay time $t_d$
  - Rise time $t_r$
  - Turn-on time $t_{on}$

- **Turn-off transient**
  - Storage time $t_s$
  - Falling time $t_f$
  - Turn-off time $t_{off}$
Second breakdown of GTR
Safe operating area (SOA) of GTR
1.4.3 Power metal-oxide-semiconductor field effect transistor—Power MOSFET

A classification

Field Effect Transistor (FET)  
- Metal-onside-semiconductor FET (MOSFET) → Power MOSFET
  - n channel
  - p channel
- Junction FET (JFET) → Static induction transistor (SIT)

Basic structure

Symbol

P channel

N channel
Structures of power MOSFET

- Also vertical structure—VMOS
  - VVMOS, VDMOS

- Multiple parallel cells
  - Polygon-shaped cells

A structure of hexagon cells
Physics of MOSFET operation

Off-state

- *p-n*⁻ junction is reverse-biased
- off-state voltage appears across *n*⁻ region
Physics of MOSFET operation

On-state

- $p$-$n$ junction is slightly reverse biased
- positive gate voltage induces conducting channel
- drain current flows through $n^-$ region and conducting channel
- on resistance = total resistances of $n^-$ region, conducting channel, source and drain contacts, etc.
Static characteristics of power MOSFET
Switching characteristics of power MOSFET

- Turn-on transient
  - Turn-on delay time $t_{d(on)}$
  - Rise time $t_r$

- Turn-off transient
  - Turn-off delay time $t_{d(off)}$
  - Falling time $t_f$
## Specifications of power MOSFET

- Drain-source breakdown voltage $U_{DS}$
- Continuous drain current $I_D$
- Peak pulsed drain current $I_{DM}$
- On (On-state) resistance $R_{DS(on)}$
- Inter-terminal capacitances
  - Short circuit input capacitance $C_{iss} = C_{GS} + C_{GD}$
  - Reverse transfer capacitance $C_{rss} = C_{GD}$
  - Short circuit output capacitance $C_{oss} = C_{DS} + C_{GD}$
- SOA of power MOSFET
  - No second breakdown
## Examples of commercial power MOSFET

<table>
<thead>
<tr>
<th>Part number</th>
<th>Rated max voltage</th>
<th>Rated avg current</th>
<th>$R_{on}$</th>
<th>$Q_g$ (typical)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRFZ48</td>
<td>60V</td>
<td>50A</td>
<td>0.018Ω</td>
<td>110nC</td>
</tr>
<tr>
<td>IRF510</td>
<td>100V</td>
<td>5.6A</td>
<td>0.54Ω</td>
<td>8.3nC</td>
</tr>
<tr>
<td>IRF540</td>
<td>100V</td>
<td>28A</td>
<td>0.077Ω</td>
<td>72nC</td>
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<tr>
<td>APT10M25BNR</td>
<td>100V</td>
<td>75A</td>
<td>0.025Ω</td>
<td>171nC</td>
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<td>IRF740</td>
<td>400V</td>
<td>10A</td>
<td>0.55Ω</td>
<td>63nC</td>
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<tr>
<td>MTM15N40E</td>
<td>400V</td>
<td>15A</td>
<td>0.3Ω</td>
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<td>APT5025BN</td>
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<td>83nC</td>
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<td>APT1001RBNR</td>
<td>1000V</td>
<td>11A</td>
<td>1.0Ω</td>
<td>150nC</td>
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</tbody>
</table>
Features and applications of power MOSFET

- Voltage-driven device, simple drive circuit
- Majority-carrier device, fast switching speed, high operating frequency (could be hundreds of kHz)
- Majority-carrier device, better thermal stability
- On-resistance increases rapidly with rated blocking voltage
  - Usually used at voltages less than 500V and power less than 10kW
  - 1000V devices are available, but are useful only at low power levels (100W)
- Part number is selected on the basis of on-resistance rather than current rating
The body diode of power MOSFET

- The body diode

- Equivalent circuit
1.4.4 Insulated-gate bipolar transistor — IGBT

Combination of MOSFET and GTR

**GTR:** 😊 low conduction losses (especially at larger blocking voltages), 😞 longer switching times, current-driven

**MOSFET:** 😊 faster switching speed, easy to drive (voltage-driven), 😞 larger conduction losses (especially for higher blocking voltages)

Features
- On-state losses are much smaller than those of a power MOSFET, and are comparable with those of a GTR
- Easy to drive — similar to power MOSFET
- Faster than GTR, but slower than power MOSFET

Application
- The device of choice in 500-1700V applications, at power levels of several kW to several MW
Structure and operation principle of IGBT

Basic structure

- Also multiple cell structure
- Basic structure similar to power MOSFET, except extra p region
- On-state: minority carriers are injected into drift region, leading to conductivity modulation
- Compared with power MOSFET: slower switching times, lower on-resistance, useful at higher voltages (up to 1700V)
Equivalent circuit and circuit symbol of IGBT
Static characteristics of IGBT

- Active region
- Saturation region (On region)
- Reverse blocking region
- Cut-off (forward blocking) region

$I_C$, $U_{RM}$, $U_{FM}$, $U_{CE}$, $U_{GE}$, $U_{GE(th)}$
Switching characteristics of IGBT

- IGBT turn-on is similar to power MOSFET turn-on

- The major difference between IGBT turn-off and power MOSFET turn-off:
  - There is current tailing in the IGBT turn-off due to the stored charge in the drift region.
Parasitic thyristor and latch-up in IGBT

- Main current path pnp transistor and the parasitic npn transistor compose a parasitic thyristor inside IGBT.
- High emitter current tends to latch the parasitic thyristor on.
- Modern IGBTs are essentially latch-up proof
Specifications of IGBT

- Collector-emitter breakdown voltage $U_{CES}$
- Continuous collector current $I_C$
- Peak pulsed collector current $I_{CM}$
- Maximum power dissipation $P_{CM}$

Other issues:
- SOA of IGBT
  - The IGBT has a rectangular SOA with similar shape to the power MOSFET.
- Usually fabricated with an anti-parallel fast diode
# Examples of commercial IGBT

<table>
<thead>
<tr>
<th>Part number</th>
<th>Rated max voltage</th>
<th>Rated avg current</th>
<th>$V_F$ (typical)</th>
<th>$t_f$ (typical)</th>
</tr>
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<tbody>
<tr>
<td>Single-chip devices</td>
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<tr>
<td>HGTG32N60E2</td>
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<td>32A</td>
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<td>0.62μs</td>
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<td>1200V</td>
<td>300A</td>
<td>2.7V</td>
<td>0.3μs</td>
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</table>
1.5 Other new power electronic devices

- Static induction transistor — SIT
- Static induction thyristor — SITH
- MOS controlled thyristor — MCT
- Integrated gate-commutated thyristor — IGCT
- Power integrated circuit and power module
Static induction transistor—SIT

- Another name: power junction field effect transistor—power JFET

- Features
  - Major-carrier device
  - Fast switching, comparable to power MOSFET
  - Higher power-handling capability than power MOSFET
  - Higher conduction losses than power MOSFET
  - Normally-on device, not convenient (could be made normally-off, but with even higher on-state losses)
Static induction thyristor—SITH

нолог other names
– Field controlled thyristor—FCT
– Field controlled diode

Features
– Minority-carrier device, a JFET structure with an additional injecting layer
– Power-handling capability similar to GTO
– Faster switching speeds than GTO
– Normally-on device, not convenient (could be made normally-off, but with even higher on-state losses)
MOS controlled thyristor—MCT

- Essentially a GTO with integrated MOS-driven gates controlling both turn-on and turn-off that potentially will significantly simplify the design of circuits using GTO.

- The difficulty is how to design a MCT that can be turned on and turned off equally well.

- Once believed as the most promising device, but still not commercialized in a large scale. The future remains uncertain.
Integrated gate-commutated thyristor — IGCT

- The newest member of the power semiconductor family, introduced in 1997 by ABB
- Actually the close integration of GTO and the gate drive circuit with multiple MOSFETs in parallel providing the gate currents
- Short name: GCT
- Conduction drop, gate driver loss, and switching speed are superior to GTO
- Competing with IGBT and other new devices to replace GTO
**Power integrated circuit and power module**

Integration of power electronic devices

- **Monolithic integration:** power integrated circuit
  - High voltage integrated circuit (HVIC)
  - Smart power integrated circuit (Smart power IC, SPIC, Smart switch)

- **Packaging integration:** power module
  - Ordinary power module: just power devices packaged together
  - Intelligent power module (IPM): power devices, drive circuit, protection circuit
  - Integrated power electronics Module (IPEM): power devices, drive circuit, protection circuit, control circuit

✦ **Two major challenges**

- Electrical isolation of high-voltage components from low-voltage components
- Thermal management—power devices usually at higher temperatures than low-voltage devices
Review of device classifications

- **Current-driven (current-controlled) devices**: thyristor, GTO, GTR
- **Voltage-driven (voltage-controlled) devices** (Field-controlled devices): power MOSFET, IGBT, SIT, SITH, MCT, IGCT
- **Pulse-triggered devices**: thyristor, GTO
- **Level-sensitive (Level-triggered) devices**: GTR, power MOSFET, IGBT, SIT, SITH, MCT, IGCT
- **Uni-polar devices** (Majority carrier devices): SBD, power MOSFET, SIT
- **Bipolar devices** (Minority carrier devices): ordinary power diode, thyristor, GTO, GTR, IGCT, IGBT, SITH, MCT
- **Composite devices**: IGBT, SITH, MCT
Comparison of the major types of devices

- Power-handling capability

**Diagram:**

- Thyristors
- GTOs (being challenged by IGCTs, IGBTs etc.)
Comparison of the major types of devices

- Maximum allowed current density as a function of the switching frequency