Power Semiconductor Devices

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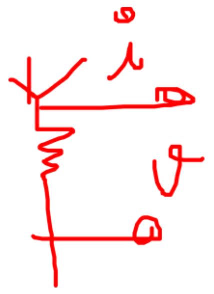
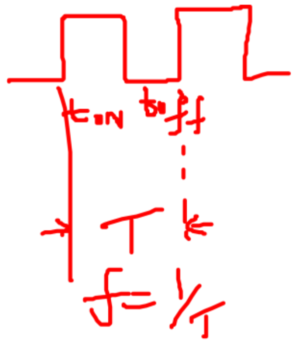
Introduction

- Power Semiconductor Electronics
  - High power handling capabilities and switching speed
  - Used as switches to turn ON and turn OFF high voltage high current circuits
  - Capable of handling current in the order of kA and voltage in the order of kV
- **Non-controllable devices : Diode**
  - ON and OFF states controlled by the power circuit
- **Semi-controllable switches: SCR (Thyristor Family)**
  - Latched ON by a control signal but must be turned OFF by the power circuit
- **Fully-Controllable switches : Power BJT, Power MOSFET, IGBT,**
  - GTO: **gate turn-off thyristor**, IGCT: integrated gate-commutated thyristor (Both are Thyristor Family)
  - Turned ON and OFF by control signals

Power Semiconductor Devices: Required Features

- Power rating:
  - Increased Voltage, Current ratings(High Power)
- Conduction loss:
  - Minimum Forward voltage drop and on state resistance
- Frequency of operation:
  - Switching speed
    - Emission and recombination of charge carriers
- Cost and Size Reduction





Power Semiconductor Devices: Required Features

- Power rating: high
  - Increased Voltage, Current ratings
- Conduction loss: min
  - Minimum Forward voltage drop, On state resistance
- Frequency of operation: high
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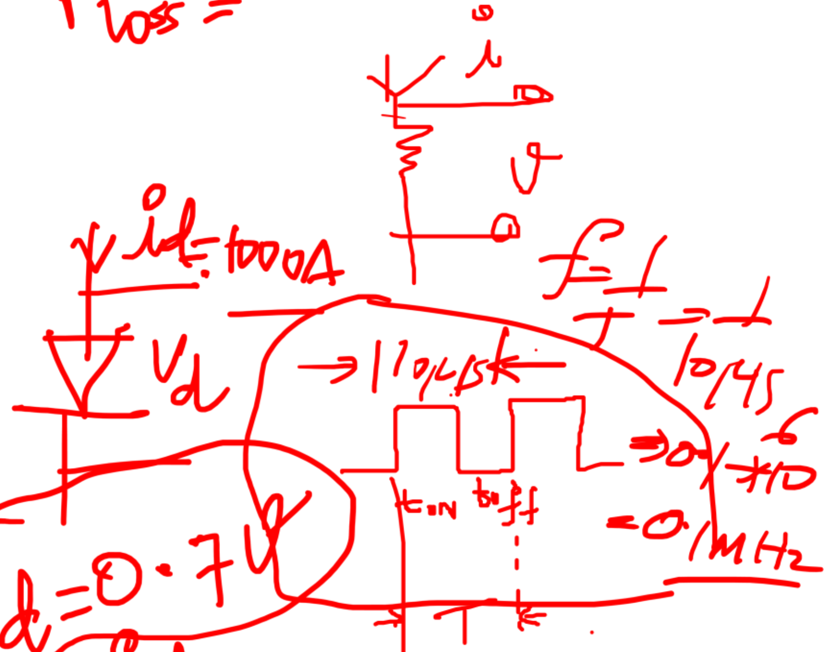
$P_{loss} = v * i$



$f = \frac{1}{T} = \frac{1}{10\mu s} = 0.1 \times 10^{6} = 0.1 MHz$

$V_d = 0.7V$

$P_{loss} = V_d * i_d = 0.7 * 1000 A = 700W$

$f = 1/T$

$f \uparrow \quad T \downarrow$

$E_{loss} = P * t = 700 * 10^{-5} = 7000$

Power semiconductor devices classification

- The power semiconductor devices can be classified on the basis of:
  - 1. Uncontrolled turn-on and turn-off (Diode)
  - 2. Controlled turn-on and uncontrolled turn-off (SCR, TRIAC)
  - 3. Controlled turn-on and controlled turn-off (BJT, MOSFET, COOLMOS, IGBT, SIT, GTO, IGCT, MCT, SITH)
  - 4. Continuous gate signal requirement (BJT, MOSFET, COOLMOS, IGBT, SIT)

N- Type semiconductor

n-type material: If pure silicon is doped with a small amount of a Group V element, such as phosphorus, arsenic, or antimony, each atom of the *dopant* forms a covalent bond within the silicon lattice, leaving a loose electron. These loose electrons greatly increase the conductivity of the material. When the silicon is lightly doped with an impurity such as phosphorus, the doping is denoted as *n-doping* and the resultant material is referred to as *n-type semiconductor*. When it is heavily doped, it is denoted as *n+* doping and the material is referred to as *n+-type semiconductor*.

p- Type semiconductor

p-type material: If pure silicon is doped with a small amount of a Group III element, such as boron, gallium, or indium, a vacant location called a *hole* is introduced into the silicon lattice. Analogous to an electron, a hole can be considered a mobile charge carrier as it can be filled by an adjacent electron, which in this way leaves a hole behind. These holes greatly increase the conductivity of the material. When the silicon is lightly doped with an impurity such as boron, the doping is denoted as *p-doping* and the resultant material is referred to as *p-type semiconductor*. When it is heavily doped, it is denoted as $p+$ doping and the material is referred to as $p+$*-type semiconductor*.

Power Diodes

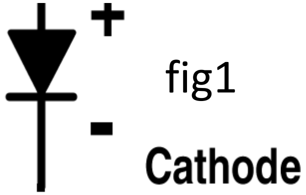


fig1

- A power diode has a P-I-N structure as compared to the signal diode having a P-N structure.
- I (in P-I-N) stands for intrinsic semiconductor: Lightly dopped
  - intrinsic semiconductor layer to bear the high-level reverse voltage as compared to the signal diode (n- , drift region layer shown in Fig.2).
  - the drawback of this intrinsic layer : it adds noticeable resistance during forward-biased condition.
  - Thus, power diode requires a proper cooling arrangement for handling large power dissipation.
- Power diodes are used in numerous applications including rectifier, voltage clamper, voltage multiplier and etc.
- Power diode symbol is the same as of the signal diode as shown in Fig.1.

fig2

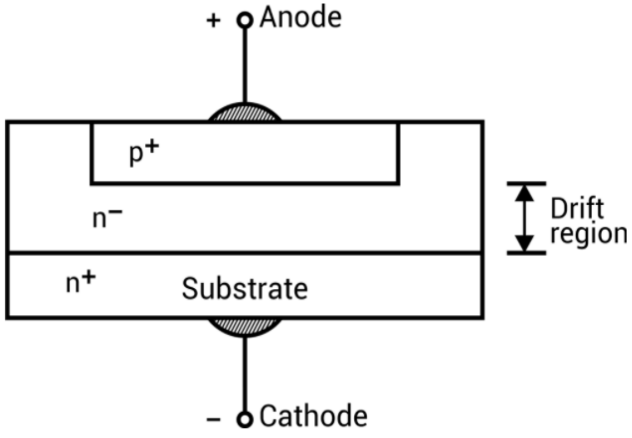


Figure 2. Structure of Power Diode

Fig.3

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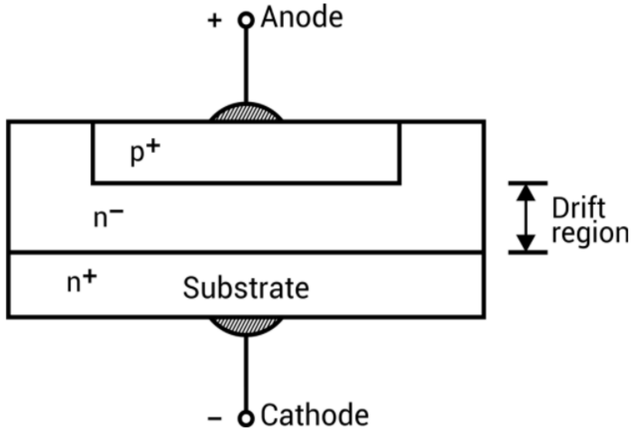

fig2

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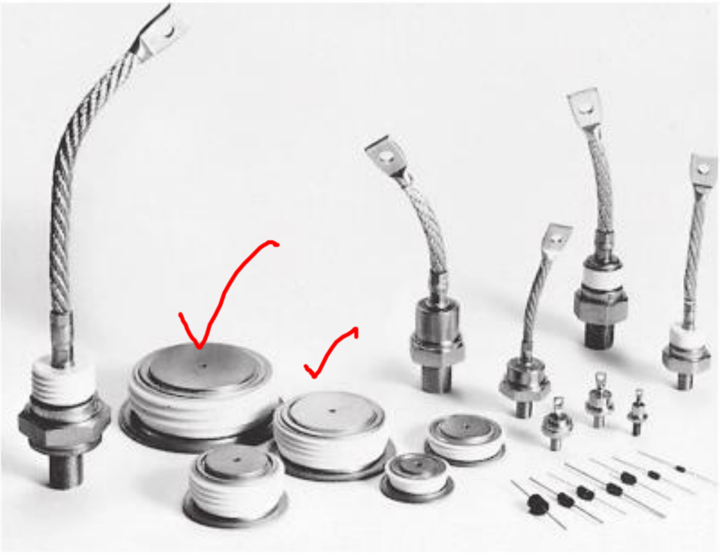
Fig.3



PIN

- P-layer: Heavily doped with acceptor impurities to create a positive charge carrier concentration.
- Intrinsic layer (I-layer): A wide, undoped region that increases the depletion region width.
- N-layer: Heavily doped with donor impurities to create a negative charge carrier concentration

Forward Bias

- When an external voltage holds the p-type material at a higher potential than the n-type material, we say that the p-n junction diode is under forward bias.

Reverse Bias

- When Cathode is positive with respect to anode
  - Breakdown in a diode occurs when the reverse voltage across the diode exceeds a critical threshold, causing a significant increase in reverse current.
  - This phenomenon can happen due to two primary mechanisms
    - Avalanche Breakdown
    - Zener Breakdown

Reference

- As shown in the figure, there is heavily doped n+ substrate with doping level of $10^{19}/cm^3$. This substrate forms a *cathode of the power diode*.
- On n+ substrate, lightly doped n- epitaxial layer is grown.
- This layer is also known as *drift region.*
- The doping level of n- layer is about $10^{14}/cm^3$.
- The the PN junction is formed by diffusing a heavily doped p+ region.
- This p+ region forms *anode of the diode*.
- The doping level of p+ region is about $10^{19}/cm^3$.
- The thickness of p+ region is 10µm. The thickness of n^+ substrate is 250µm.
- **The thickness of n- drift region depends upon the breakdown voltage of the diode.**
- **The drift region determines the reverse breakdown voltage of the diode.**
- Its function is to absorb the depletion layer of the reverse biased p+n- junction.
- As it is lightly doped, it will add significant ohmic resistance to the diode when it is forward biased.
- For higher breakdown voltages, the drift region is wide.
- The n- drift region is absent in low power signal diodes
- When the power diode is forward biased (anode is made positive with respect to cathode), the holes will be injected from the p+ region into the drift region.
- Some of the holes combine with the electrons in the drift region.
- Since injected holes are large, they attract electrons from the n+ layer.
- Thus holes and electrons are injected in the drift region simultaneously.
- Hence resistance of the drift region reduces significantly.
- Thus diode current goes on increasing, ***but drift region resistance remains constant***.
- So on-state losses in the diode are reduced. This phenomenon is called as *Conductivity modulation* of drift region.

Characteristics of Power Diode

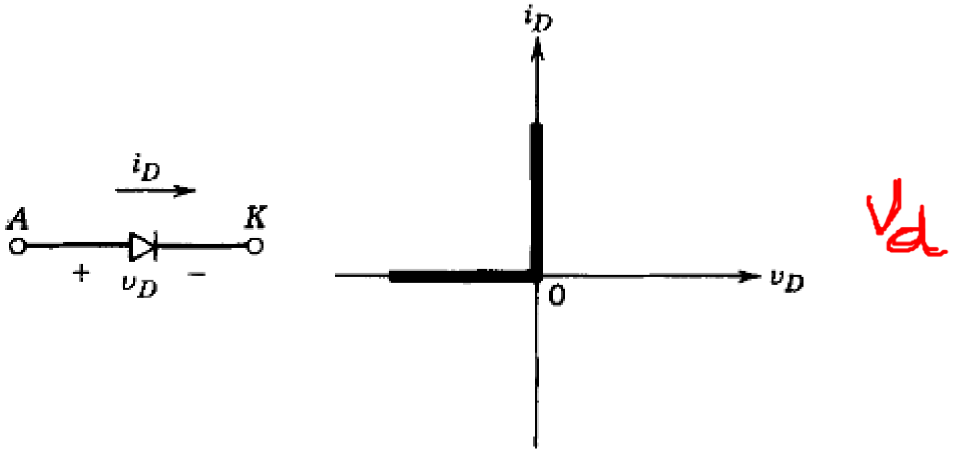
- Any semiconductor device can have 2 type of characteristics
  - Static characteristics
    - describe the steady-state behavior of a semiconductor device when a constant voltage or current is applied.
    - Voltage across and current through
  - Dynamic characteristics
    - describe how the device responds to changes in voltage or current over time, particularly during switching or under high-frequency signals.
    - High-frequency Pulse behavior.

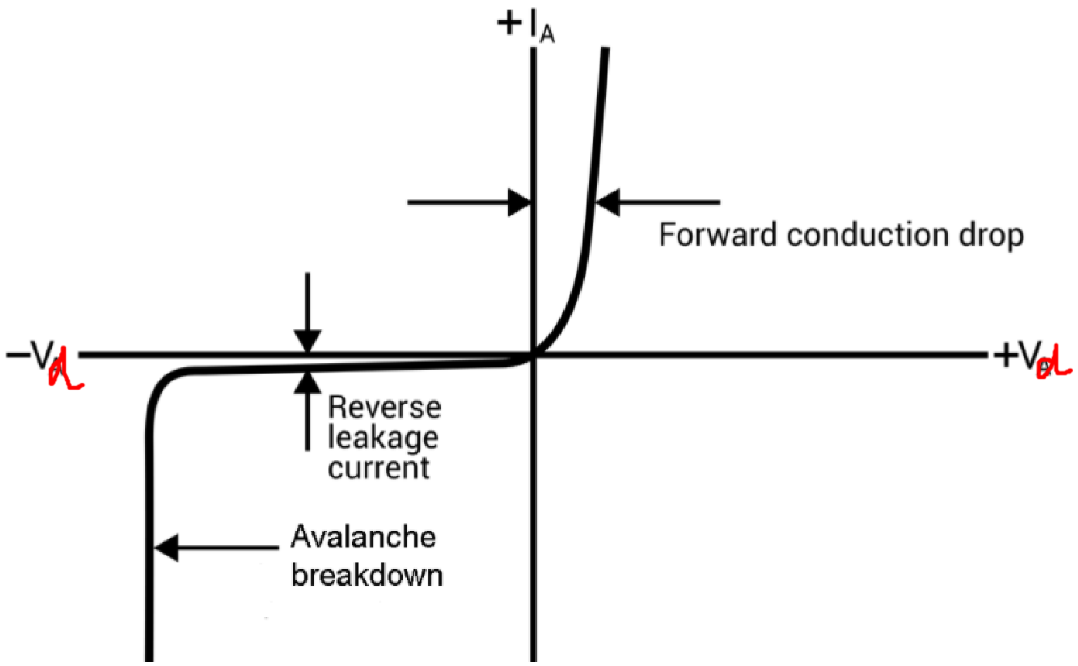
- The two types of characteristics of a power diode are
  - (i) Amp-volt characteristics *(i-v characteristics) :*
  - (ii) Turn-off characteristics *(or reverse-recovery characteristics)*

Amp-volt/ Static/*i-v characteristics)*

- Cut-in voltage is the value of the minimum voltage for **V_A** (anode voltage) to make the diode works in forward conducting mode.
- *Cut-in voltage of signal diode is 0.7 V* ***while in power diode it is 1 V.***
- So, its typical forward conduction drop is larger.
- Under forward-bias condition, signal diode current increases exponentially and then increases linearly.
- **In the case of the power diode, it almost increases linearly with the applied voltage as all the layers of P-I-N remain saturated with minority carriers under forward bias.**
- Thus, a high value of current results in voltage drop which mask the exponential part of the curve.
- In reverse-bias condition, small leakage current flows due to minority carriers until the avalanche breakdown appears as shown in Fig. 3.

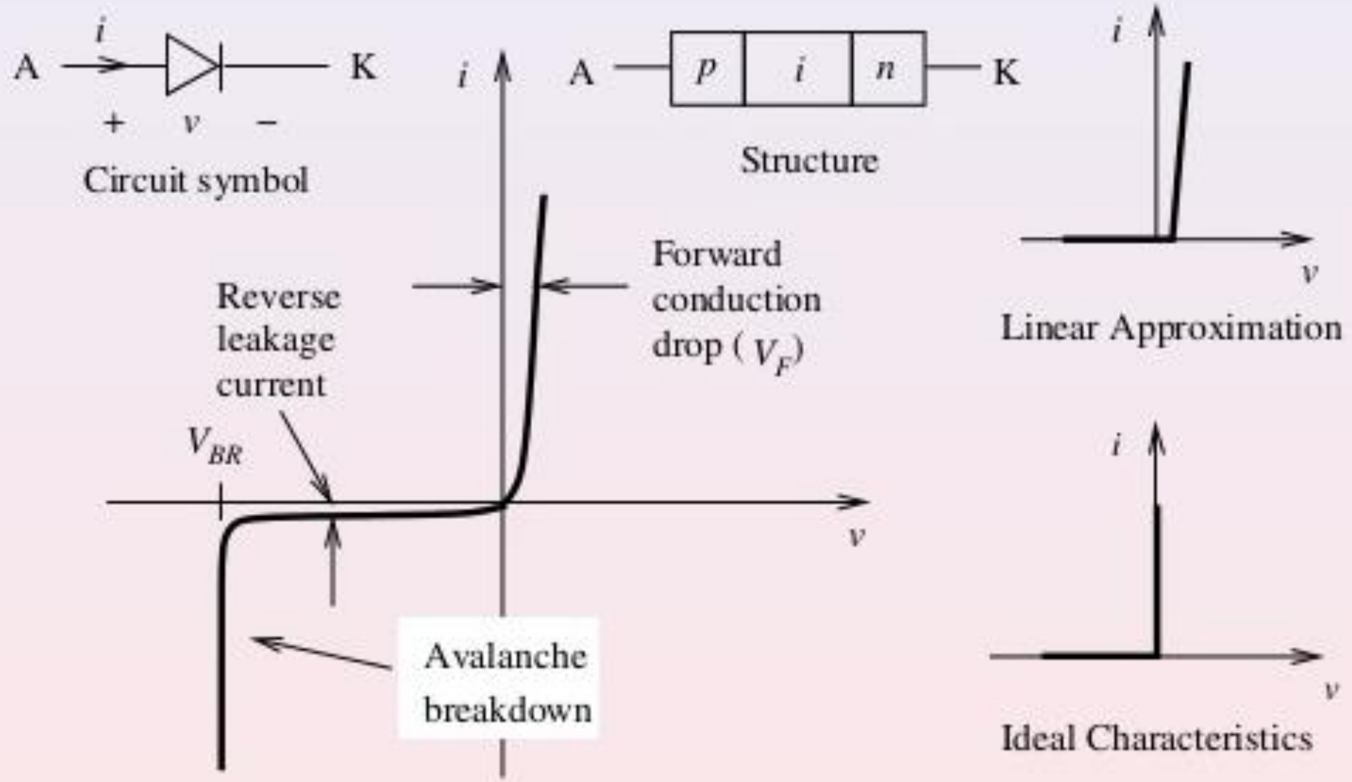
Ideal diode chara





Actual power diode chara

Static Characteristics Power Diodes



Reverse recovery/Dynamic Characteristics

- imagine that one reverse biases this voltage by inverting the polarities connected to the terminals of the diode.
- Ideally, the act of doing so should bring the diode from its ON state to OFF state immediately.
- That is, the diode which is conducting current in its forward direction is expected to stop conducting instantly.
- ***However, practically, this cannot be experienced as the flow of majority charge carriers through the diode does not cease right at the moment of reversing the bias.***
- They will, in fact, take a finite amount of time before stopping and this time is known as reverse recovery time of the diode.

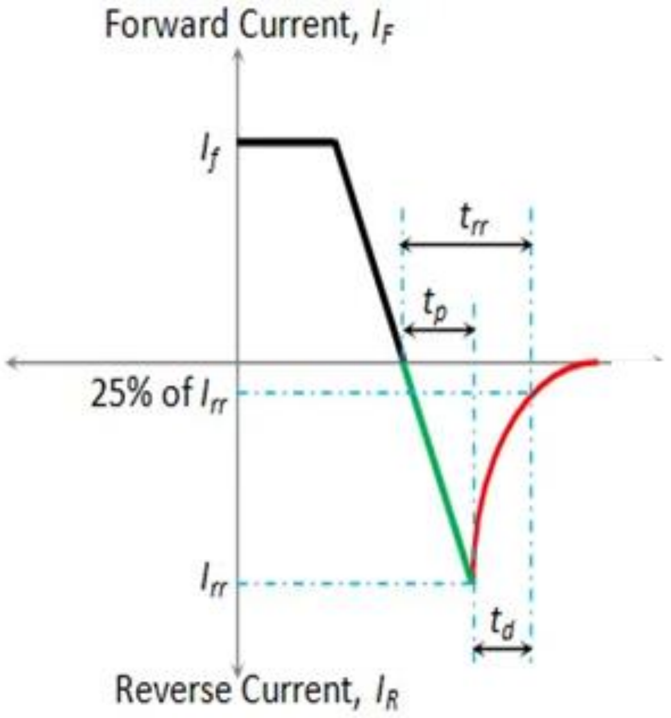


Figure 1 Reverse Recovery Characteristics of the Diode

- During this reverse recovery time of the diode, one can see that there will be fairly large amount of current flowing through the diode, but in the opposite direction (Irr in Figure 1).
- However its magnitude reduces and gets saturated to a value of reverse saturation current, once the time-line crosses reverse recovery time (trr) of the diode.
- Graphically one can describe the reverse recovery time of the diode as the total time which starts from the instant at which the reverse current starts to flow through the diode to the time instant at which it reaches to zero (or any other pre-defined low level, say 25% of Irr in the figure) while decaying (td), on reaching its negative maxima (tp).

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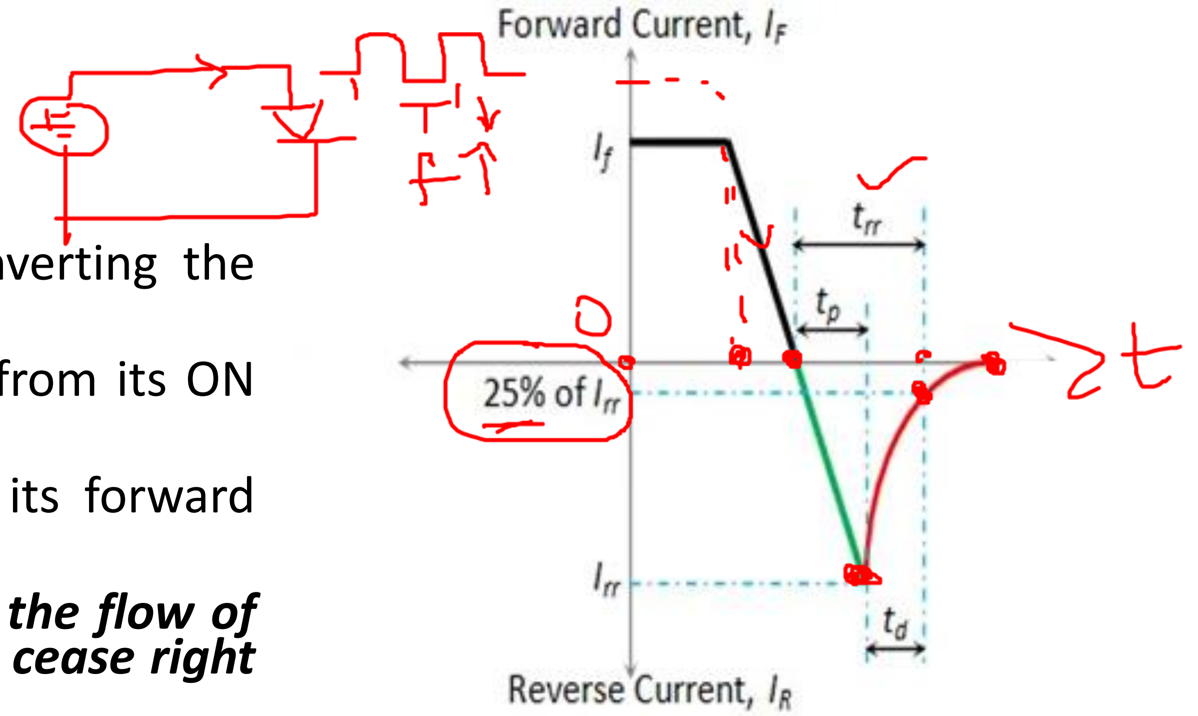

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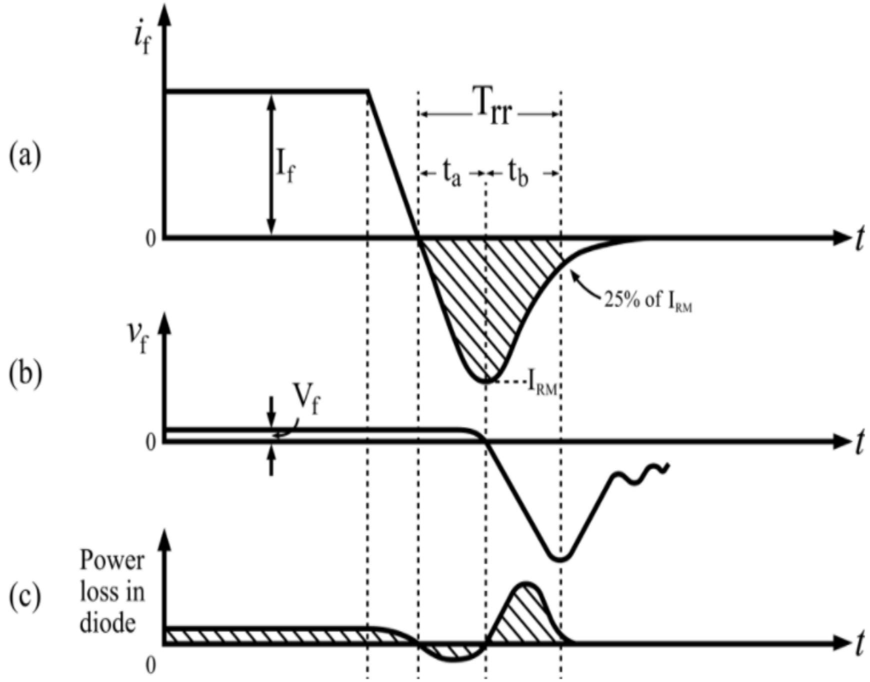
Reverse recovery/Dynamic Characteristics

- After the forward diode comes to null, the diode continues to conduct in the opposite direction because of the presence of stored charges in the depletion layer and the p or n-layer.
- The diode current flows for a reverse-recovery time T_{rr}.
- It is the time between the instant forward diode current becomes zero and the instant reverse-recovery current decays to 25 % of its reverse maximum value.
- Time t_a : Charges stored in the depletion layer removed.
- Time t_b : Charges from the semiconductor layer is removed.
- Shaded area in Fig 4.a represents stored charges Q_R which must be removed during reverse-recovery time t_{rr}.
- Power loss across diode = $v_f * i_f$ (shown in Fig. 4.c)
- As shown, major power loss in the diode occurs during the period t_b.



Turn-Off Characteristics of Power Diode: a) Variation of Forward Current i_f ; b) Variation of Forward Voltage Drop v_f ; c) Variation of Power Loss

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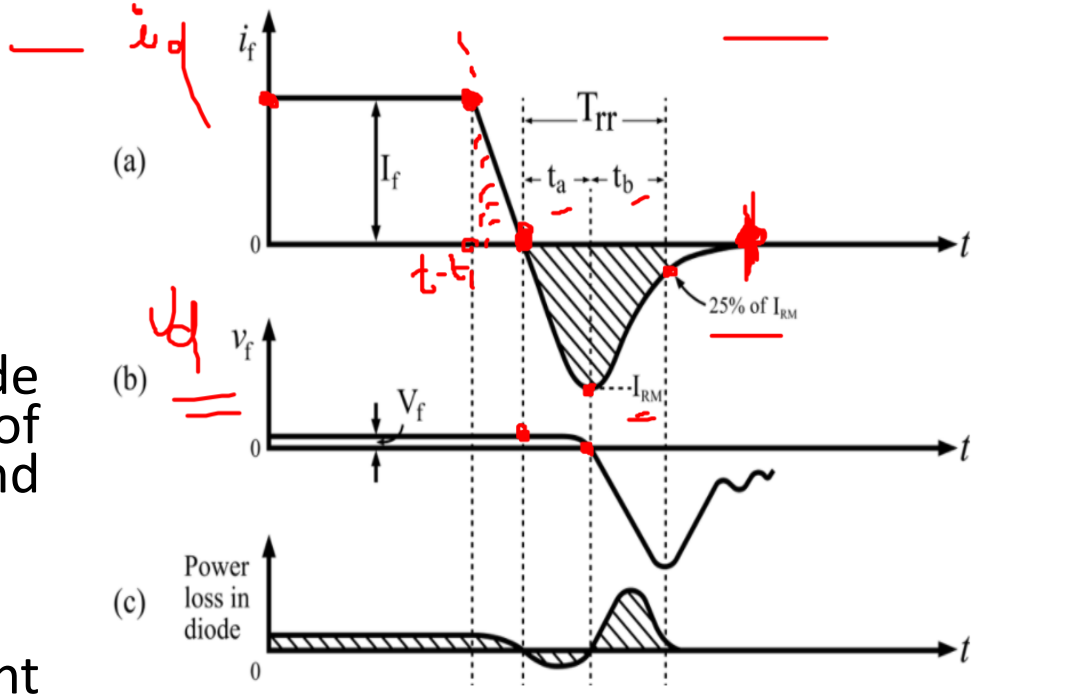
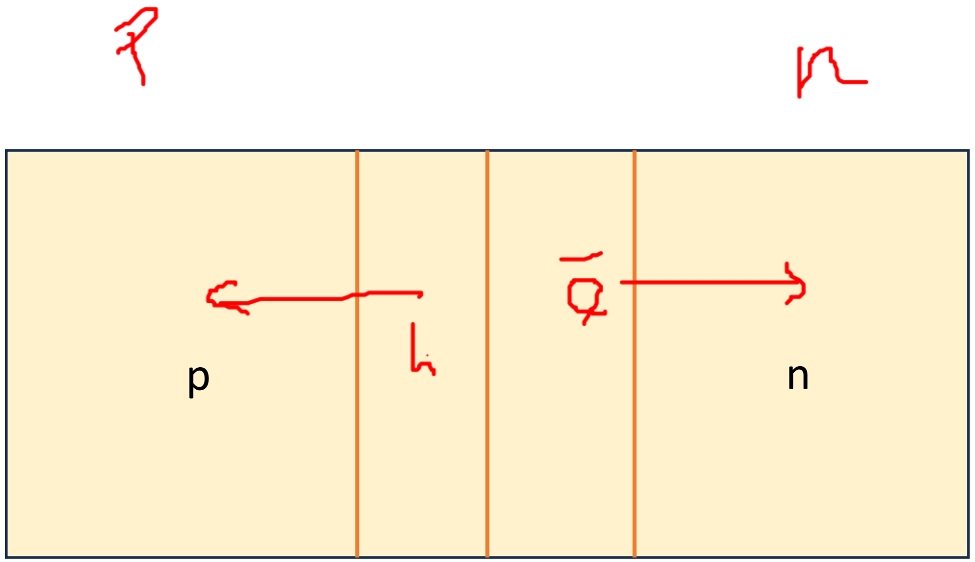


Turn-Off Characteristics of Power Diode: a) Variation of Forward Current i_f ; b) Variation of Forward Voltage Drop v_f ; c) Variation of Power Loss

$P_{loss} = V_d * i_d$

$\frac{di}{dt} \to 0$



p
n

Reverse recovery Characteristics

The current in a forward-biased junction diode is due to the net effect of majority and minority carriers. Once a diode is in a forward conduction mode and then its forward current is reduced to zero (due to the natural behavior of the diode circuit or application of a reverse voltage), the diode continues to conduct due to minority carriers that remain stored in the *pn*-junction and the bulk semiconductor material. The minority carriers require a certain time to recombine with opposite charges and to be neutralized. This time is called the *reverse recovery time* of the diode.

During the reverse recovery time t_{rr}, the diode behaves effectively as a short circuit and is not capable of blocking reverse voltage, allowing reverse current flow, and then suddenly disrupting the current. Parameter t_{rr} is important for switching applications.

This reverse-recovery (negative) current is required to sweep out the excess carriers in the diode and allow it to block a negative polarity voltage.

The reverse-recovery current can lead to overvoltages in inductive circuits.

$$V_L = L \times \frac{di}{dt}$$

Importance of t_{rr}

- Greater is the reverse recovery time; slower will be the diode and vice-versa.
- ***Thus the diodes with lesser reverse recovery time are preferred, especially when the requirement is of high switching speed.***
- Moreover, during this time interval, there will be a significant amount of current-flow back towards the supply which provides power to the diode.
- Hence the reverse recovery time of the diode is an important design factor which we should consider while designing the power supplies

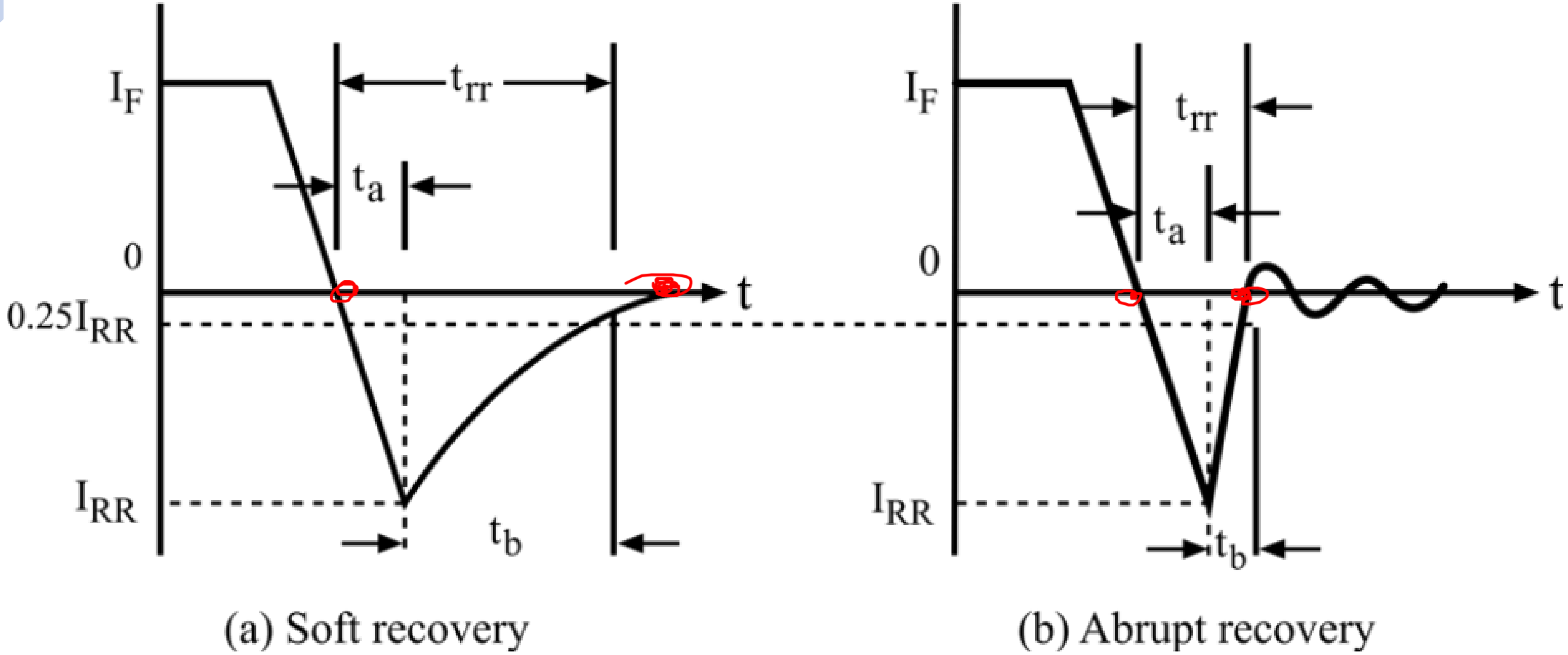
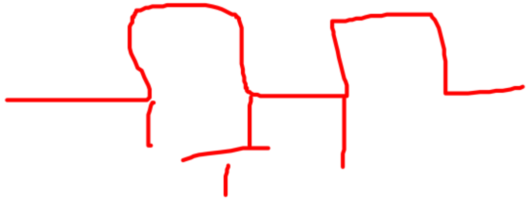


Figure 5. Reverse-Recovery Characteristics for Power Diode

Depending on the recovery characteristics and manufacturing techniques, the power diodes can be classified into the following three categories:

1. Standard or general-purpose diodes
2. Fast-recovery diodes
3. Schottky diodes



Rectifier 50Hz → 20ms

General-Purpose Diodes

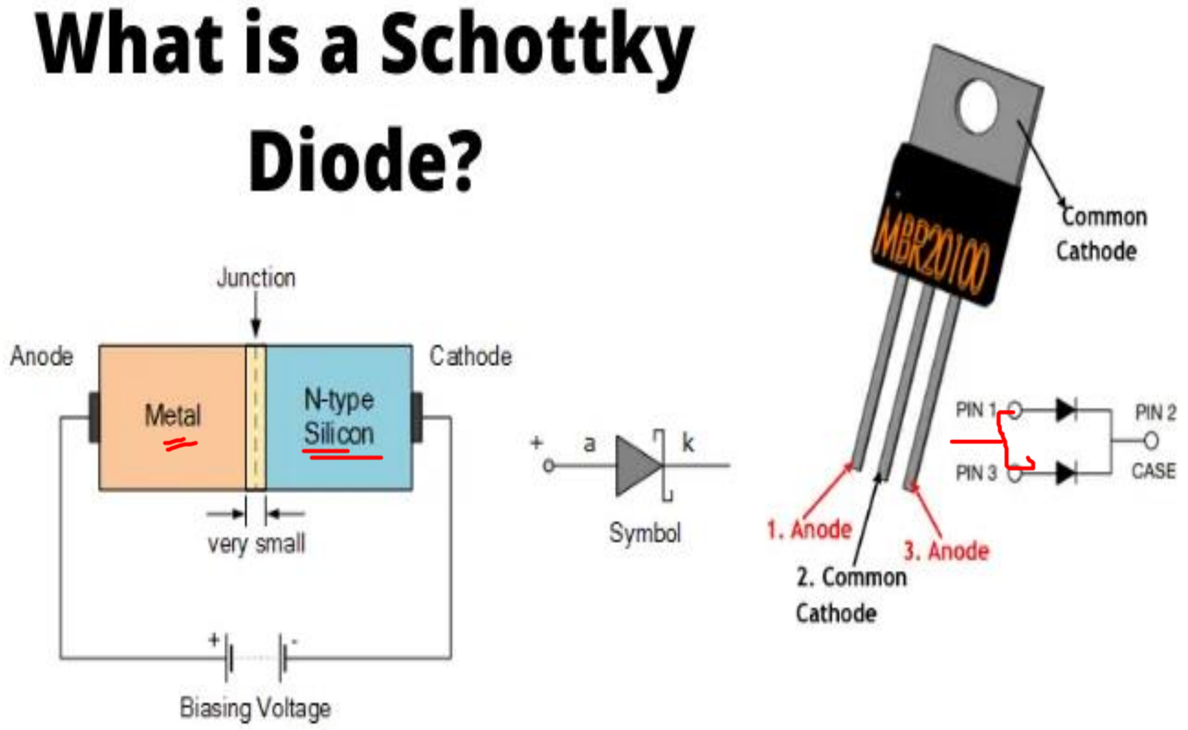
The general-purpose rectifier diodes have relatively high reverse recovery time, typically 25 μs; and are used in low-speed applications, where recovery time is not critical (e.g., diode rectifiers and converters for a low-input frequency up to 1-kHz applications and line-commutated converters). These diodes cover current ratings from less than 1 A to several thousands of amperes, with voltage ratings from 50 V to around 5 kV. These diodes are generally manufactured by diffusion. However, alloyed types of rectifiers that are used in welding power supplies are most cost-effective and rugged, and their ratings can go up to 1500 V, 400 A.

$t_{rr} \downarrow$

Fast-Recovery Diodes

The fast-recovery diodes have low recovery time, normally less than 5 μs. They are used in dc–dc and dc–ac converter circuits, where the speed of recovery is often of critical importance. These diodes cover current ratings of voltage from 50 V to around 3 kV, and from less than 1 A to hundreds of amperes.

Schottky diodes.



- These diodes are used where a low forward voltage drop (typically 0.3 V) is needed in very low output voltage circuits.
- These diodes are limited in their blocking voltage capabilities to 50- 100 V.

. The current ratings of Schottky diodes vary from 1 to 400 A. The Schottky diodes are ideal for high-current and low-voltage dc power supplies. However, these diodes are also used in low-current power supplies for increased efficiency.

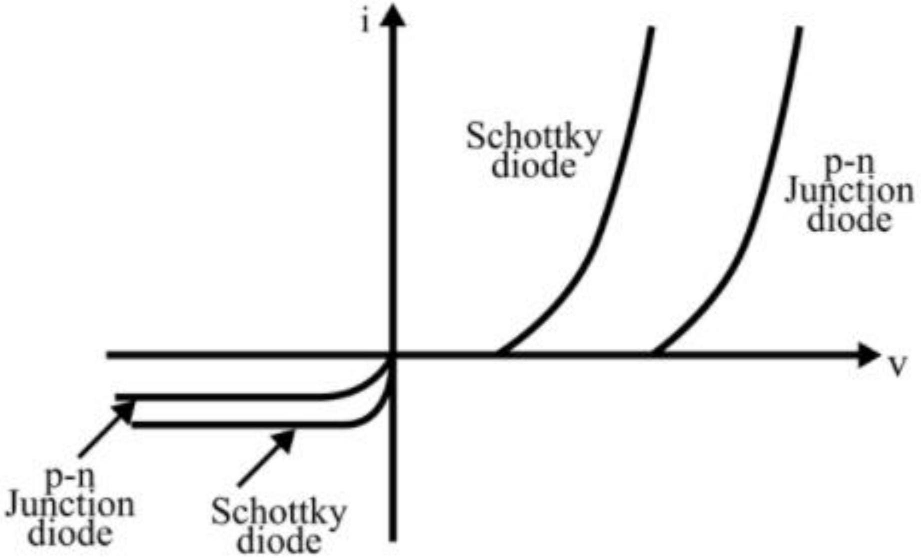
Schottky Diode:

- It has an aluminum-silicon junction where the silicon is an n-type.
- As the metal has no holes, there is no stored charge and no reverse-recovery time.
- Therefore, there is only the movement of the majority carriers (electrons) and the turn-off delay caused by recombination process is avoided.
- It can also switch off much faster than a p-n junction diode.
- As compared to the p-n junction diode it has:

    (a) Lower cut-in voltage

    (b) Higher reverse leakage current

    (c) Higher operating frequency
- Application: high-frequency instrumentation and switching power supplies.



High bandgap devices

Silicon carbide (SiC) (compound material in Group IV of the periodic table) is a promising new material for high-power/high-temperature applications [9]. SiC has a high bandgap, which is the energy needed to excite electrons from the material's valence band into the conduction band. Silicon carbide electrons need about three times as much energy to reach the conduction band as compared to silicon. As a result, SiC-based devices withstand far higher voltages and temperatures than their silicon counterparts. Silicon devices, for example, can't withstand electric fields in excess of about 300 kV/cm. Because electrons in SiC require more energy to be pushed into the conduction band, the material can withstand much stronger electric fields, up to about 10 times the maximum for silicon. As a result, an SiC-based device can have the same dimensions as a silicon device but can withstand 10 times the voltage. Also, an SiC device can be less than a tenth the thickness of a silicon device but carry the same voltage rating. These thinner devices are faster and have less resistance, which means less energy is lost to heat when a silicon carbide diode or transistor is conducting electricity.

Wide Band Gap (WBG) Devices

- Wide band gap (WBG) devices are semiconductor devices made from materials with a band gap energy greater than that of traditional silicon ($E_g \sim 1.1 eV$).
- These devices leverage the unique material properties of wide band gap semiconductors like silicon carbide (SiC) and gallium nitride (GaN) to achieve superior performance, especially in power electronics and high-frequency applications.

Key WBG Materials

1. Silicon Carbide (SiC):
   1. Band gap: ~3.26 eV
   2. Applications: High-power and high-voltage devices, e.g., SiC MOSFETs, diodes.
   3. Advantages: High thermal conductivity, high breakdown field, excellent performance in harsh environments.
2. Gallium Nitride (GaN):
   1. Band gap: ~3.4 eV
   2. Applications: High-frequency, high-efficiency power converters, RF amplifiers, and 5G applications.
   3. Advantages: Higher electron mobility than SiC, compact designs, low capacitance.

Benefits of WBG Devices

1. Higher Breakdown Voltage:
   1. WBG materials have a high critical electric field, allowing devices to operate at higher voltages without breakdown.
   2. This is particularly beneficial in high-voltage applications, such as electric vehicles, industrial drives, and grid power converters.
2. Higher Thermal Conductivity:
   1. WBG materials can handle higher temperatures without degradation.
   2. SiC devices, for example, can operate at temperatures above 200°C, reducing cooling requirements.
3. Faster Switching Speeds:
   1. Lower switching losses and faster switching speeds make WBG devices ideal for high-frequency applications.
   2. This improves system efficiency in switching power supplies, inverters, and RF applications.
4. Higher Efficiency:
   1. Reduced conduction and switching losses lead to more efficient power conversion, especially at high voltages and currents.
5. Compact and Lightweight Systems:
   1. WBG devices enable smaller passive components (like inductors and capacitors) due to higher operating frequencies.
   2. This reduces system size and weight, critical for applications like electric vehicles (EVs) and aerospace systems.

A higher Ec allows a semiconductor device to operate at higher voltages without breakdown, enabling compact and efficient designs.Ec is usually measured in **MV/cm** (megavolts per centimeter).

Applications of WBG Devices

1. **Electric Vehicles (EVs):**
   1. SiC-based inverters for traction drives reduce losses and improve battery range.
   2. GaN-based chargers and DC-DC converters enable faster charging.
2. **Renewable Energy:**
   1. SiC devices are widely used in **solar inverters** and **wind turbines**, increasing energy efficiency.
3. **Data Centers:**
   1. WBG devices improve the efficiency of power supplies, reducing energy consumption in data centers.
4. **RF and Microwave Applications:**
   1. GaN devices are ideal for **5G communication**, radar, and satellite systems due to their high-frequency performance.
5. **Aerospace and Defense:**
   1. High thermal stability and reliability of WBG devices are essential for harsh environments.
6. **Industrial Applications:**
   1. SiC devices are used in motor drives, robotics, and industrial automation to improve efficiency.

Differences in Behavior compared to Si devices

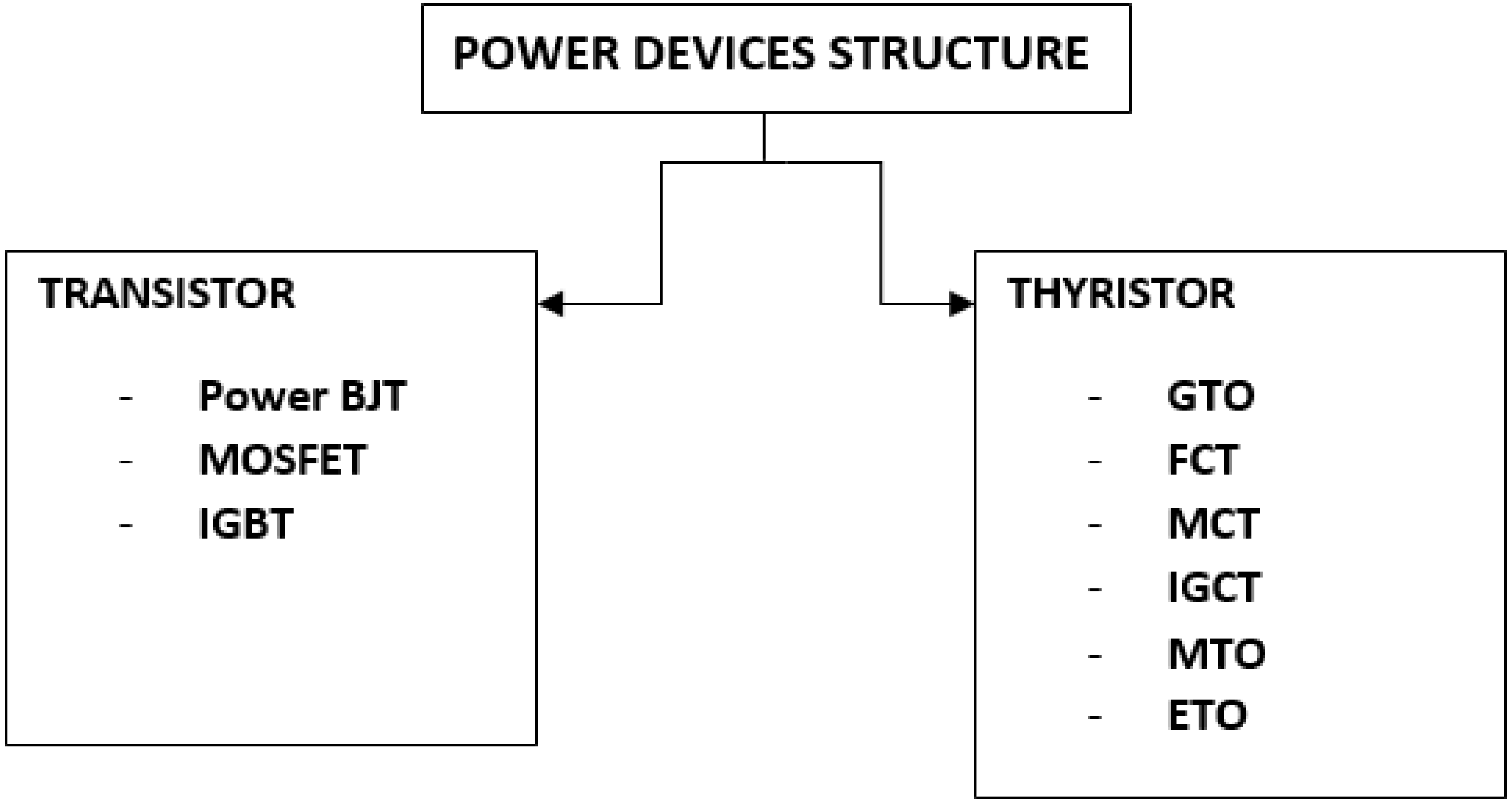
- While the working principle is the same, practical performance and behavior differ due to the superior material characteristics of SiC:

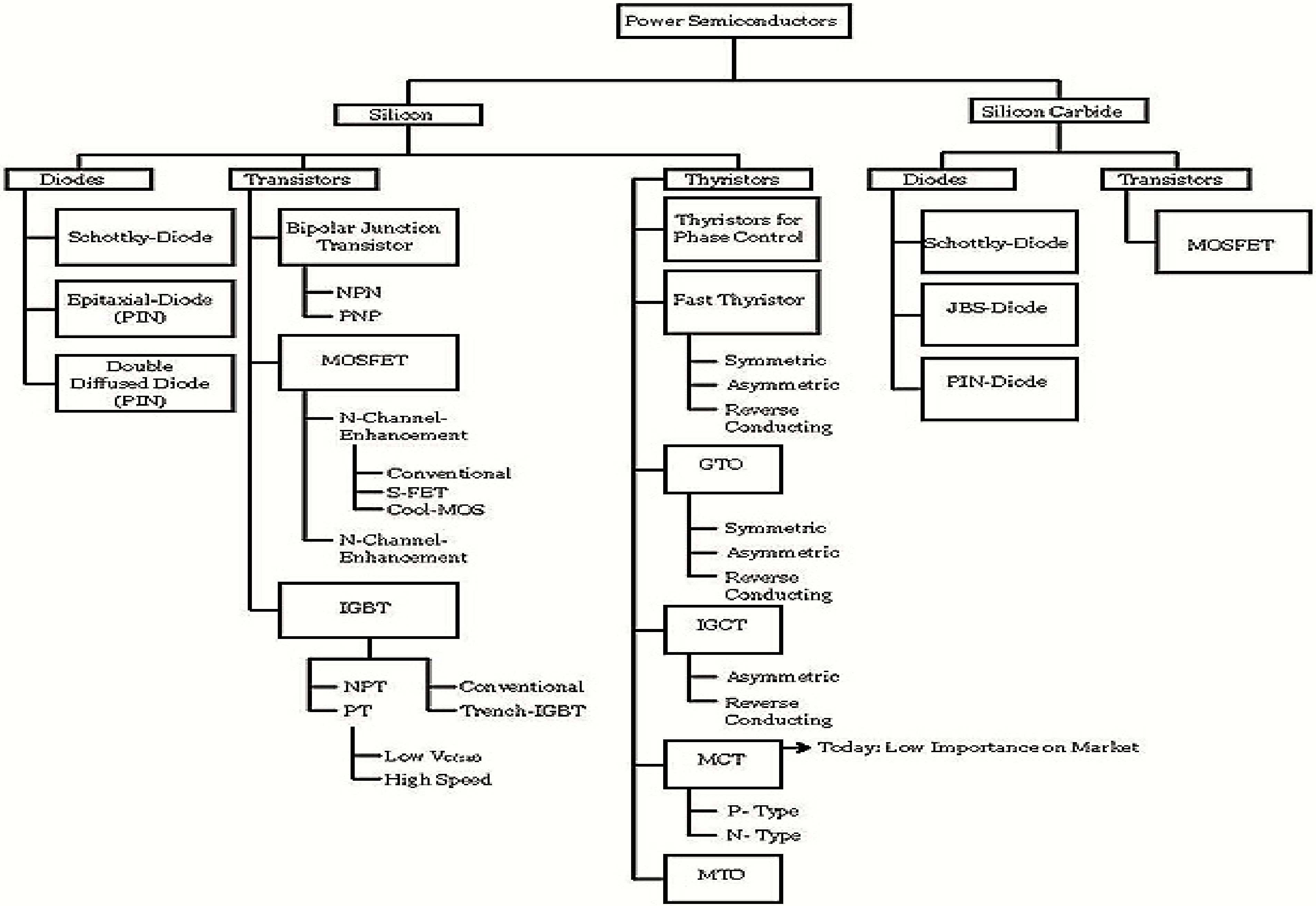
1. Faster Switching:
    1. SiC devices switch faster, requiring careful gate drive circuit design to avoid issues like ringing or overshoot.
2. Higher dv/dt and di/dt Ratings:
    1. SiC devices can tolerate much higher rate of voltage (dv/dt) and rate of current (di/dt) changes, making them suitable for high-speed circuits.
3. Gate Drive Voltage:
    1. SiC devices often require higher gate drive voltages (e.g., 18-20 V for SiC MOSFETs compared to ~10-15 V for Si).
4. Reverse Recovery:
    1. SiC devices, such as SiC Schottky diodes, have negligible reverse recovery losses, making them ideal for high-frequency applications.

Thanks for Listening

Power Semiconductor Devices: Required Features

- 1. On-state characteristics
  - (i) High current rating
  - (ii) Low forward voltage drop
- 2. Off-state characteristics
  - (i) High forward and reverse voltage blocking capability
  - (ii) Low leakage current
- 3. Switching characteristics
  - (i) Low and controllable turn-on and turn-off time
  - (ii) High dv/dt and di/dt rating
  - (iii) Low switching power losses
- 4. Gate characteristics
  - (i) Low gate-drive voltage and low gate-drive current
  - (ii) Low gate drive power
- 5 Fault withstanding capability
  - (i) High value of i2 t to withstand fault current for a long time.
- 6. Thermal stability.
  - (i) Low thermal impedance from the internal junction to the ambient coefficient


POWER DEVICES STRUCTURE
TRANSISTOR
- Power BJT
- MOSFET
- IGBT
THYRISTOR
- GTO
- FCT
- MCT
- IGCT
- MTO
- ETO



Power Semiconductors
Silicon
Silicon Carbide
Diodes
Schottky-Diode
Epitaxial-Diode (PIN)
Double Diffused Diode (PIN)
Transistors
Bipolar Junction Transistor
NPN
PNP
MOSFET
N-Channel-Enhancement
Conventional
S-FET
Cool-MOS
N-Channel-Enhancement
IGBT
NPT
PT
Low Vcesat
High Speed
Conventional
Trench-IGBT
Thyristors
Thyristors for Phase Control
Fast Thyristor
Symmetric
Asymmetric
Reverse Conducting
GTO
Symmetric
Asymmetric
Reverse Conducting
IGCT
Asymmetric
Reverse Conducting
MCT
Today: Low Importance on Market
P- Type
N- Type
MTO
Diodes
Schottky-Diode
JBS-Diode
PIN-Diode
Transistors
MOSFET