Basic Power Electronics Components

SI Units

Quantity	Quantity symbol	Unit	Unit symbol
Capacitance	C	Farad	F
Charge	Q	Coulomb	C
Current	I	Ampere	A
Electromotive force	E	Volt	V
Frequency	f	Hertz	Hz
Inductance (self)	L	Henry	H
Period	T	Second	s
Potential difference	V	Volt	V
Power	P	Watt	W
Resistance	R	Ohm	Ω
Temperature	T	Kelvin	K
Time	t	Second	s

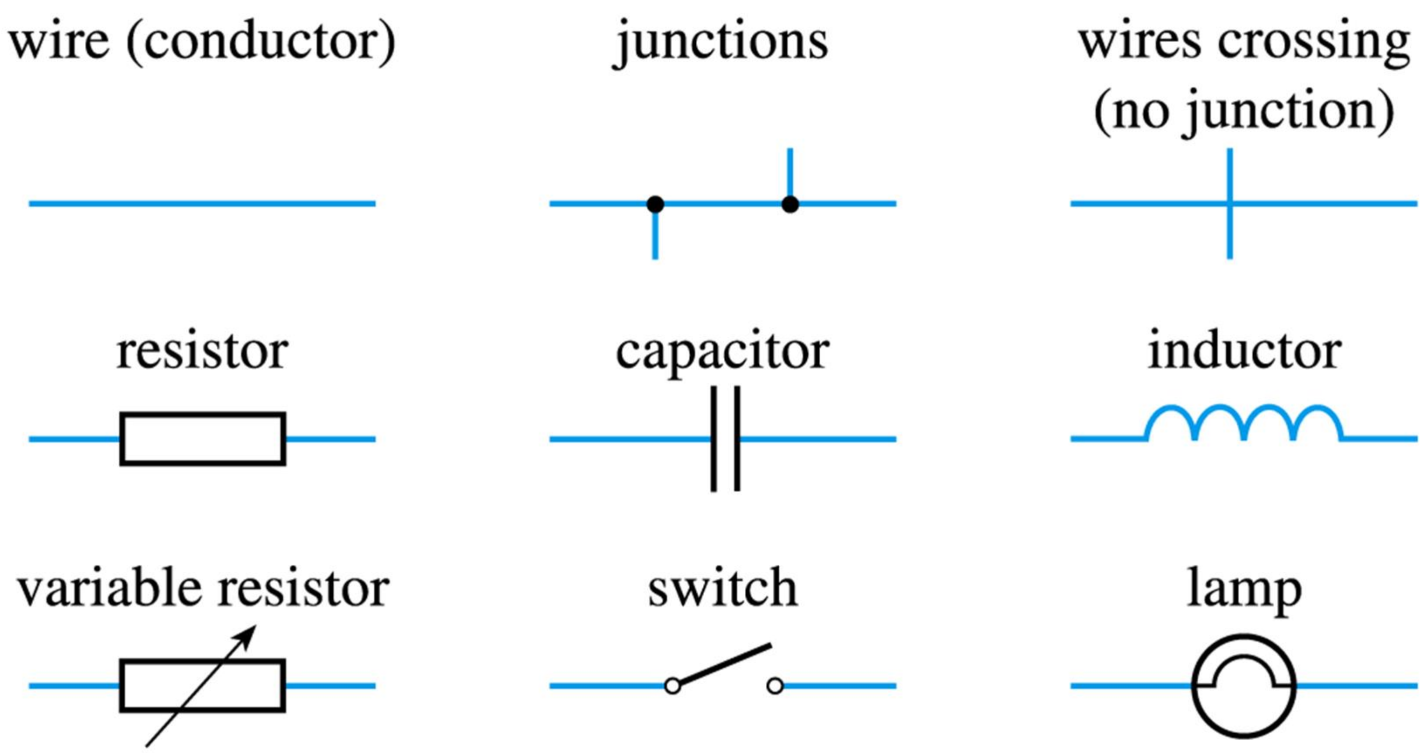
Common Prefixes

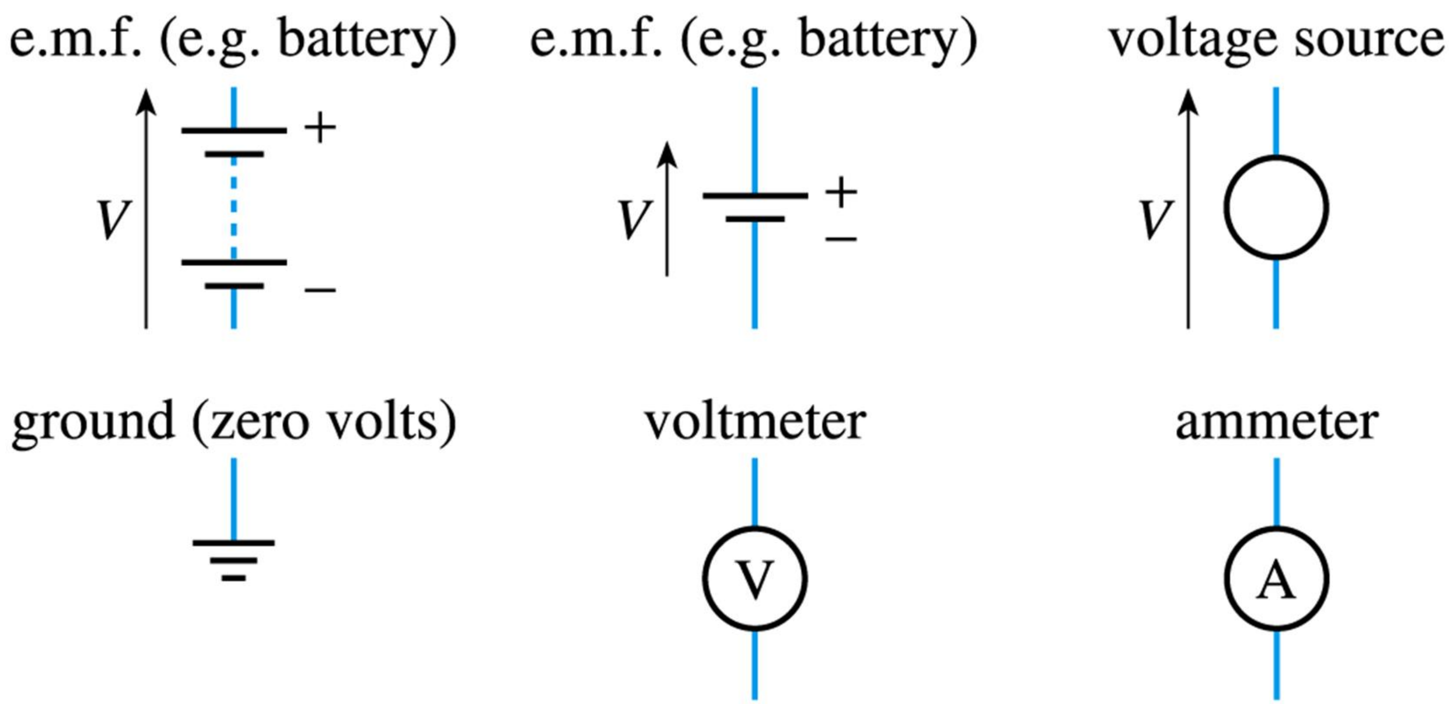
Prefix	Name	Meaning (multiply by)
T	tera	10^{12}
G	giga	10^{9}
M	mega	10^{6}
k	kilo	10^{3}
m	milli	10^{-3}
μ	micro	10^{-6}
n	nano	10^{-9}
p	pico	10^{-12}

Resistors, Capacitors and Inductors

- **Resistors** provide resistance
  - they oppose the flow of electricity
  - measured in Ohms (Ω)
- **Capacitors** provide capacitance
  - they store energy in an electric field
  - measured in Farads (F)
- **Inductors** provide inductance
  - they store energy in a magnetic field
  - measured in Henry (H)

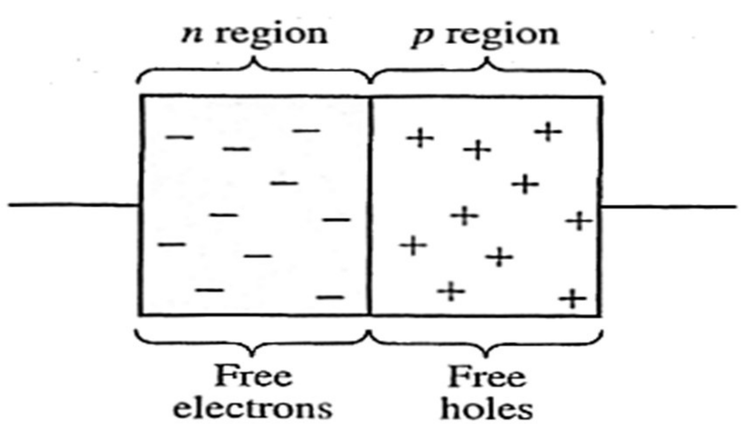
Circuit Symbols

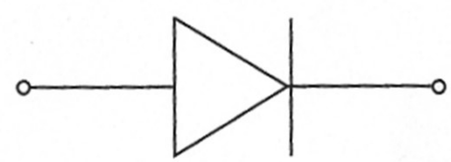



e.m.f. (e.g. battery)
V
+
−
e.m.f. (e.g. battery)
V
+
−
voltage source
V
ground (zero volts)
voltmeter
V
ammeter
A

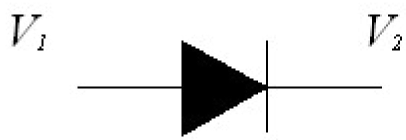
Diodes

It is represented by the following symbol, where the arrow indicates the direction of positive current flow.

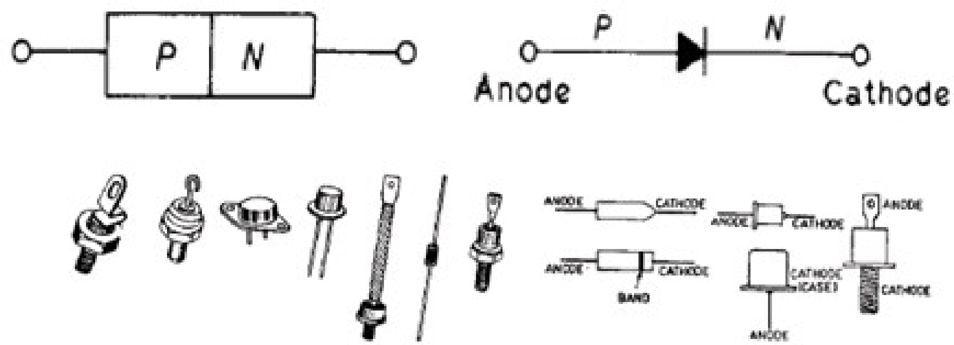




P-N Junction

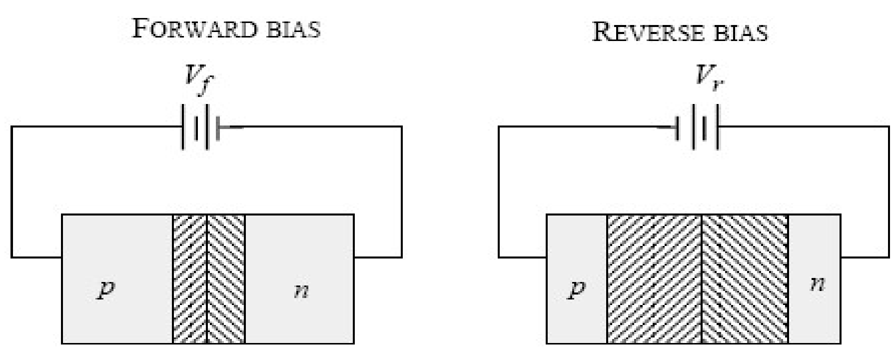


- $V_1 > V_2$, current →
- $V_1 < V_2$, no current

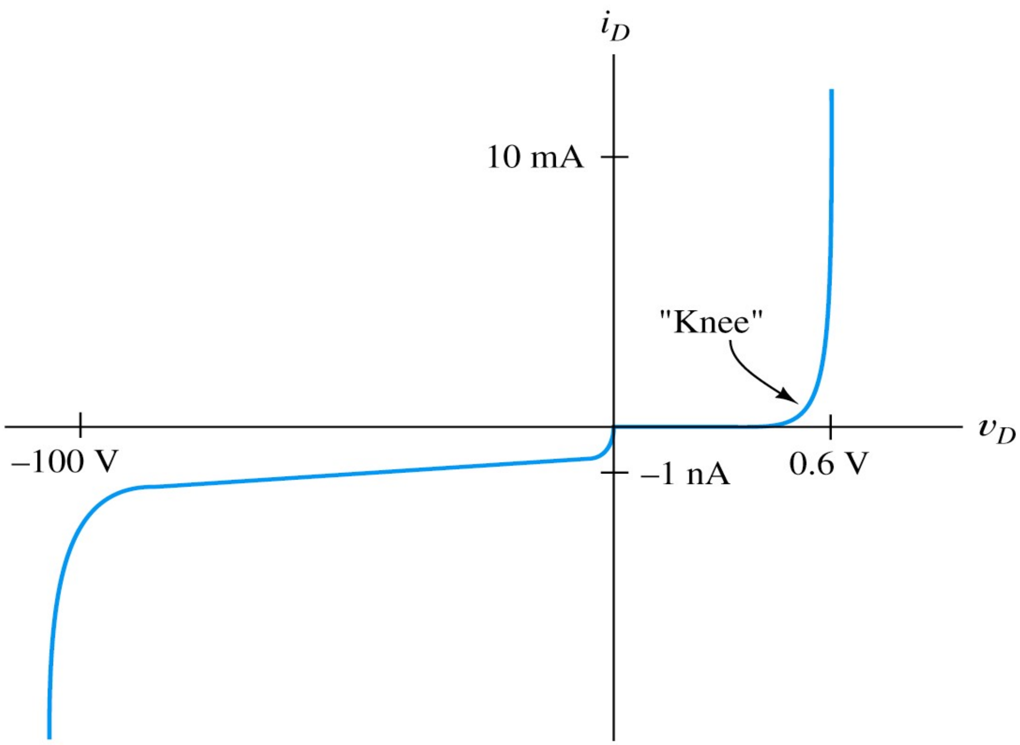


Forward Bias and Reverse Bias

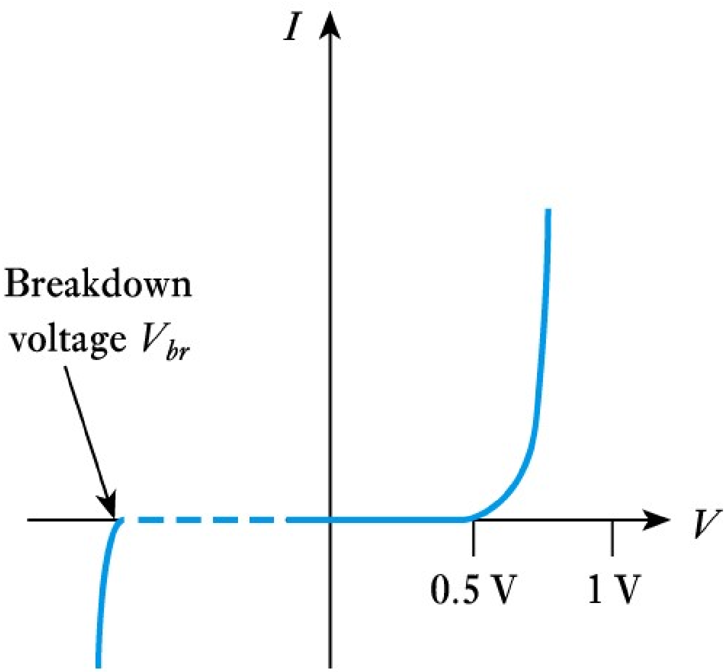
- Forward Bias : Connect positive of the Diode to positive of supply…negative of Diode to negative of supply
- Reverse Bias: Connect positive of the Diode to negative of supply…negative of diode to positive of supply.



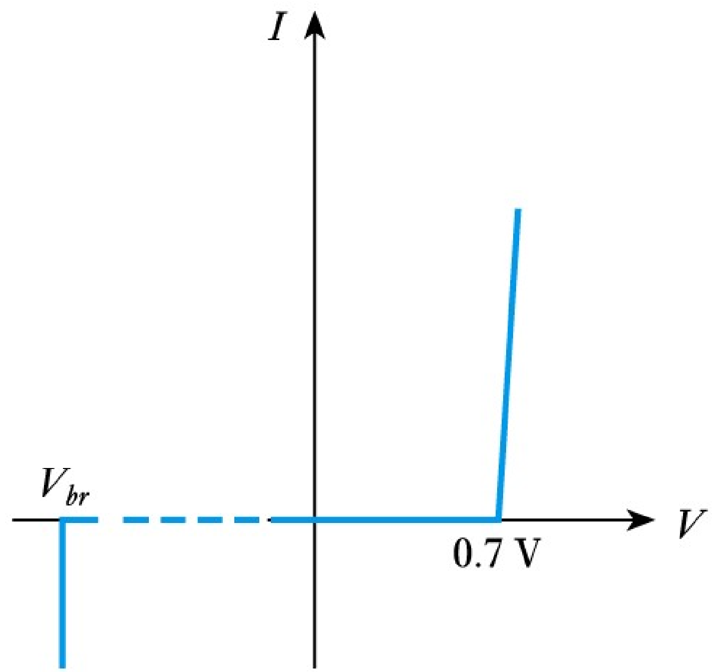
I-V Characteristics of Practical Diode



- **Turn-on** and **breakdown voltages** for a silicon



(a) A silicon diode



(b) Straight-line approximation to silicon diode characteristics

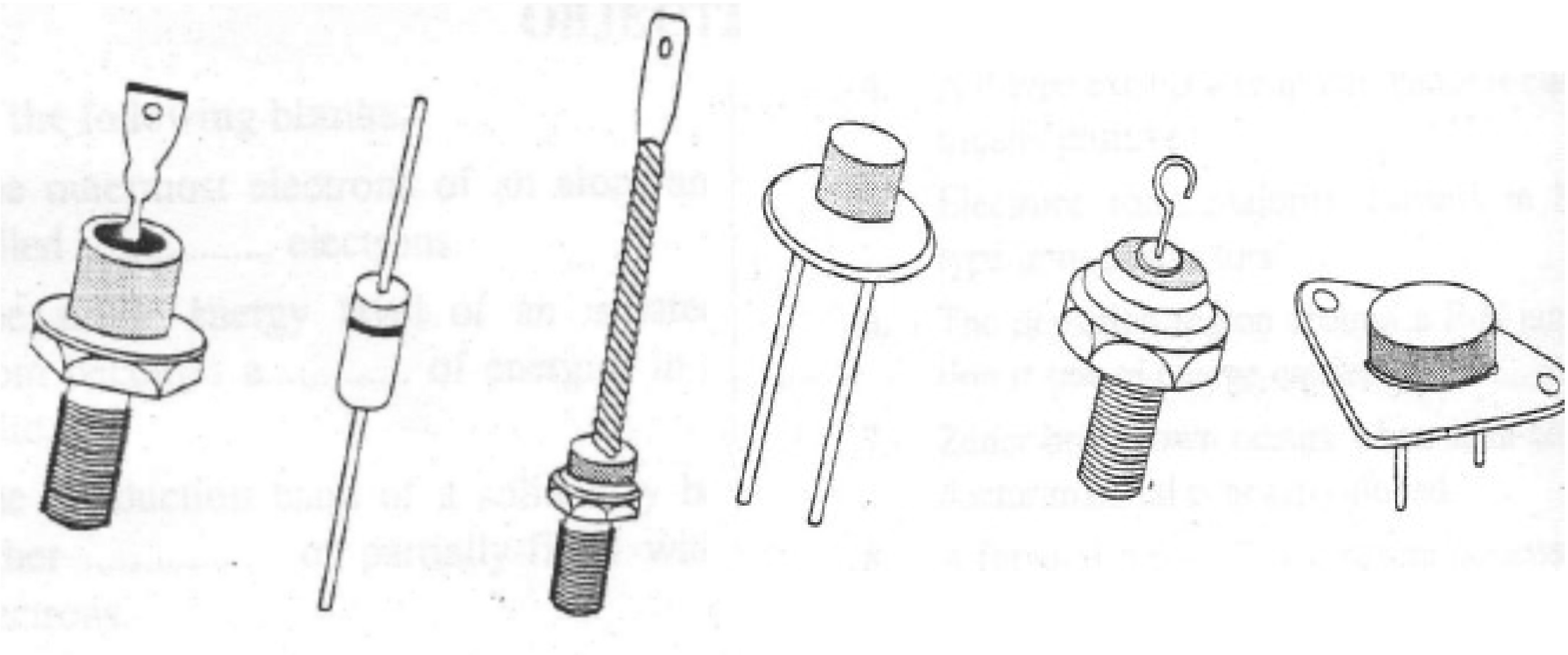
Shockley Equation

$$i_D = I_s\left[\exp\left(\frac{v_D}{nV_T}\right) - 1\right] \qquad V_T = \frac{kT}{q}$$

$$V_T \cong 26\,\text{mV}$$

I_s is the saturation current ~10 $^{-14}$
V_d is the diode voltage
n – emission coefficient (varies from 1 - 2)
$k = 1.38 \times 10^{-23}$ J/K is Boltzmann's constant
$q = 1.60 \times 10^{-19}$ C is the electrical charge of an electron.
At a temperature of 300 K, we have

Physical structures



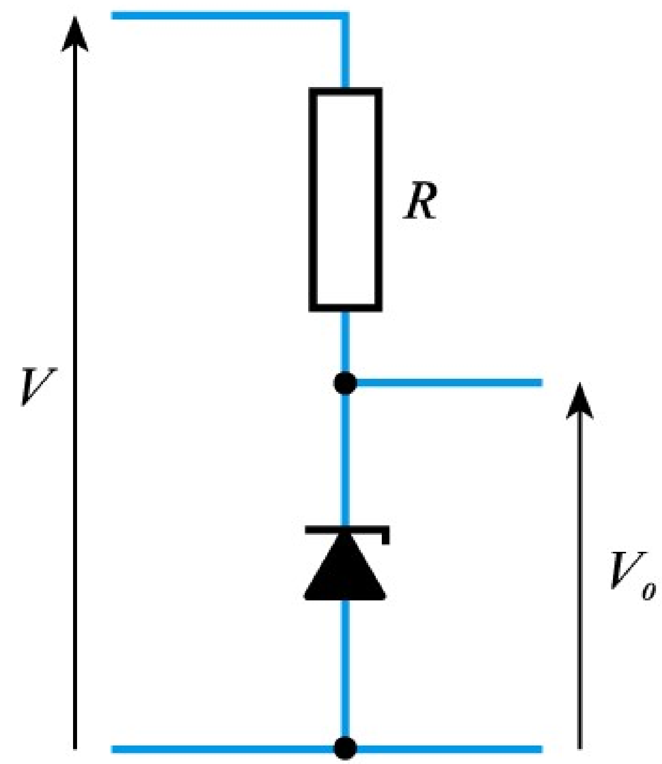
- **Silicon diodes**
  - generally have a turn-on voltage of about 0.5 V
  - generally have a conduction voltage of about 0.7 V
  - have a breakdown voltage that depends on their construction
    - perhaps 75 V for a **small-signal diode**
    - perhaps 400 V for a **power device**
  - have a maximum current that depends on their construction
    - perhaps 100 mA for a **small-signal diode**
    - perhaps many amps for a **power device**

- **Schottky diodes**
  - formed by the junction between a layer of metal (e.g. aluminium) and a semiconductor
  - action relies only on majority charge carriers
  - much faster in operation than a *pn* junction diode
  - has a low forward voltage drop of about 0.25 V
  - used in the design of high-speed logic gates

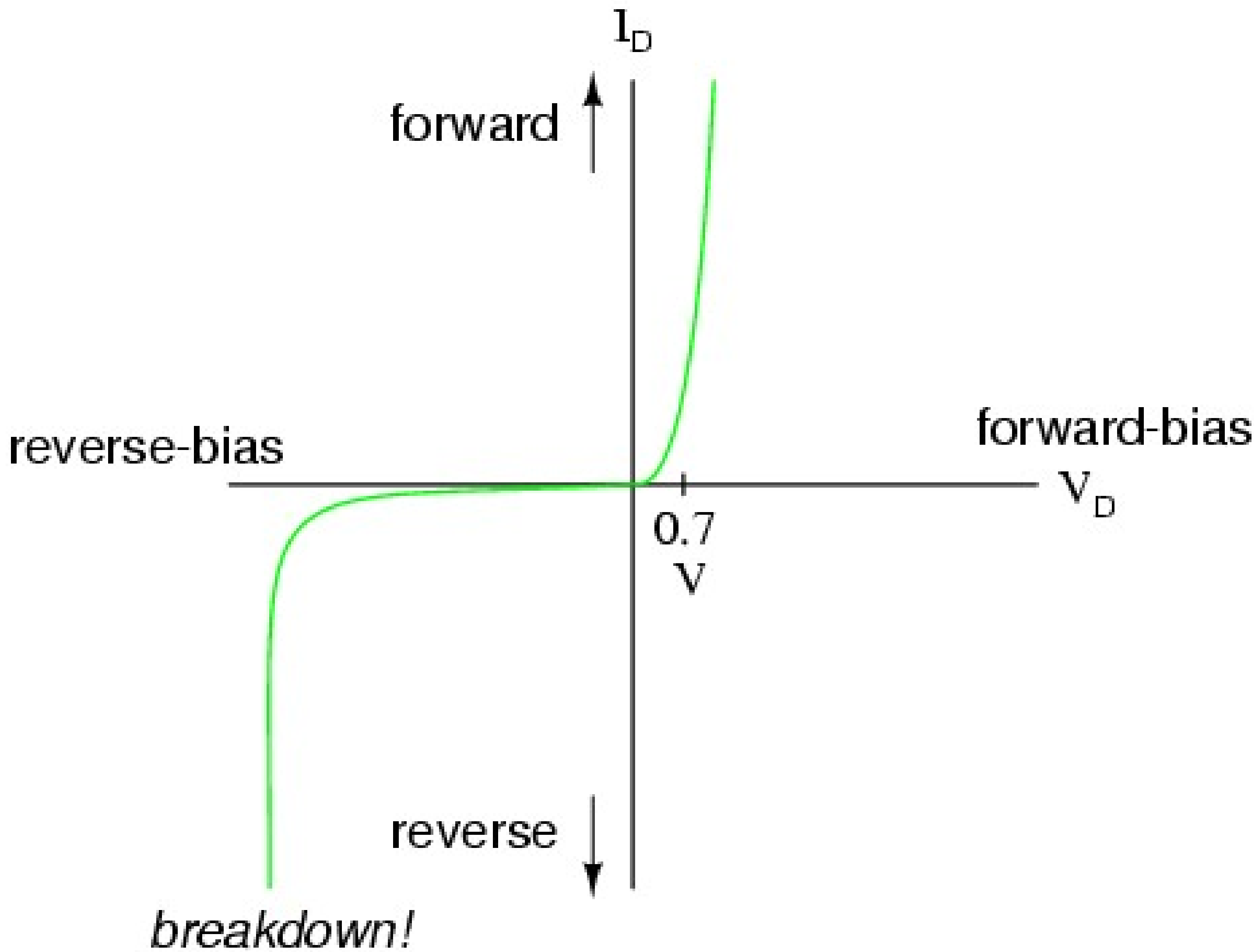
Zener diodes

- A Zener diode is a pn silicon junction diode that is reverse biased and with the supply voltage sufficient to produce the ‘avalanche’ or ‘breakdown’ effect.
- A zener diode must be used in conjunction with a ‘current-limiting’ resistor to keep the current flow through the diode to a safe level.
- A zener diode is used to produce a stable voltage from a supply which is fluctuating.

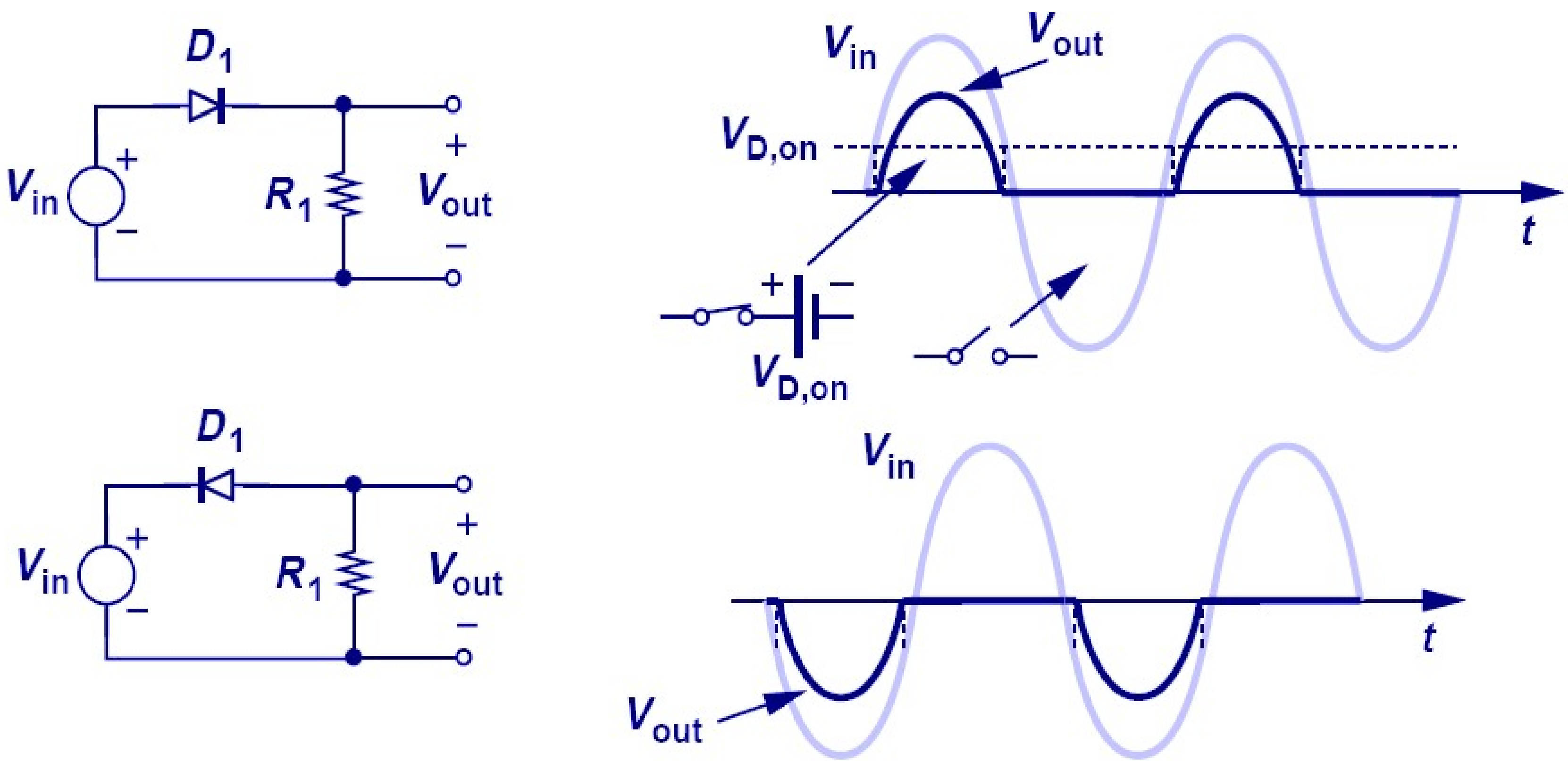
- **Zener diodes**
  - uses the relatively constant reverse breakdown voltage to produce a voltage reference
  - breakdown voltage is called the **Zener voltage**, V_Z
  - output voltage of circuit shown is equal to V_Z despite variations in input voltage V
  - a resistor is used to limit the current in the diode



V/I CHARACTERISTICS

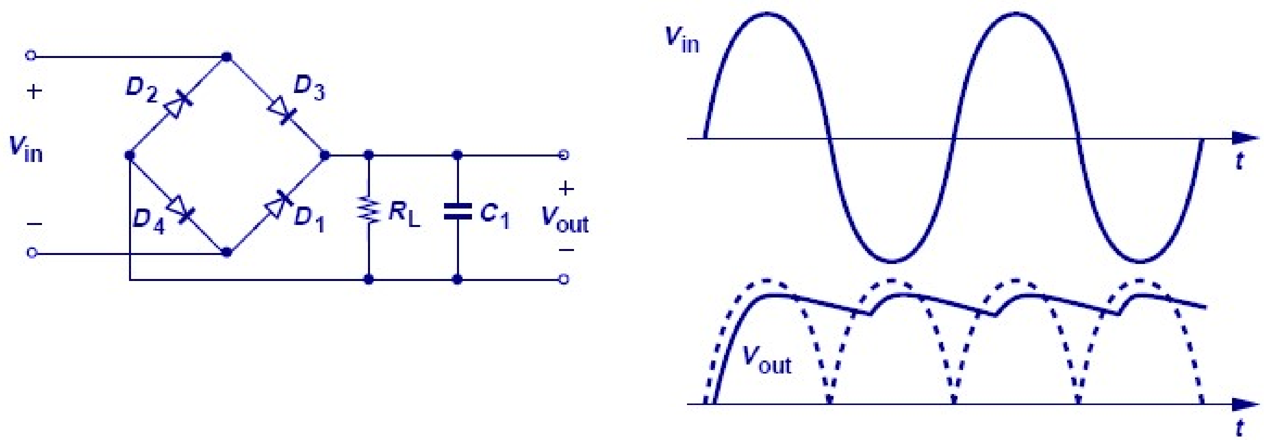


Half-Wave Rectifier

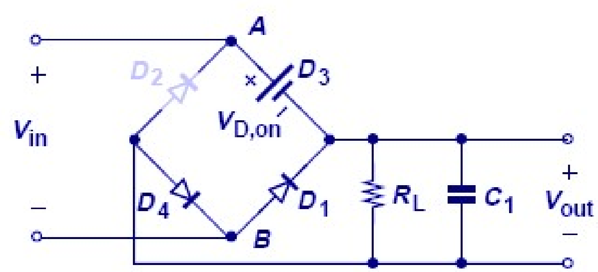


- A very common application of diodes is half-wave rectification, where either the positive or negative half of the input is blocked.

Complete Full-Wave Rectifier

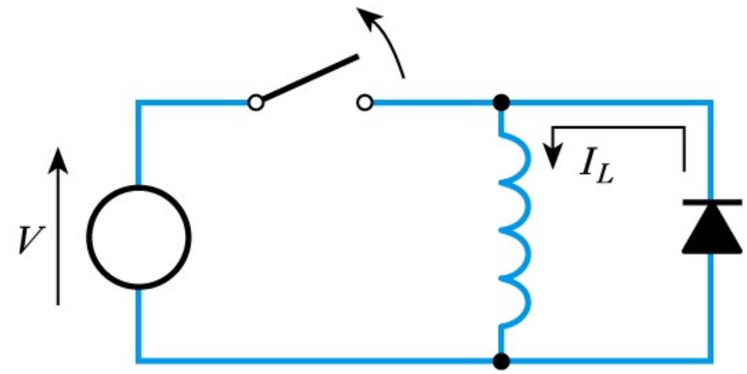


(a)



(b)

- **Catch diode**
  - used when switching inductive loads
  - the large back e.m.f. can cause problems such as arcing in switches



  - **catch diodes** provide a low impedance path across the inductor to dissipate the stored energy
  - the applied voltage reverse-biases the diode which therefore has no effect
  - when the voltage is removed the back e.m.f. forward biases the diode which then conducts

Diode Ratings

Peak inverse voltage (PIV)

Maximum forward current (I_F)

Maximum forward voltage drop (V_F)

Reverse leakage current (I_R)

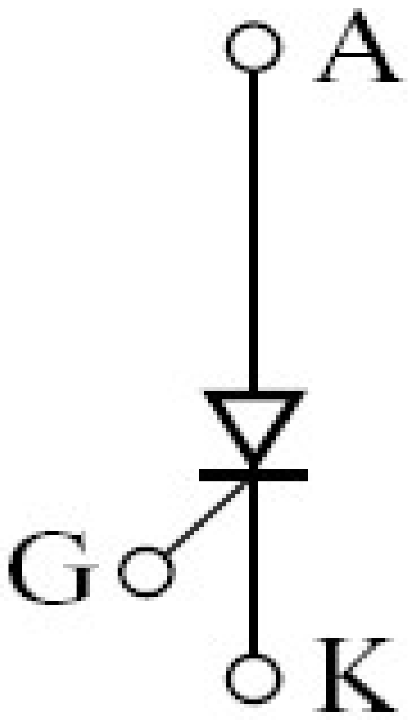
Diode handling and installation

Diodes are polarized and must be installed in with correct orientation.

Many diodes are modestly susceptible to ESD damage, so normal ESD precautions should be taken.

Mechanical stress due to lead bending should be minimized.

Thyristor



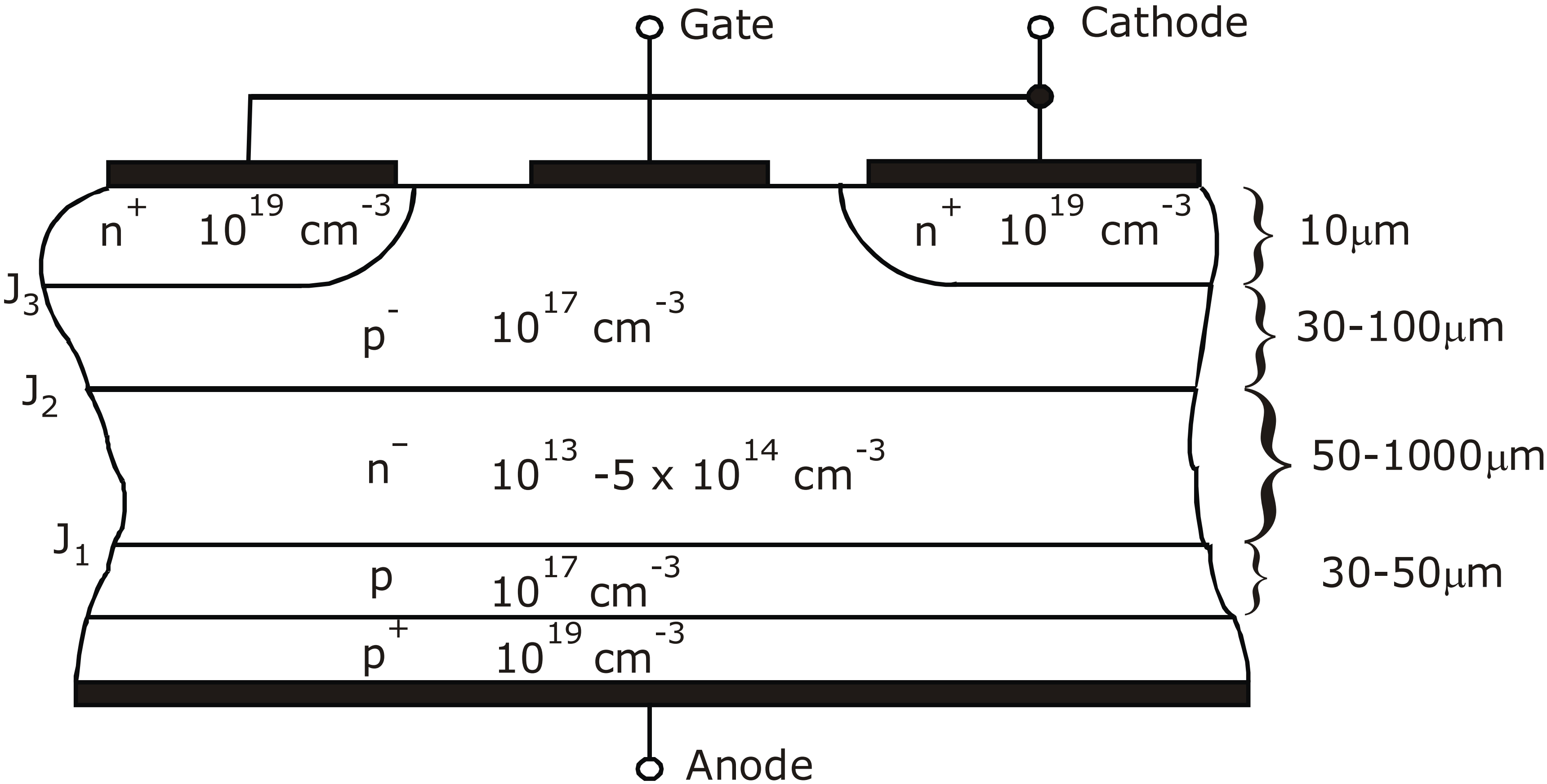
Symbol of Thyristor

Thyristors

- Most important type of power semiconductor device.
- Have the highest power handling capability.they have a rating of 5000V / 6000A with switching frequencies ranging from 1KHz to 20KHz.

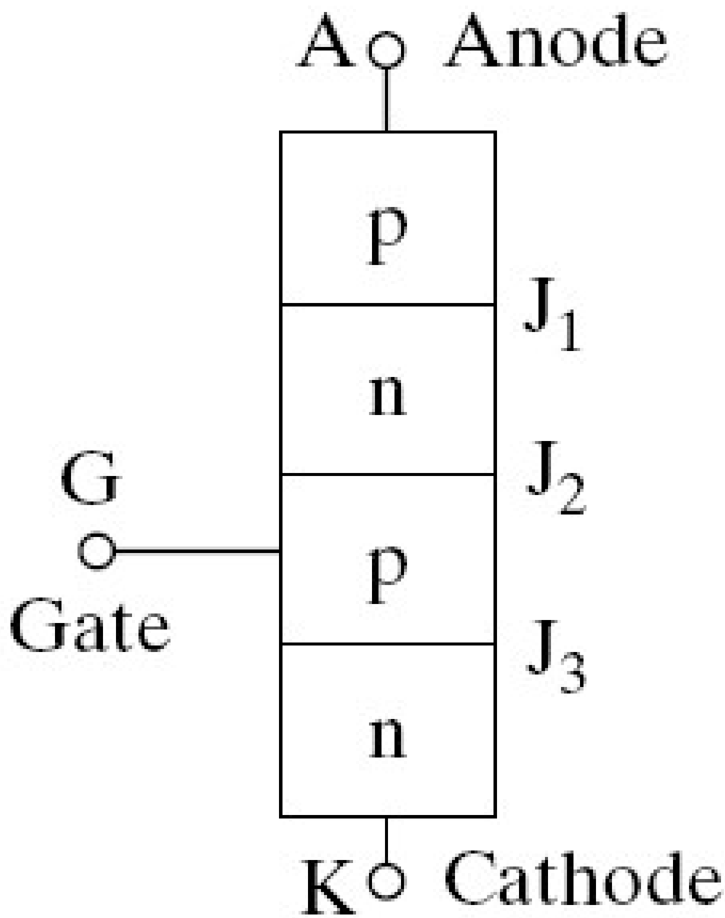
- Is inherently a slow switching device compared to BJT or MOSFET.
- Used as a latching switch that can be turned on by the control terminal but cannot be turned off by the gate.

Structure

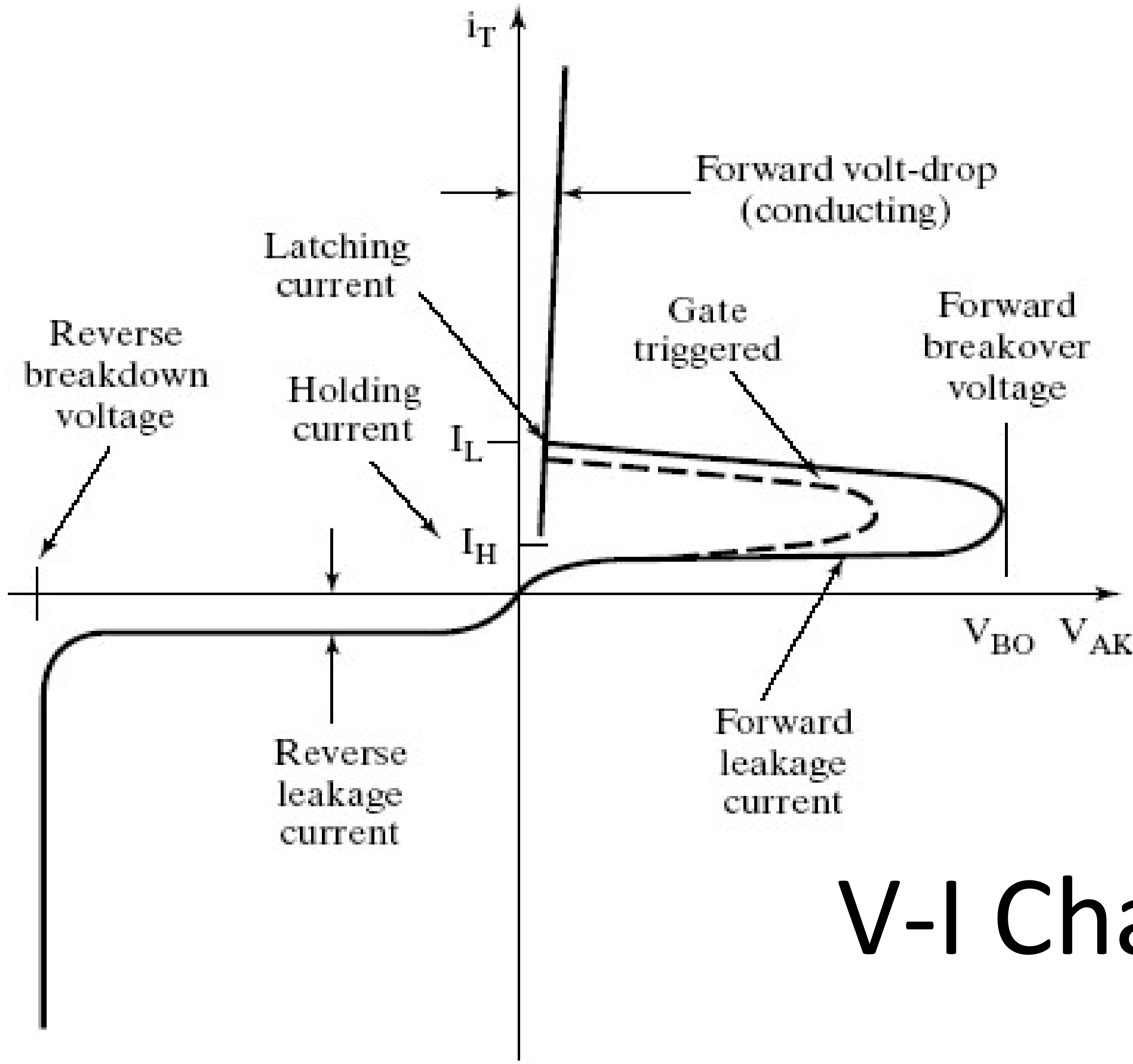


Gate
Cathode
n+ 10^19 cm^-3
n+ 10^19 cm^-3
10µm
J3
p- 10^17 cm^-3
30-100µm
J2
n− 10^13 -5 x 10^14 cm^-3
50-1000µm
J1
p 10^17 cm^-3
30-50µm
p+ 10^19 cm^-3
Anode

Device Operation

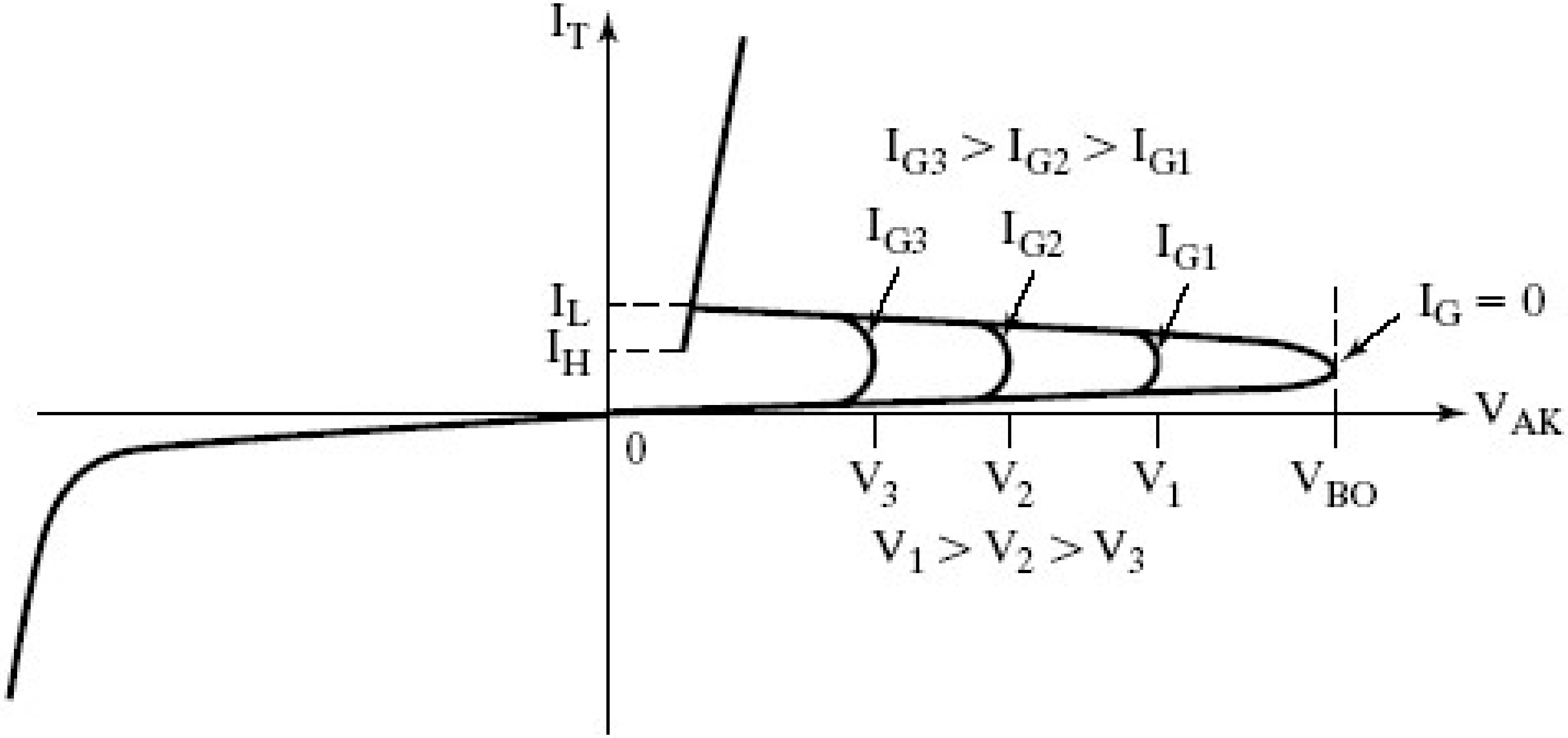


Simplified model of a thyristor

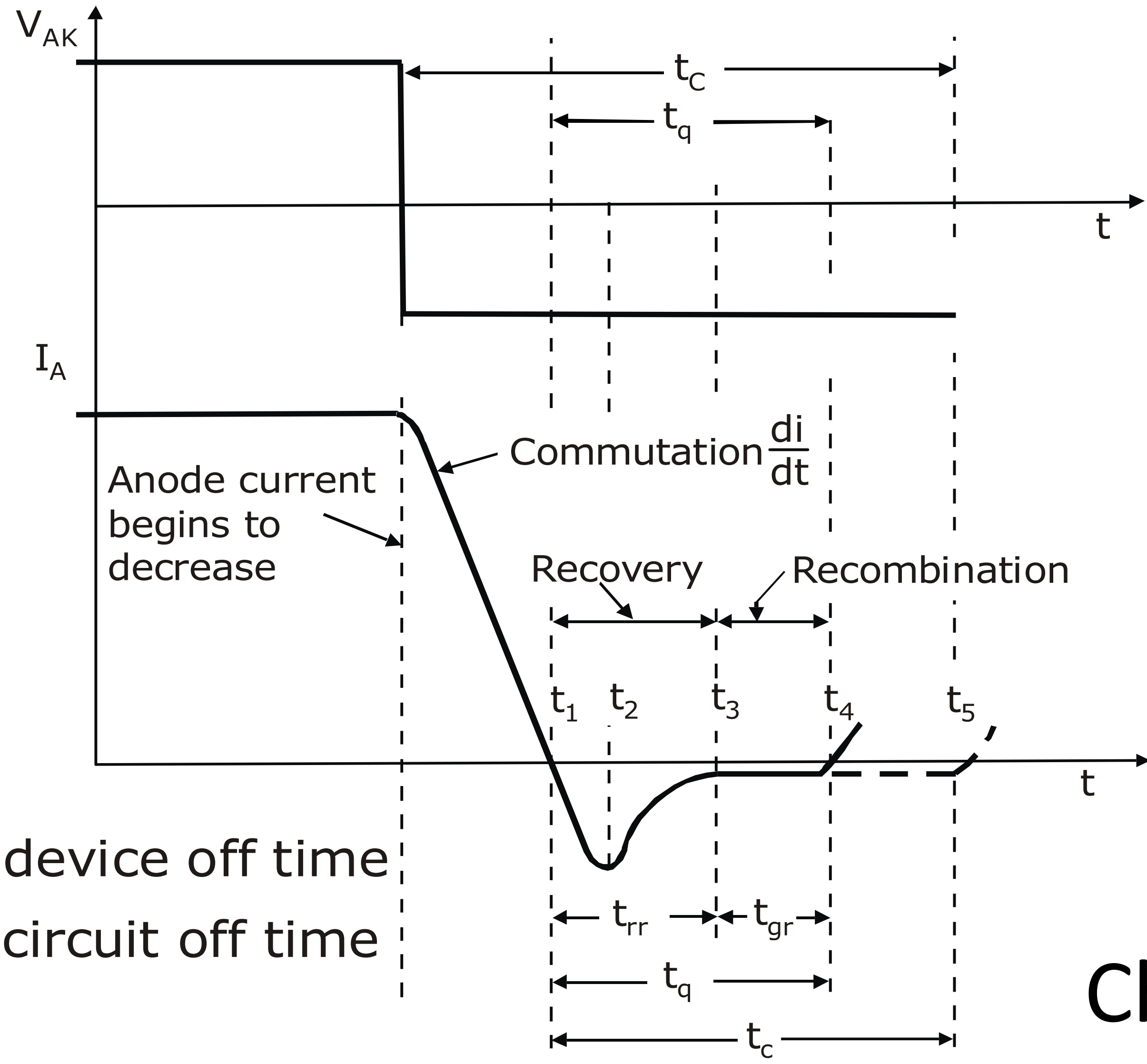


V-I Characteristics

Effects of gate current



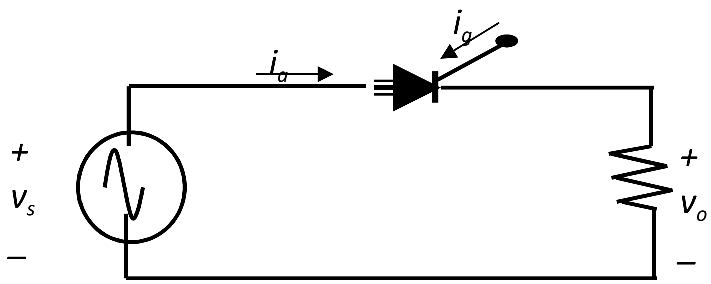
Turn-off Characteristics

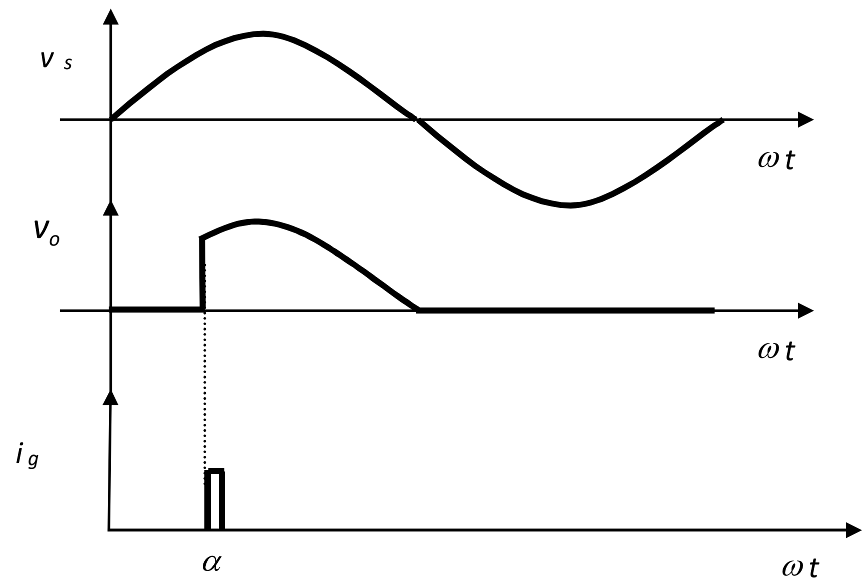


t_q=device off time

t_c=circuit off time

Thyristor Conduction





Methods of Thyristor Turn-on

- Thermal Turn-on.
- High Voltage.
- Gate Current.
- dv/dt.

Thyristor Types

- Phase-control Thyristors (SCR's).
- Fast-switching Thyristors (SCR's).
- Gate-turn-off Thyristors (GTOs).
- Bidirectional triode Thyristors (TRIACs).

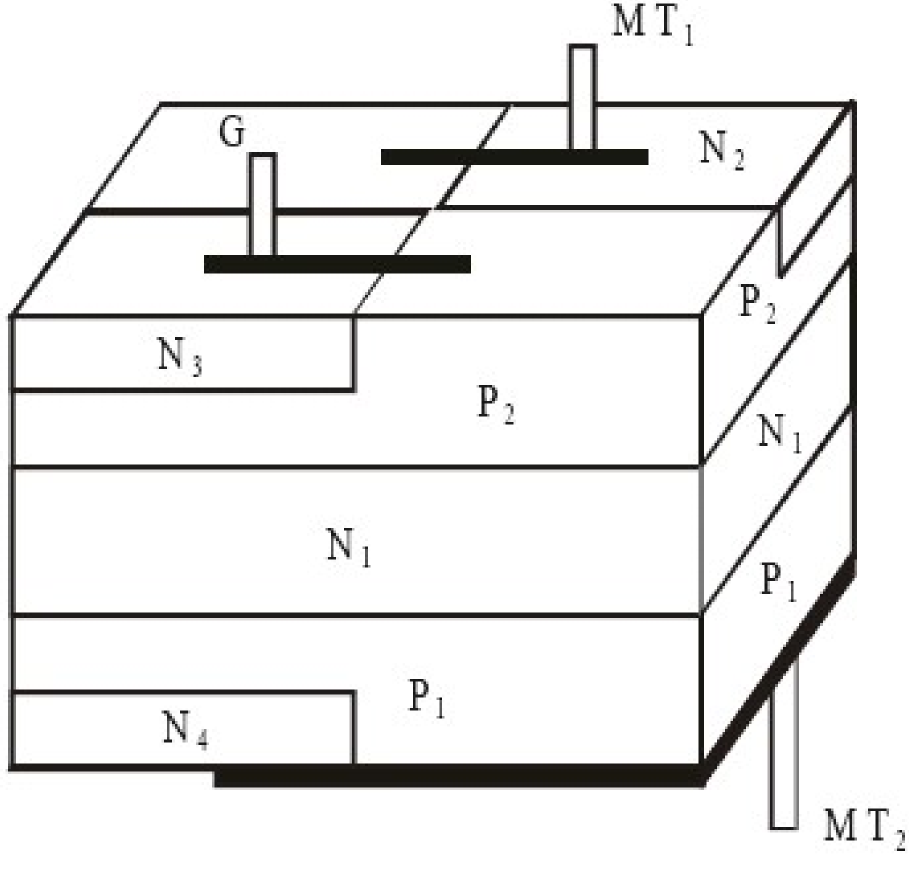
Phase Control Thyristor

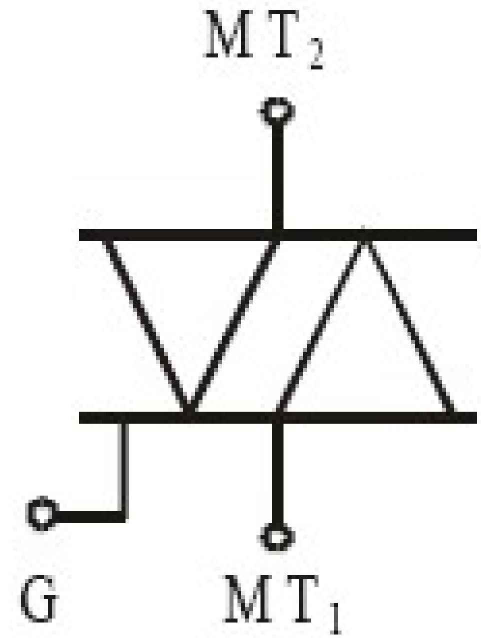
- These are converter thyristors.
- The turn-off time t_q is in the order of 50 to 100μsec.
- Used for low switching frequency.
- Commutation is natural commutation
- On state voltage drop is 1.15V for a 600V device.

Fast Switching Thyristors

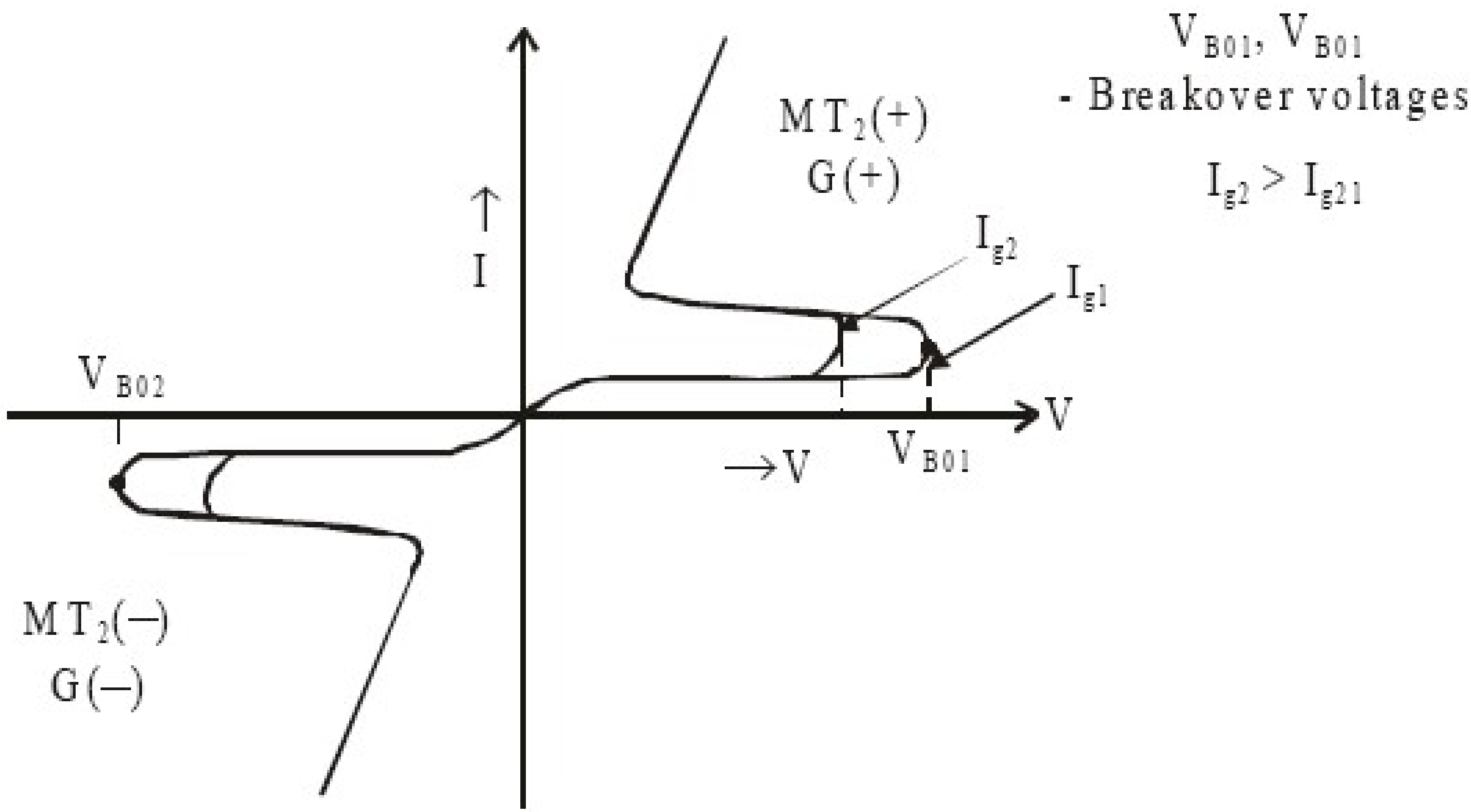
- Also called inverter thyristors.
- Used for high speed switching applications.
- Turn-off time t_q in the range of 5 to 50μsec.
- On-state voltage drop of typically 1.7V for 2200A, 1800V thyristor.
- High dv/dt and high di/dt rating.

Bidirectional Triode Thyristors (TRIAC)





Triac Characteristics



Gate Turn-off Thyristors

- Turned on by applying positive gate signal.
- Turned off by applying negative gate signal.
- On state voltage is 3.4V for 550A, 1200V GTO.
- Controllable peak on-state current I_{TGQ} is the peak value of on-state current which can be turned-off by gate control.

Advantages over SCRs

- Elimination of commutating components.
- Reduction in acoustic & electromagnetic noise due to elimination of chokes.
- Faster turn-off, therefore can be used for higher switching frequencies.
- Improved efficiency of converters.

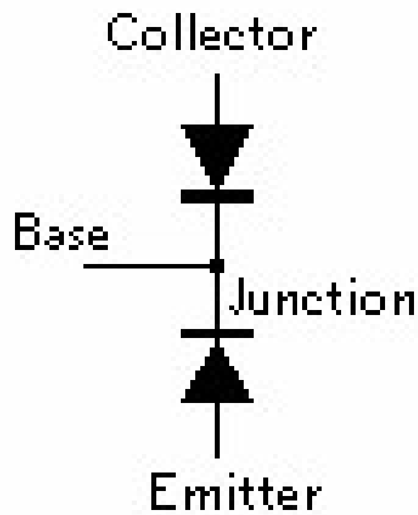
Advantages over BJTs

- Higher voltage blocking capabilities.
- High on-state gain.
- High ratio of peak surge current to average current.
- A pulsed gate signal of short duration only is required.

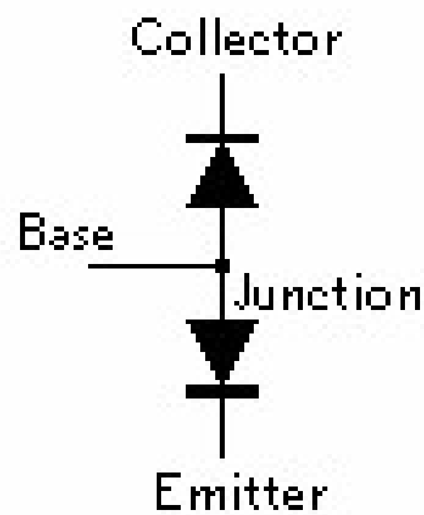
Disadvantages of GTOs

- On-state voltage drop is more.
- Due to multi cathode structure higher gate current is required.
- Gate drive circuit losses are more.
- Reverse blocking capability is less than its forward blocking capability.

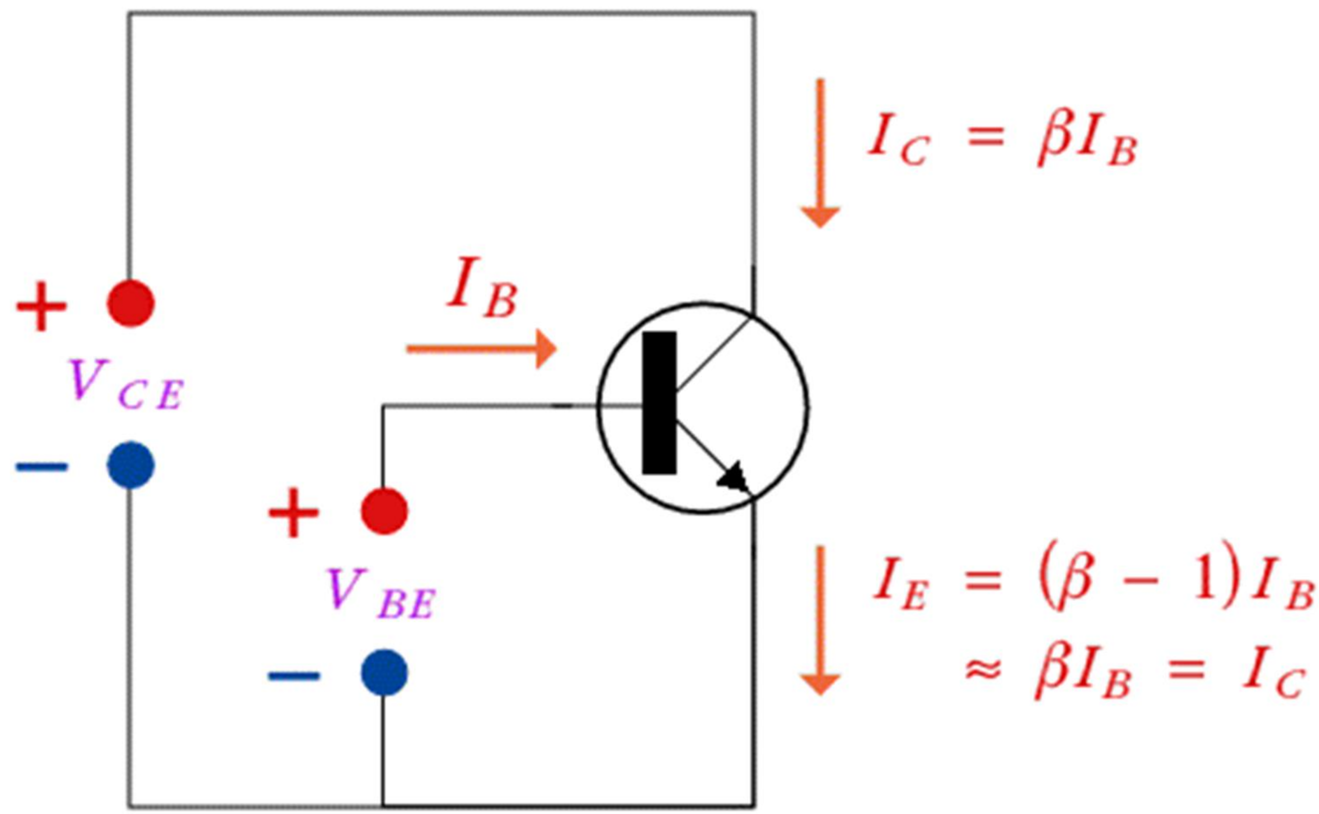
Bipolar Transistor



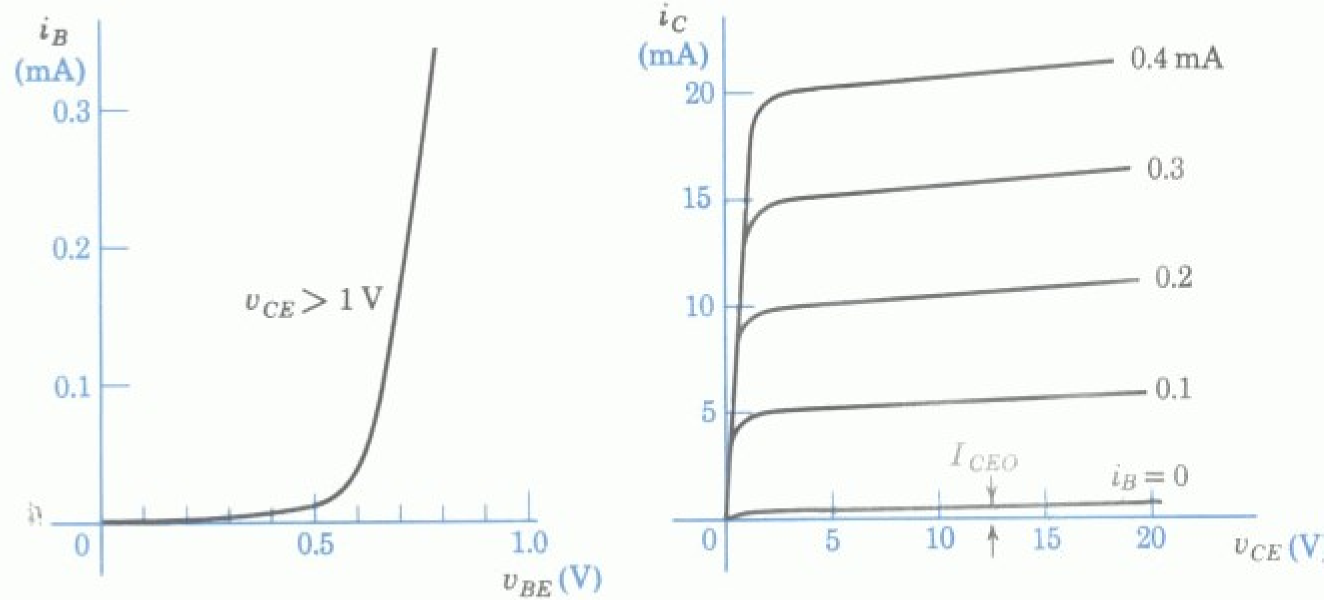
PNP Transistor
Equivalent Circuit



NPN Transistor
Equivalent Circuit



‘Conventional’ view of the NPN Bipolar Transistor



(a) Base characteristics

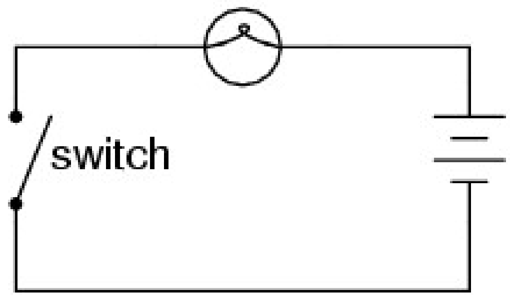
(b) Collector characteristics

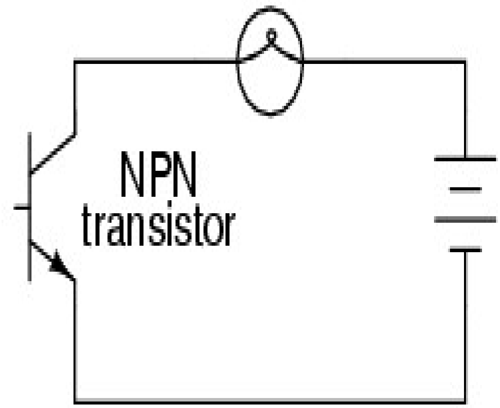
TRANSISTOR AS A SWITCH

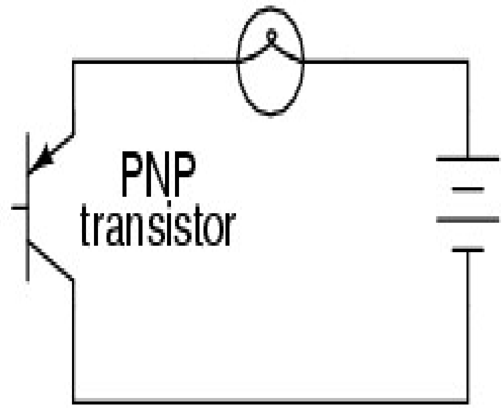
Transistors may be used as switching elements to control DC power to a load.

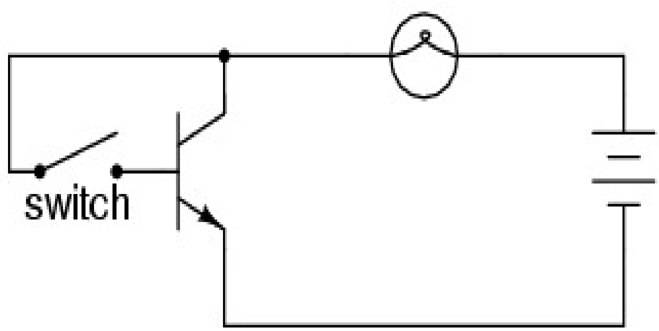
The switched (controlled) current goes between emitter and collector, while the controlling current goes between emitter and base.
When a transistor has zero current through it, it is said to be in a state of *cutoff* (fully non conducting).
When a transistor has maximum current through it, it is said to be in a state of *saturation* (fully conducting).

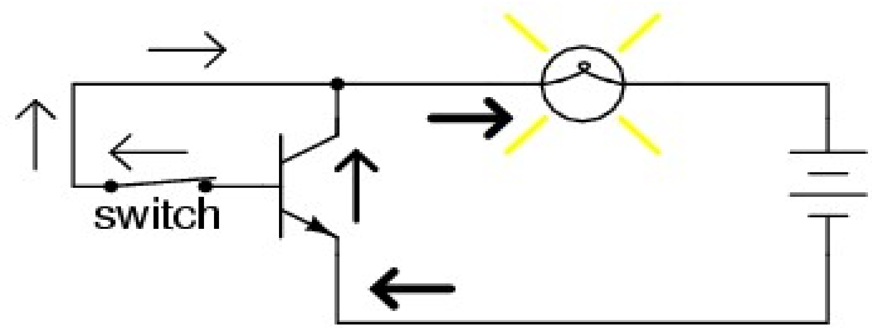
TRANSISTOR AS A SWITCH





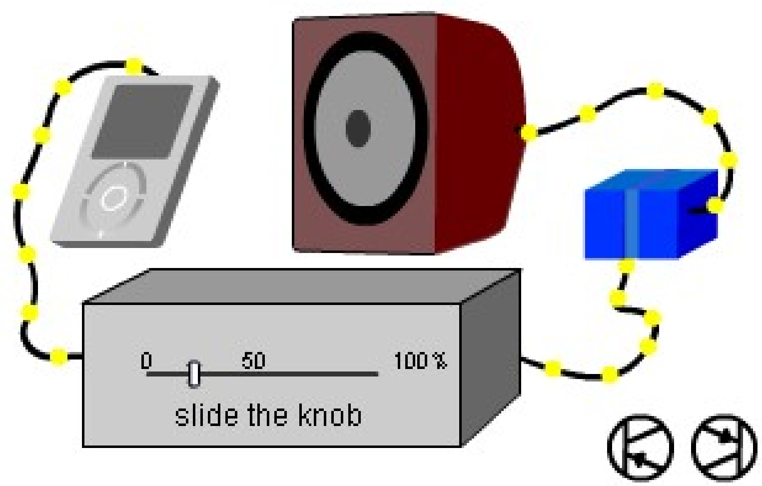




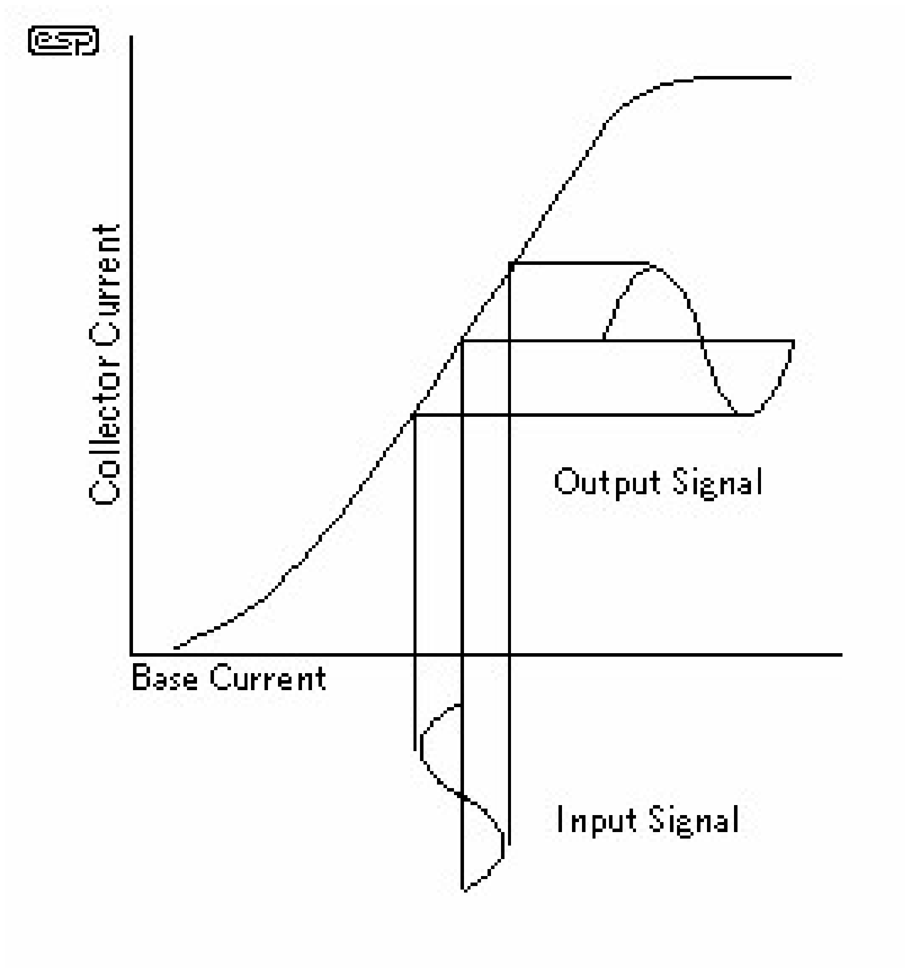


TRANSISTOR AS AN AMPLIFIER

A transistor can also amplify current. A low-level voltage (represented by the headphone output of the mp3 player), connected to the transistor's base through the volume control, will regulate the larger current powering the loudspeaker. But be careful--turn it up too high, and the transistor will be overloaded and may overheat.

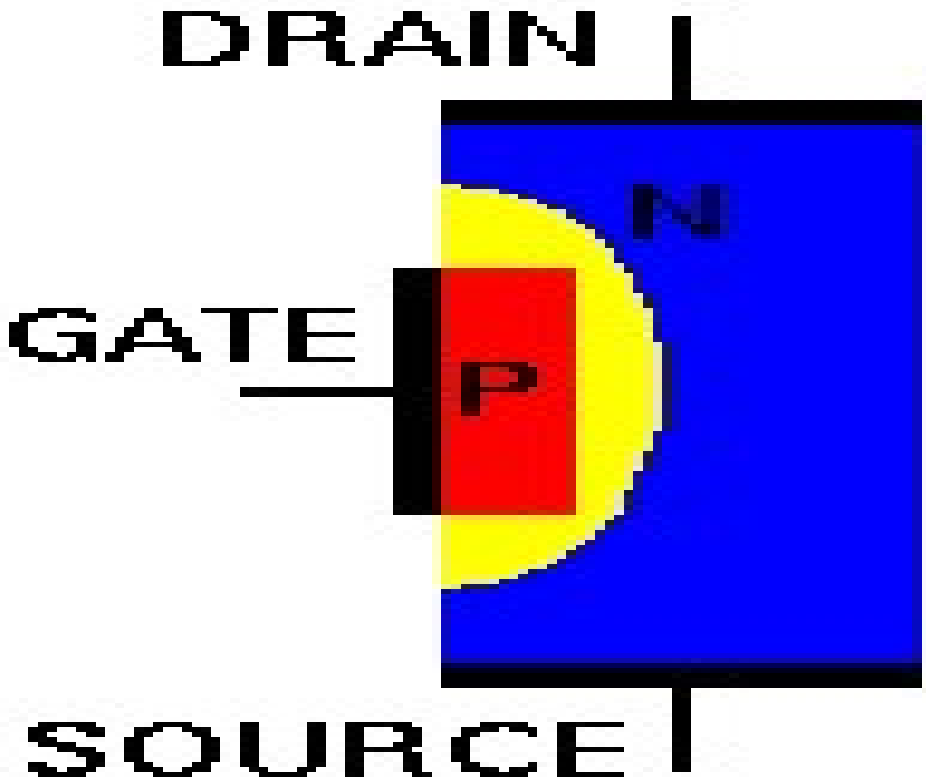


TRANSISTOR AS AN AMPLIFIER

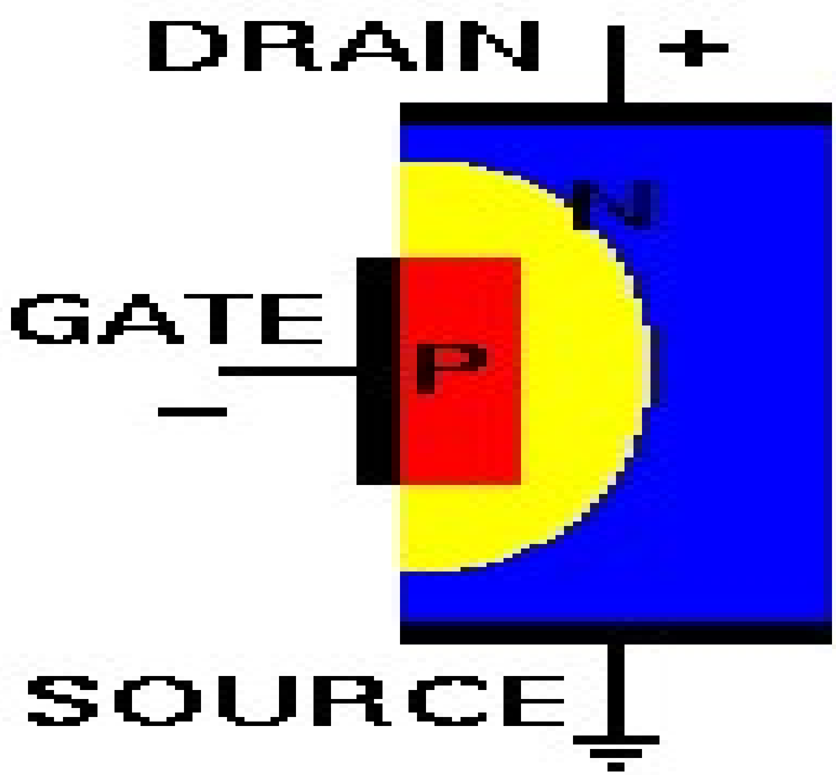


Field Effect Transistor (FET)

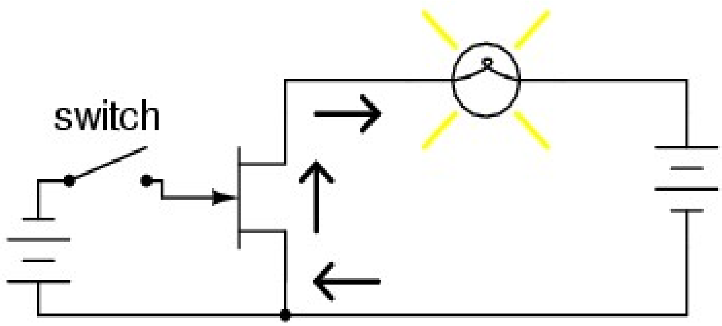
FET: N-Channel

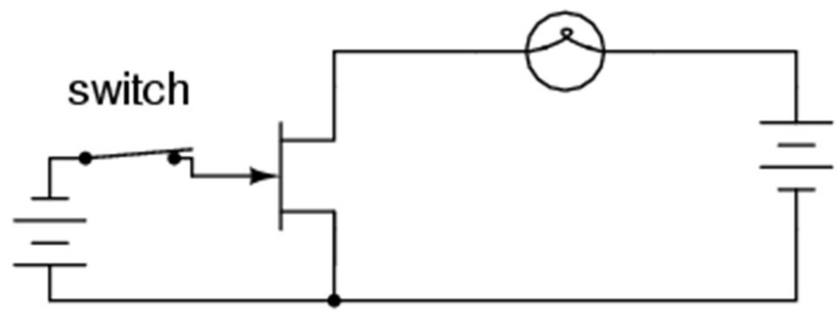


FET: P-Channel

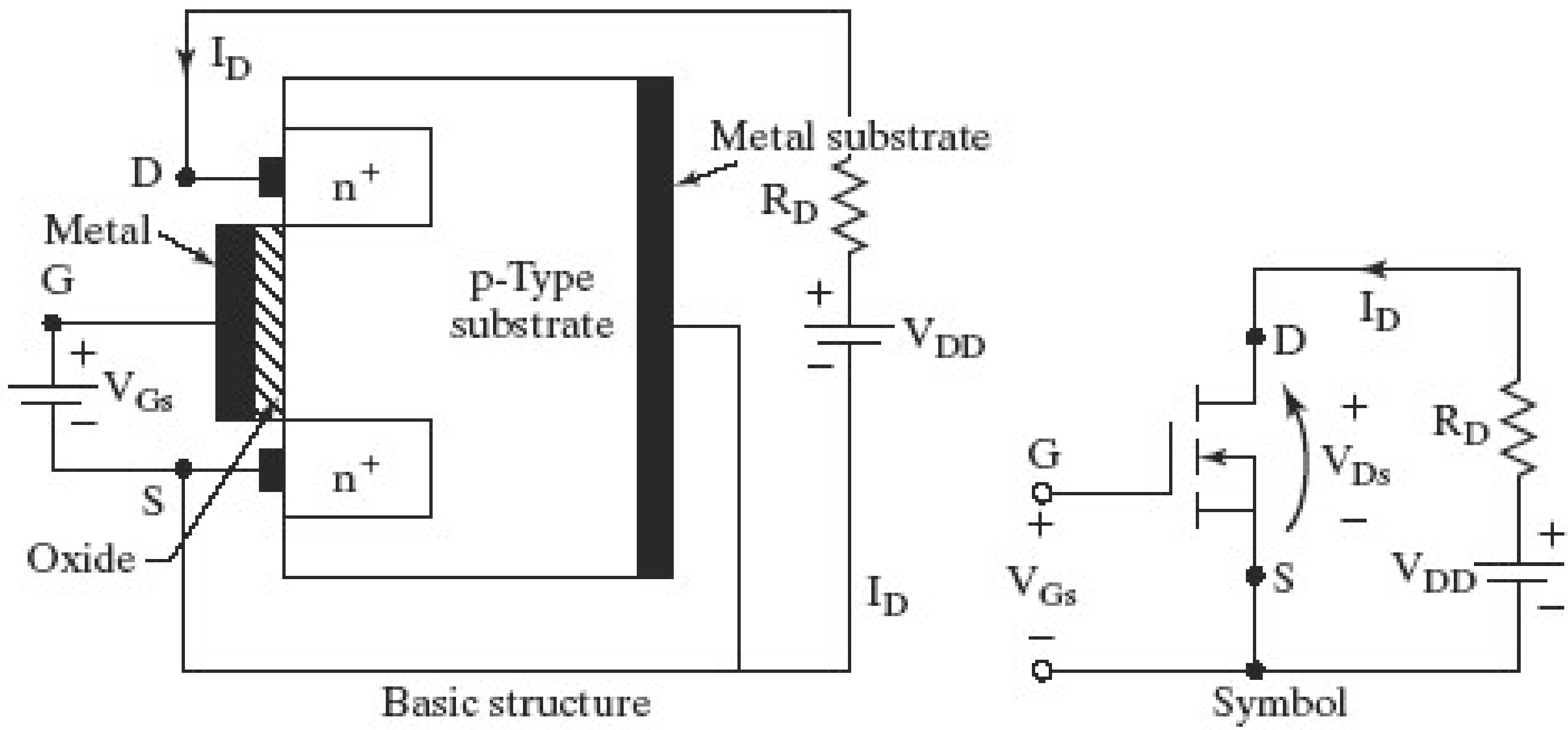


FET: As a switch

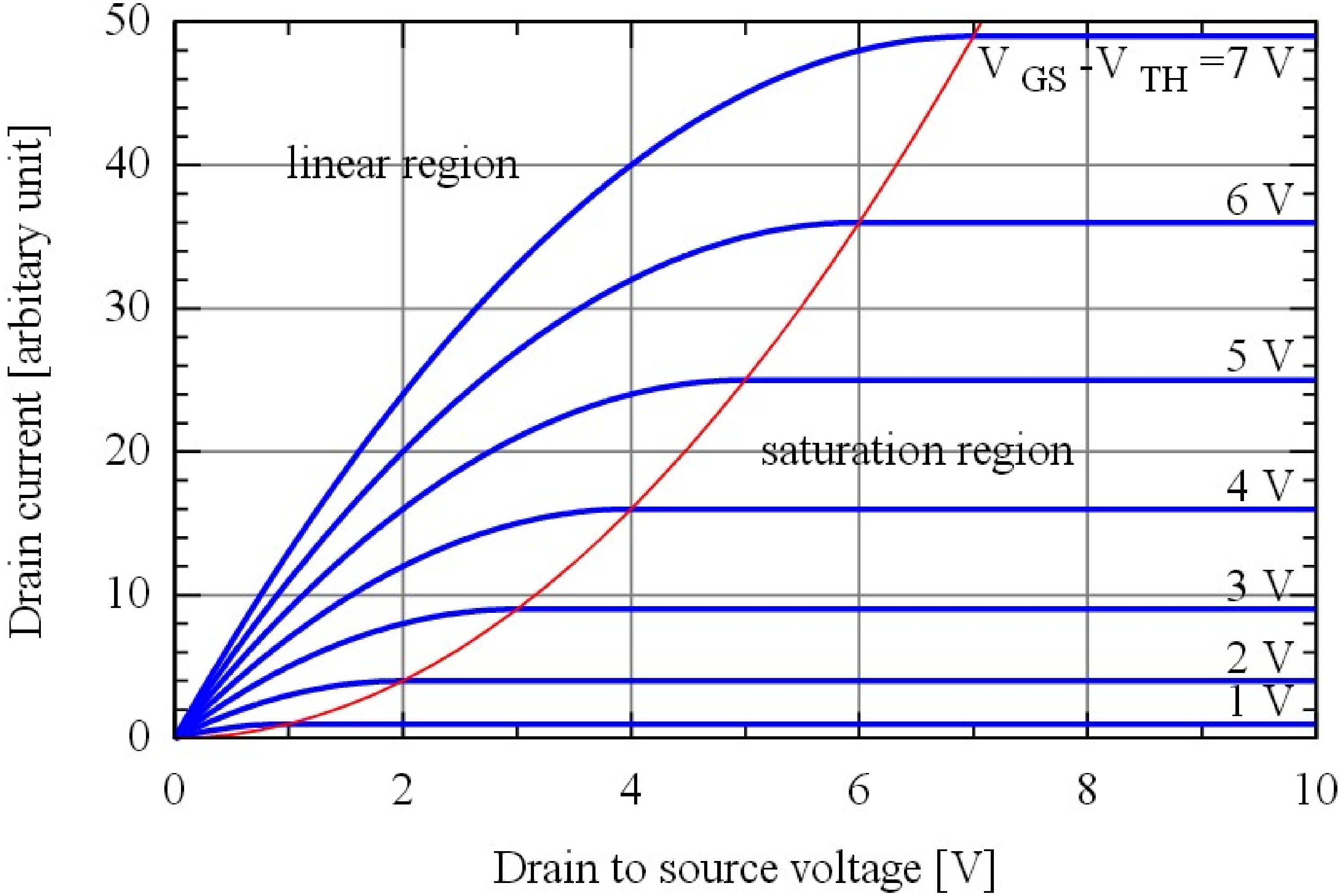




MOSFET

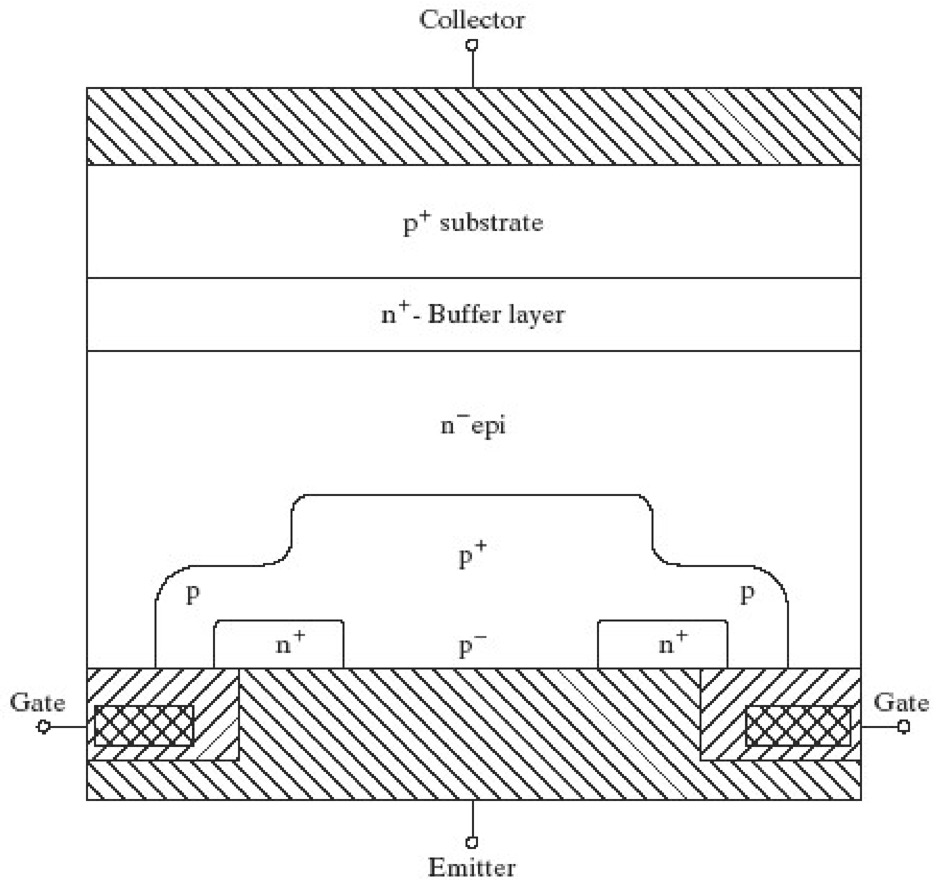


(a) n-Channel enhancement-type MOSFET



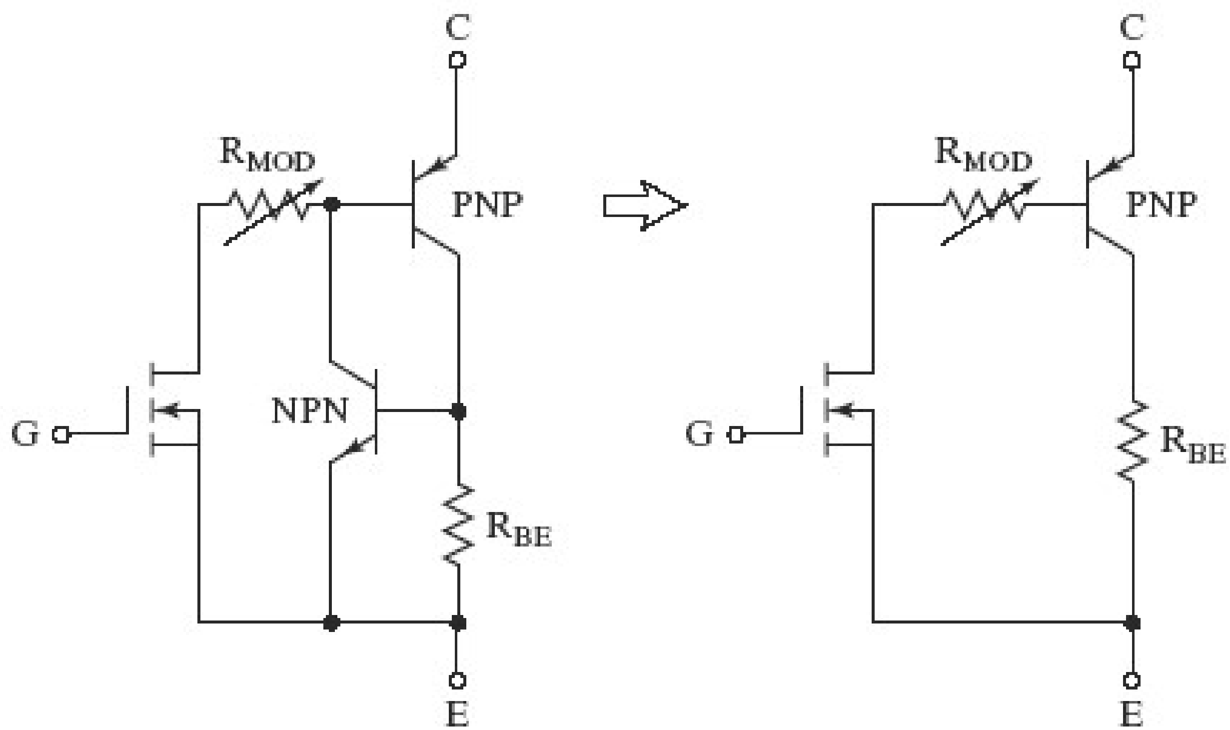
V GS -V TH =7 V
6 V
5 V
4 V
3 V
2 V
1 V
linear region
saturation region
Drain current [arbitary unit]
Drain to source voltage [V]
0
10
20
30
40
50
0
2
4
6
8
10

Semiconductor Cross-section of IGBT



(a) Cross section

IGBT



(b) Equivalent circuit

(c) Simplified circuit

Advantages of IGBT

- Combines the advantages of BJT & MOSFET
- High input impedance like MOSFET
- Voltage controlled device like MOSFET
- Simple gate drive, Lower switching loss
- Low on state conduction power loss like BJT
- Higher current capability & higher switching speed than a BJT. (Switching speed lower than MOSFET)

Applications of IGBT

- ac and dc motor controls.
- General purpose inverters.
- Uninterrupted Power Supply (UPS).
- Welding Equipments.
- Numerical control, Cutting tools.
- Robotics & Induction heating.

Example of Inverter Grade Thyristor Ratings

- V / I rating: 4500V / 3000A.
- Max. Frequency: 20KHz.
- Switching time: 20 to 100μsec.
- On state resistance: 0.5mΩ.

Example of Triac Ratings

- Used in heat / light control, ac motor control circuit
- V / I rating: 1200V / 300A.
- Max. Frequency: 400Hz.
- Switching time: 200 to 400μsec.
- On state resistance: 3.6mΩ.

Example of Power Transistor Ratings

- PT ratings go up to 1200V / 400A.
- PT normally operated as a switch in CE config.
- Max. Frequency: 400Hz.
- Switching time: 200 to 400μsec.
- On state resistance: 3.6mΩ.

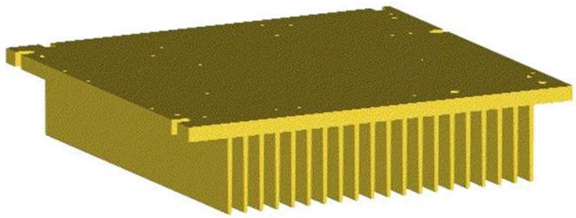
Example of Power MOSFET Ratings

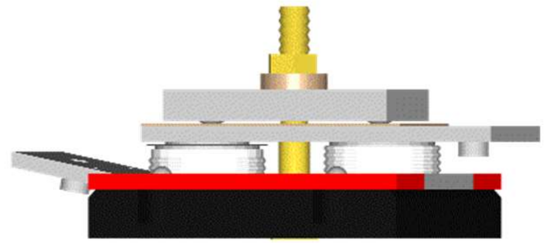
- Used in high speed power converters like inverters & choppers.
- Ratings up to 1000V / 100A.
- Example: MOSFET 800V / 7.5A rating.
- Max. Frequency: 100KHz.
- Switching time: 1.6μsec.
- On state resistance: 1.2mΩ.

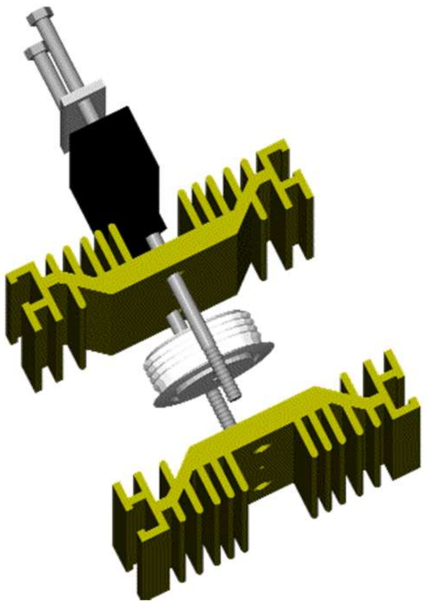
Example of IGBT Ratings

- Used in high voltage / current & high frequency switching power applications (Inverters, SMPS).
- Example: IGBT 2500V / 2400A.
- Max. Frequency: 20KHz.
- Switching time: 5 to μsec.
- On state resistance: 2.3mΩ.

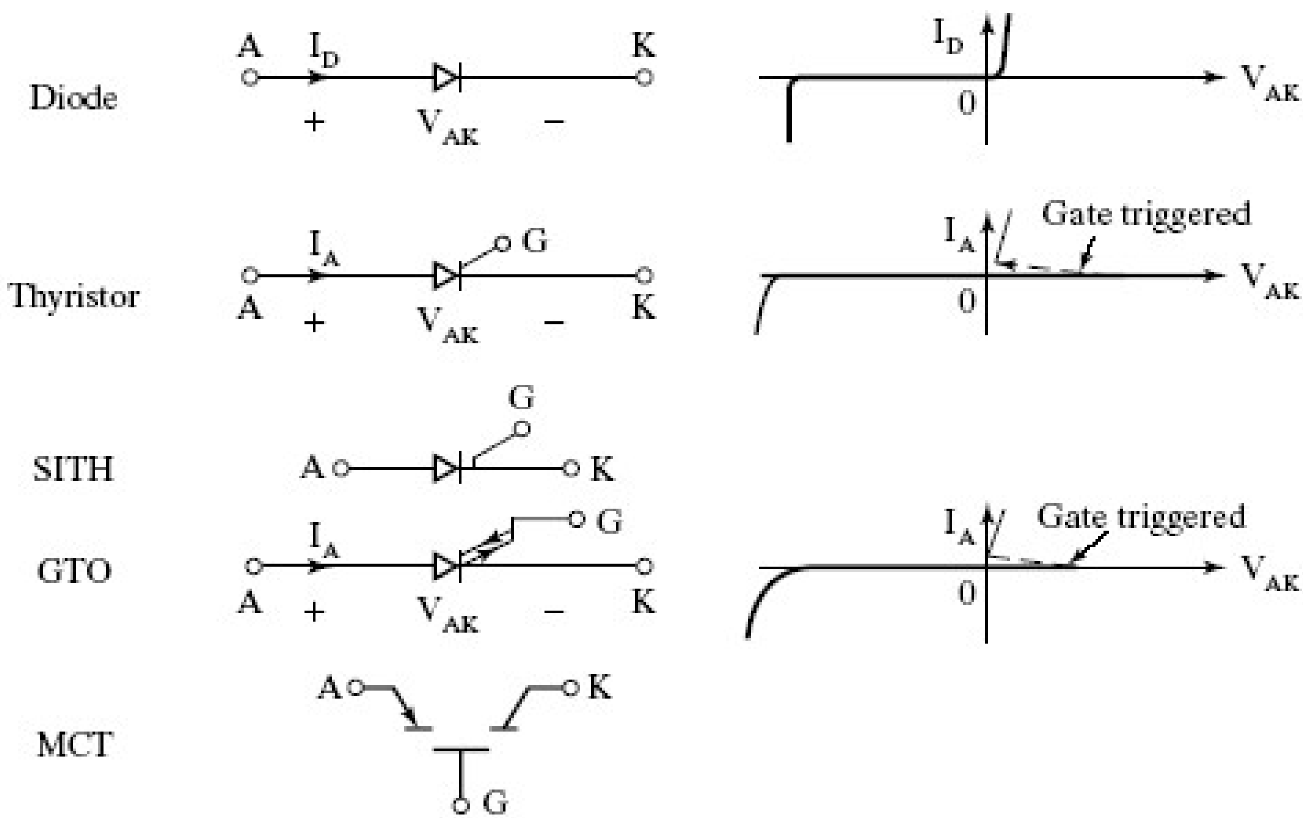
Designing – Heat Sinking



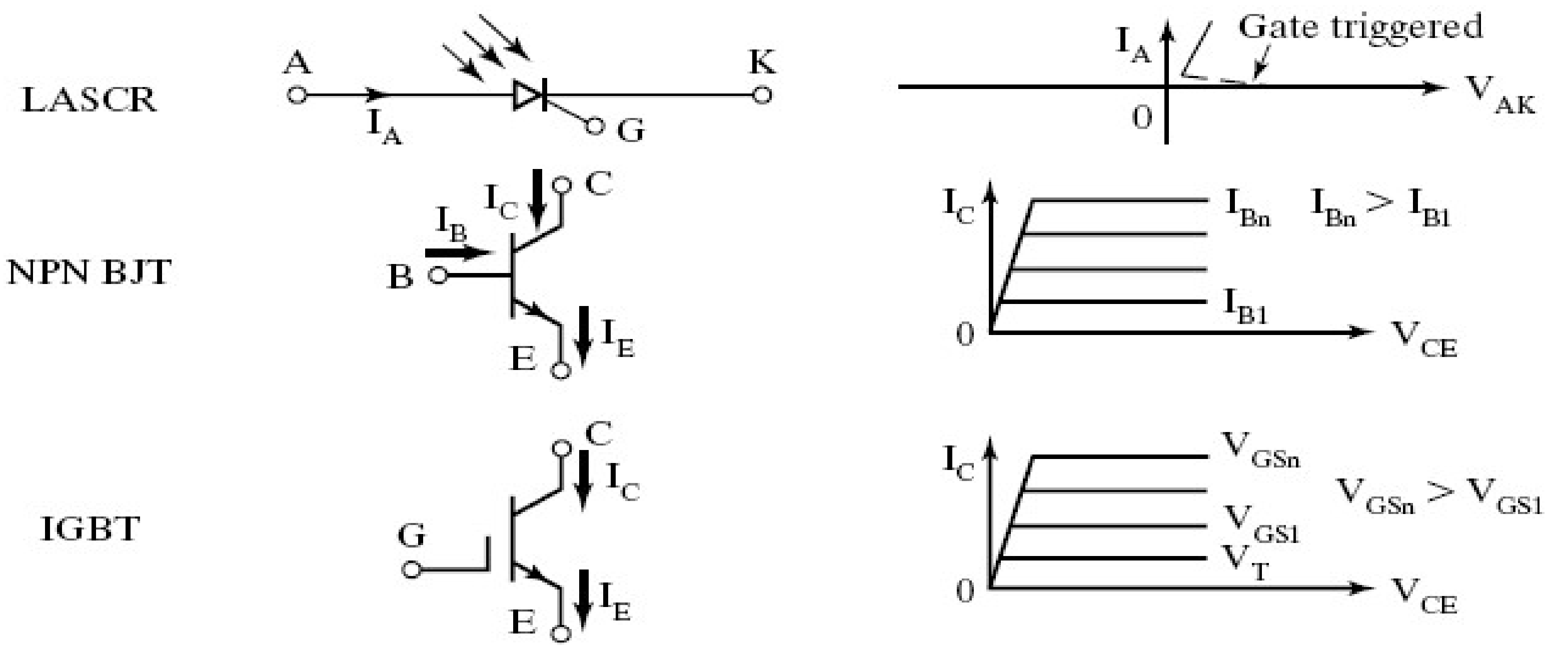


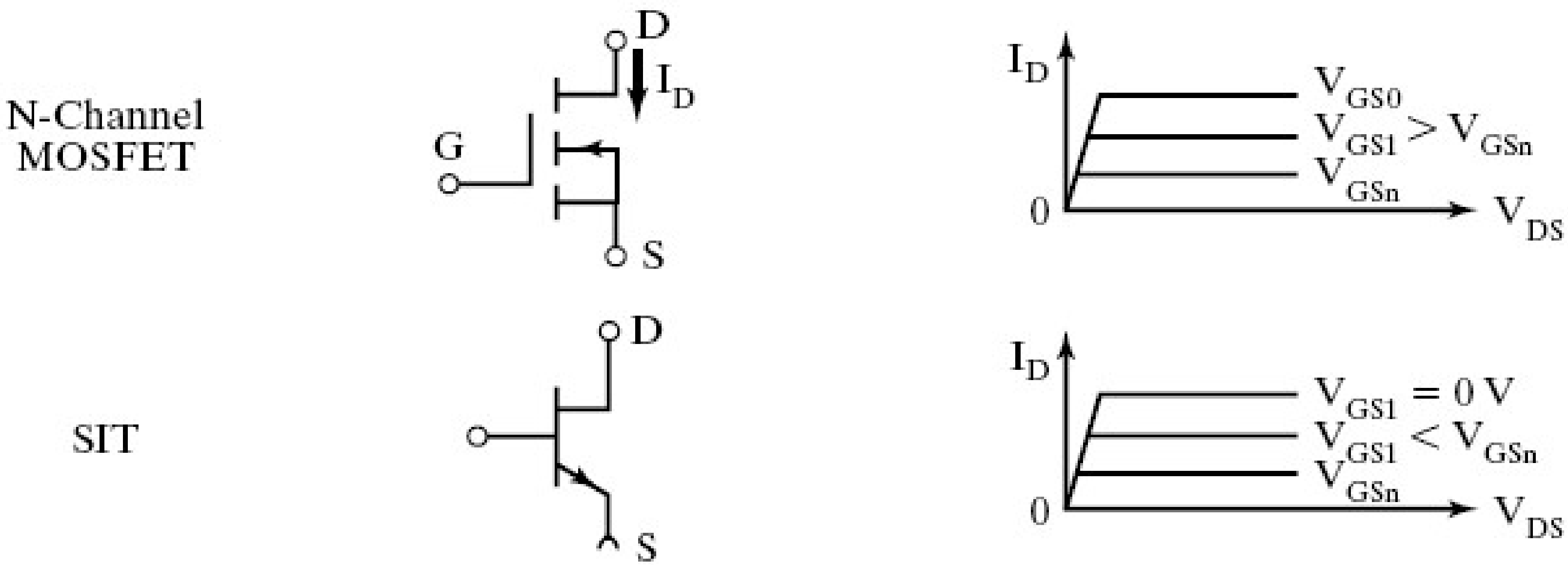


Power Semiconductor Devices, their Symbols & Characteristics

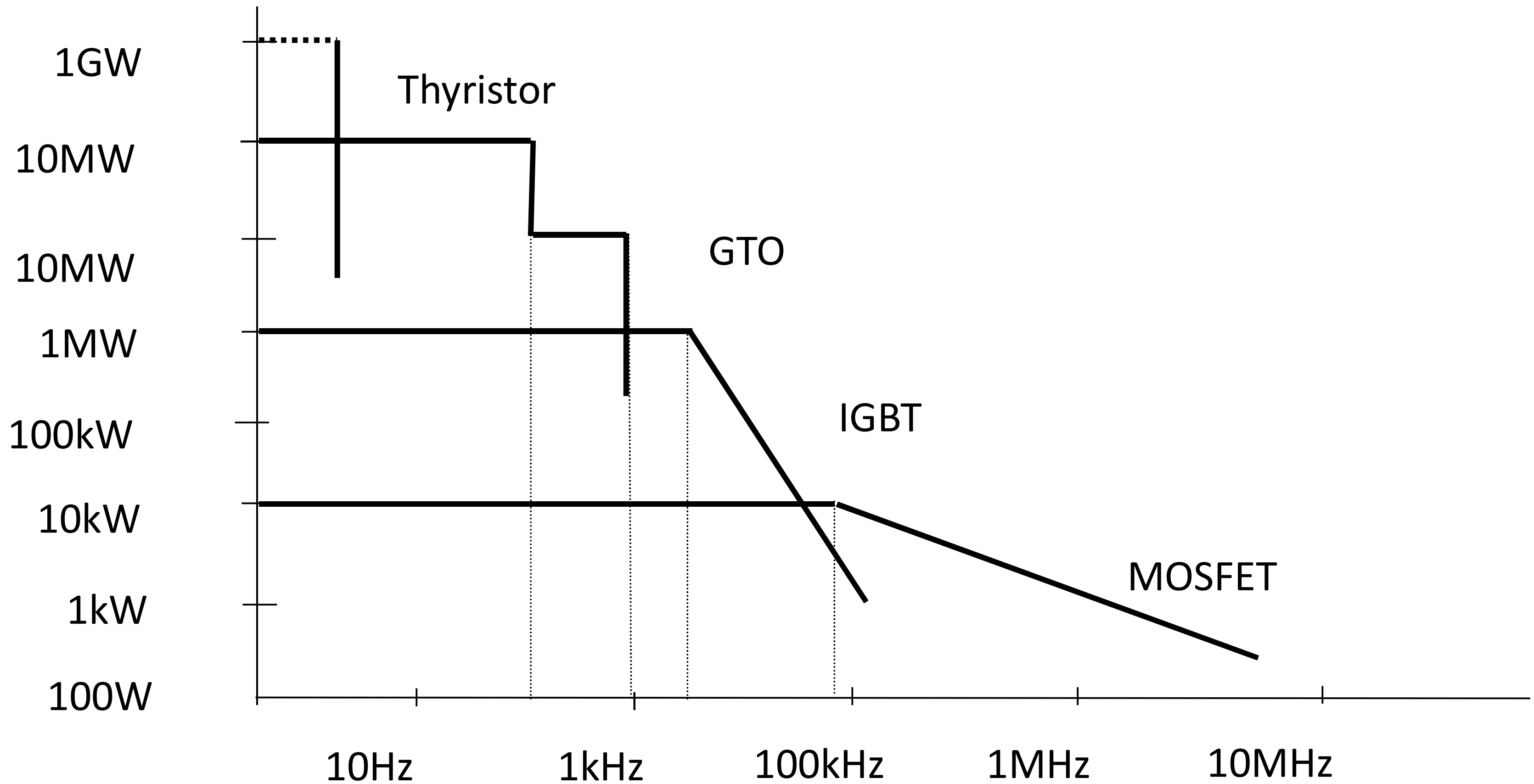


DEVICE SYMBOLS & CHARACTERISTICS




N-Channel
MOSFET
D
I_D
G
S
I_D
V_{GS0}
$V_{GS1} > V_{GSn}$
V_{GSn}
0
V_{DS}
SIT
D
S
I_D
$V_{GS1} = 0$ V
$V_{GS1} < V_{GSn}$
V_{GSn}
0
V_{DS}

Power Switches: Power Ratings



	Thy	BJT	FET	GTO	IGBT	IGCT
Avail-abilty	Early 60s	Late 70s	Early 80s	Mid 80s	Late 80s	Mid 90's
State of Tech.	Mature	Mature	Mature/ improve	Mature	Rapid improve	Rapid improvement
Voltage ratings	5kV	1kV	500V	5kV	3.3kV	6.5kV
Current ratings	4kA	400A	200A	5kA	1.2kA	4kA
Switch Freq.	na	5kHz	1MHz	2kHz	100kHz	1kHz
On-state Voltage	2V	1-2V	I* Rds (on)	2-3V	2-3V	3V
Drive Circuit	Simple	Difficult	Very simple	Very difficult	Very simple	Simple
Comm-ents	Cannot turn off using gate signals	Phasing out in new product	Good performance in high freq.	King in very high power	Best overall performance.	Replacing GTO