Power Electronics

Chapter 1

Power Electronic Devices

(Part I)

Power Electronics

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

Power Electronics

1.1 An introductory overview of power electronic devices

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

Power Electronics

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

  power electronic devices
  - 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

Power Electronics

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

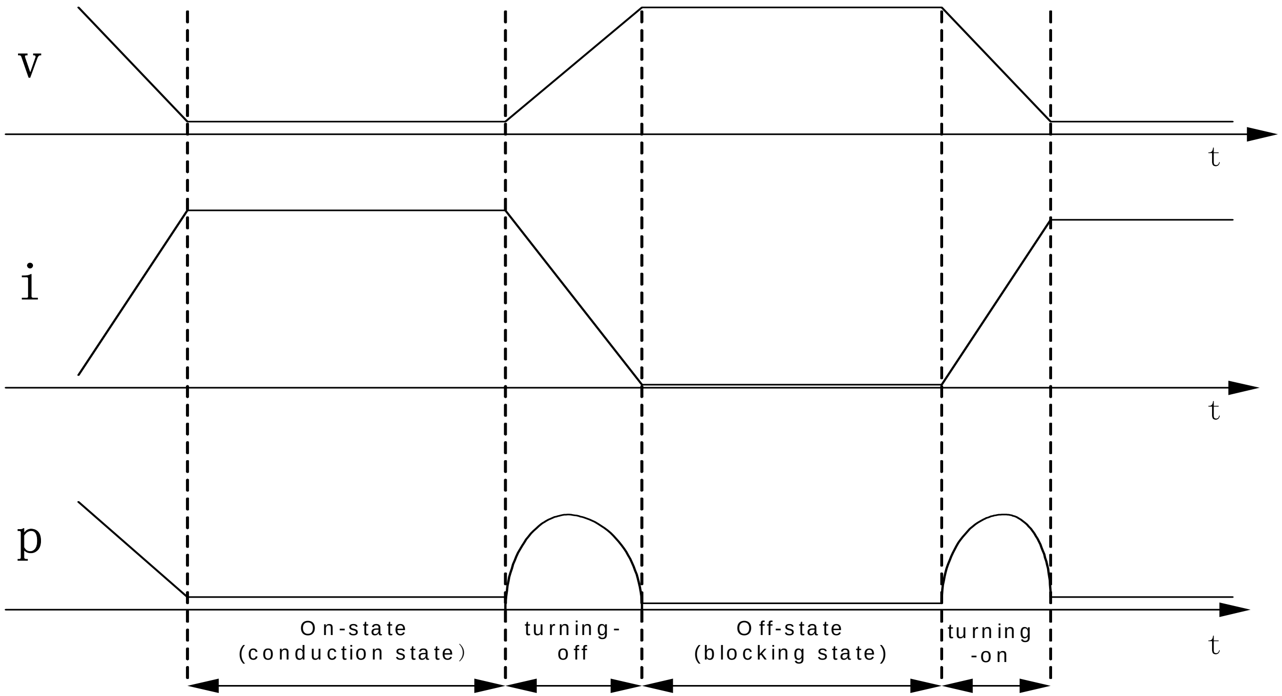
Power Electronics

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



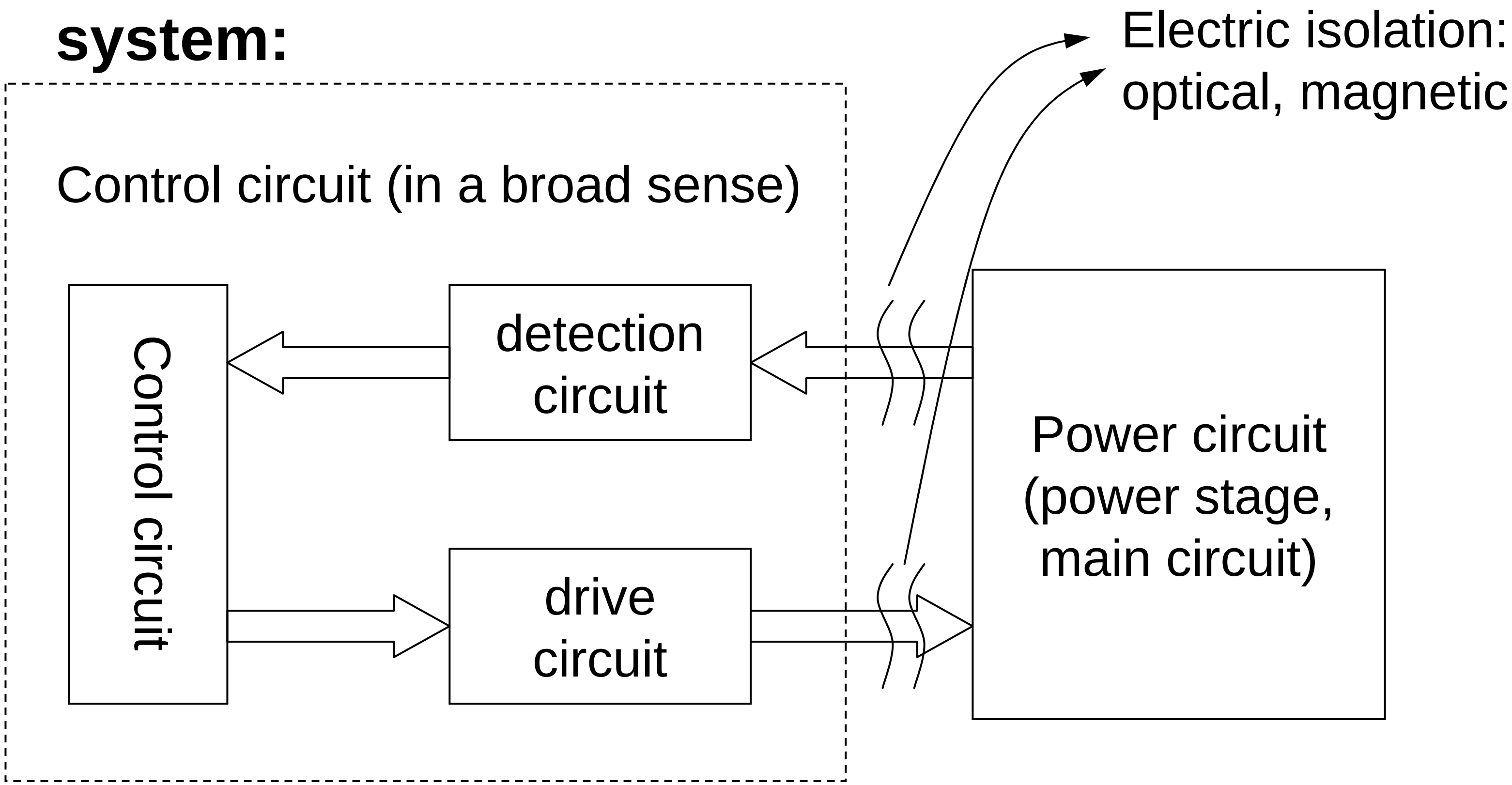
Total power loss on power semiconductor = conduction loss + turn-off loss + off-state loss + turn-on loss

(on-state loss)

Switching loss

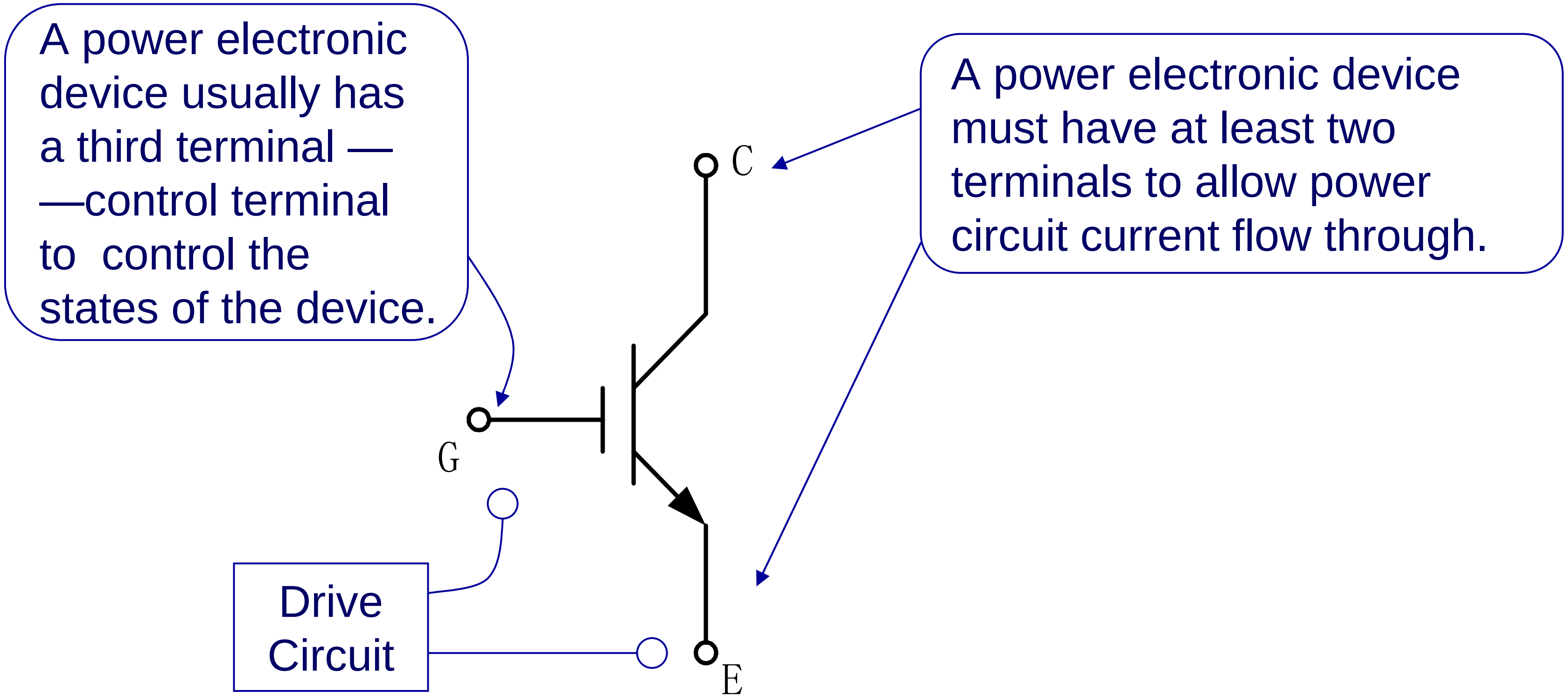
Configuration of systems using power electronic devices

Power electronic system:



- Protection circuit is also very often used in power electronic system especially for the expensive power semiconductors.

Terminals of a power electronic device



- Control signal from drive circuit must be connected between the control terminal and a fixed power circuit terminal (therefore called common terminal).

Power Electronics

A classification of power electronic devices

- Uncontrolled device: diode
  (Uncontrollable device)

  has only two terminals and can not 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.

Power Electronics

Other classifications

- power electronic devices
  - Current-driven (current-controlled) devices
  - Voltage-driven (voltage-controlled) devices (Field-controlled devices)

- power electronic devices
  - Pulse-triggered devices
  - Level-sensitive (level-triggered) devices

- power electronic devices
  - Unipolar devices (Majority carrier devices)
  - Bipolar devices (Minority carrier devices)
  - Composite devices

Power Electronics

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

Power Electronics

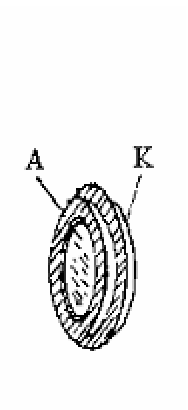
Passive components in power electronic circuit

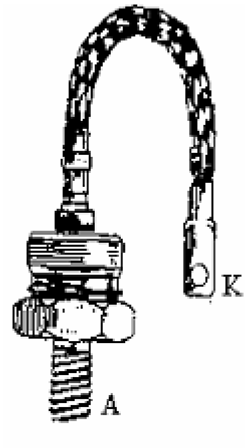
- Transformer, inductor, capacitor and resistor:
  these are passive components in a power electronic circuit since they can not be controlled by control signal and their characteristics are usually constant and linear.

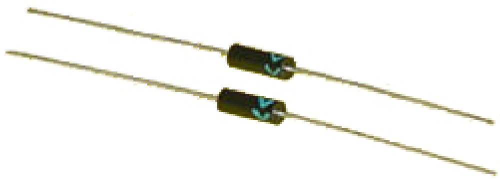
- The requirements for these passive components by power electronic circuits could be very different from those by ordinary circuits.

1.2 Uncontrolled device Power diode

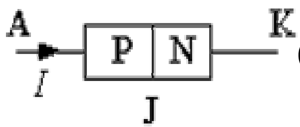
Appearance





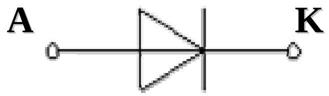




Structure

Anode


Cathode

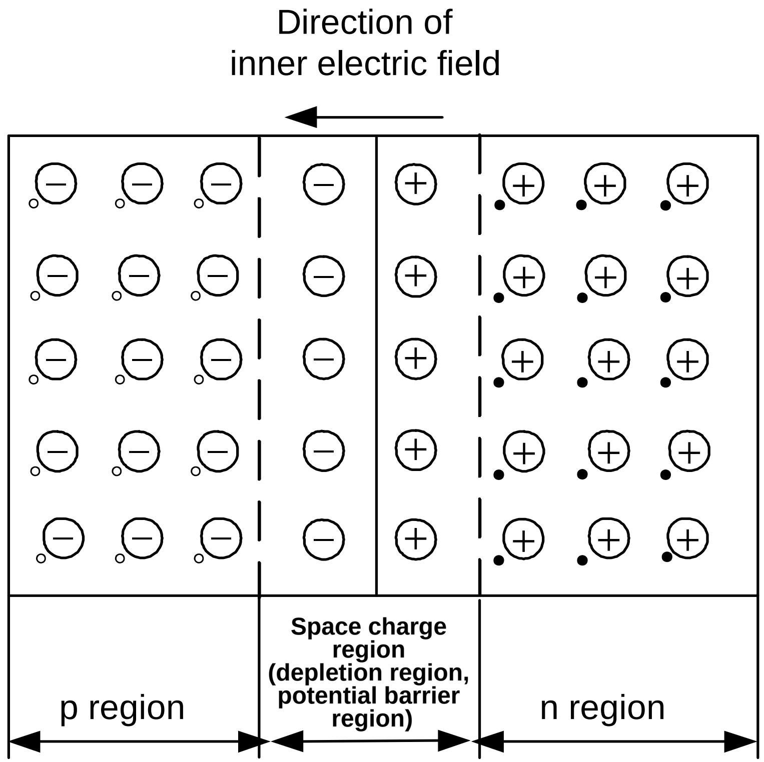
Symbol

Anode


Cathode

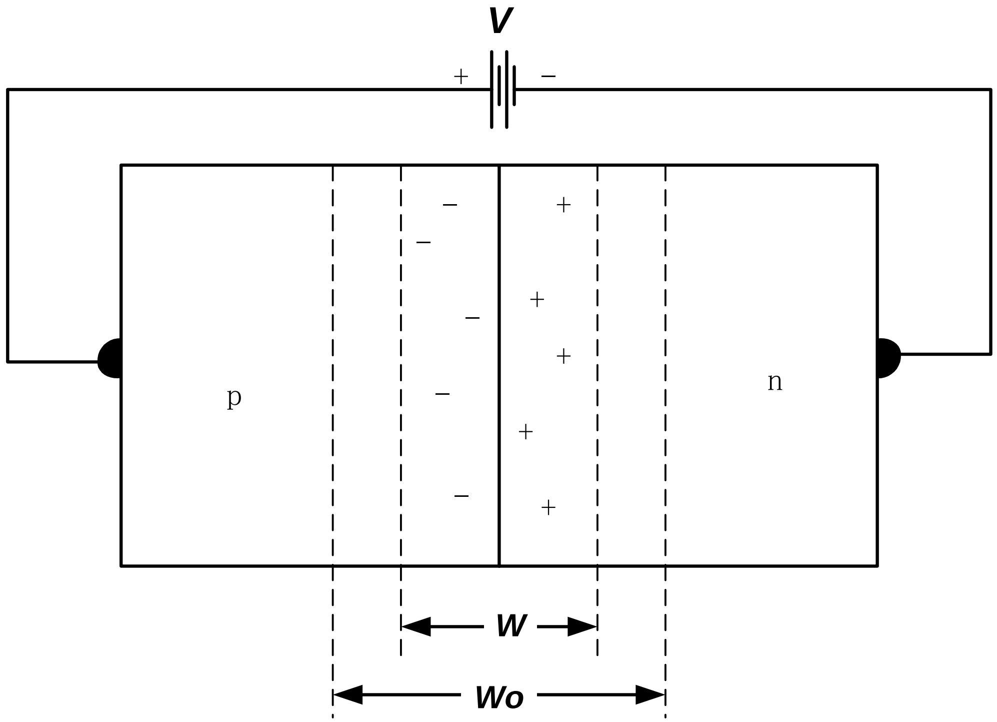
Power Electronics

PN junction

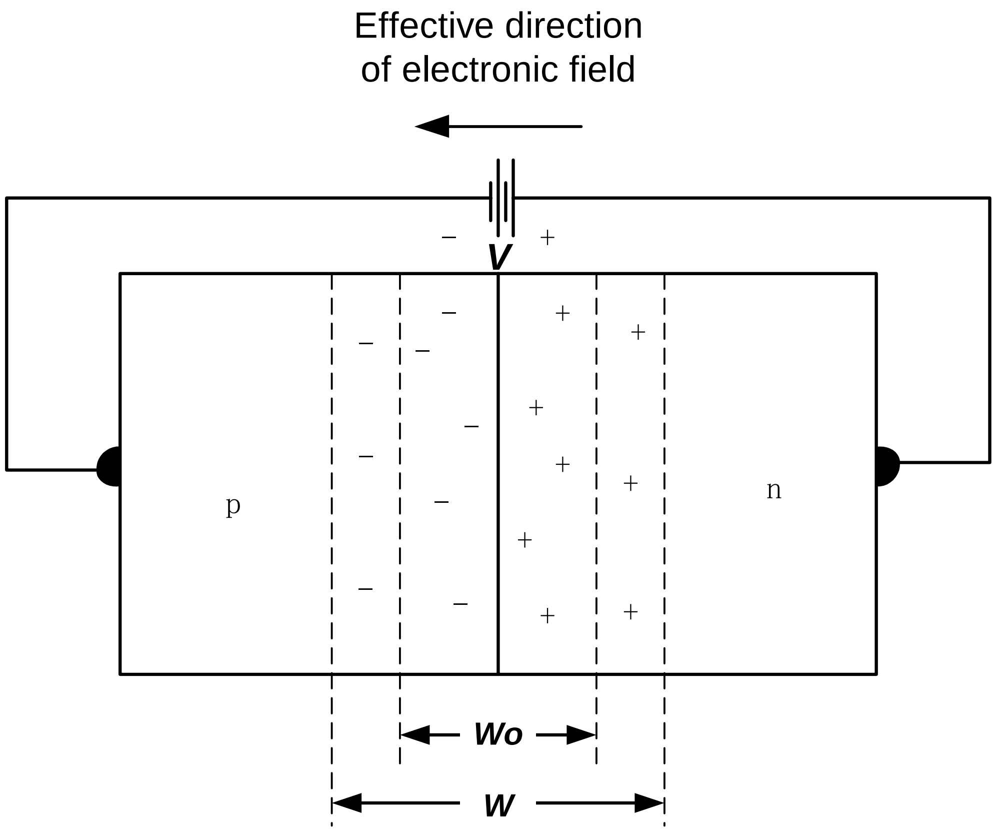


- Semiconductor (Column IV element, Si)
- Electrons and holes.
- Pure semiconductor (intrinsic semiconductor)
- Doping, p-type semiconductor. N-type semiconductor
- PN junction
- Equilibrium of diffusion and drift

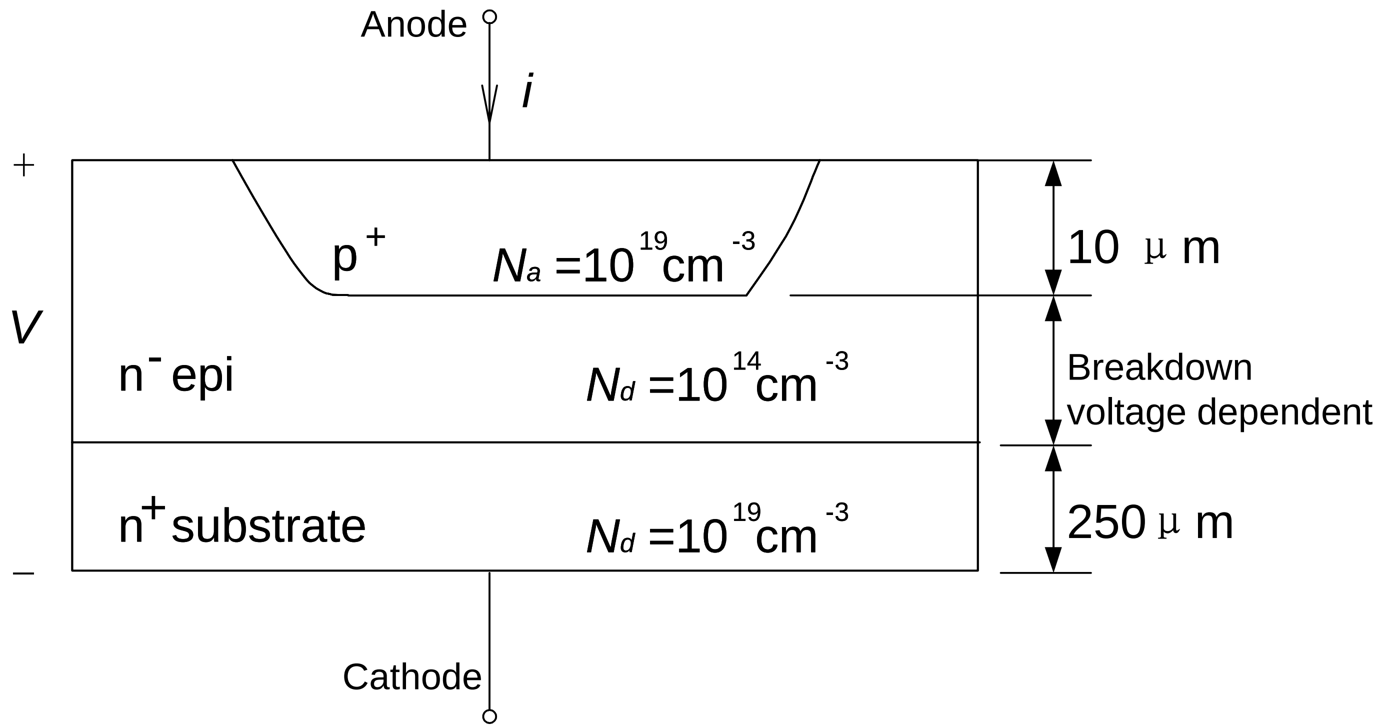
PN junction with voltage applied in the forward direction



PN junction with voltage applied in the reverse direction

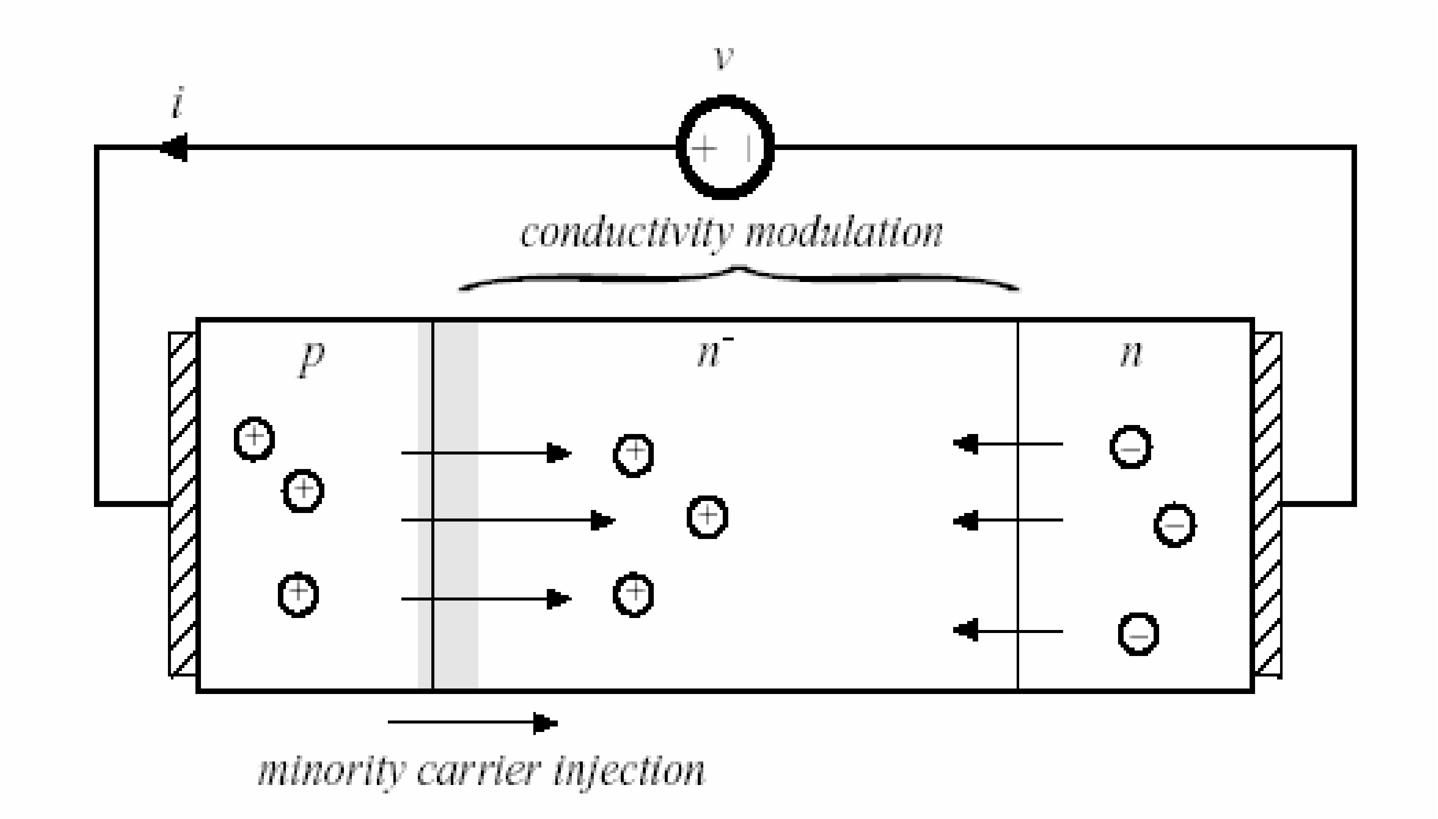


Construction of a practical power diode



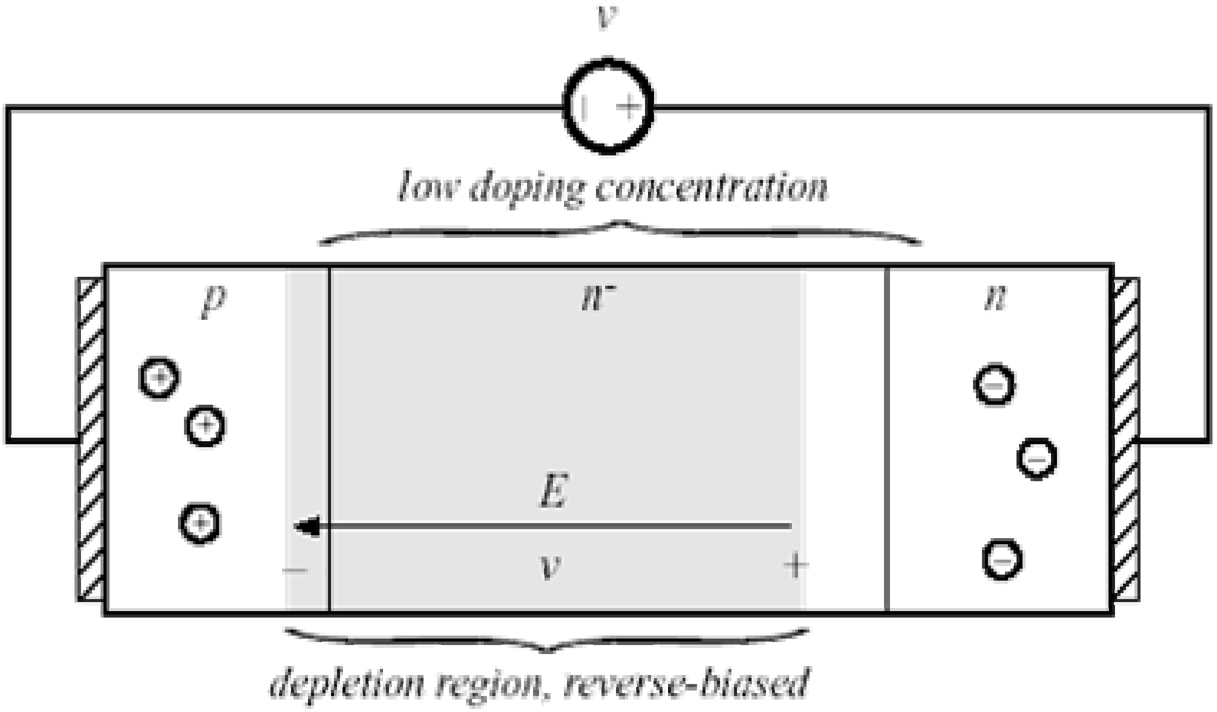
- Features different from low-power (information electronic) diodes
  - Larger size
  - Vertically oriented structure
  - n^{-} drift region (p-i-n diode)
  - Conductivity modulation

Forward-biased power diode



Power Electronics

Reverse-biased power diode



- Breakdown
  - Avalanche breakdown
  - Thermal breakdown

Junction capacitor

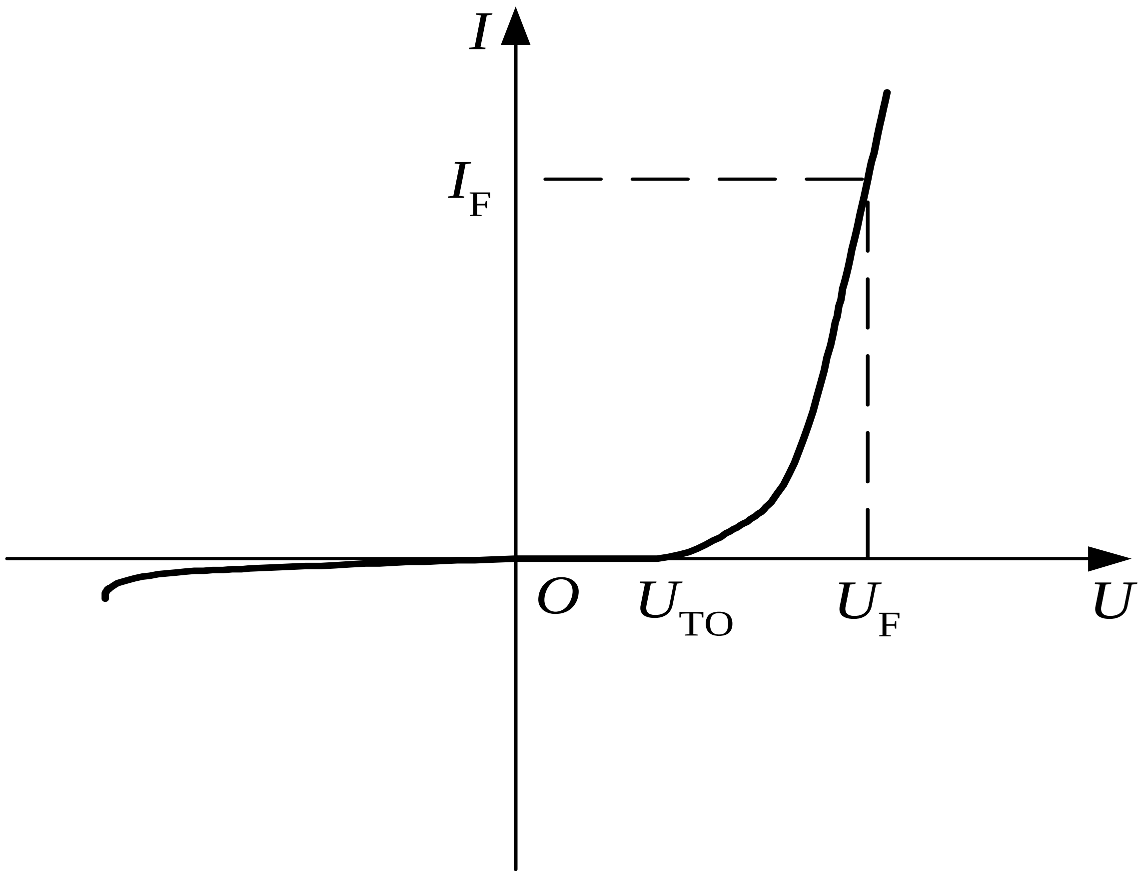
- The positive and negative charge in the depletion region is variable with the changing of external voltage.
  ——Junction capacitor C_J .

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

- Junction capacitor influences the switching characteristics of power diode.

Power Electronics

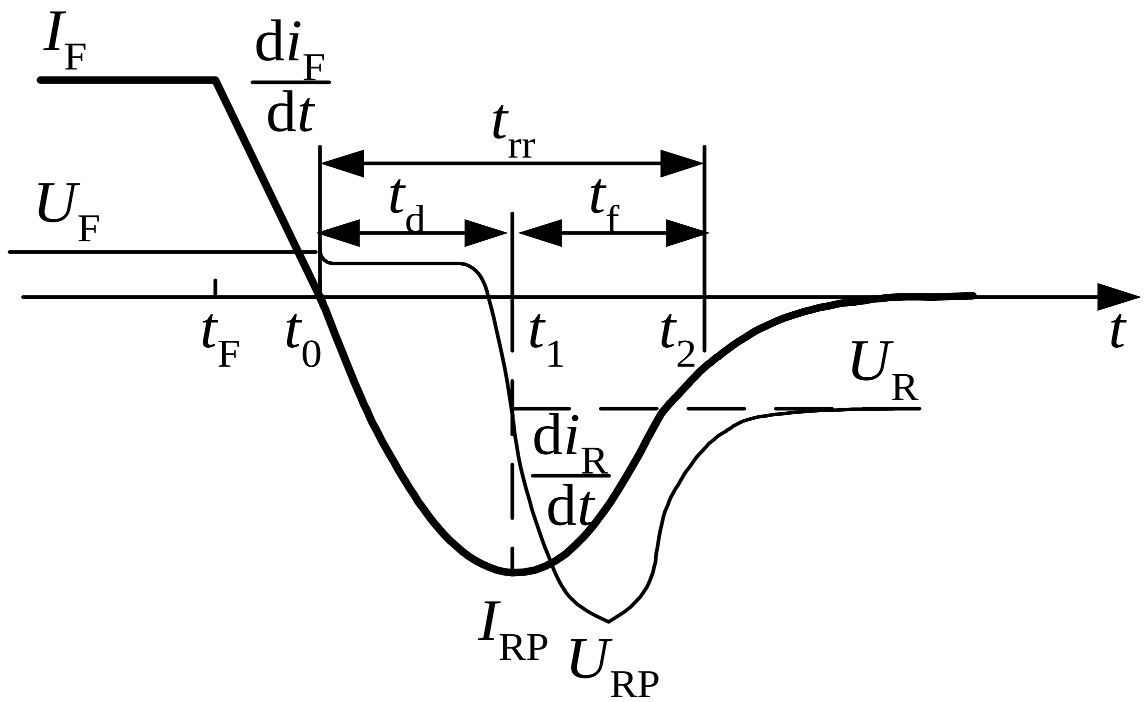
Static characteristics of power diode



The I-V characteristic of power diode

Switching (dynamic) characteristics of power diode

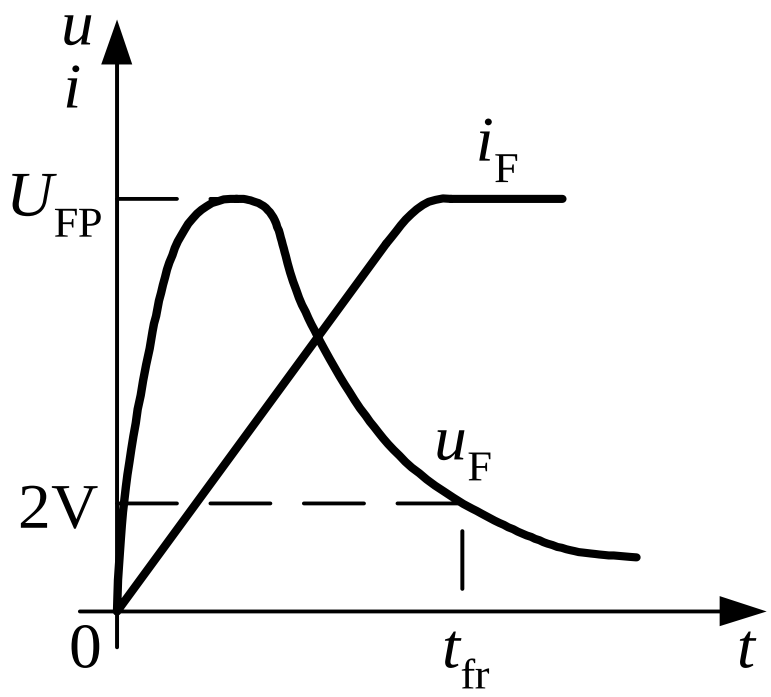
Turn-off transient



- 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

Power Electronics

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}

Power Electronics

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 μs, 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)

Power Electronics

Examples of commercial power diodes

Part number	*Rated max voltage*	*Rated avg current*	V_F *(typical)*	t_r *(max)*
Fast recovery rectifiers				
1N3913	400V	30A	1.1V	400ns
SD453N25S20PC	2500V	400A	2.2V	2μs
Ultra-fast recovery rectifiers				
MUR815	150V	8A	0.975V	35ns
MUR1560	600V	15A	1.2V	60ns
RHRU100120	1200V	100A	2.6V	60ns
Schottky rectifiers				
MBR6030L	30V	60A	0.48V	
444CNQ045	45V	440A	0.69V	
30CPQ150	150V	30A	1.19V	

Power Electronics

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

Power Electronics

History

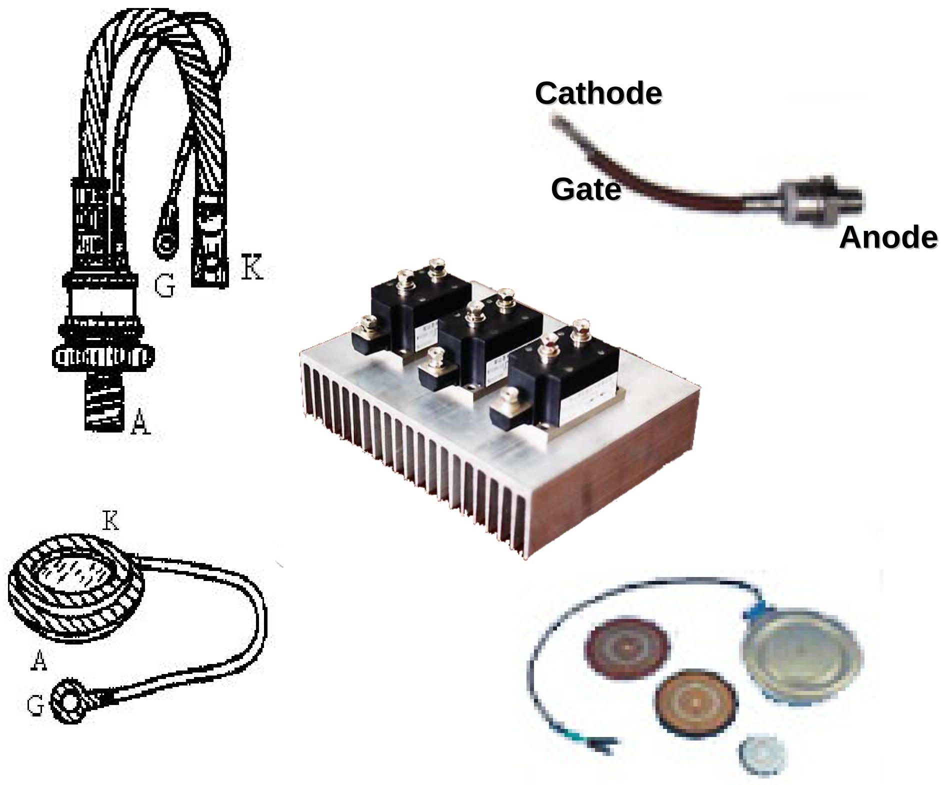
- Another name: SCR—silicon controlled rectifier

- 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.

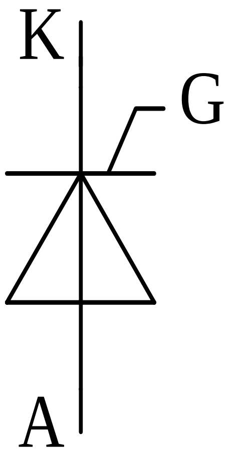
- Still in use in high power situation. Thyristor till has the highest power-handling capability.

Appearance and symbol of thyristor

Appearance

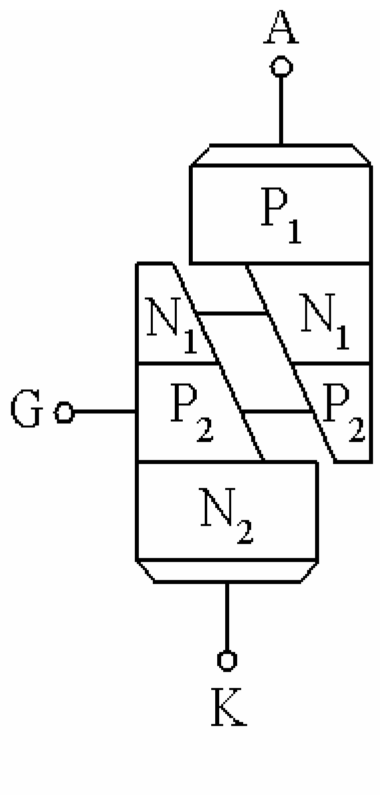


Symbol



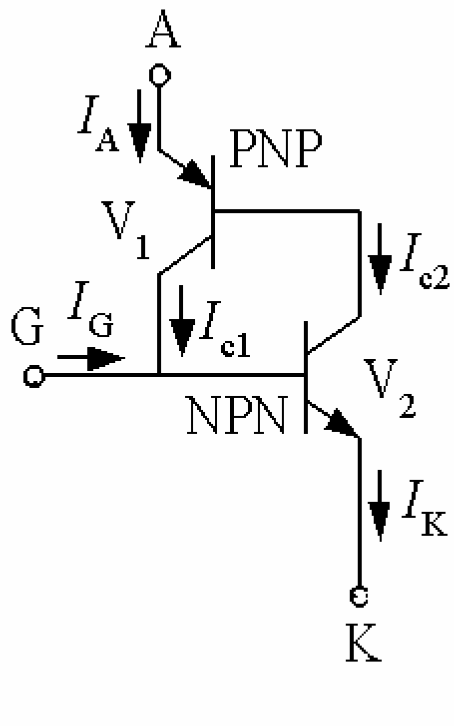
Structure and equivalent circuit of thyristor

- Structure



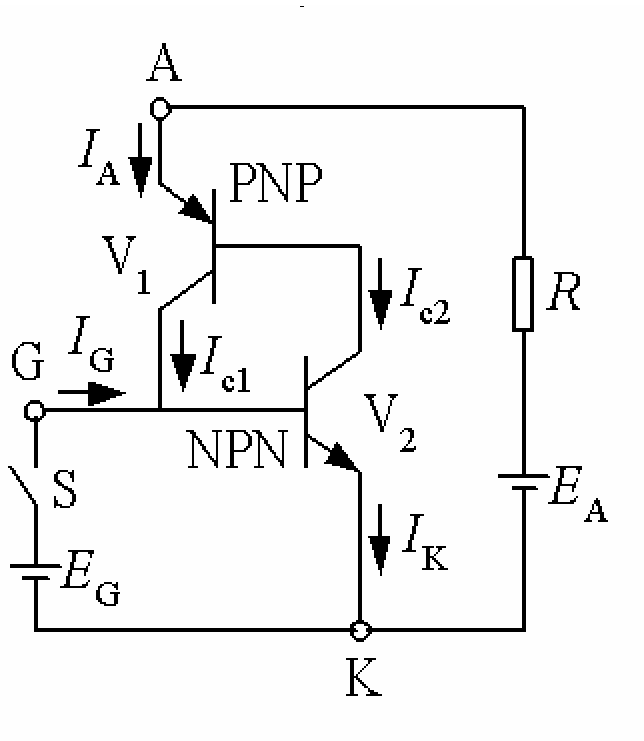
a)

- Equivalent circuit



b)

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

$$I_{c1}=\alpha_1 I_A + I_{CBO1} \quad (1\text{-}1)$$

$$I_{c2}=\alpha_2 I_K + I_{CBO2} \quad (1\text{-}2)$$

$$I_K=I_A+I_G \quad (1\text{-}3)$$

$$I_A=I_{c1}+I_{c2} \quad (1\text{-}4)$$

$$I_A=\frac{\alpha_2 I_G + I_{CBO1}+I_{CBO2}}{1-(\alpha_1+\alpha_2)} \quad (1\text{-}5)$$

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.

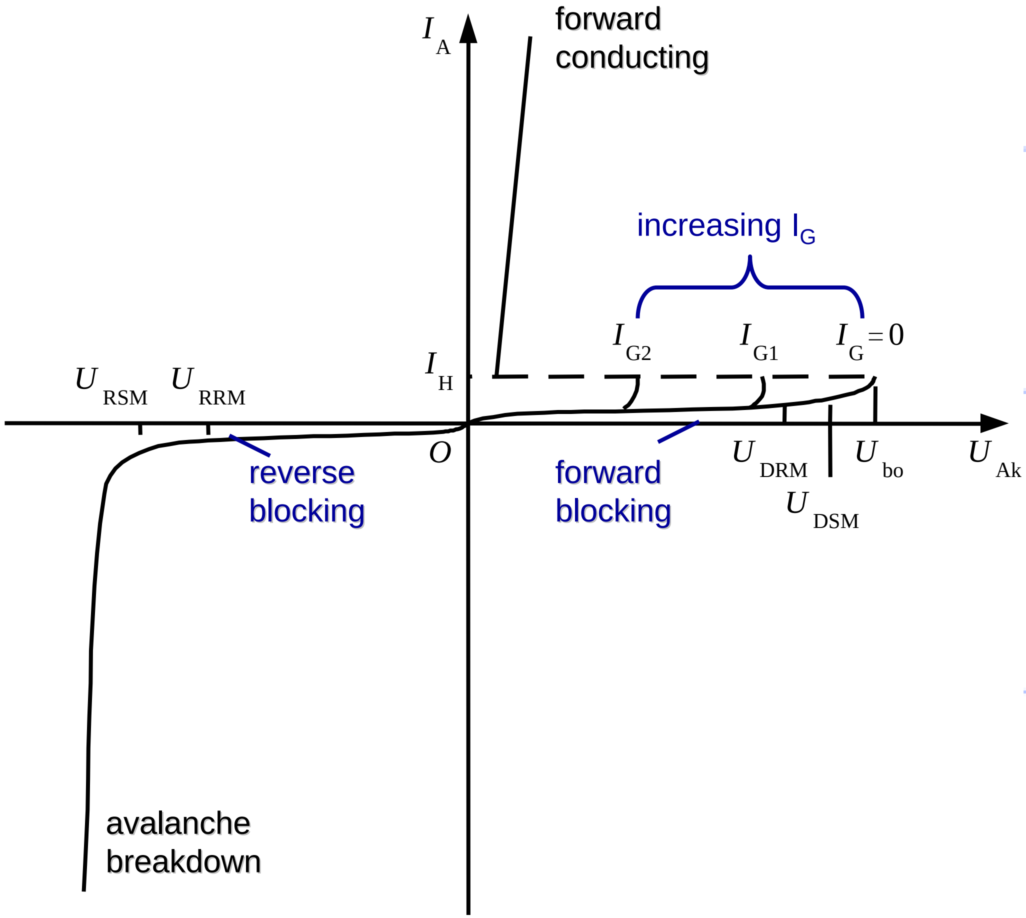
PEREC

Power Electronics

Other methods to trigger thyristor on

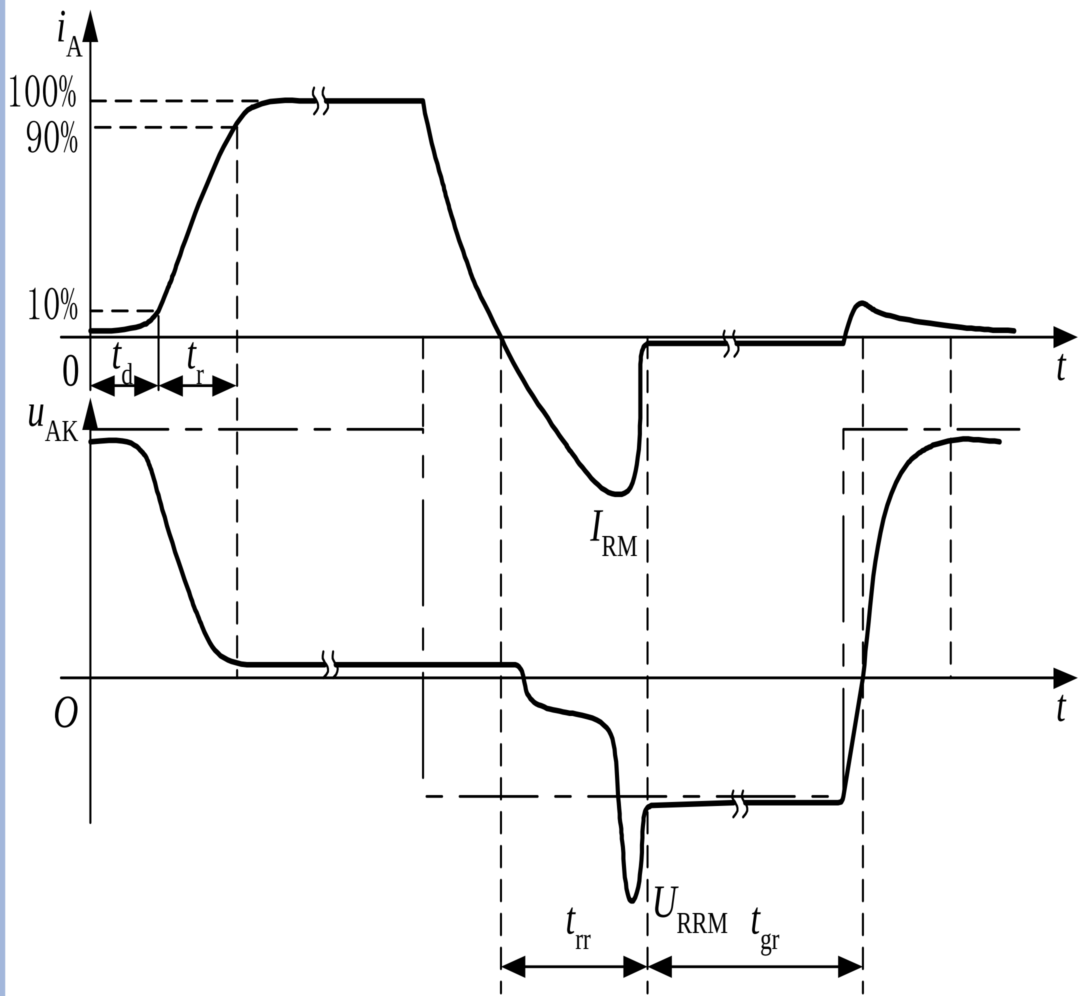
- High voltage across anode and cathode—avalanche breakdown
- High rising rate of anode voltagte — du/dt too high
- High junction temperature
- Light activation

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

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

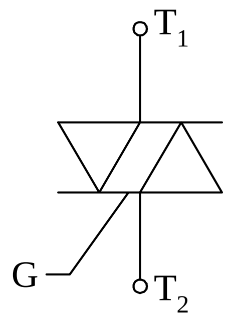
Power Electronics

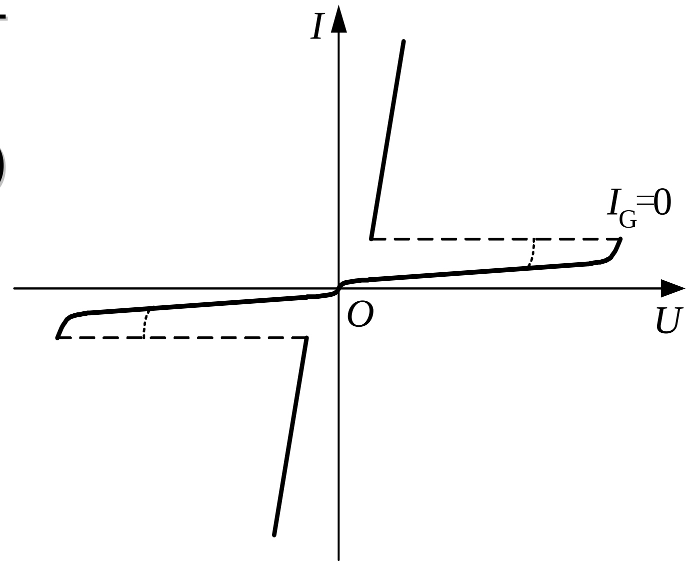
Specifications of thyristor

- 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

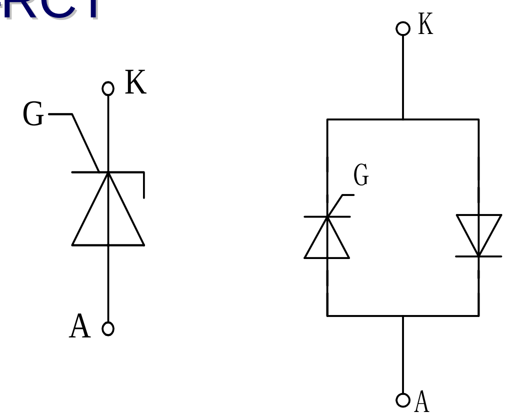
The family of thyristors

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

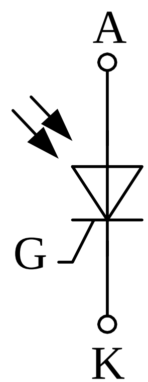




- Reverse-conducting thyristor —RCT



Light-triggered (activited) thyristor —LTT



Power Electronics

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

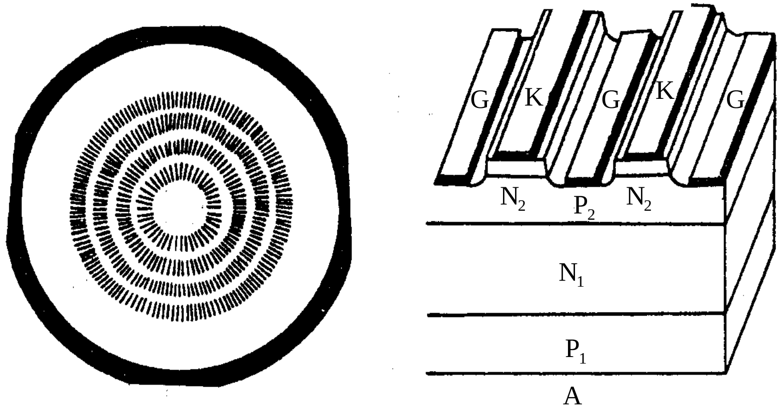
- IC fabrication technology, fully-controllable, high frequency

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.

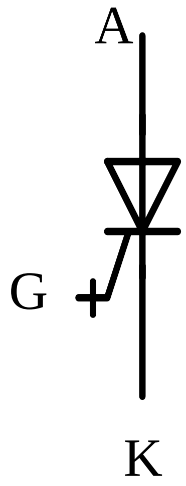
1.4.1 Gate-turn-off thyristor—GTO

Structure



a) b)

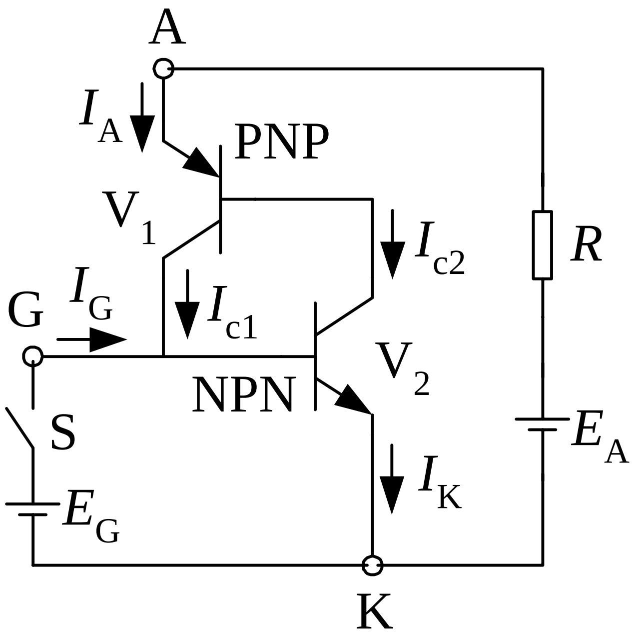
Symbol



- 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



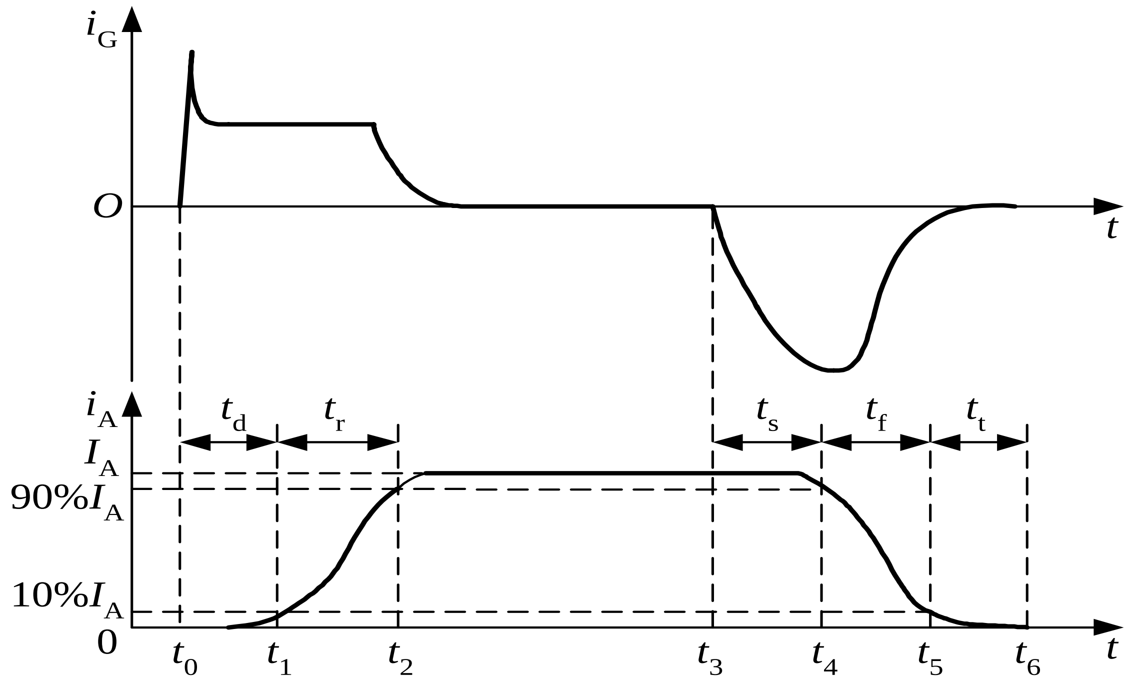
- The basic operation of GTO is the same as that of the conventional thyristor.
- The principal differences lie in the modifications in the structure to achieve gate turn-off capability.
  - Large α_2
  - $\alpha_1+\alpha_2$ is just a little larger than the critical value 1.
  - Short distance from gate to cathode makes it possible to drive current out of gate.

Power Electronics

Characteristics of GTO

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

- Switching characteristic



Power Electronics

Specifications of GTO

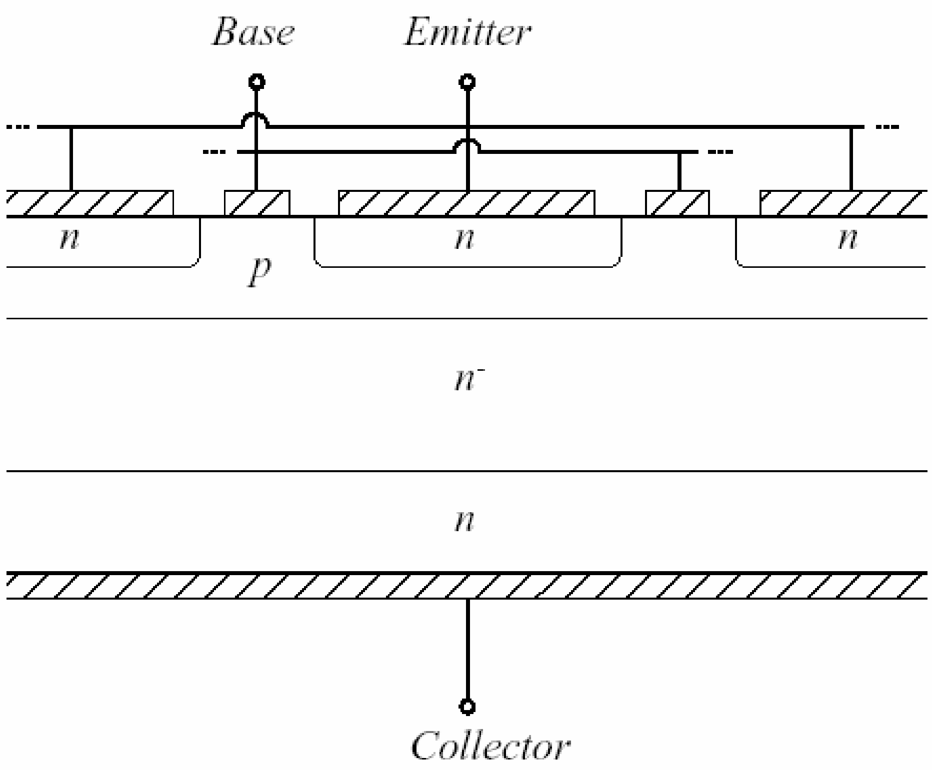
- Most GTO specifications have the same meanings as those of conventional thyristor.

- Specifications different from thyristor's
  - Maximum controllable anode current I_{ATO}
  - Current turn-off gain β_{off}
  - Turn-on time t_{on}
  - Turn-off time t_{off}

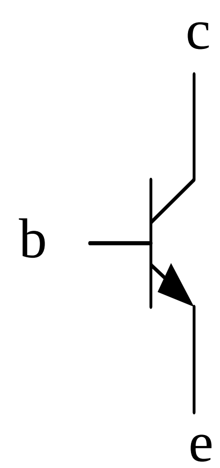
1.4.2 Giant Transistor—GTR

- 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.

Basic structure

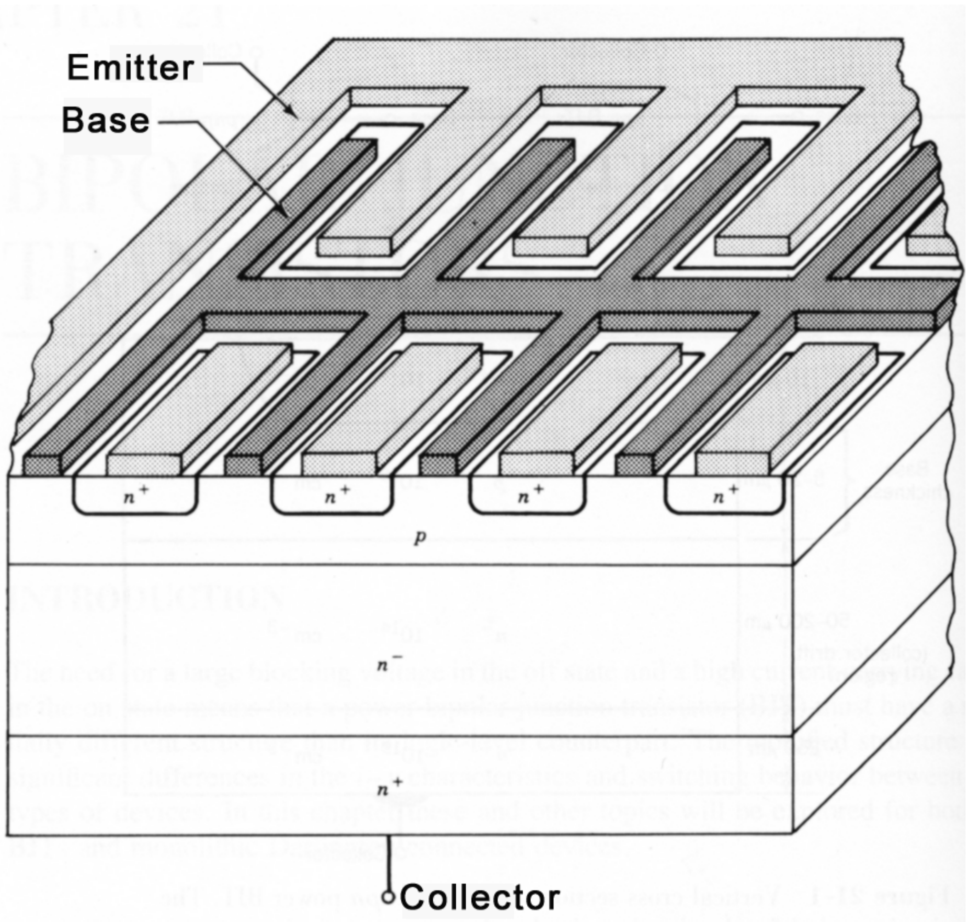


Symbol

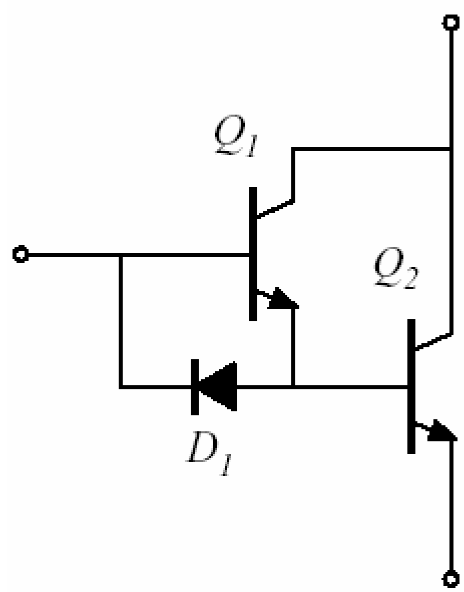


Structures of GTR different from its information-processing counterpart

Multiple-emitter structure



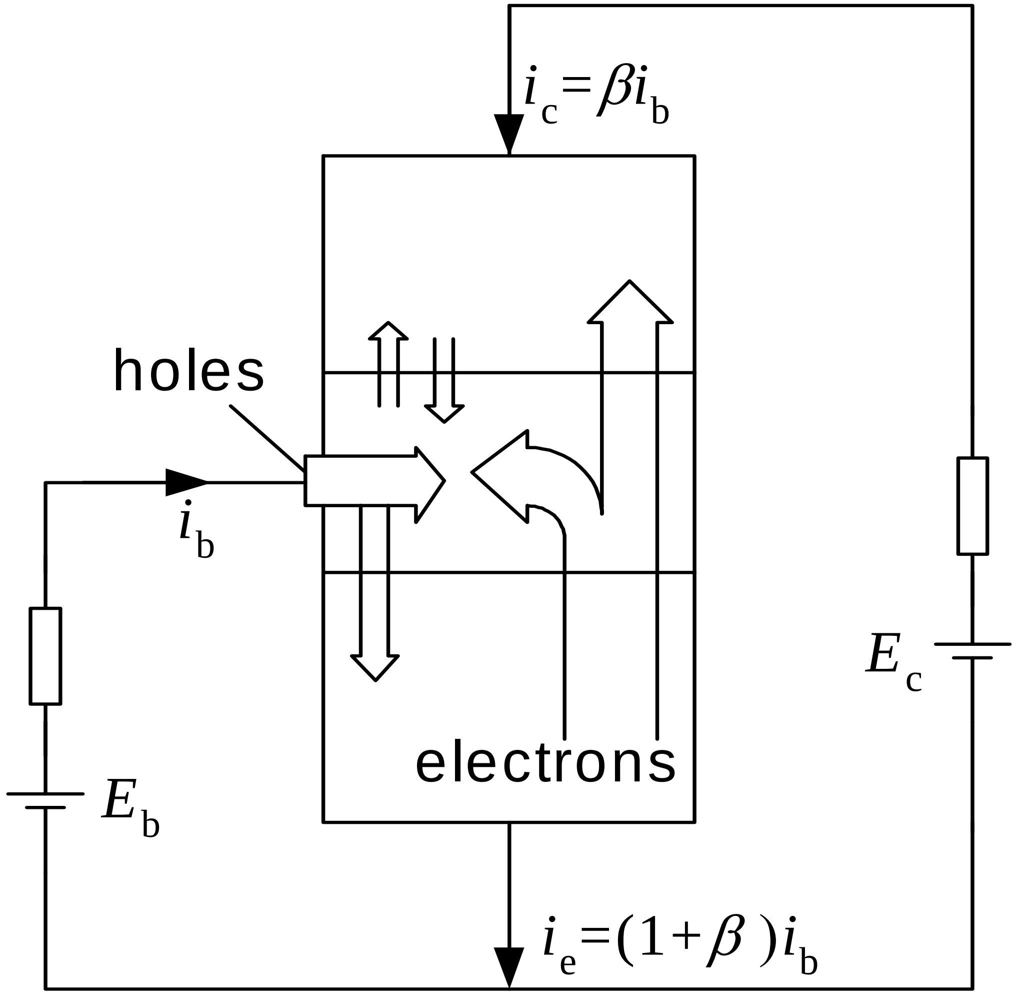
Darlington configuration



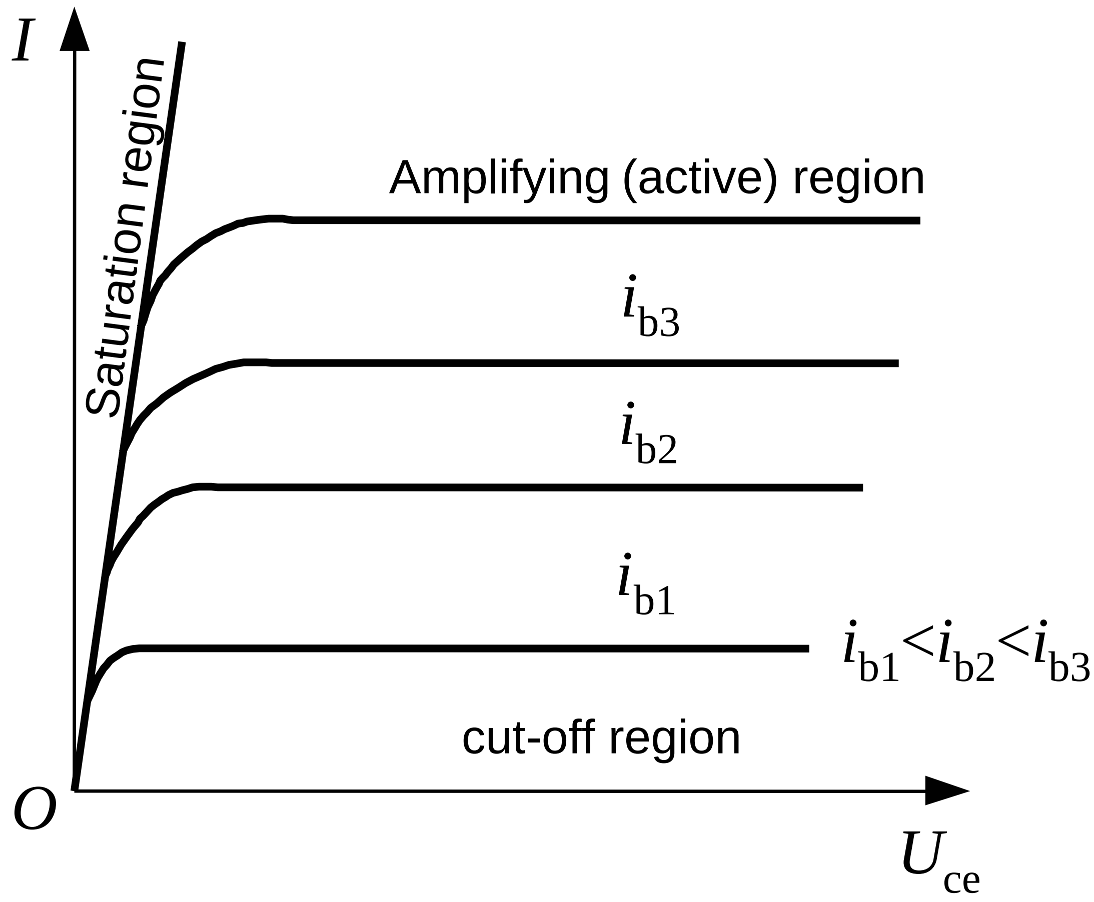
Power Electronics

Physics of GTR operation

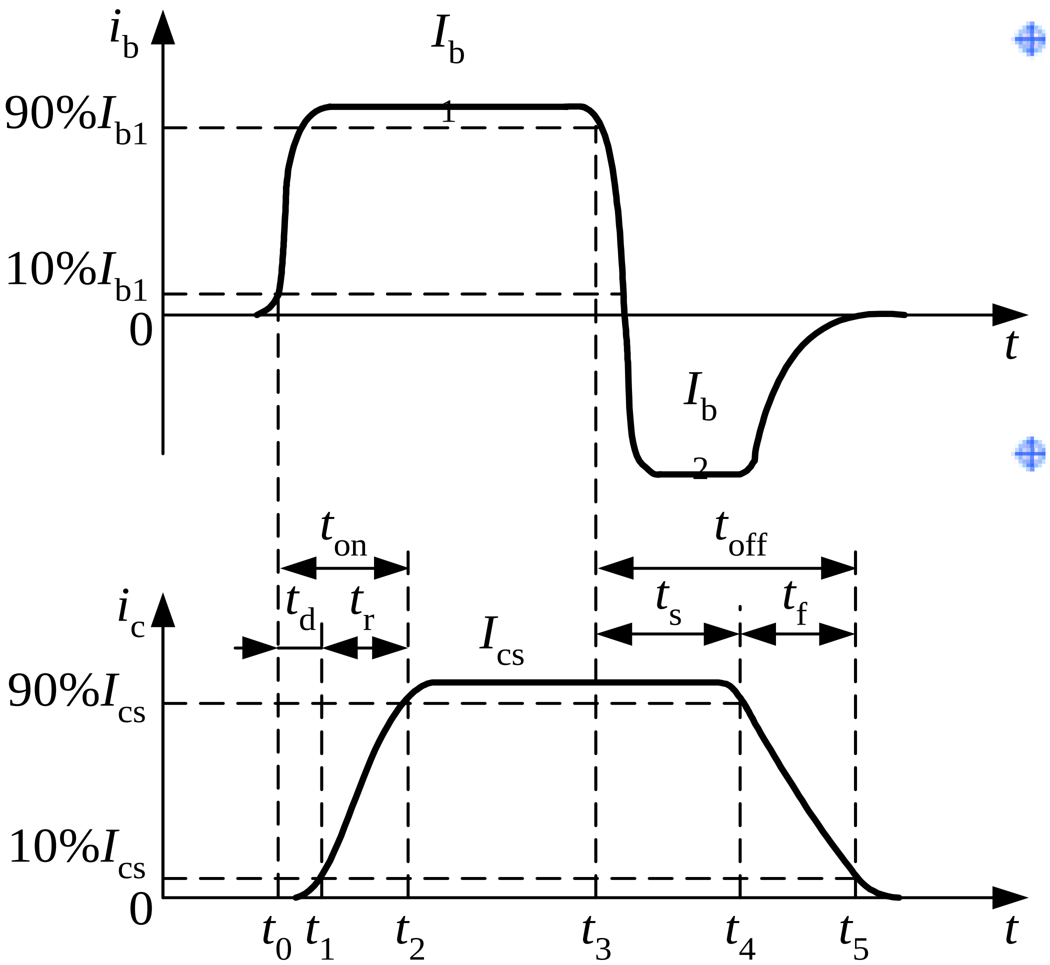
- Same as information BJT device



Static characteristics of GTR

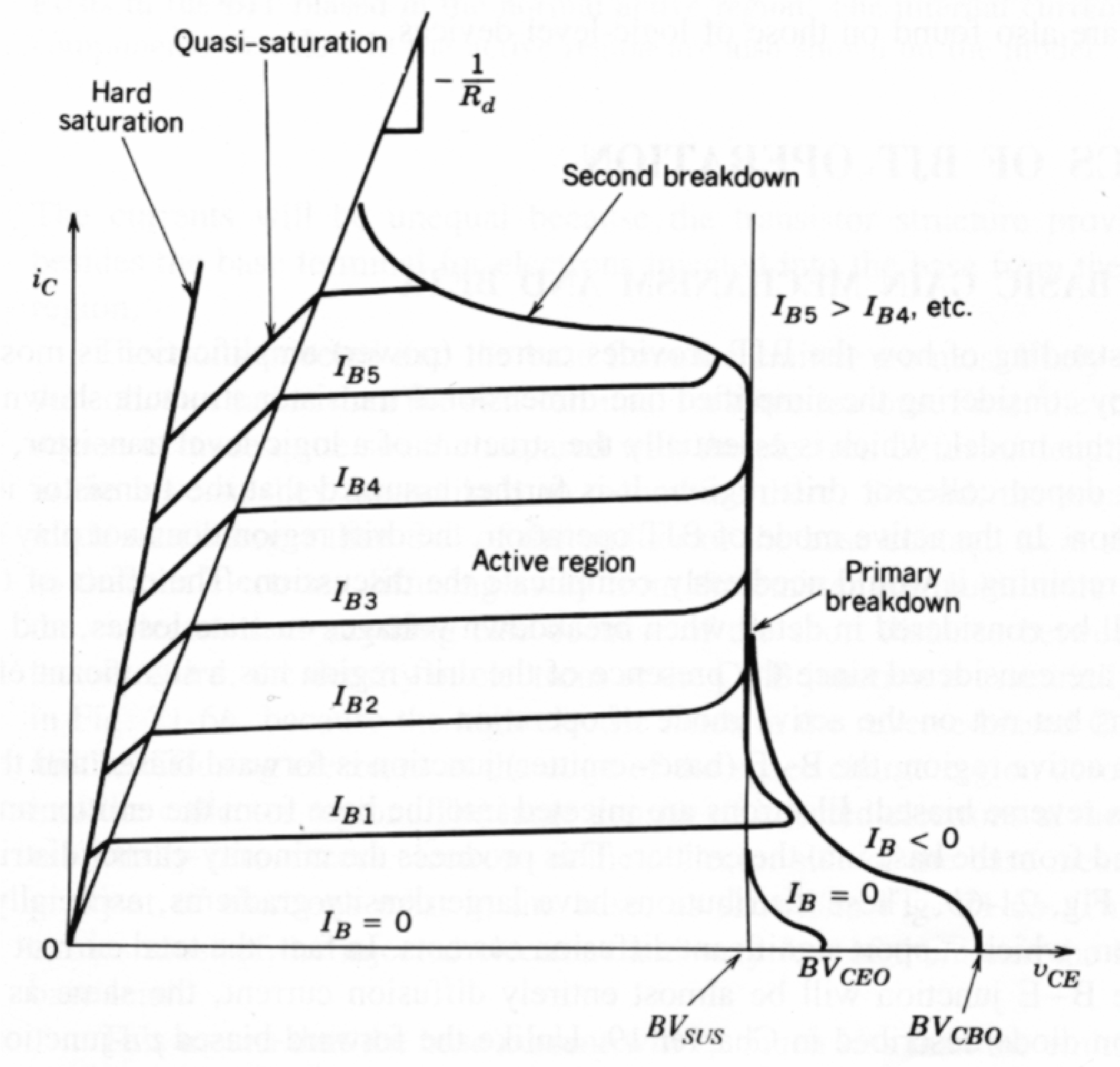


Switching characteristics of GTR

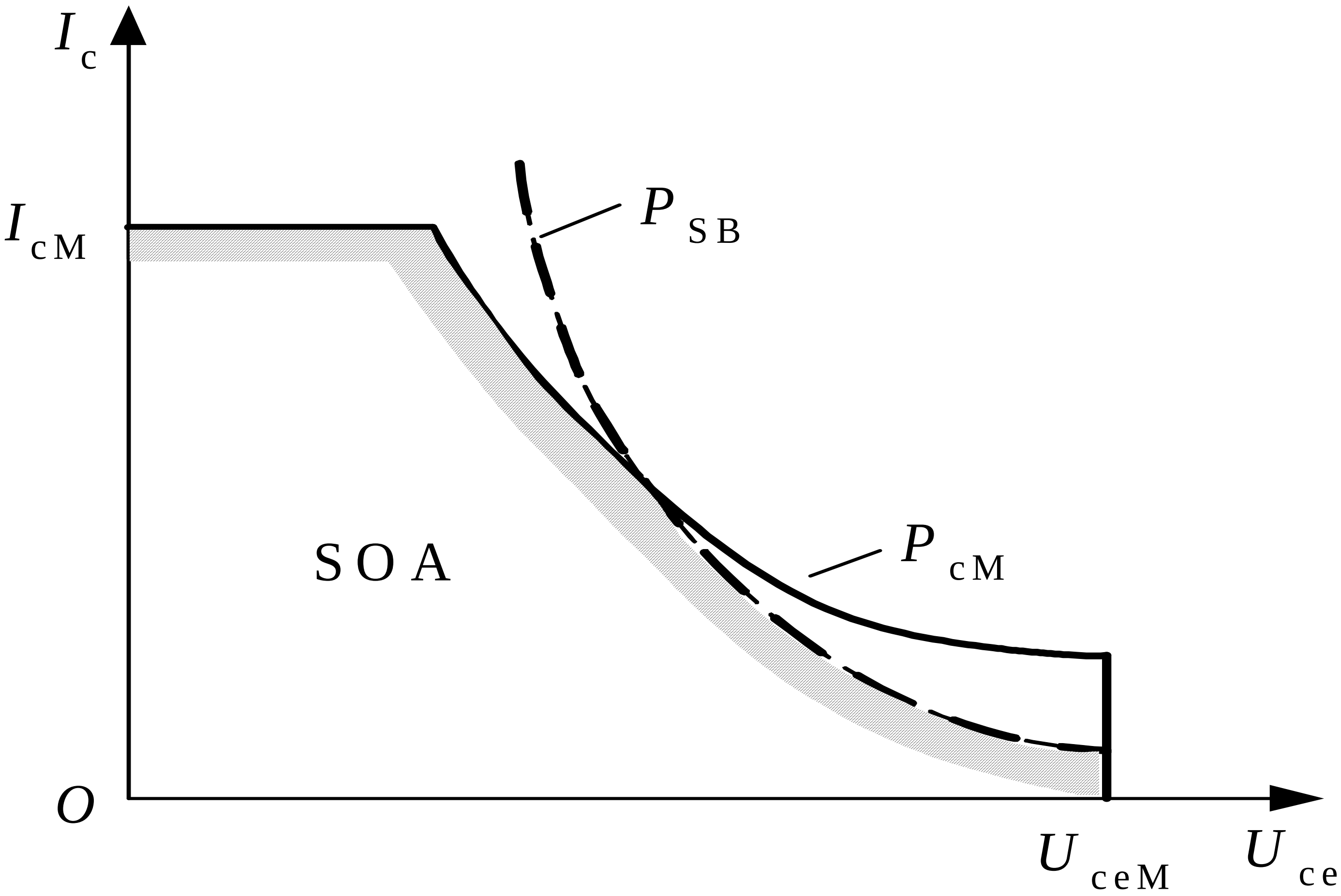


- Turn-on transient
  - Turn-on delay time t_d
  - Rise time t_r
  - Turn-on time t_{on}
- Turn-off transient
  - Storage time t_s
  - Falling time t_f
  - Turn-off time t_{off}

Second breakdown of GTR



Safe operating area (SOA) of GTR

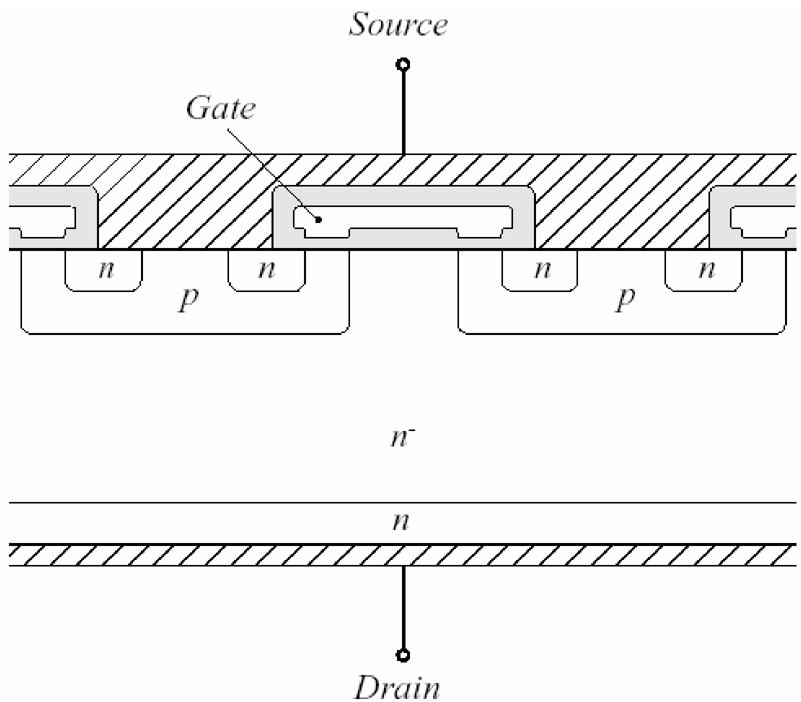


1.4.3 Power metal-oxide-semiconductor field effect transistor—Power MOSFET

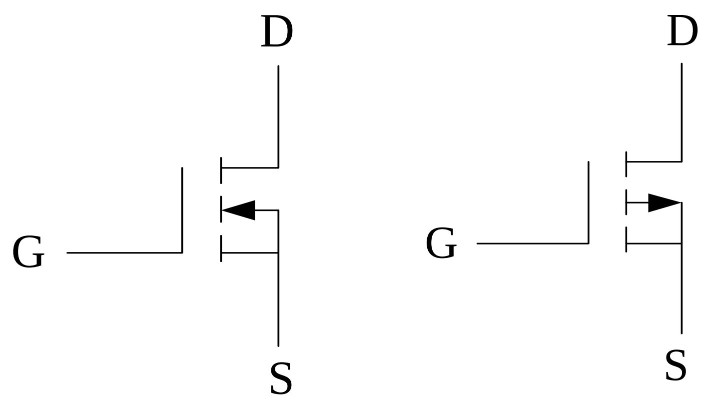
A classification

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

Basic structure



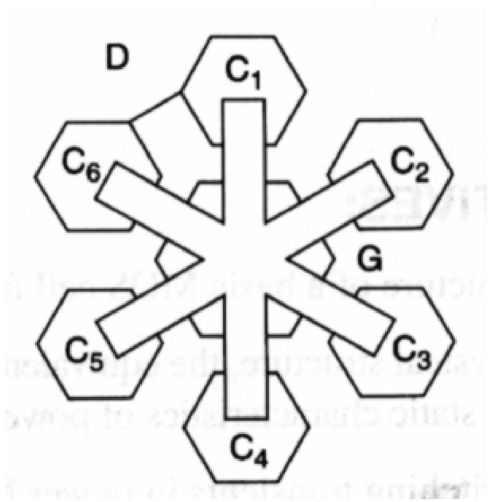
Symbol



N channel P channel

Structures of power MOSFET

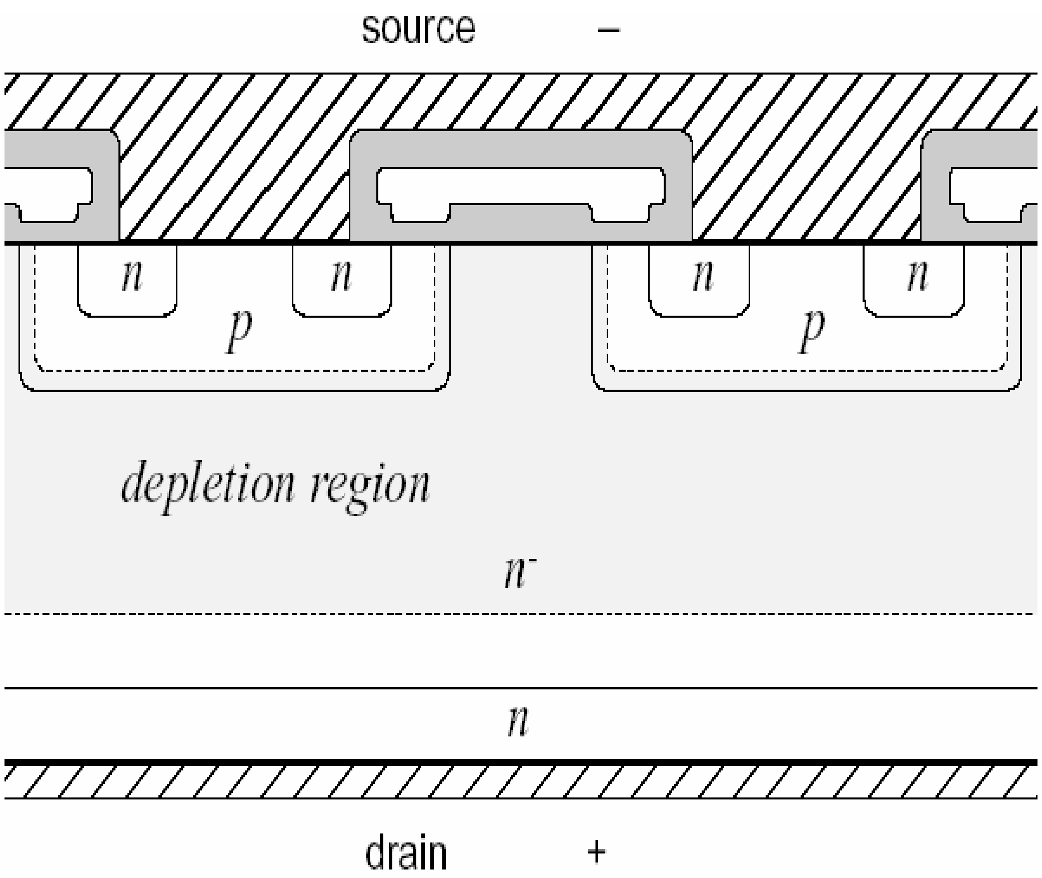
- Also vertical structure—VMOS
  - VVMOS, VDMOS
- Multiple parallel cells
  - Polygon-shaped cells



A structure of hexagon cells

Physics of MOSFET operation

Off-state

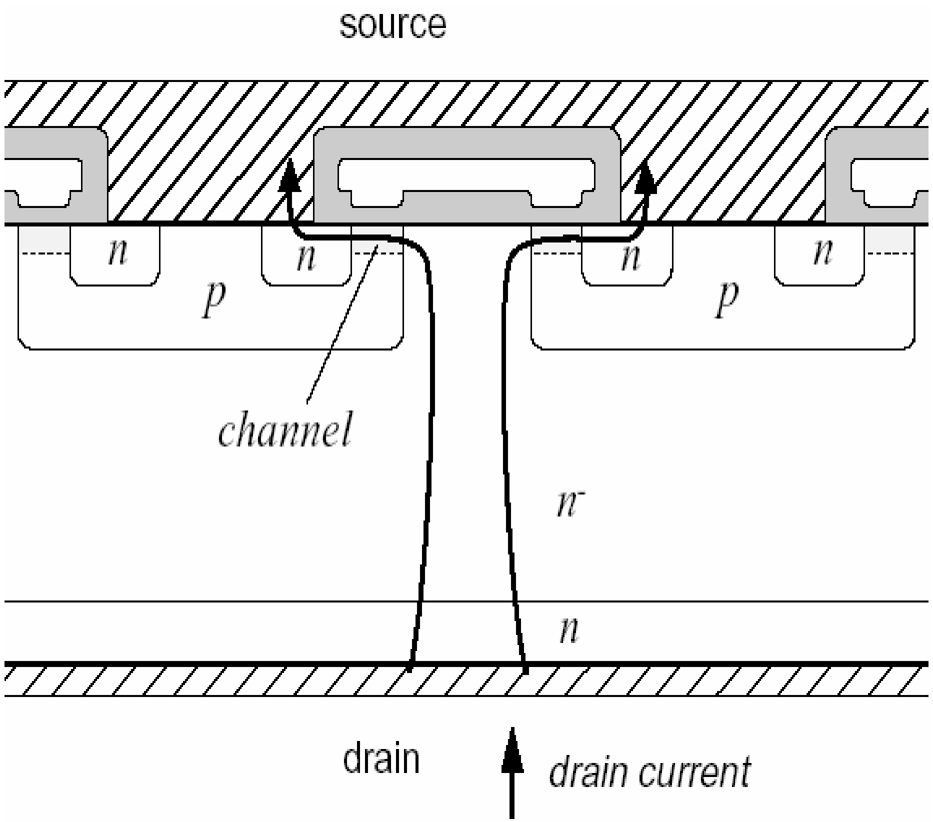


- *p*-*n*⁻ junction is reverse-biased
- off-state voltage appears across n⁻ region

Power Electronics

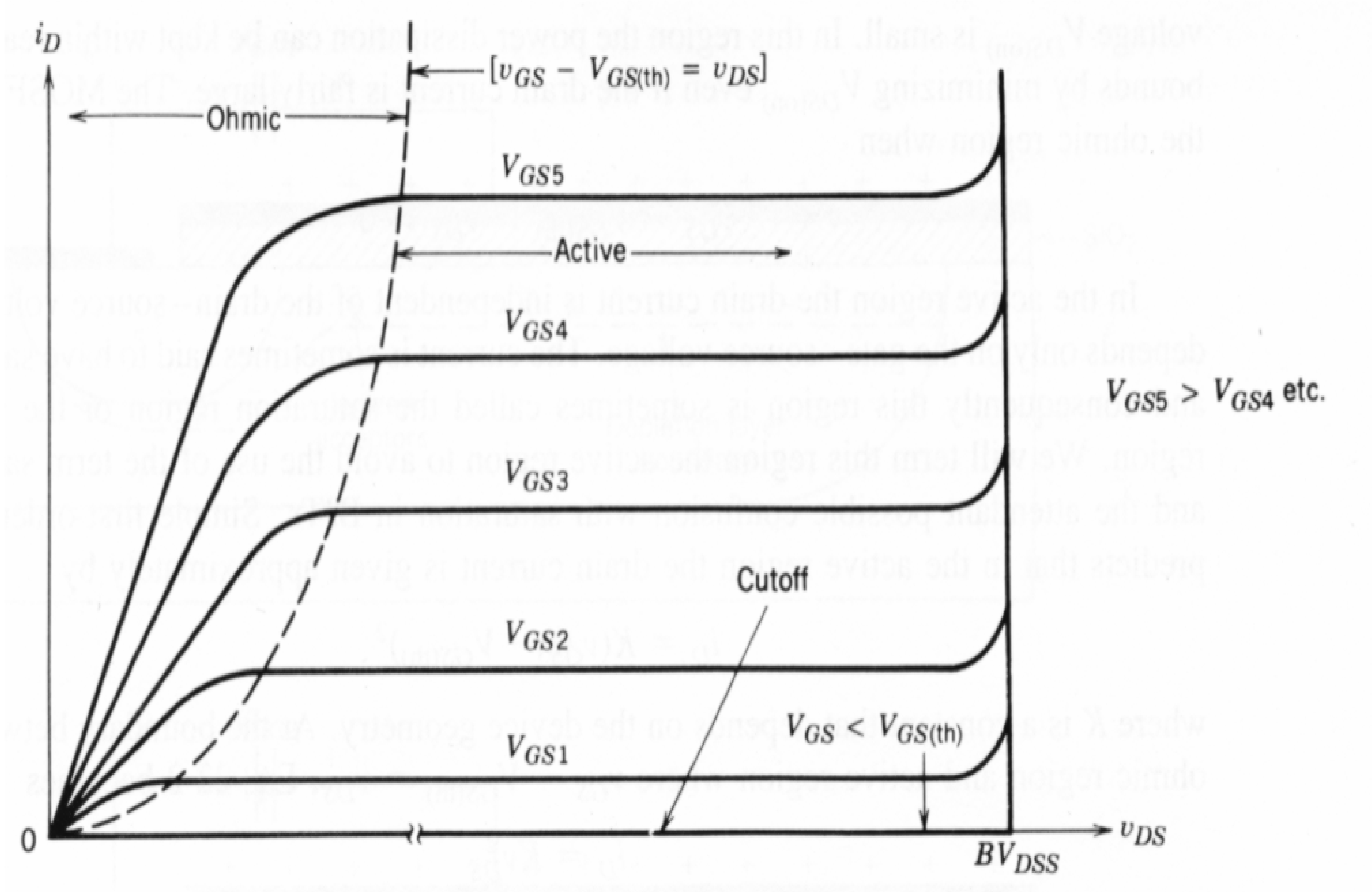
Physics of MOSFET operation

On-state



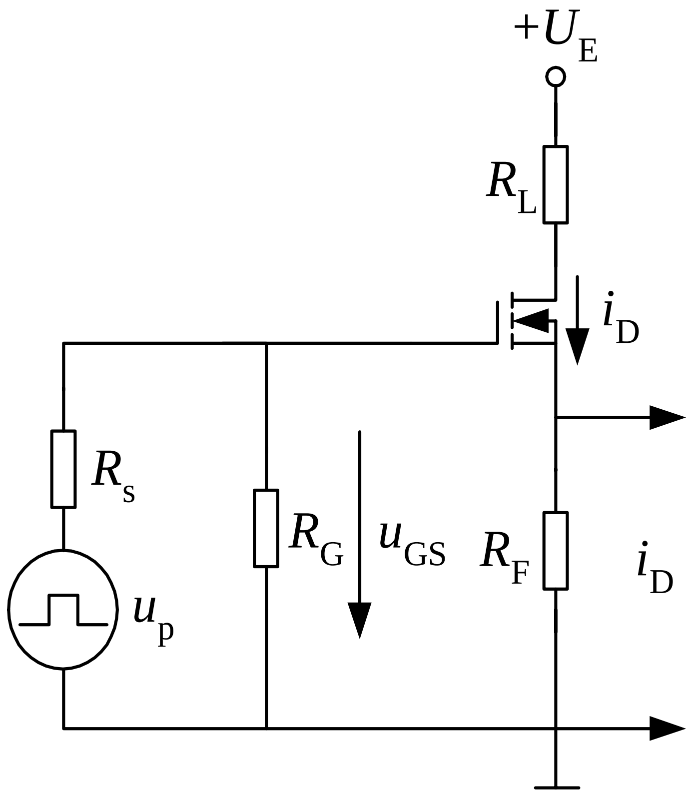
- p-n^- junction is slightly reverse biased
- positive gate voltage induces conducting channel
- drain current flows through n^- region and conducting channel
- on resistance = total resistances of n^- region, conducting channel,source and drain contacts, etc.

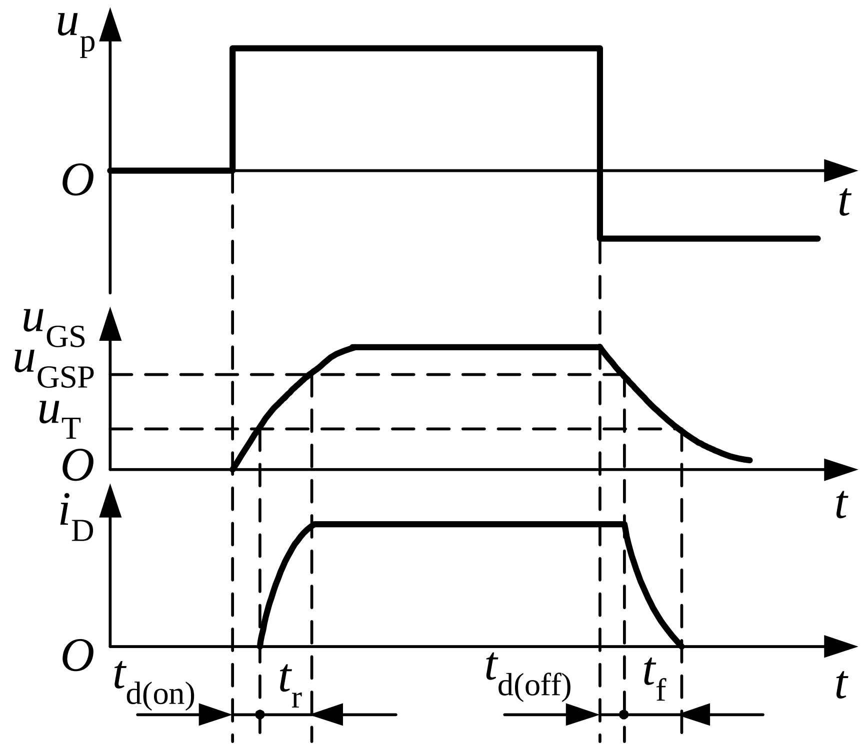
Static characteristics of power MOSFET



Power Electronics

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

Power Electronics

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

Power Electronics

Examples of commercial power MOSFET

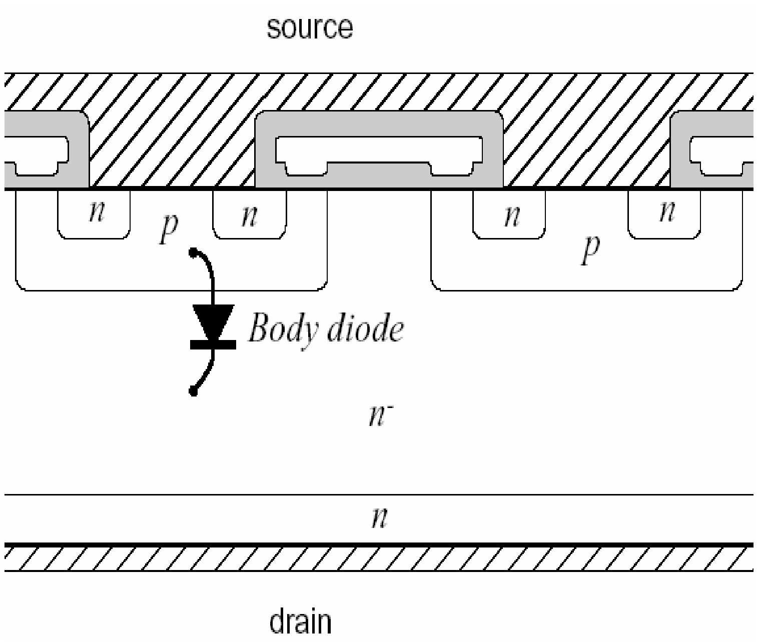
Part number	*Rated max voltage*	*Rated avg current*	R_{on}	Q_g *(typical)*
IRFZ48	60V	50A	0.018Ω	110nC
IRF510	100V	5.6A	0.54Ω	8.3nC
IRF540	100V	28A	0.077Ω	72nC
APT10M25BNR	100V	75A	0.025Ω	171nC
IRF740	400V	10A	0.55Ω	63nC
MTM15N40E	400V	15A	0.3Ω	110nC
APT5025BN	500V	23A	0.25Ω	83nC
APT1001RBNR	1000V	11A	1.0Ω	150nC

Features and applications of power MOSFET

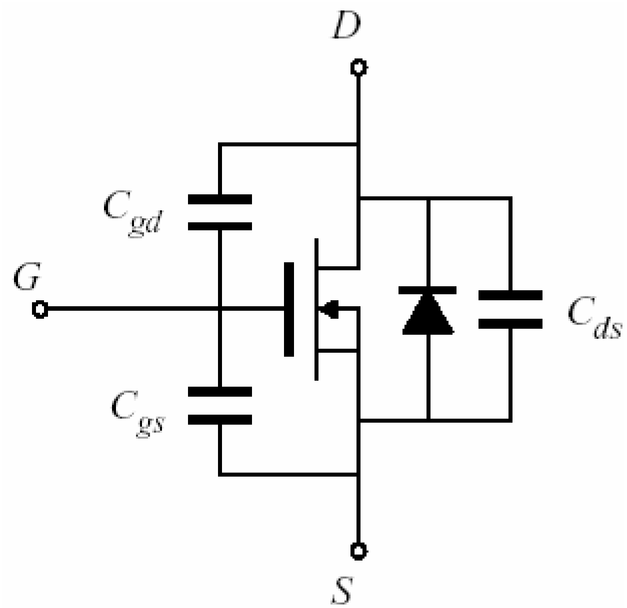
- Voltage-driven device, simple drive circuit
- Majority-carrier device, fast switching speed, high operating frequency (could be hundreds of kHz)
- Majority-carrier device, better thermal stability
- On-resistance increases rapidly with rated blocking voltage
  - Usually used at voltages less than 500V 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

→ IGBT

MOSFET: ☺ faster switching speed, easy to drive (voltage-driven),

☹ larger conduction losses (especially for higher blocking voltages)

Features

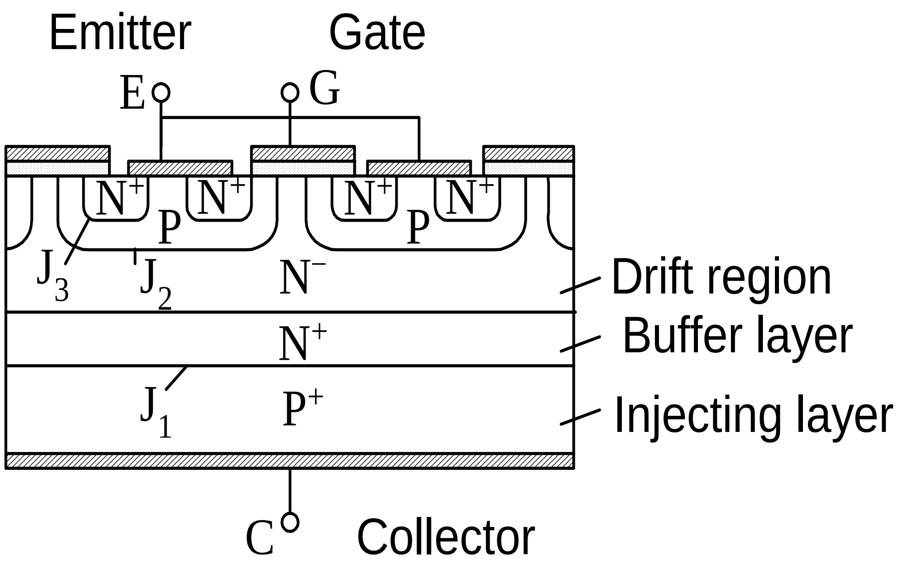
- On-state losses are much smaller than those of a power MOSFET, and are comparable with those of a GTR
- Easy to drive —similar to power MOSFET
- Faster than GTR, but slower than power MOSFET

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

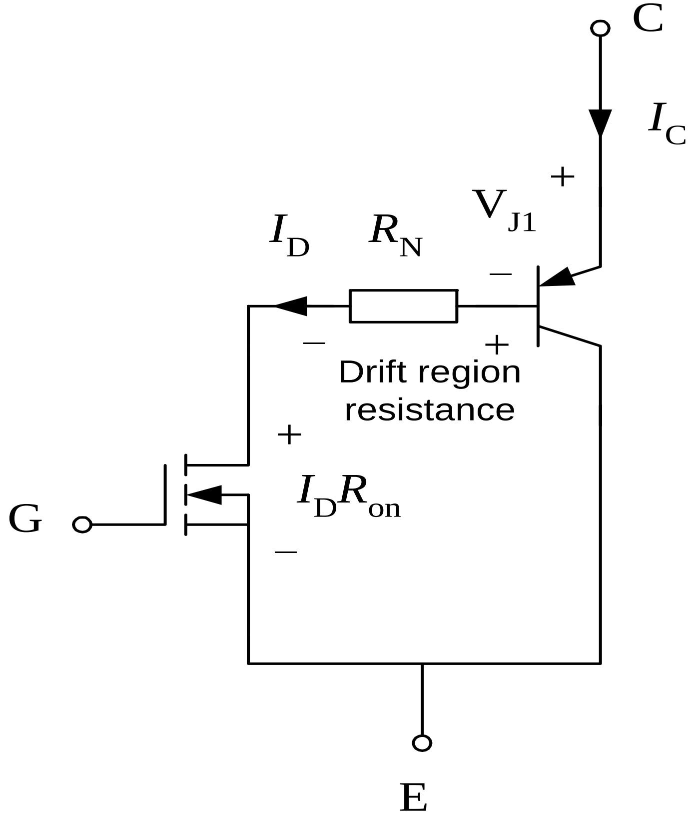


a)

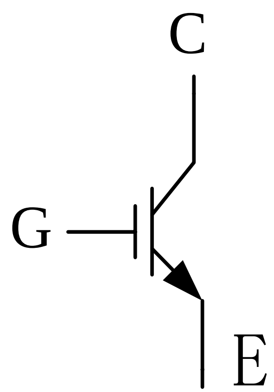
- Also multiple cell structure
- Basic structure similar to power MOSFET, except extra p region
- On-state: minority carriers are injected into drift region, leading to conductivity modulation
- compared with power MOSFET: slower switching times, lower on-resistance, useful at higher voltages (up to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

Equivalent circuit and circuit symbol of IGBT

Equivalent circuit

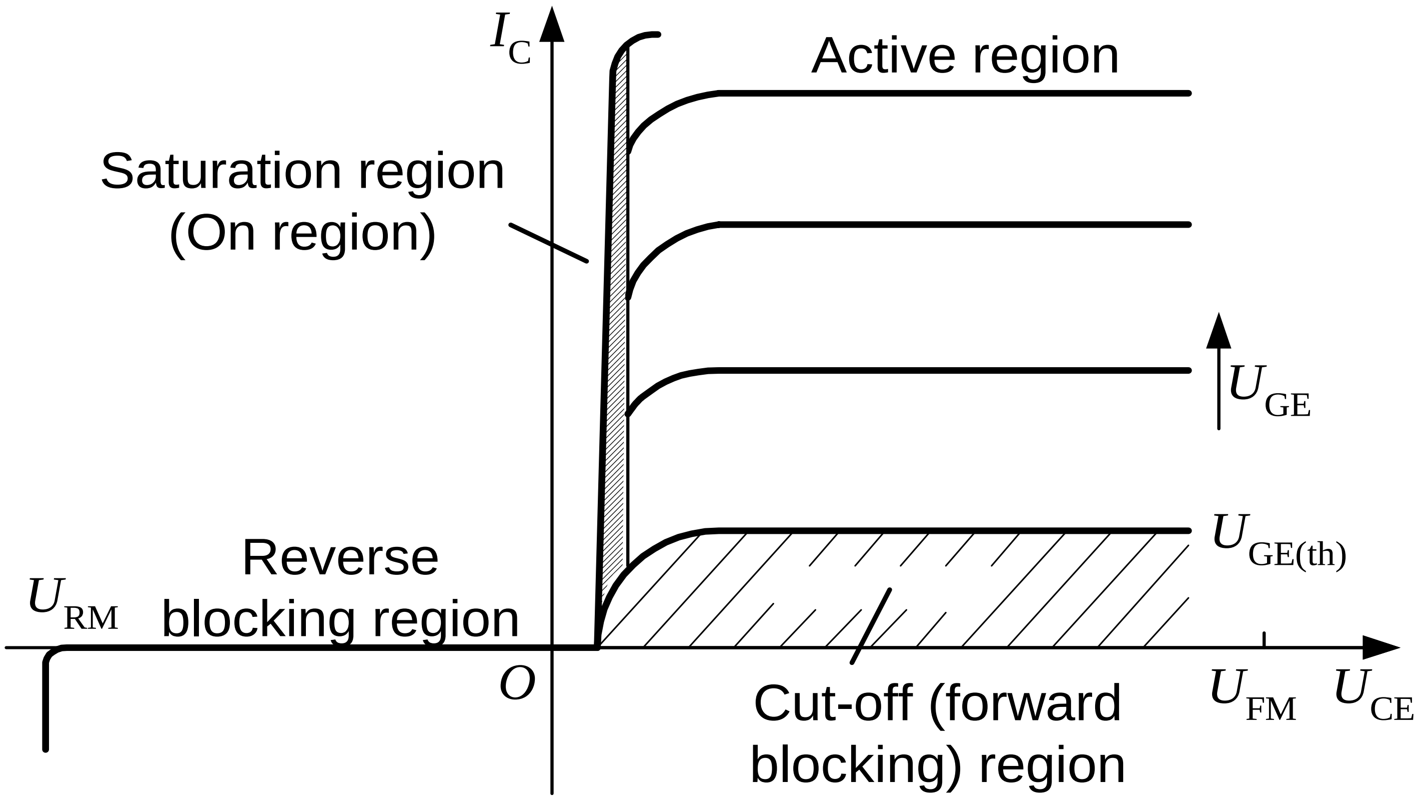


Circuit symbol

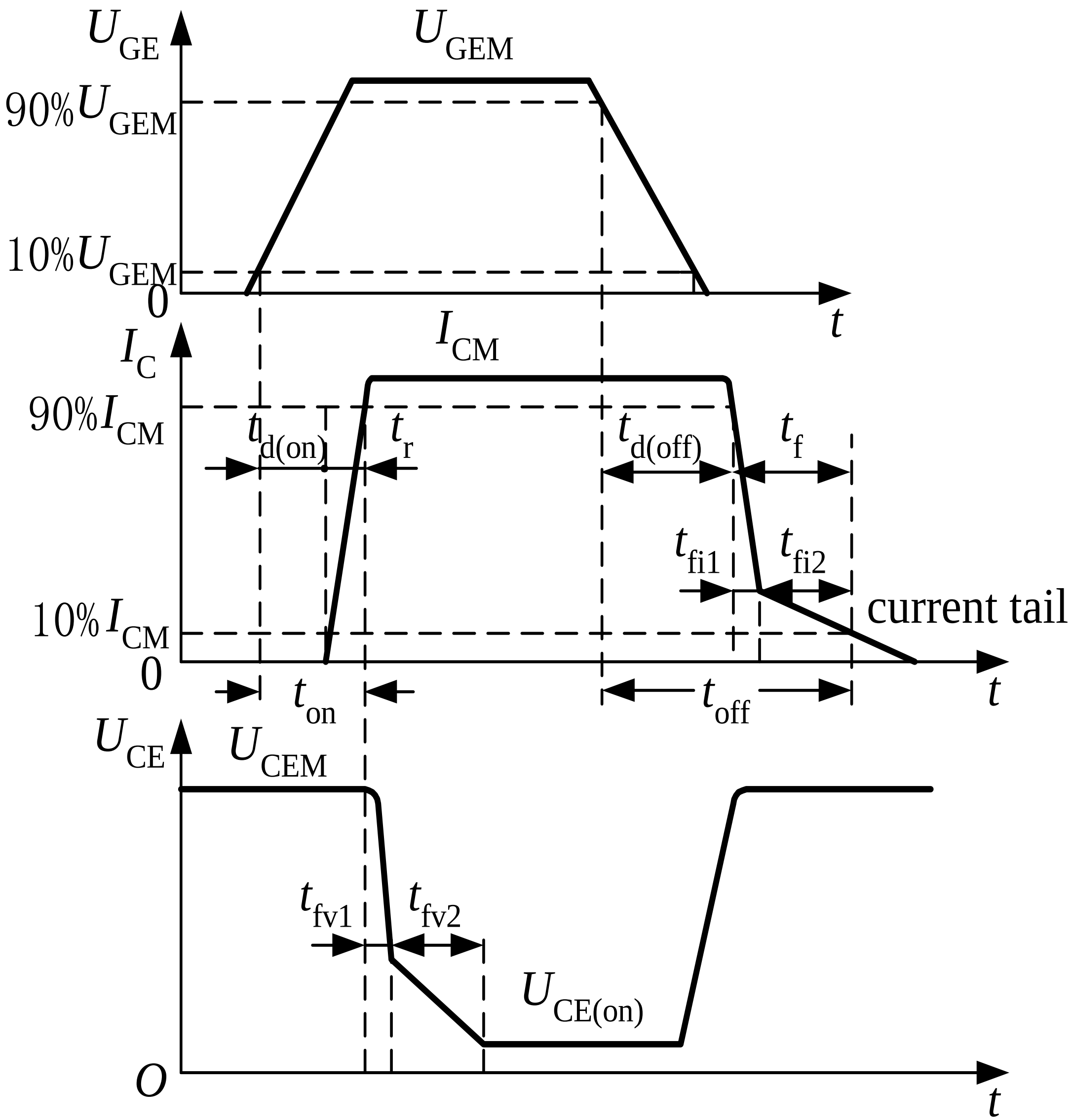


Power Electronics

Static characteristics of IGBT



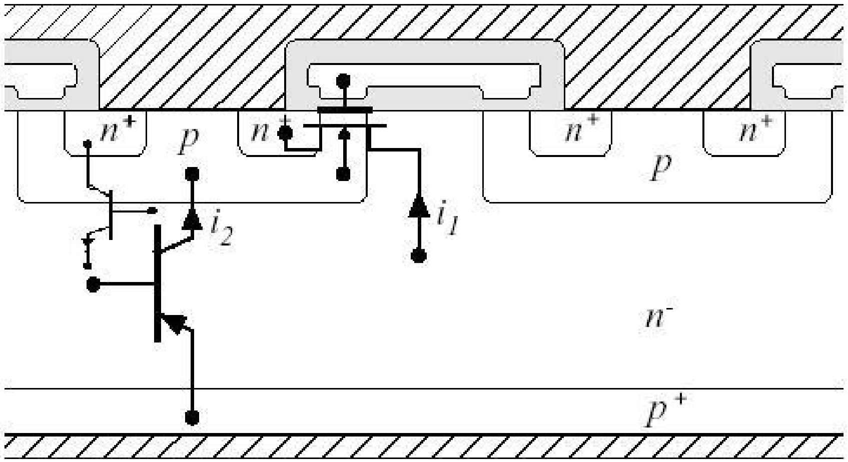
Switching characteristics of IGBT



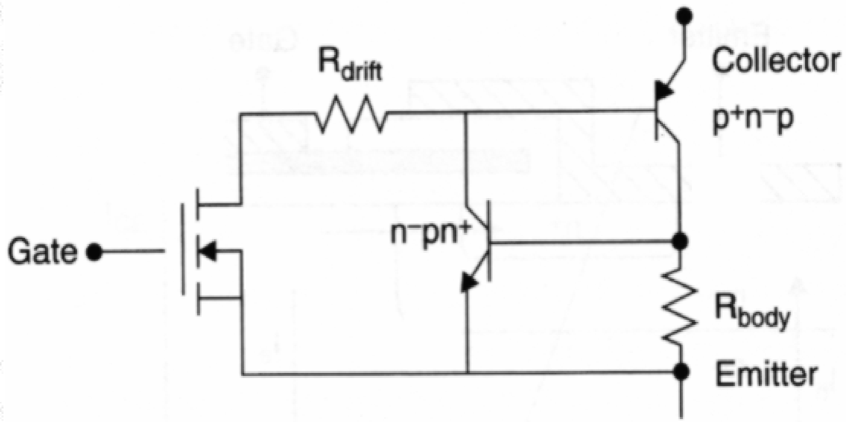
- IGBT turn-on is similar to power MOSFET turn-on
- The major difference between IGBT turn-off and power MOSFET turn-off:
  - There is current tailing in the IGBT turn-off due to the stored charge in the drift region.

Parasitic thyristor and latch-up in IGBT

Location of equivalent devices



Complete IGBT equivalent circuit



- 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

Power Electronics

Examples of commercial IGBT

Part number	Rated max voltage	Rated avg current	V_F (typical)	t_f (typical)
Single-chip devices				
HGTG32N60E2	600V	32A	2.4V	0.62µs
HGTG30N120D2	1200V	30A	3.2A	0.58µs
Multiple-chip power modules				
CM400HA-12E	600V	400A	2.7V	0.3µs
CM300HA-24E	1200V	300A	2.7V	0.3µs

Power Electronics

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

Power Electronics

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

- 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)

Power Electronics

MOS controlled thyristor—MCT

- Essentially a GTO with integrated MOS-driven gates controlling both turn-on and turn-off that potentially will significantly simply 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.

Power Electronics

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 Electronics

PEREC

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

power electronic devices
- Current-driven (current-controlled) devices: thyristor, GTO, GTR
- Voltage-driven (voltage-controlled) devices (Field-controlled devices):power MOSFET, IGBT, SIT, SITH, MCT, IGCT

power electronic devices
- Pulse-triggered devices: thyristor, GTO
- Level-sensitive (Level-triggered) devices: GTR,power MOSFET, IGBT, SIT, SITH, MCT, IGCT

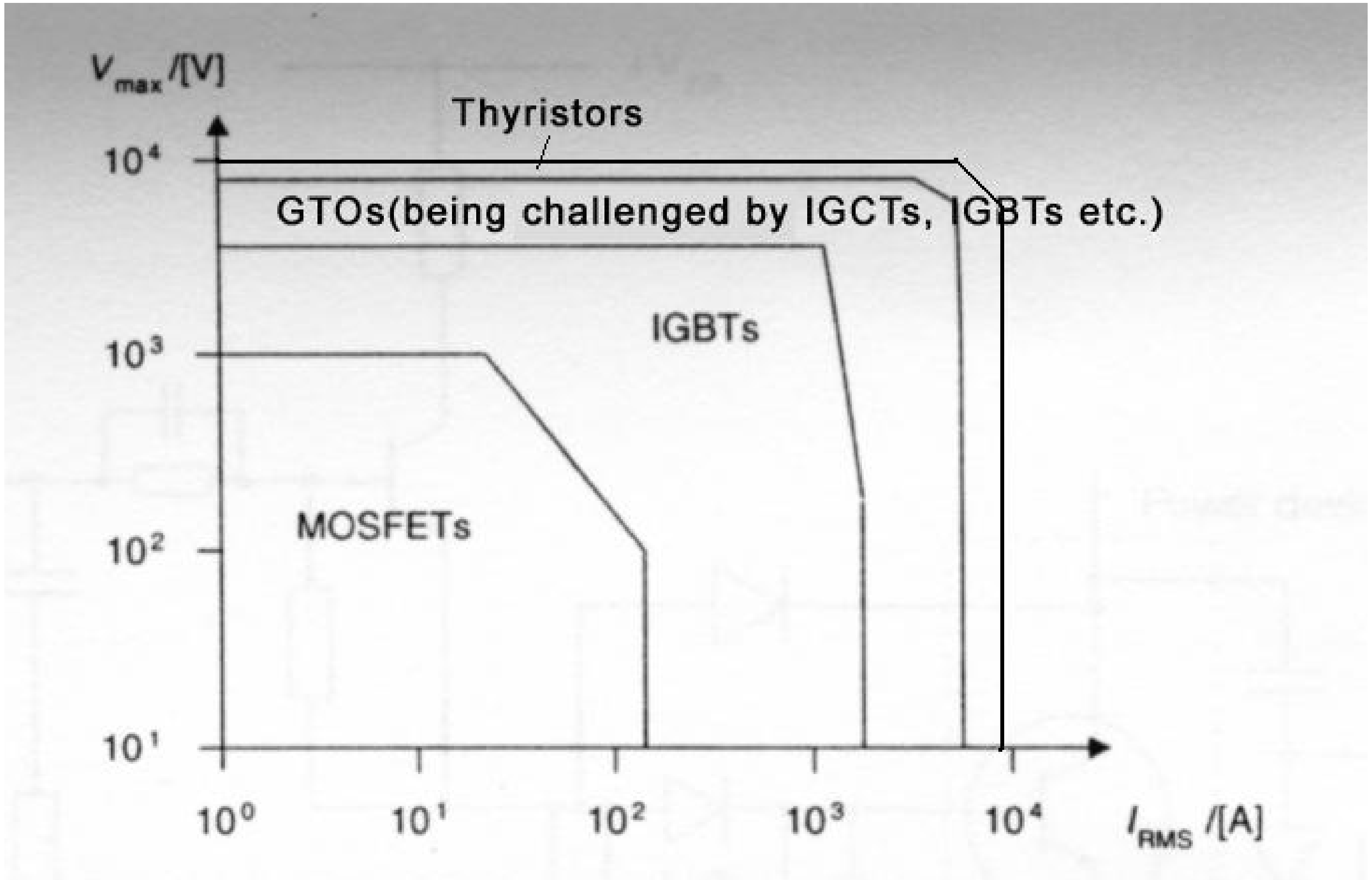
power electronic devices
- Uni-polar devices (Majority carrier devices): SBD, power MOSFET, SIT
- Bipolar devices (Minority carrier devices): ordinary power diode, thyristor, GTO, GTR, IGCT, IGBT, SITH, MCT
- Composite devices: IGBT, SITH, MCT

Power Electronics

Power Electronics

Comparison of the major types of devices

- Power-handling capability



Comparison of the major types of devices

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