Fundamentals of PN Junction Semiconductor Diodes

Text Books

1. Electronic Devices and Circuit Theory

by R Boylestad and L Nashelsky

2. Op-Amps and Linear Integrated Circuits

by Ramakant A. Gayakwad

3. Microelectronic Circuits Analysis and Design

by Muhammad H. Rashid

4. Electronic Principles 7th Edition

by Albert Malvino, David Bates

Topics to be covered:

- Electronics and its purpose
- Semiconductor and its types
- Semiconductor diodes, operation and characteristics
- Static and Dynamic resistance
- Important terminologies, PIV, RRT, etc
- Diode models (equivalent circuits)
- Diode Specification Sheet
- Diode Testing and terminal identification

Electronics and its purpose:

- Sub-branch of electrical engineering.
- Creation, manipulation and control of conduction in semiconductors.
- Physics, engineering and technology of semiconductor devices and their applications in signal processing.
- Example: rectification, amplification, etc.

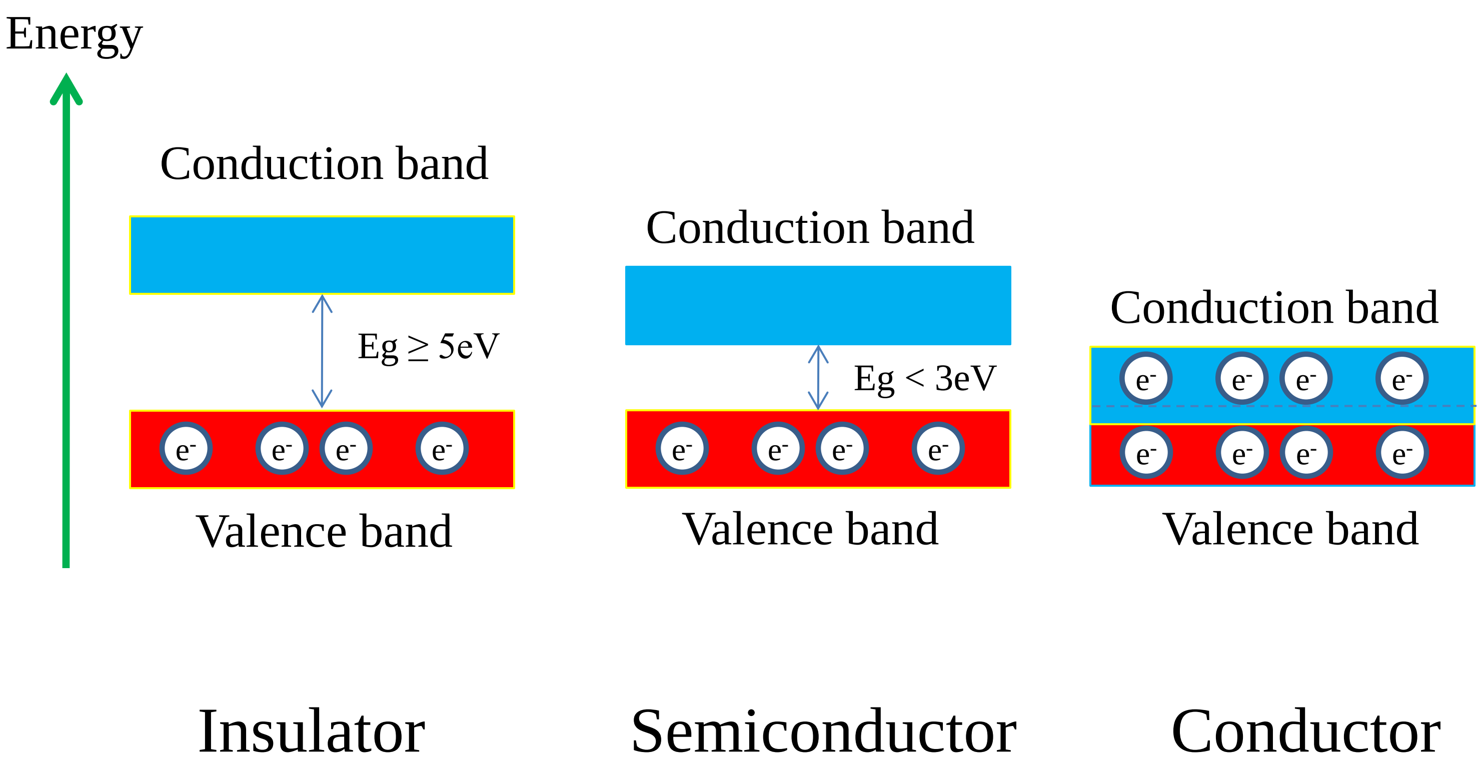
Semiconductor

- Materials having conductivity in between conductors and insulators.
- Example: Ge, Si, GaAs etc.

Typical resistivity (ρ) values		
Conductor	Semiconductor	Insulator
10^{-6} Ω-cm (Cu)	50 Ω-cm (Ge) 50×10^{3} Ω-cm (Si)	10^{12} Ω-cm (mica)

- Semiconductors have negative temperature coefficient.

Energy band diagram



Why Ge and Si?

TABLE 1.1 Typical Resistivity Values		
Conductor	*Semiconductor*	*Insulator*
$\rho \cong 10^{-6}$ Ω-cm (copper)	$\rho \cong 50$ Ω-cm (germanium) $\rho \cong 50 \times 10^{3}$ Ω-cm (silicon)	$\rho \cong 10^{12}$ Ω-cm (mica)

1. Purification
2. Alterable characteristics
3. Availability

Atomic and Crystal Structure

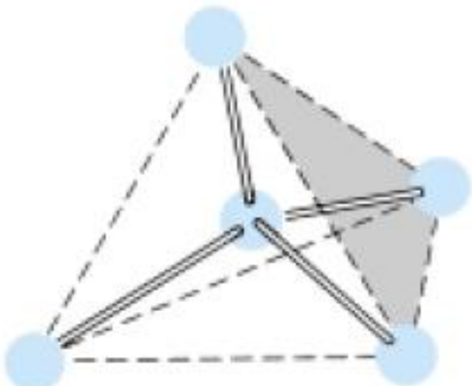


Figure 1.5 Ge and Si single-crystal structure.

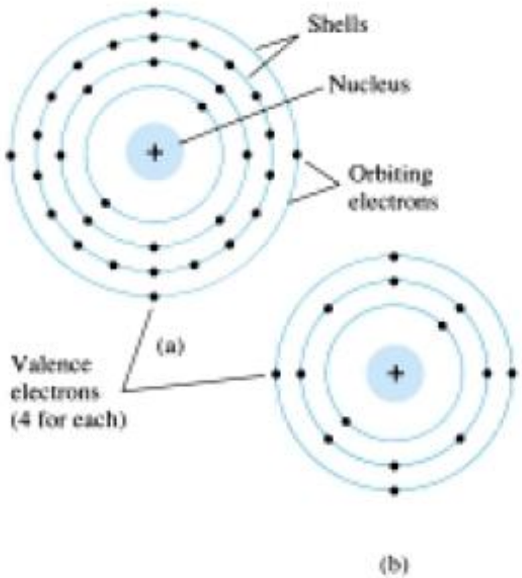


Figure 1.6 Atomic structure: (a) germanium; (b) silicon.

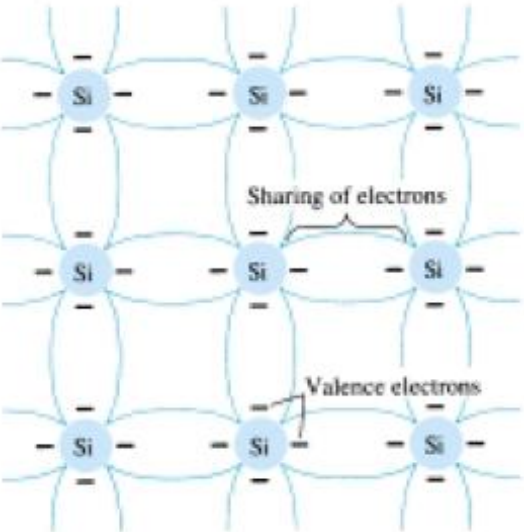


Figure 1.7 Covalent bonding of the silicon atom.

Intrinsic and extrinsic semiconductor

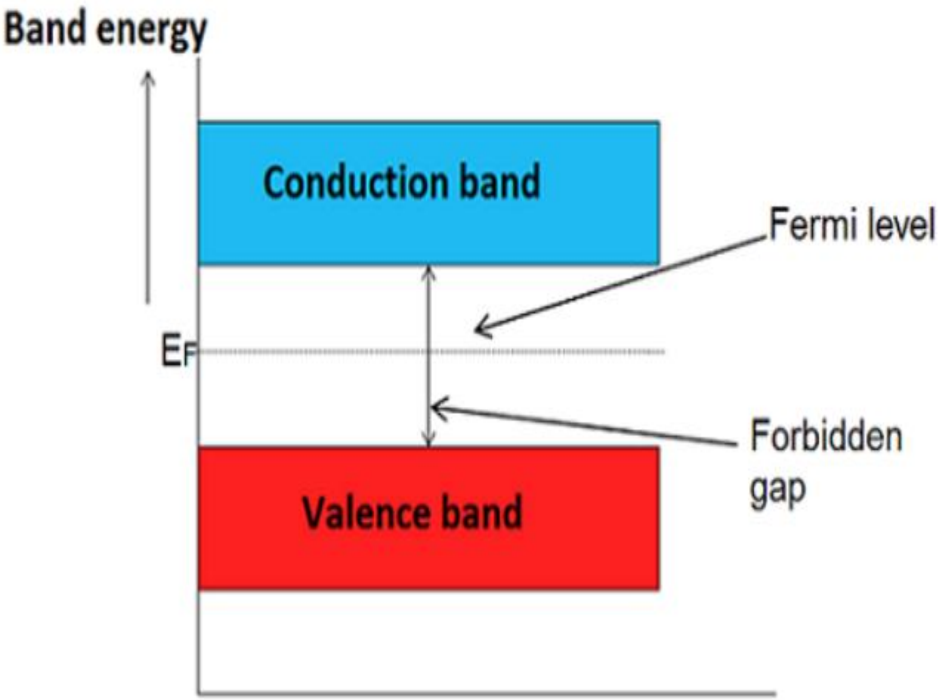
Intrinsic semiconductor

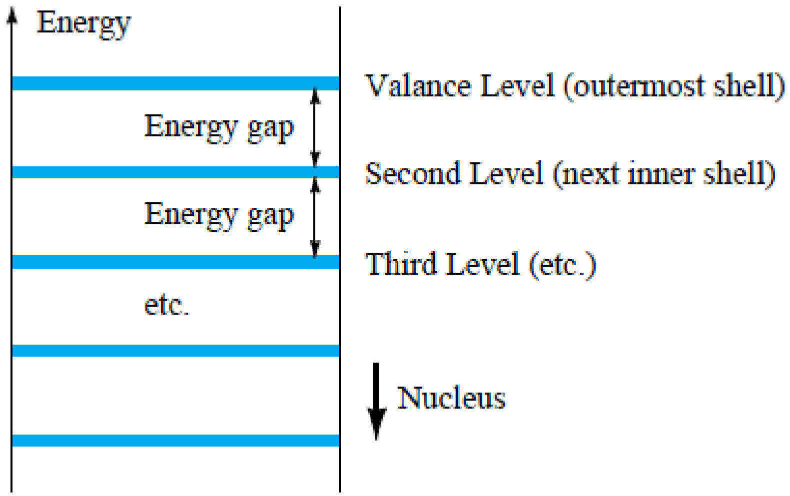
- Semiconductor in its pure form
- Level of purity, 1:10000000000 (one in 10 billion)
- Carriers present in such materials is called intrinsic carriers, due to photo-ionization and thermal-ionization.
- Bonding of atoms strengthen by the sharing of electrons

Extrinsic semiconductor

- Semiconductors subjected to doping process
- Extrinsic semiconductors are of p and n types

Fermi level and Fermi energy



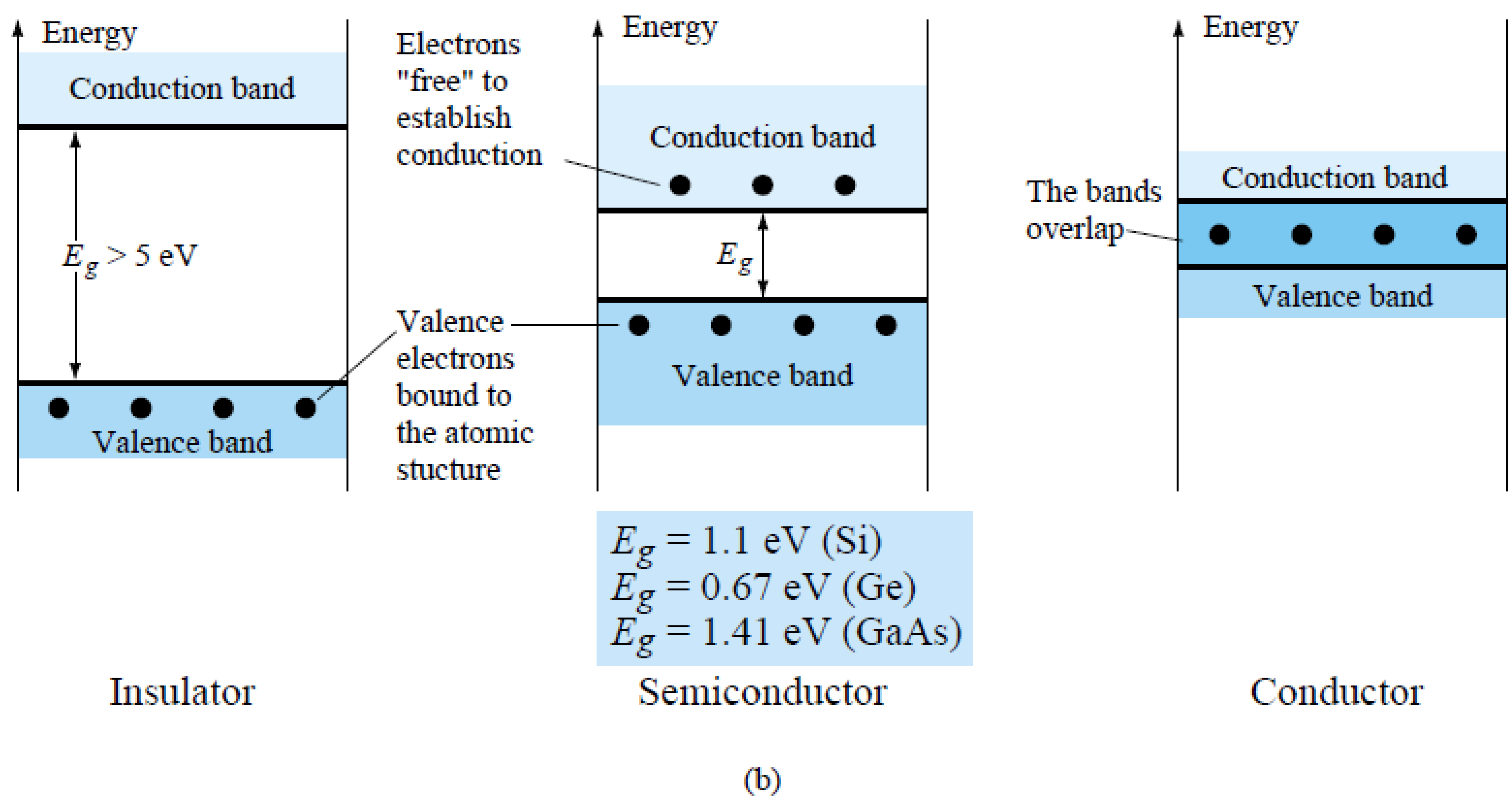


Energy levels: discrete levels in isolated atomic structures

What is Fermi Level?

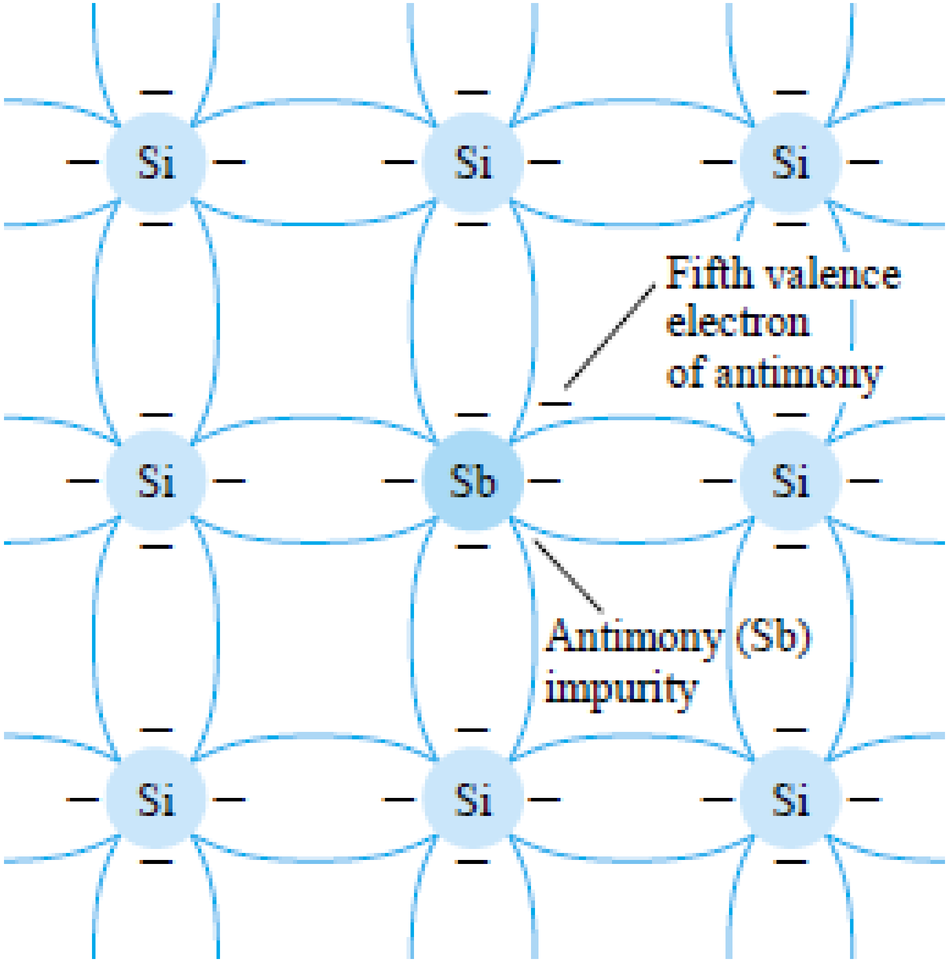
- The highest energy level that an electron can occupy at the absolute zero temperature is known as the Fermi Level.
- The Fermi level lies between the valence band and conduction band because at absolute zero temperature, the electrons are all in the lowest energy state.

Energy levels:



Conduction and valence bands of an insulator, semiconductor, and conductor.

n-type Semiconductor

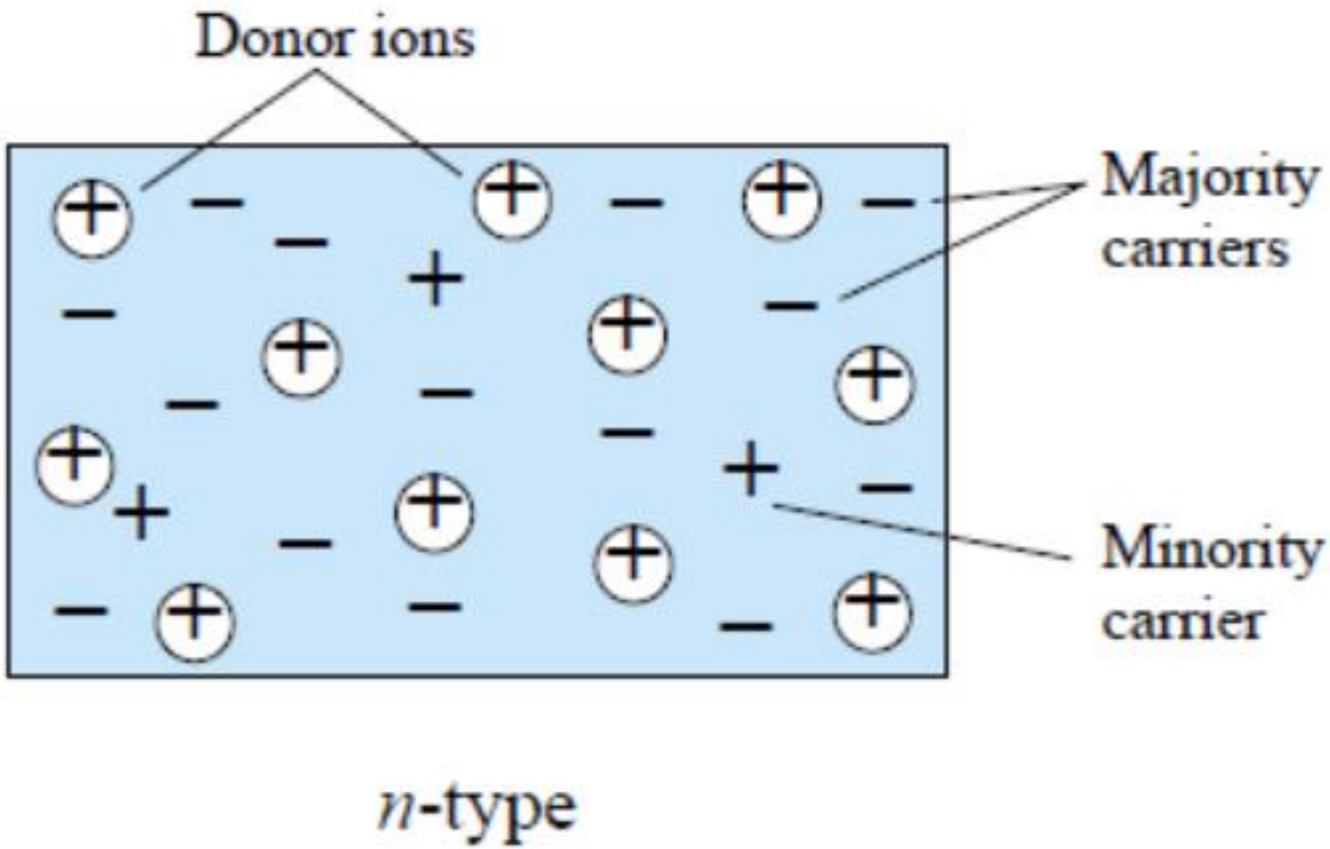


Diffused impurities with five valence electrons are called donor atoms.

n- type semiconductor

- Semiconductors with impurity having five valence electrons (pentavalent atoms) are called n-type semiconductor.
- Antimony, arsenic, phosphorus etc have five valence electrons
- Impurities having five valence electrons are called donor atoms.
- Carrier concentration increases to 100000:1
- Eg becomes 0.005eV (Si) or 001eV (Ge)
- n-type semiconductors are electrically neutral as there are equal numbers of positive and negative charged carriers.
- Fermi level lies close to the conduction band.

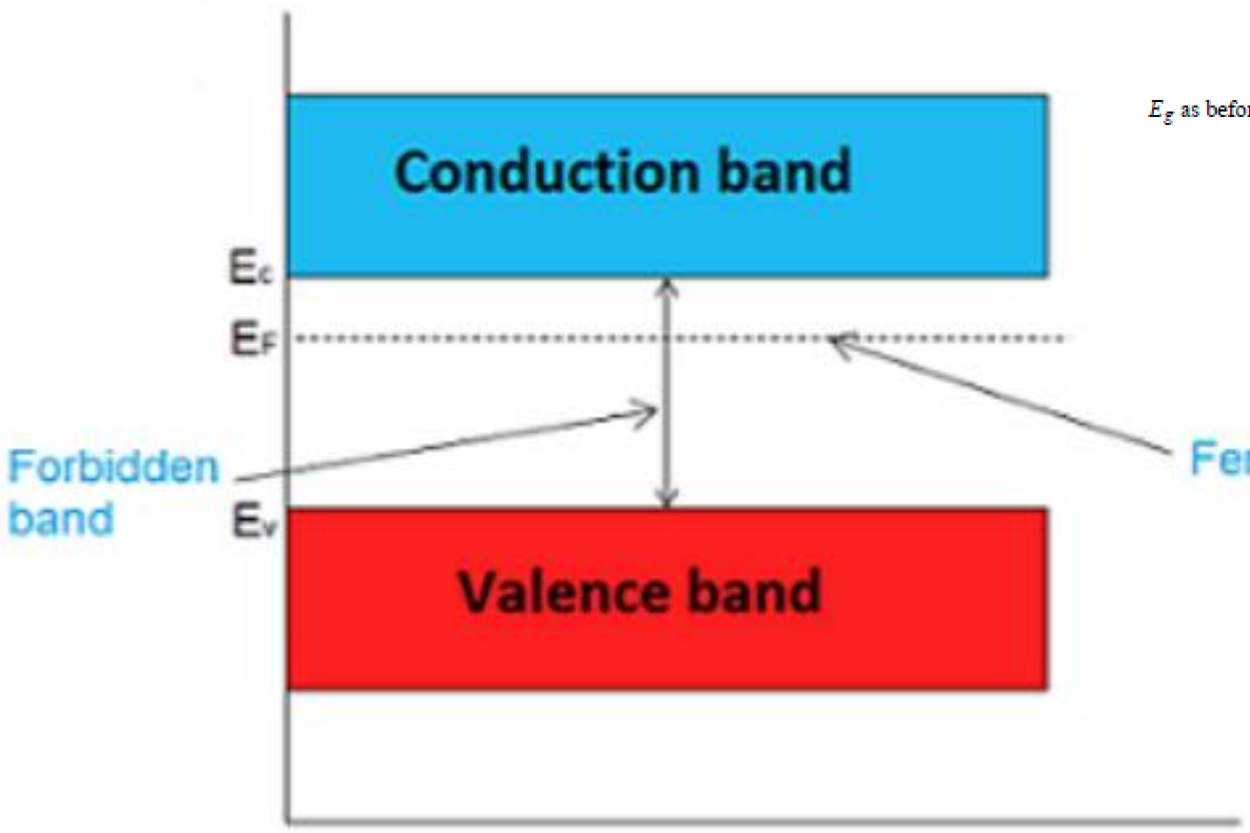
n-type semiconductor

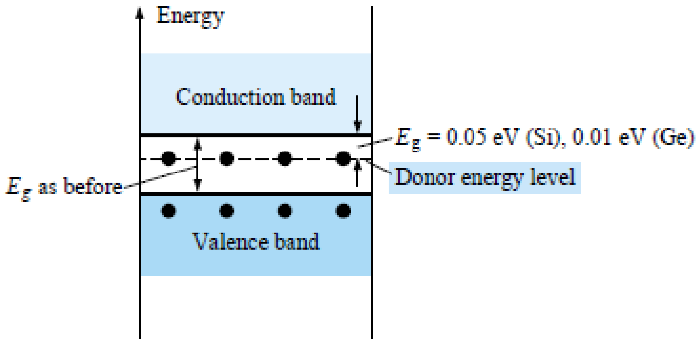


In an n-type material, the electron is called the majority carrier and the hole the minority carrier.

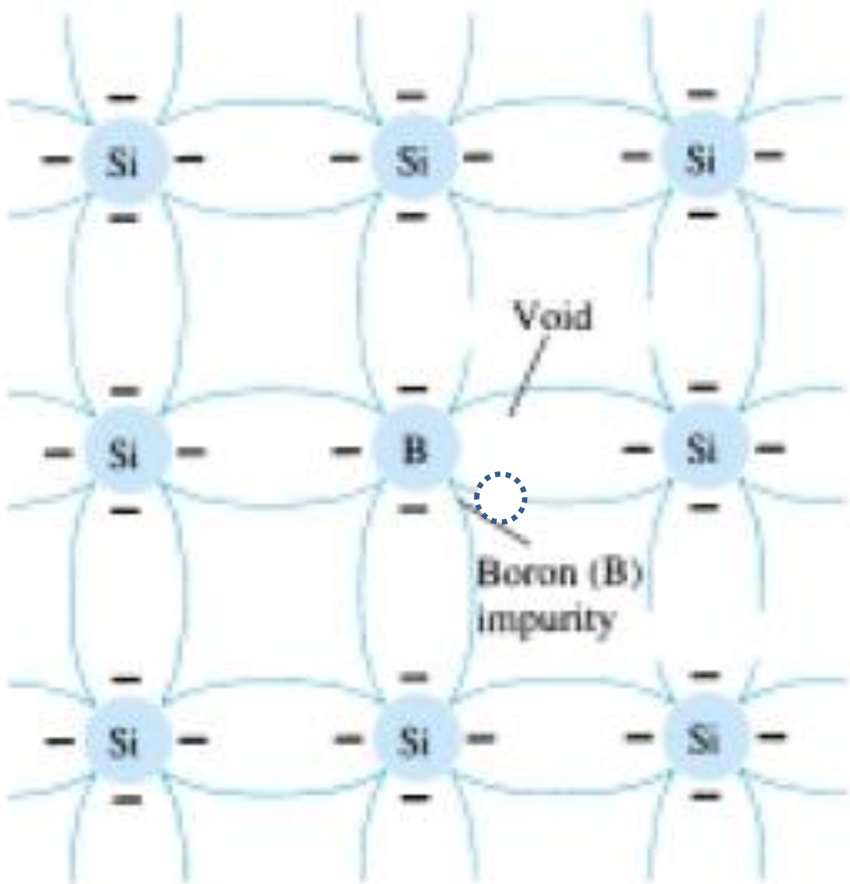
Importantly, the donor impurity in the n-type semiconductor loses an electron and becomes a positive ion. The acceptor impurity in the p-type accepts this electron, forming a negative ion

Fermi level in n-type semiconductor





p-type semiconductor

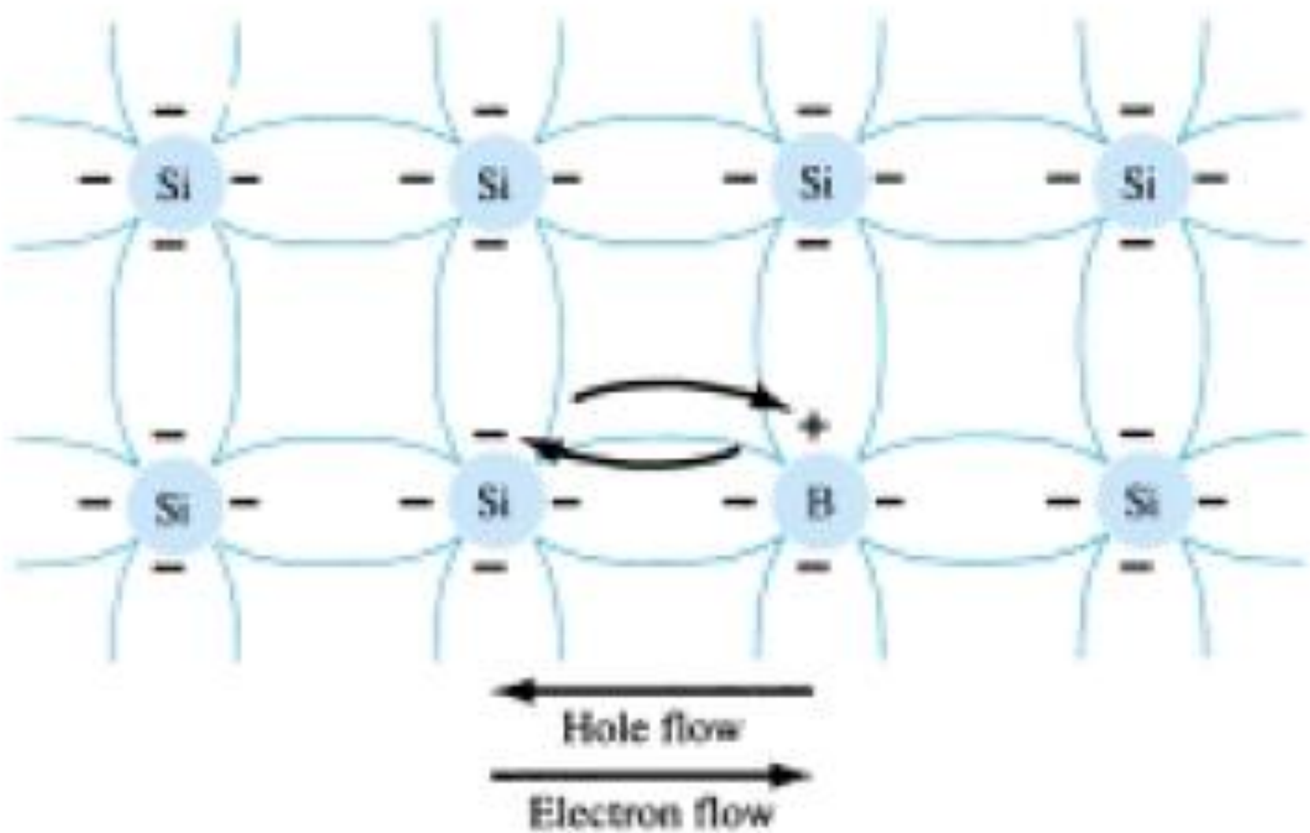


The diffused impurities with three valence electrons are called acceptor atoms.

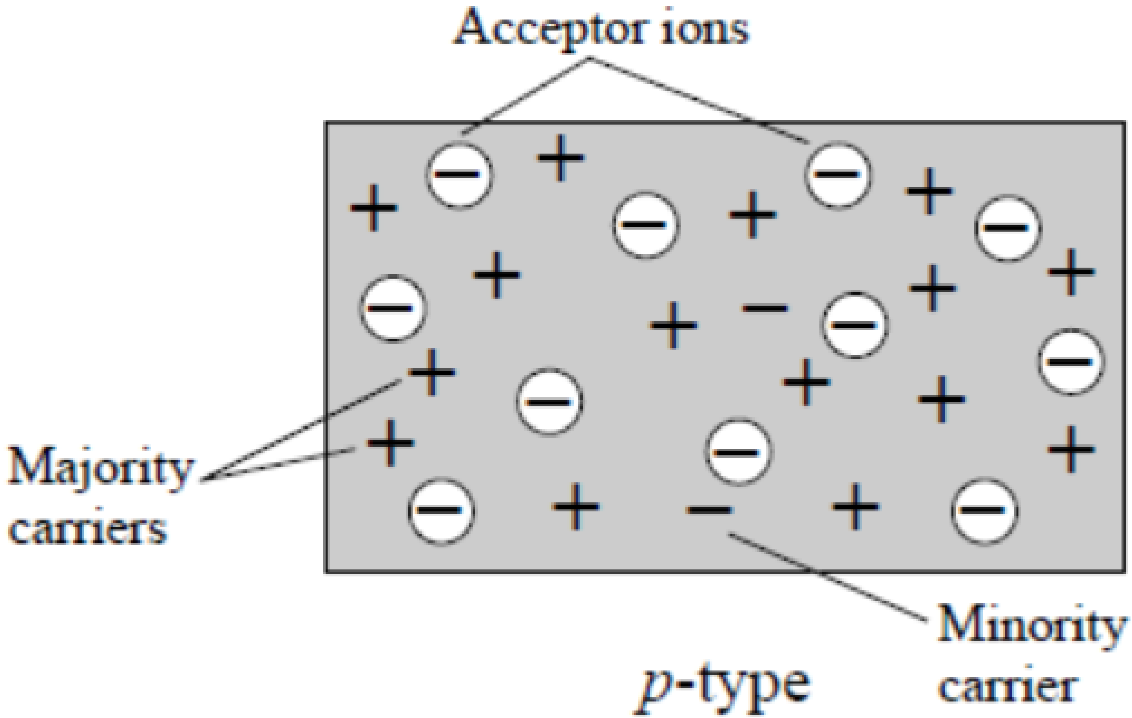
p- type semiconductor

- Semiconductors with impurity having three valence electrons (trivalent atoms) are called p-type semiconductor.
- Boron, Gallium, Indium etc have three valence electrons
- Impurities having three valence electrons are called acceptor atoms.
- Carrier concentration increases to 100000:1
- Eg becomes 0.005eV (Si) or 001eV (Ge)
- p-type semiconductors are electrically neutral as there are equal numbers of positive and negative charged carriers.
- Fermi level lies close to the valence band.

Electron vs Hole Flow



p-type semiconductor



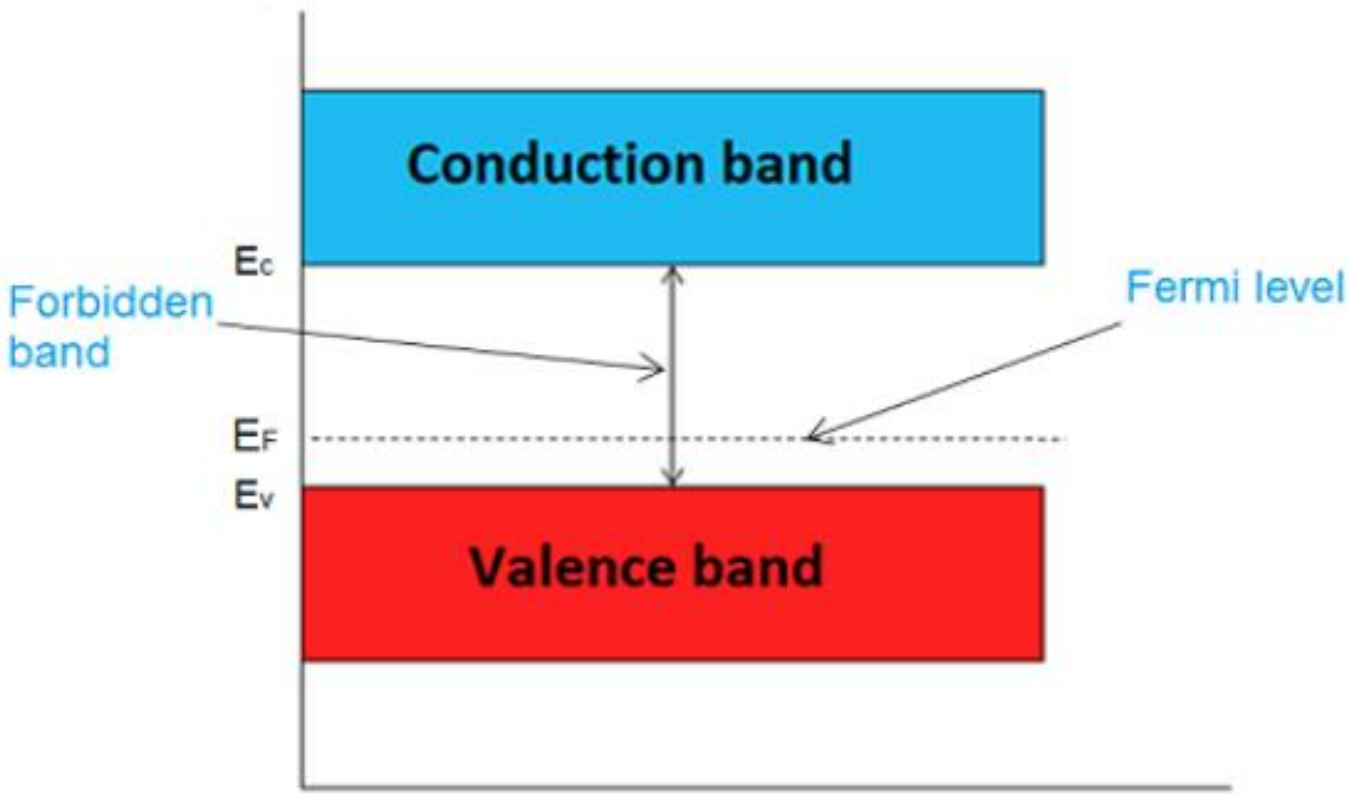
Remember, ions and carriers are different in this case

In a p-type material the hole is the majority carrier and the electron is the minority carrier.

Holes are nothing but creation of void due to the release of electron marked as + sign here

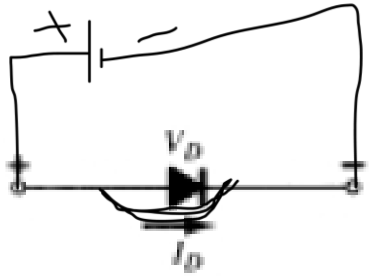
Importantly, the donor impurity in the n-type semiconductor loses an electron and becomes a positive ion. The acceptor impurity in the p-type accepts this electron, forming a negative ion

Fermi level in p-type semiconductor



Ideal Diode and Switch

- A two terminal semiconductor device
- Made up of either Ge and Si
- Characteristics similar to an ideal switch
- Conducts current in one direction
- Used as an uncontrolled switch



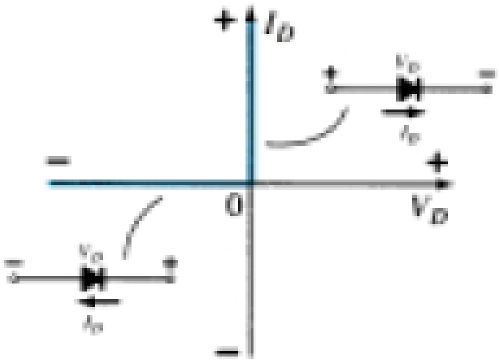


Figure 1.1 Ideal diode: (a) symbol; (b) characteristics.

Ideal Diode States

- Short circuit (closed switch) during conduction
- Open circuit (open switch) during non-conduction

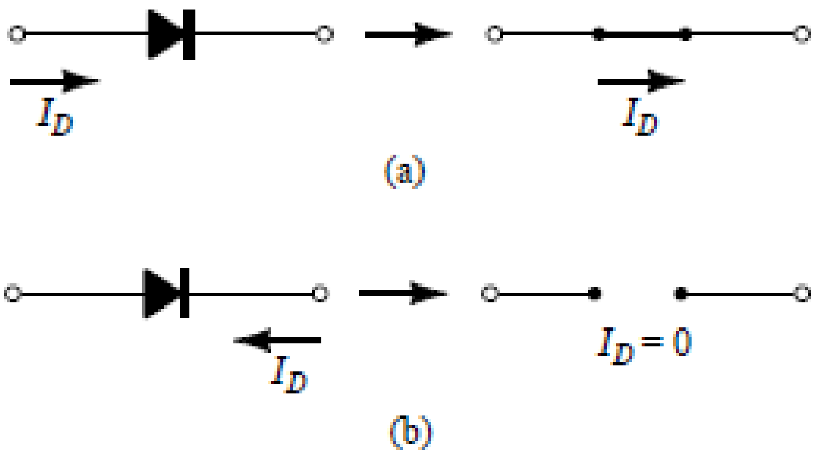


Figure 1.3 (a) Conduction and (b) nonconduction states of the ideal diode as determined by the direction of conventional current established by the network.

Ideal Diode Characteristics

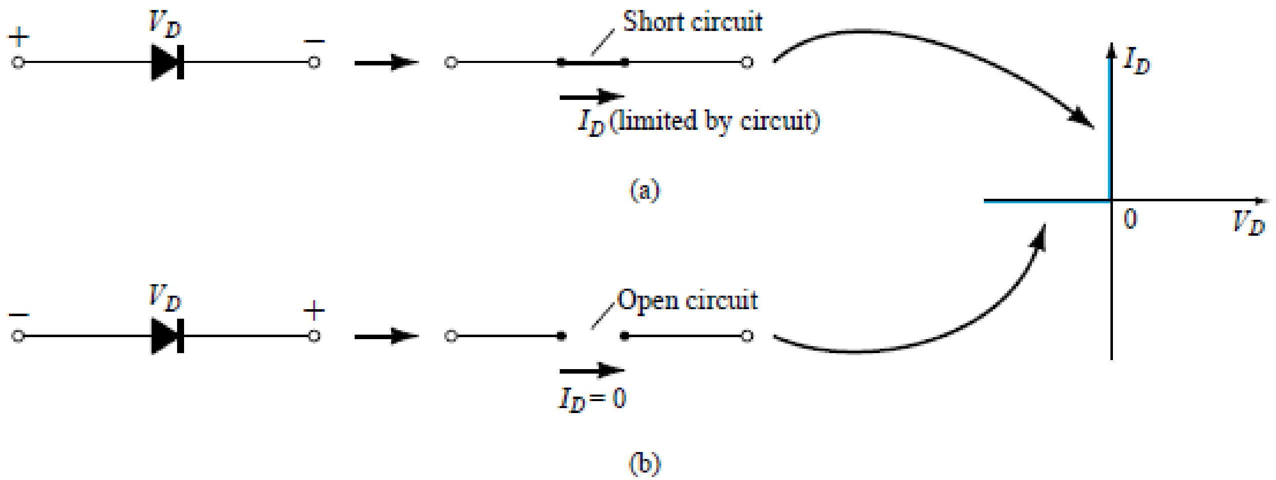


Figure 1.2 (a) Conduction and (b) nonconduction states of the ideal diode as determined by the applied bias.

Forward resistance

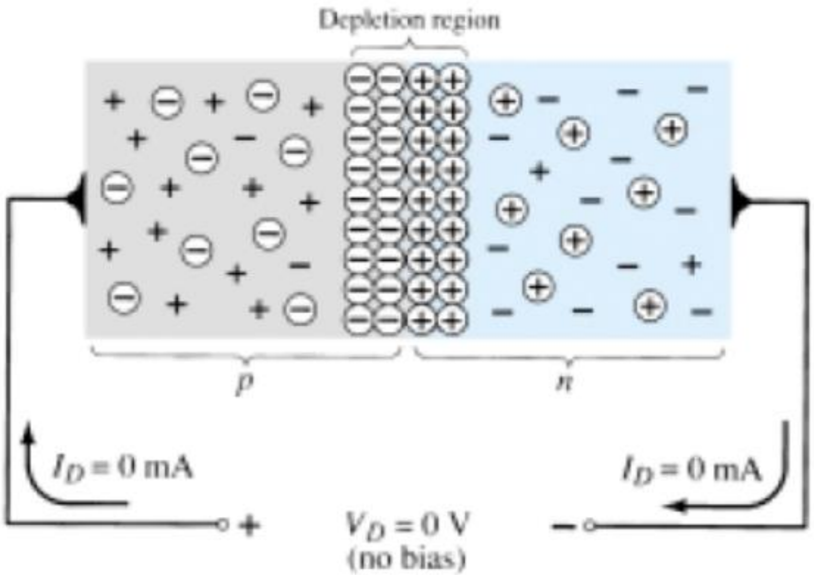
$$R_F = \frac{V_F}{I_F} = \frac{0\ \text{V}}{2, 3, \text{mA}, \ldots, \text{ or any positive value}} = 0\ \Omega \quad \text{(short circuit)}$$

Reverse resistance

$$R_R = \frac{V_R}{I_R} = \frac{-5, -20, \text{ or any reverse-bias potential}}{0\ \text{mA}} = \infty\ \Omega \quad \text{(open-circuit)}$$

p-n junction under no bias

In the absence of an applied bias voltage, the net flow of charge in any one direction for a semiconductor diode is zero.



Remember, ions and carriers are different in this case

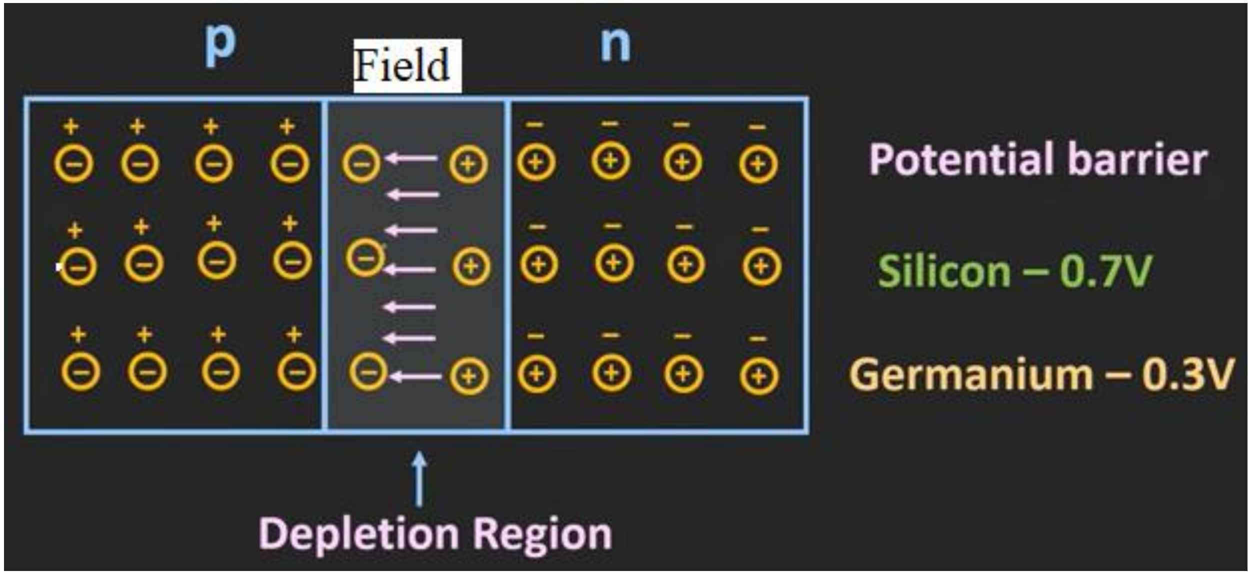
$$V_T = 0.7V\ (Si)$$
$$= 0.3V\ (Ge)$$

- Near Junction, electron from n-type comes to p-type and recombine with hole, only + (round) is available in n-type side and – (round) is available in p-type side. That's how depletion region created.
- That means, free carriers (electron and hole) will diffuse and produce diffusion current
- Importantly, + (round) and – (round) are immobile charge, can not move.

This region of uncovered positive and negative ions is called the depletion region due to the depletion of carriers in this region.

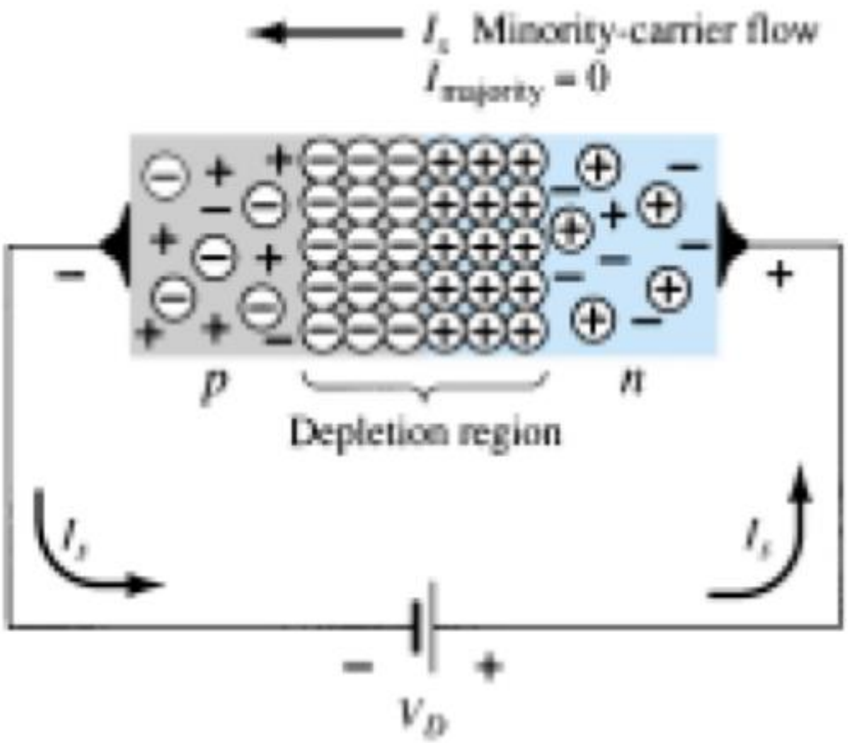
p-n junction under no bias

- This positive and negative ions (in the depletion region) set up the electric field from positive to negative direction.
- These remaining ions (in the depletion region) are immobile and creates a barrier potential which is 0.7 V for Silicon and 0.3 V for Ge.



- Under no-bias (no applied voltage) conditions, any minority carriers (holes) (remember that minority carrier will exist in depletion region as well, they are still everywhere) in the *n*-type material that find themselves within the depletion region will pass directly into the *p*-type material due to the barrier potential. They produce a current called drift current.
- Similar discussion can be applied to the minority carriers (electrons) of the *p*-type material.
- Diffusion current (due to majority carriers recombination or diffusion) and drift current are equal and opposite, so net current under no bias condition is zero.

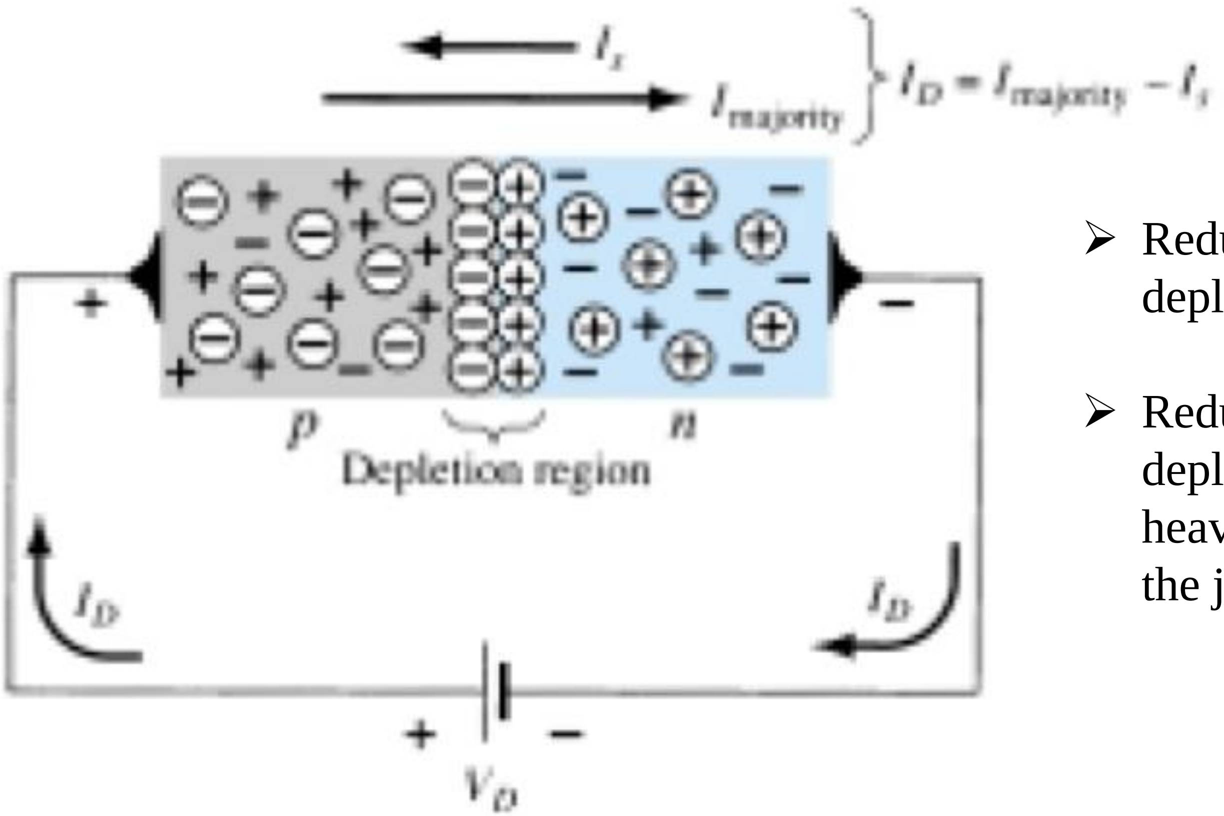
p-n junction under reverse bias



- The number of uncovered ions in the depletion region *will increase due to the large* number of "free" carriers drawn by the applied voltage.
- The net effect, therefore, is a widening of the depletion region.
- This widening of the depletion region will establish too great a barrier for the majority carriers to overcome, effectively reducing the majority carrier flow to zero
- The number of minority carriers in the depletion region will not change, resulting in minority-carrier flow.

The current that exists under reverse-bias conditions is called the reverse saturation current and is represented by Is.

p-n junction under forward bias



- Reduce the width of the depletion region.
- Reduction in the width of the depletion region results in a heavy majority flow across the junction.

A semiconductor diode is forward-biased when the association p-type and positive and n-type and negative has been established.

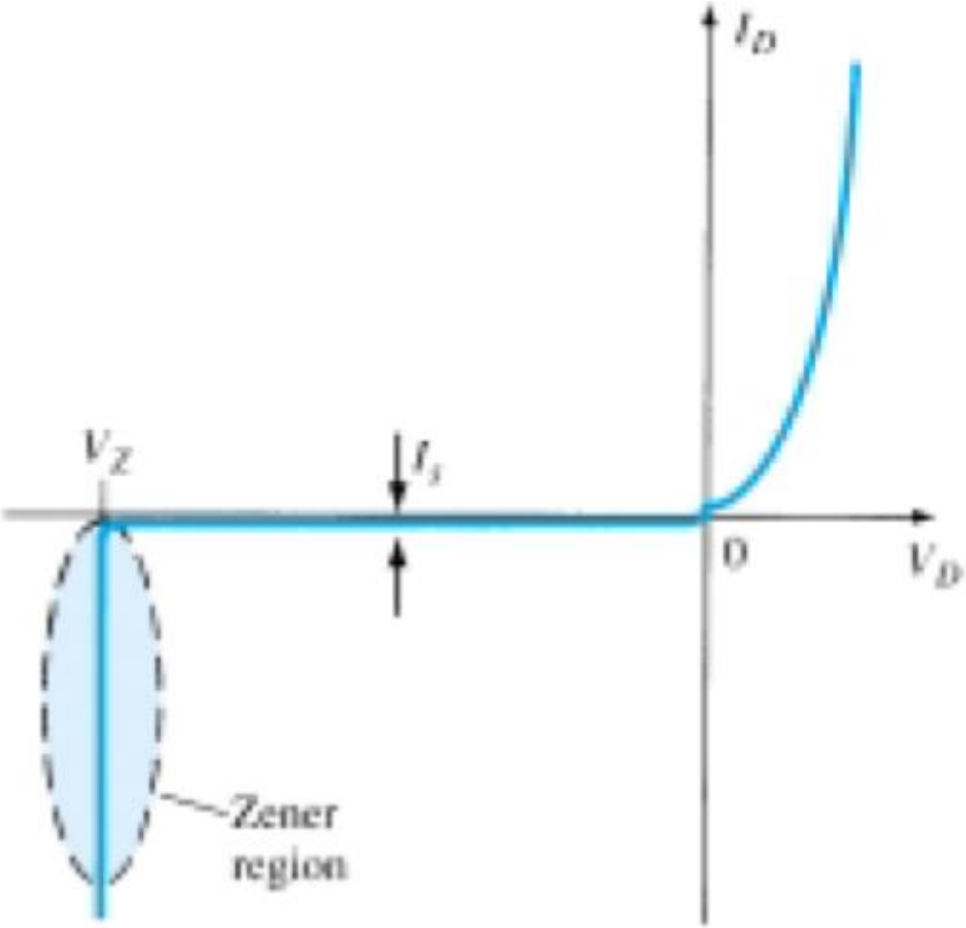
Diode equation and characteristic

$$i_d = I_s(e^{v_d/nV_t} - 1)$$

$$i_d = I_s e^{v_d/nV_t} - I_s$$

- ❖ there is a point where the application of too negative a voltage with a reverse polarity will result in a sharp change in the characteristics: the current increases at a very rapid rate in a direction opposite to that of + voltage region.

- ❖ The amount of – voltage responsible for this situation is called Breakdown / zener voltage.



Avalanche and Zener mechanism

- With increase in the reverse voltage, the velocity of the minority carriers responsible for the reverse saturation current *Is* also increases. When the kinetic energy of the carriers sufficient (at Vz) to release additional carriers through collisions with other atoms. That is called impact ionization.

- These additional carriers can then aid the ionization process to the point where a high *avalanche current* is established and the avalanche breakdown region determined.

- Increasing the doping level reduces the Vz. At reverse voltage below 5V, Zener mechanism dominates. Here, a strong electric field in the junction disrupts the bonding forces within the atom and “generate” carriers.

Si and Ge characteristics

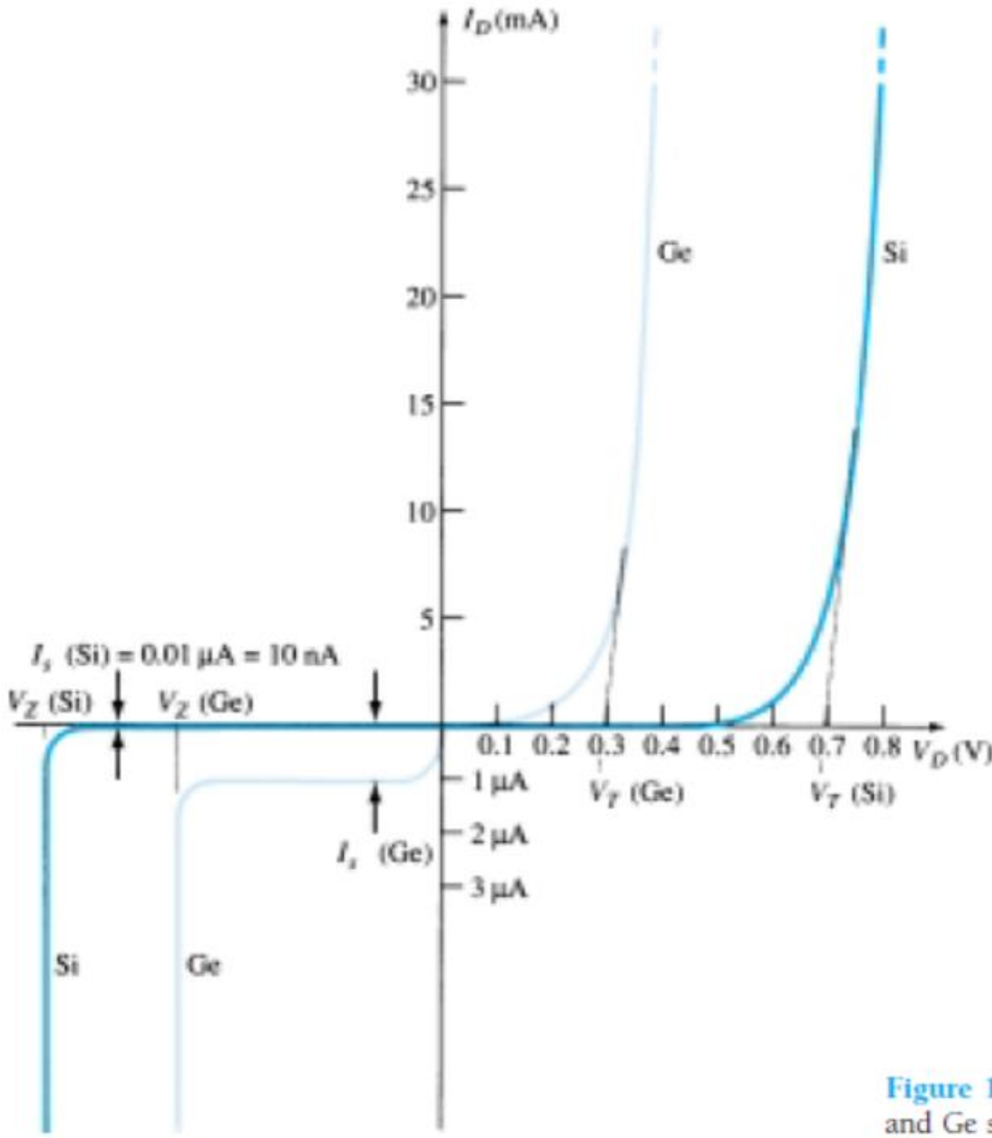


Figure 1.23 Comparison of Si and Ge semiconductor diodes.

Effect of temperature

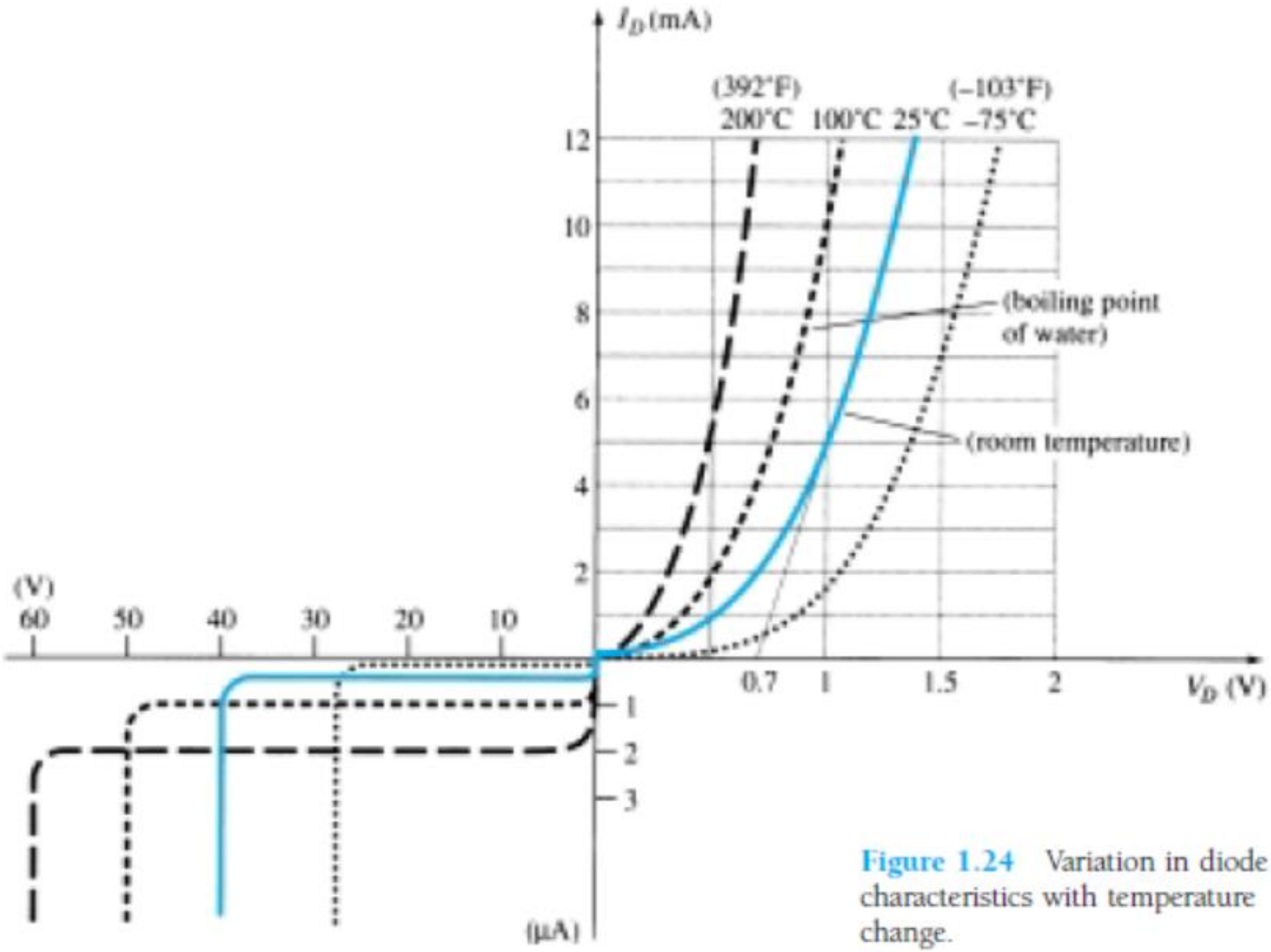
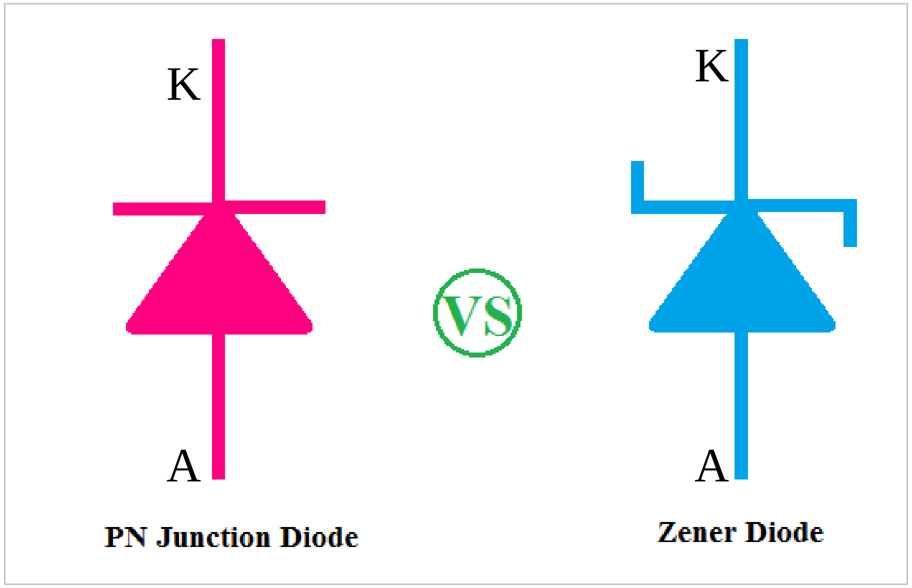


Figure 1.24 Variation in diode characteristics with temperature change.

Light-Emitting Diode (LED)

Zener diode

- Zener diodes are specially designed diodes.



- It is used as a voltage regulator.
- Act as a protection device
- It is used to establish reference voltage level

Zener diode i-v characteristic

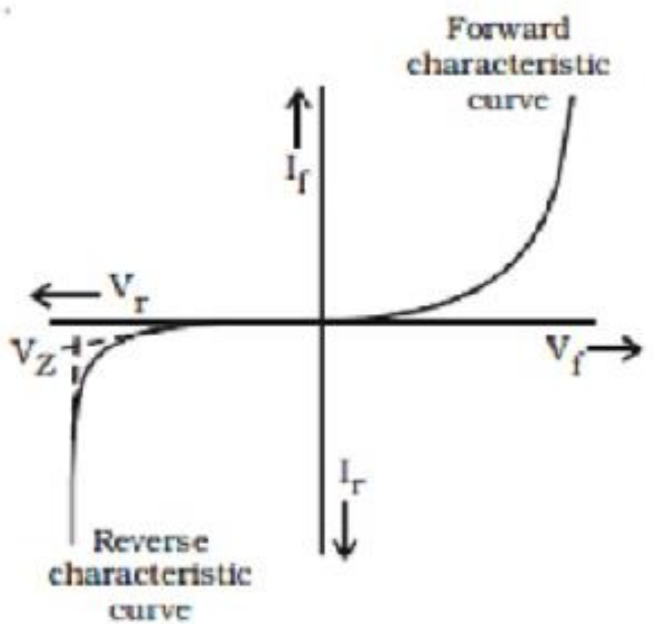


Fig V - I characteristics of a Zener diode.

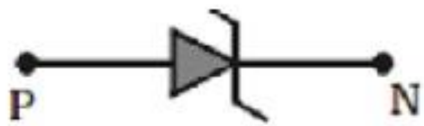


Fig Symbol for Zener diode

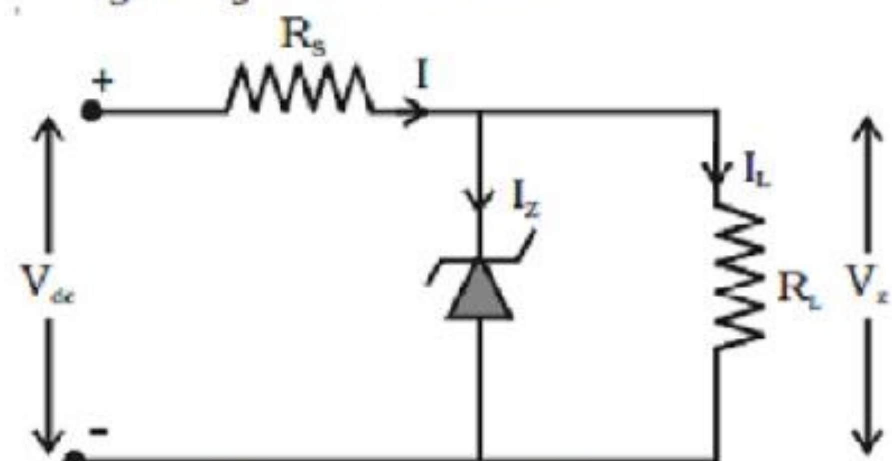
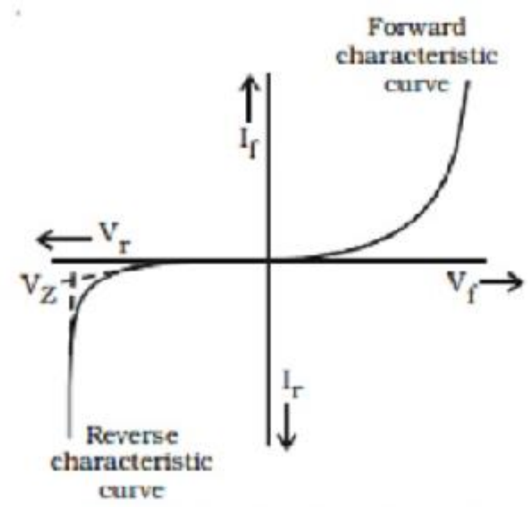
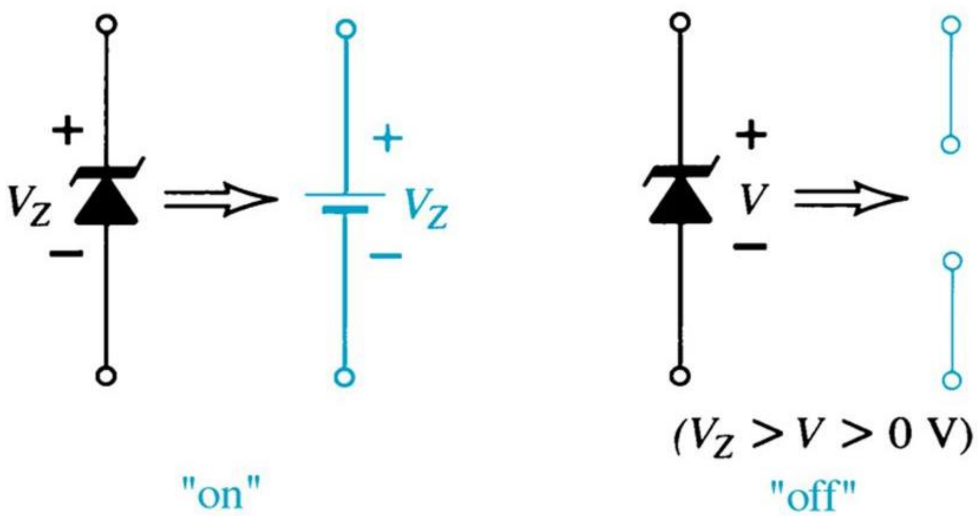


Fig Zener diode as a voltage regulator

Zener diode's state of operation





PIV or PRV

- *The maximum reverse-bias potential that can be applied before entering the Zener region.*
- *PIV or PRV should be slightly less than Vz.*
- *Where, Vz is the breakdown or zener potential.*

Ideal Vs Practical

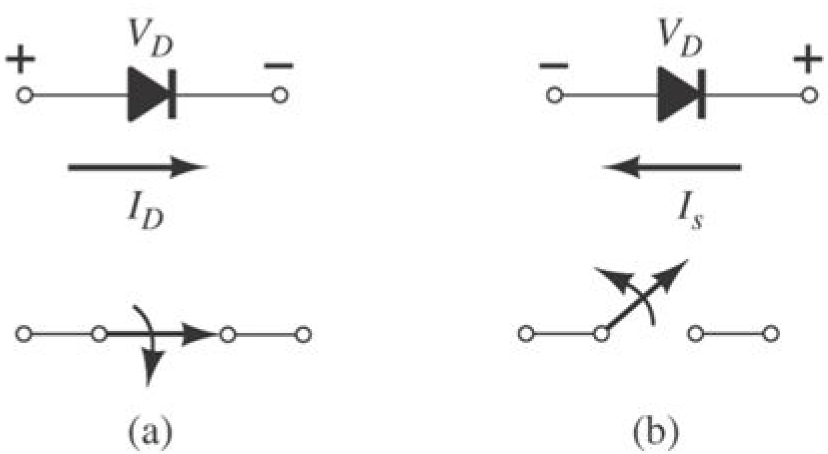


Fig. 1.21 Ideal semiconductor diode: (a) forward-biased; (b) reverse-biased.

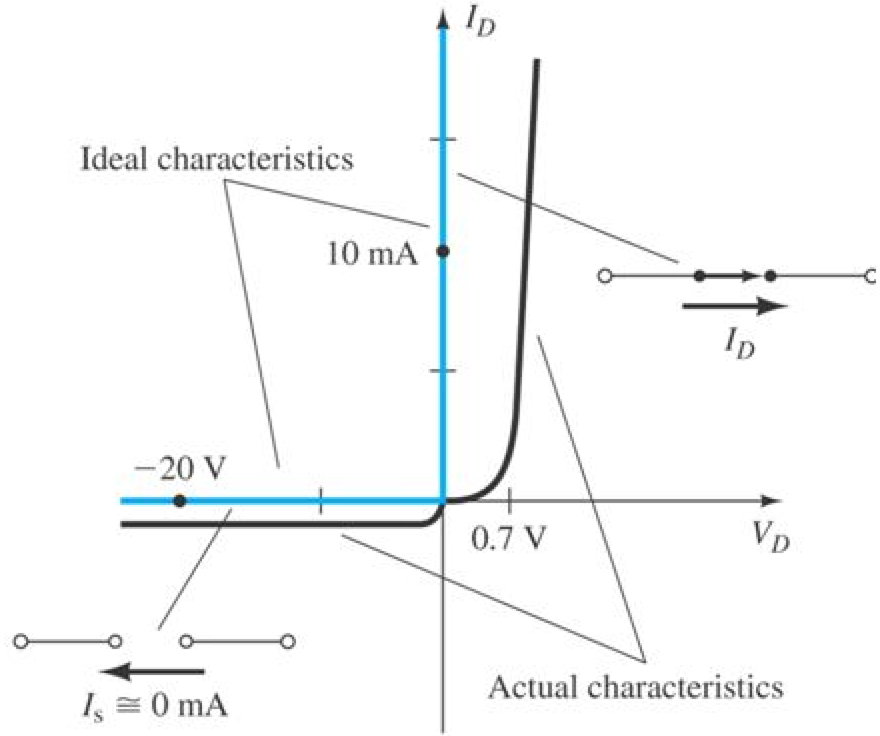


Fig. 1.22 Ideal versus actual semiconductor characteristics.

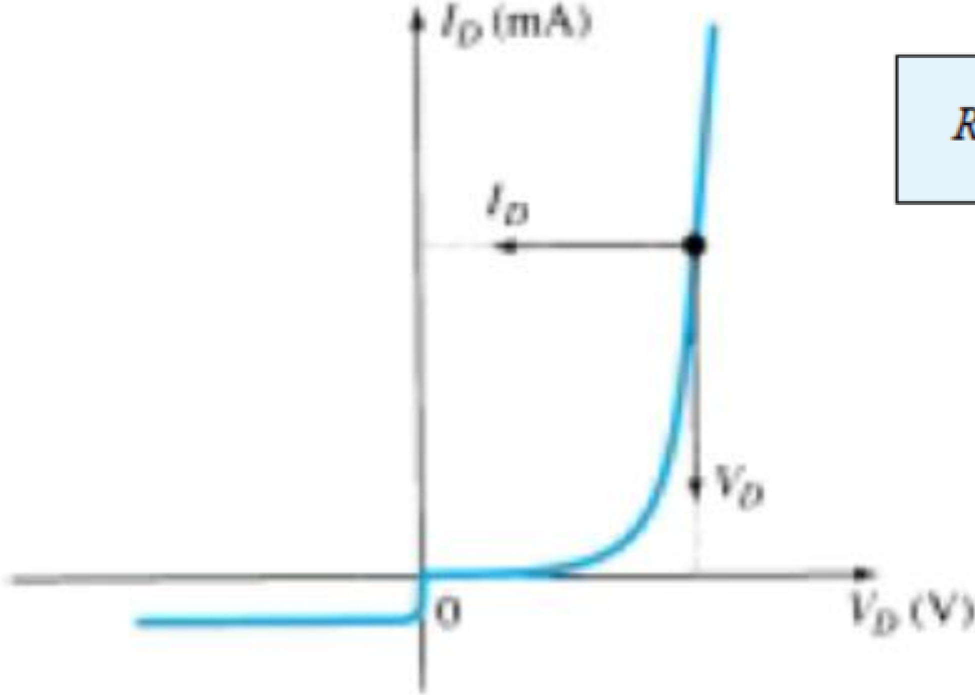
$$R_F = \frac{V_D}{I_D} = \frac{0V}{5mA} = 0\Omega$$

(Short circuit equivalent –fwd bias, actual case R ≠ 0)

$$R_R = \frac{V_D}{I_D} = \frac{20V}{0mA} = \infty\Omega$$

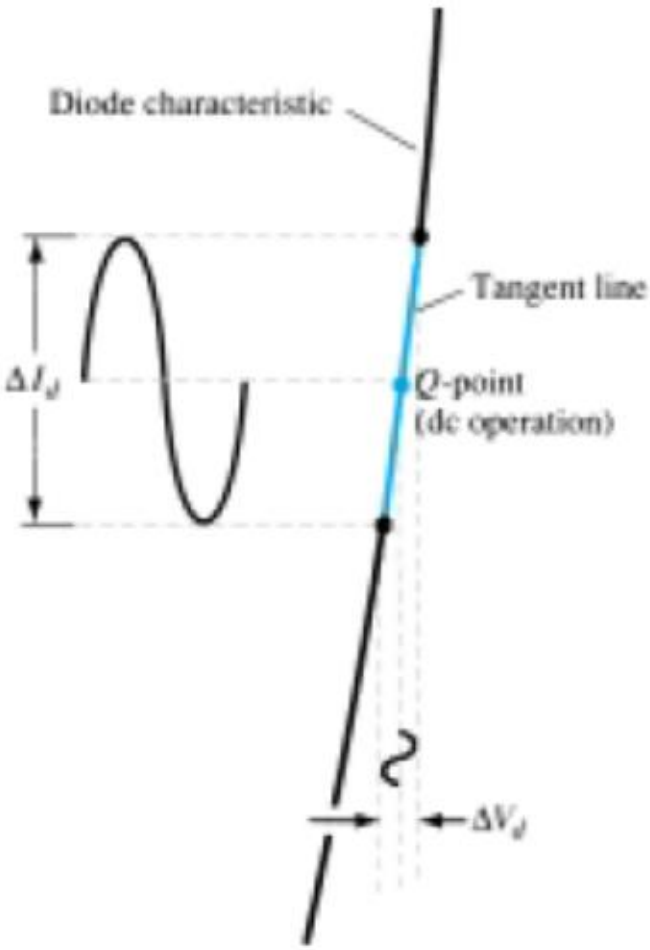
(Open circuit equivalent – Reverse bias, actual case saturation current Is ≠ 0)

DC or Static resistance of Practical diodes

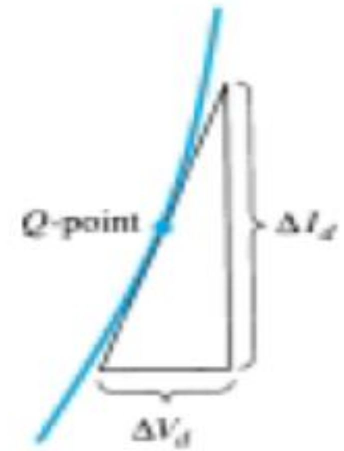


$$\boxed{R_D = \frac{V_D}{I_D}}$$

AC or Dynamic resistance



$$r_d = \frac{\Delta V_d}{\Delta I_d}$$



$$r_d = \frac{26 \text{ mV}}{I_D}$$

Ge,Si

Derivation of dynamic resistance

$$\frac{d}{dV_D}(I_D) = \frac{d}{dV}[I_s(e^{kV_D/T_K} - 1)]$$

and
$$\frac{dI_D}{dV_D} = \frac{k}{T_K}(I_D + I_s)$$

following a few basic maneuvers of differential calculus. In general, $I_D \gg I_s$ in the vertical slope section of the characteristics and

$$\frac{dI_D}{dV_D} \cong \frac{k}{T_K} I_D$$

Substituting $\eta = 1$ for Ge and Si in the vertical-rise section of the characteristics, we obtain

$$k = \frac{11{,}600}{\eta} = \frac{11{,}600}{1} = 11{,}600$$

and at room temperature,

$$T_K = T_C + 273° = 25° + 273° = 298°$$

so that
$$\frac{k}{T_K} = \frac{11{,}600}{298} \cong 38.93$$

and
$$\frac{dI_D}{dV_D} = 38.93 I_D$$

Flipping the result to define a resistance ratio ($R = V/I$) gives us

$$\frac{dV_D}{dI_D} \cong \frac{0.026}{I_D}$$

or
$$\boxed{r_d = \frac{26\text{ mV}}{I_D}}_{\text{Ge,Si}} \qquad (1.7)$$

Id = Is(exp^ (qV/[kT])-1)

where Is is the reverse saturation current , k is Boltzmann's constant, c
proton, and T is the temperature in Kelvin. exp is the natural exponen

Take the derivative of Id with respect to V to get 1/rd

1/rd = d Id/dV = (q/[kT])(Is(exp^[qV/(kT)]) = ~ (q/[kT]])Id

rd = kT/(q*Id)

at room temperature (~26 degrees Celsius) T = ~290 K

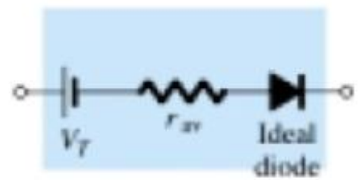
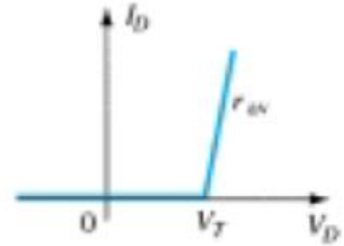
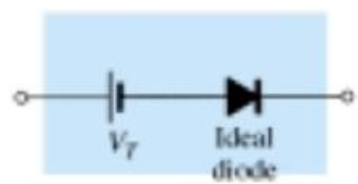
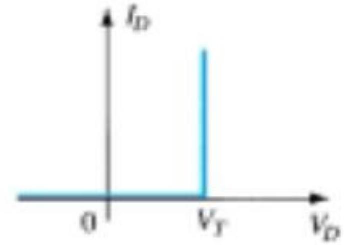
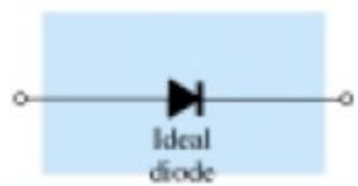
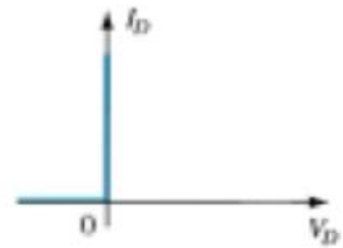
And kT/q =~ 26 mV

rd = 26 mV/ Id

V_T is called thermal voltage

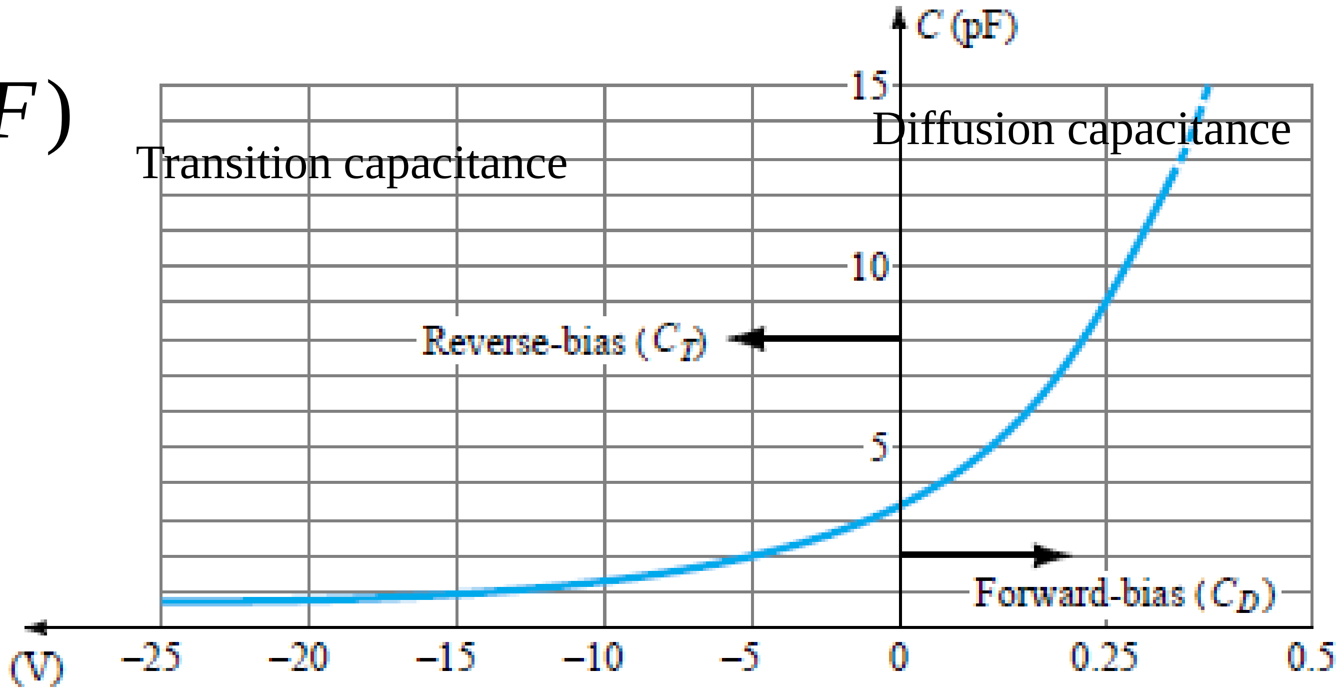
= KT/q

Diode models

TABLE 1.3 Diode Equivalent Circuits (Models)			
Type	*Conditions*	*Model*	*Characteristics*
Piecewise-linear model			
Simplified model	$R_{network} \gg r_{av}$		
Ideal device	$R_{network} \gg r_{av}$ $E_{network} \gg V_T$		

TRANSITION AND DIFFUSION CAPACITANCE

$$C = \frac{\varepsilon A}{d} \quad (F)$$

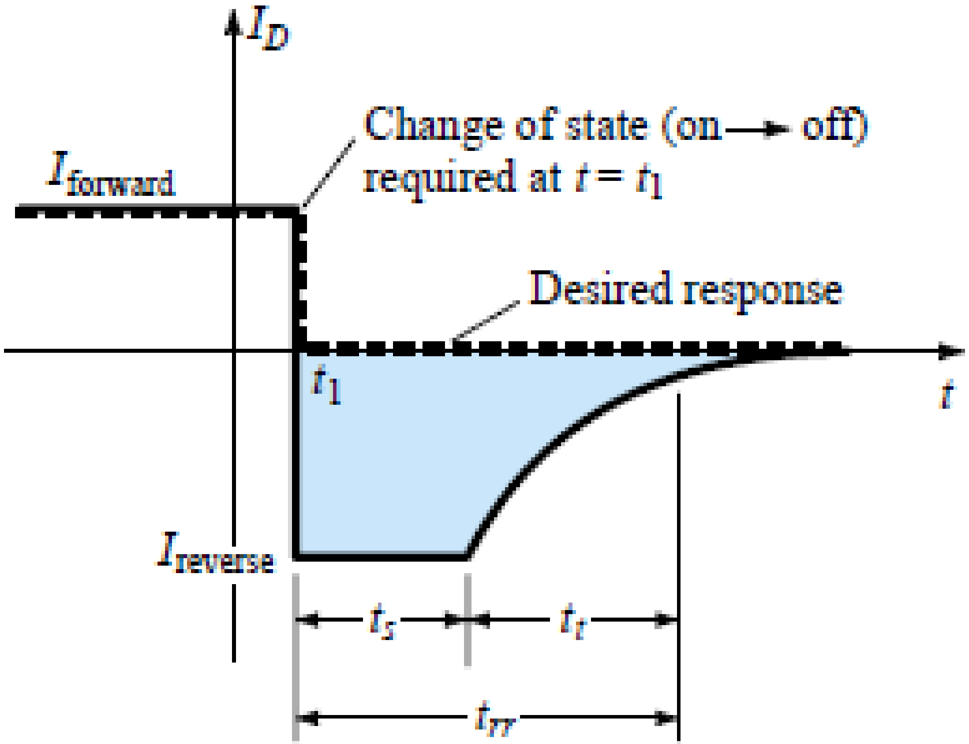


- The transition capacitance is the predominant capacitive effect in the reverse bias region
- The diffusion capacitance is the predominant capacitive effect in the forward bias region

Reverse Recovery Time

- When a FB diode is switched to RB, state of carrier changed.

- This large number of minority carriers result in a large reverse current until the carriers come back to their original majority state.



Diode Specification

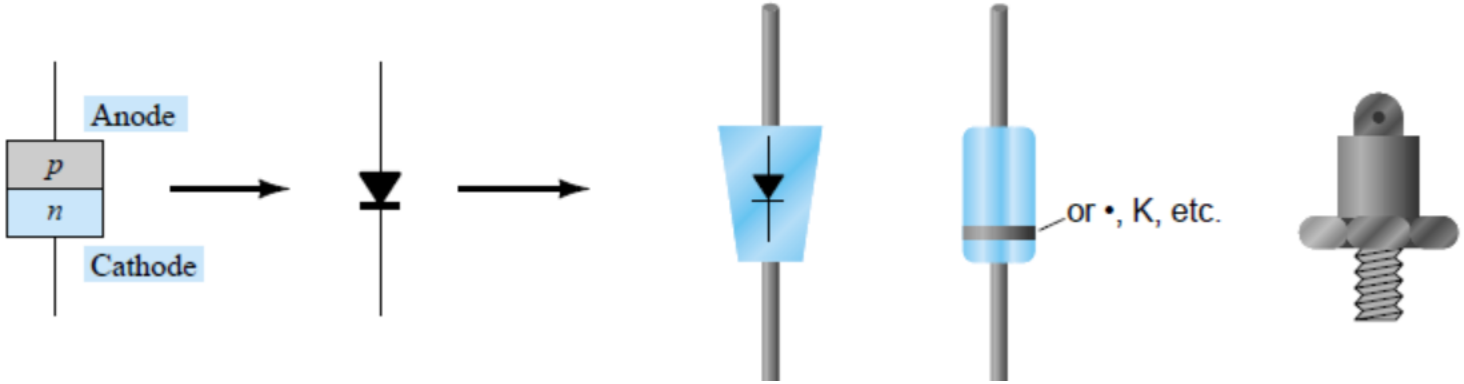
1. The forward voltage V_F (at a specified current and temperature)
2. The maximum forward current I_F (at a specified temperature)
3. The reverse saturation current I_R (at a specified voltage and temperature)
4. The reverse-voltage rating [PIV or PRV or V(BR), where BR comes from the term "breakdown" (at a specified temperature)]
5. The maximum power dissipation level at a particular temperature
6. Capacitance levels (as defined in Section 1.10)
7. Reverse recovery time t_{rr} (as defined in Section 1.11)
8. Operating temperature range

Power dissipation level

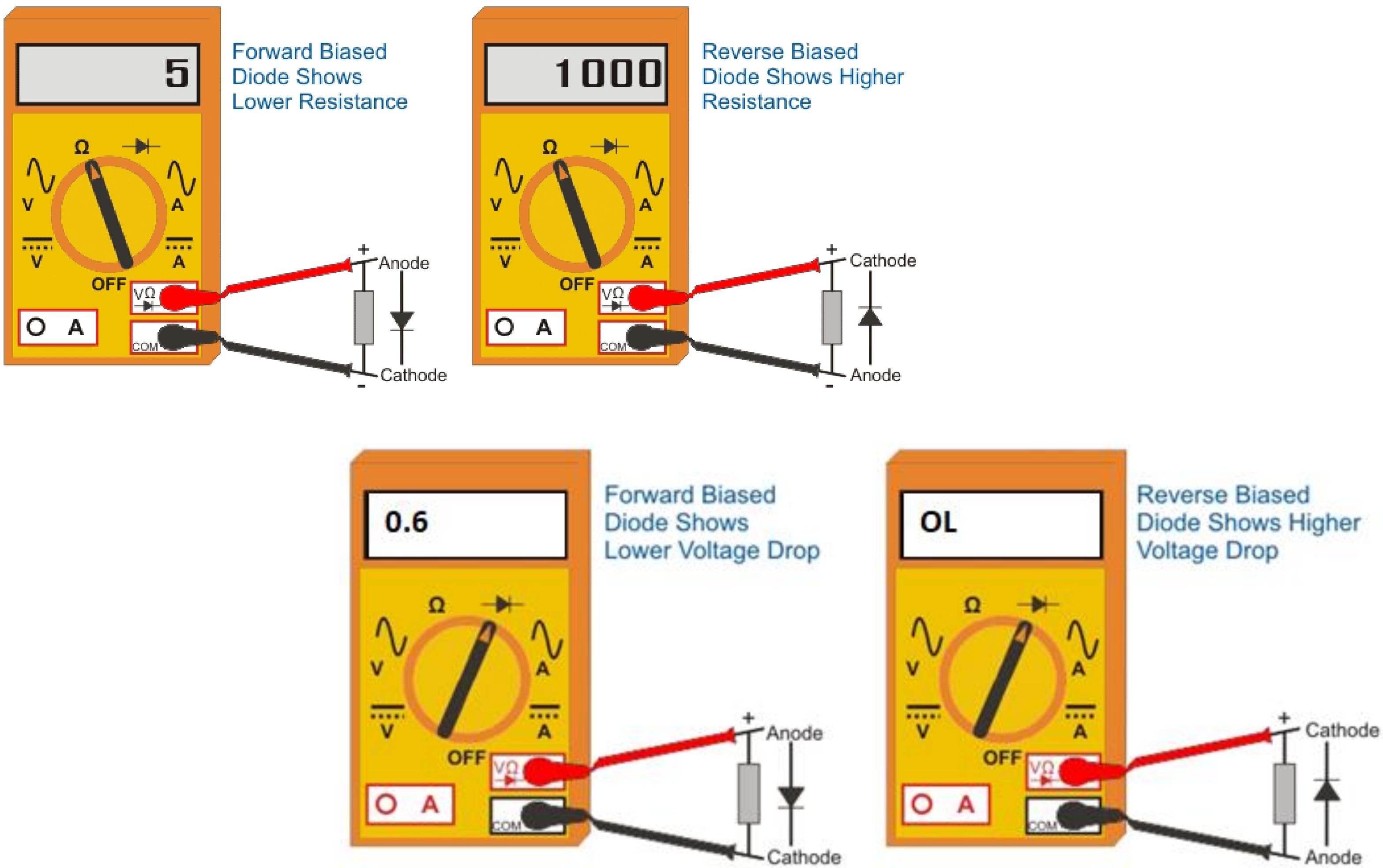
$$P_D = V_D I_D$$

$$P_{D\max} = V_{D\max} I_{D\max}$$

$$\boxed{P_{\text{dissipated}} \cong (0.7\ \text{V}) I_D}$$



Diode testing



Thank you