Jimma University
College of Natural Sciences
Department of Physics

Lecture Notes : *Electronics I (Phys 2062)*

Chapter Two: The physics of semiconductors

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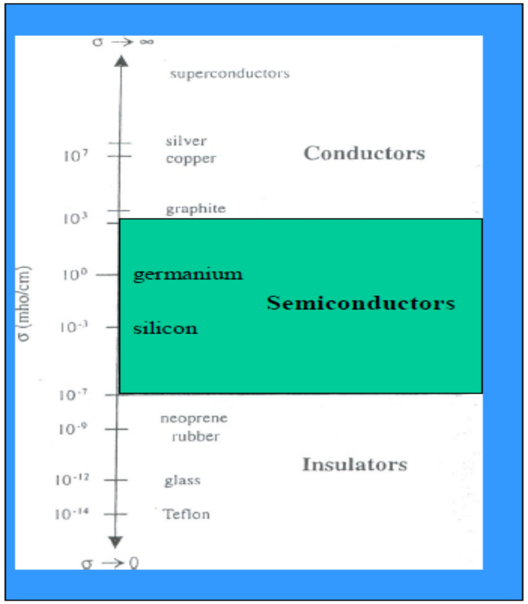
Outline of the Chapter

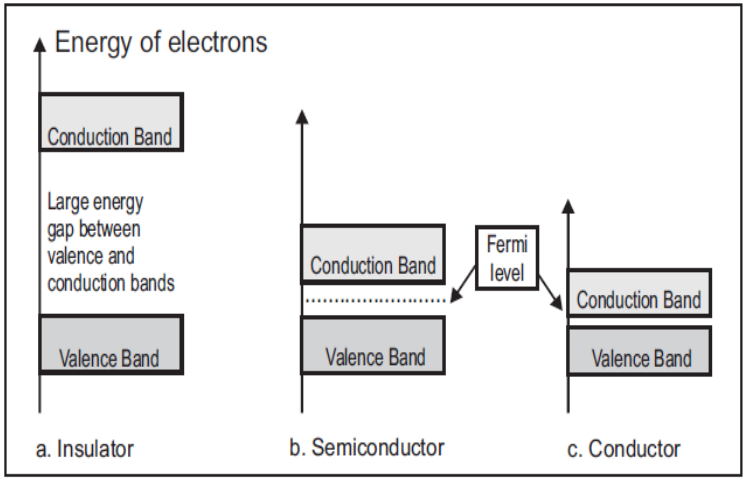
- Formation of energy bands
- Metals, insulators and semiconductors
- Intrinsic and extrinsic semiconductors
- P type and N type extrinsic semiconductors
- Carrier mobility, drift velocity and drift current density
- The PN junction
- V-I characteristics of a PN junction diode
- Ideal diode equation
- PN junction breakdowns
- Diode circuit analysis
- Diode as a rectifier
- Half wave and Full wave rectifier
- How effectively a rectifier converts AC in to DC
- Types of diodes

Introduction: Semiconductor

- ➢ Materials that permit flow of electrons are called conductors (e.g., gold, silver, copper, etc.).
- ➢ Materials that block flow of electrons are called insulators (e.g., rubber, glass, Teflon, mica, etc.).
- ➢ Materials whose conductivity falls between those of conductors and insulators are called
- ➢ semiconductors. Semiconductors are “part-time” conductors whose conductivity can be controlled.
- ➢ Silicon is the most common material used to build semiconductor devices

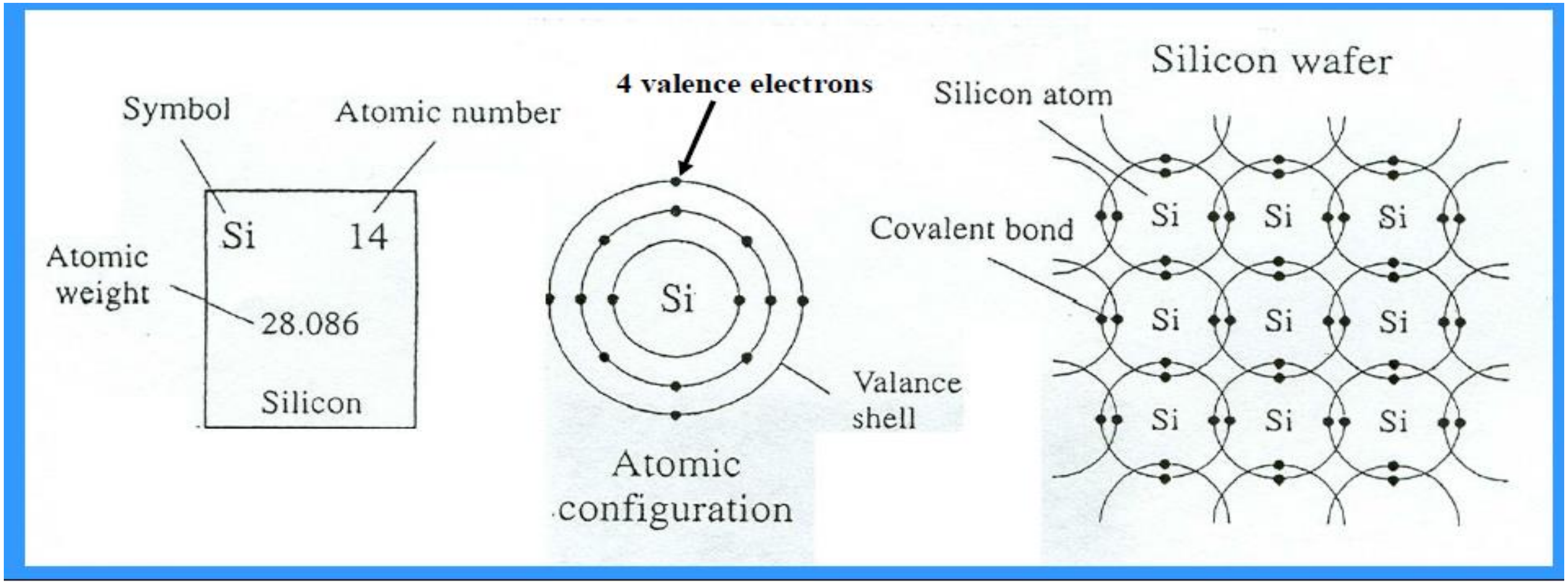


- ❑ Atoms in a pure silicon wafer contains four electrons in outer orbit (called valence electrons).
  - ✓ Germanium is another semiconductor material with four valence electrons.



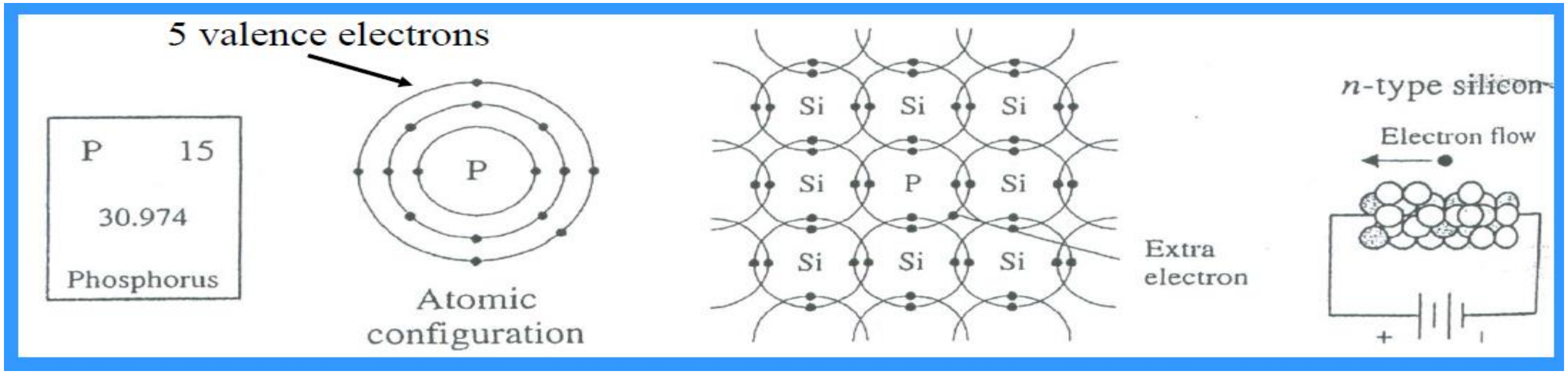
Introduction: Semiconductors

- In the crystalline lattice structure of Si, the valence electrons of every Si atom are locked up in covalent bonds with the valence electrons of four neighboring Si atoms.
  - ✓ In pure form, Si wafer does not contain any free charge carriers.
  - ✓ An applied voltage across pure Si wafer does not yield electron flow through the wafer.
  - ✓ A pure Si wafer is said to act as an insulator.
- In order to make useful semiconductor devices, materials such as phosphorus (P) and boron (B) are added to Si to change Si's conductivity.



N-Type Silicon

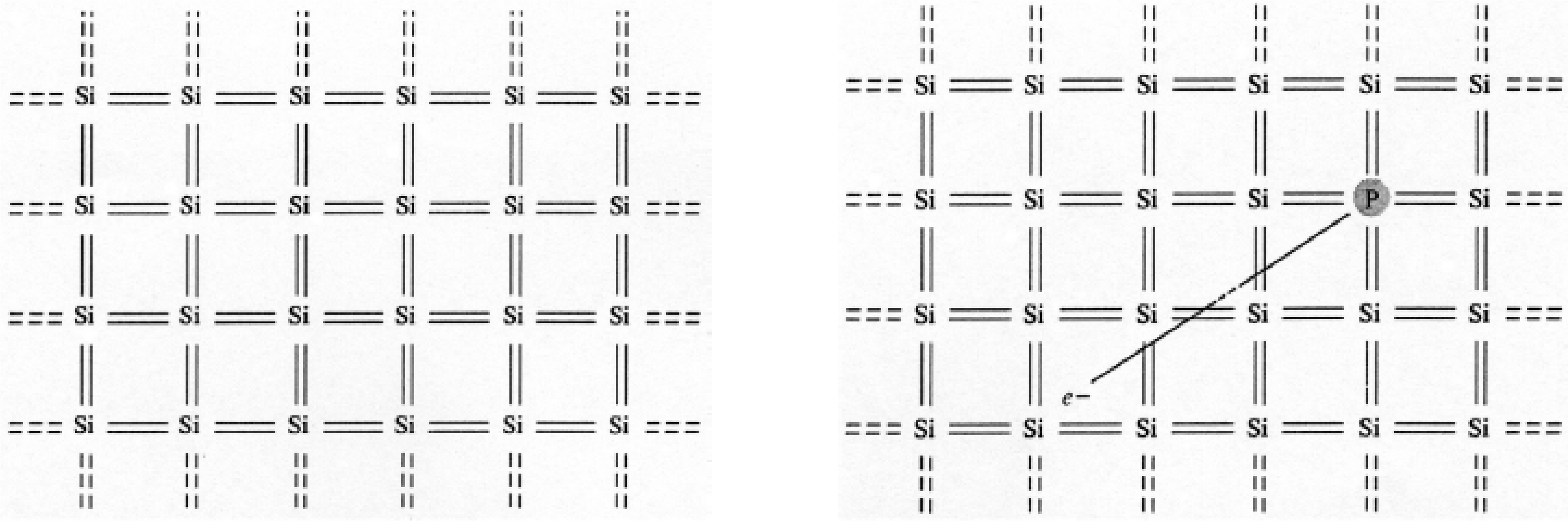
- Pentavalent impurities such as phosphorus, arsenic, antimony, and bismuth have 5 valence electrons.
- When phosphorus impurity is added to Si, every phosphorus atom's four valence electrons are locked up in covalent bond with valence electrons of four neighboring Si atoms.
- However, the 5th valence electron of phosphorus atom does not find a binding electron and thus remains free to float.
- When a voltage is applied across the silicon-phosphorus mixture, free electrons migrate toward the positive voltage end.
- When phosphorus is added to Si to yield the above effect, we say that Si is doped with phosphorus. The resulting mixture is called N-type silicon (N: negative charge carrier silicon).
- The pentavalent impurities are referred to as donor impurities.



Semiconductor

Donor Atoms and Energy Levels

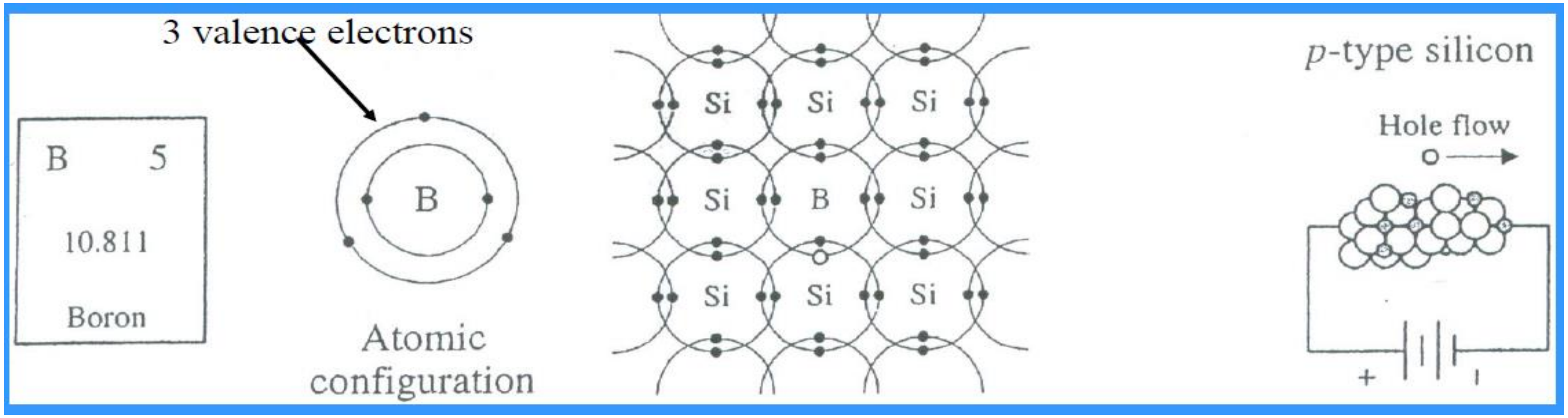
The real power of semiconductors is realized by adding controlled amounts of a specific dopant, or impurity atoms. The doped semiconductor is called an **extrinsic** material. Doping is the primary reason that we can fabricate various semiconductor devices.



Add **a group V element**, such as phosphorus, to silicon as a substitutional impurity. The group V element has five valence electrons. Four of these will contribute to the covalent bonding with silicon atoms, leaving the fifth more loosely bound to the phosphorus atom.

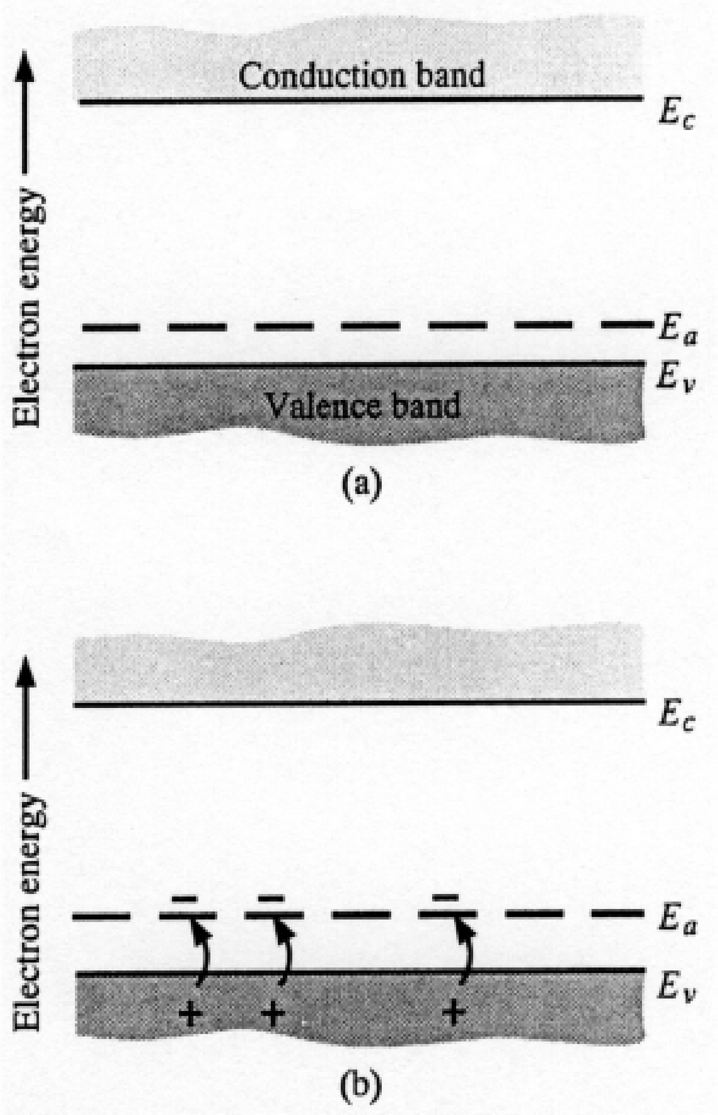
P-Type Silicon

- Trivalent impurities e.g., boron, aluminum, indium, and gallium have 3 valence electrons.
- When boron is added to Si, every boron atom’s three valence electrons are locked up in covalent bond with valence electrons of three neighboring Si atoms.
- However, a vacant spot “hole” is created within the covalent bond between one boron atom and a neighboring Si atom. The holes are considered to be positive charge carriers.
- When a voltage is applied across the silicon-boron mixture, a hole moves toward the negative voltage end while a neighboring electron fills in its place.
- When boron is added to Si to yield the above effect, we say that Si is doped with boron. The resulting mixture is called P-type silicon (P: positive charge carrier silicon).
- The trivalent impurities are referred to as acceptor impurities.



Extrinsic semiconductor

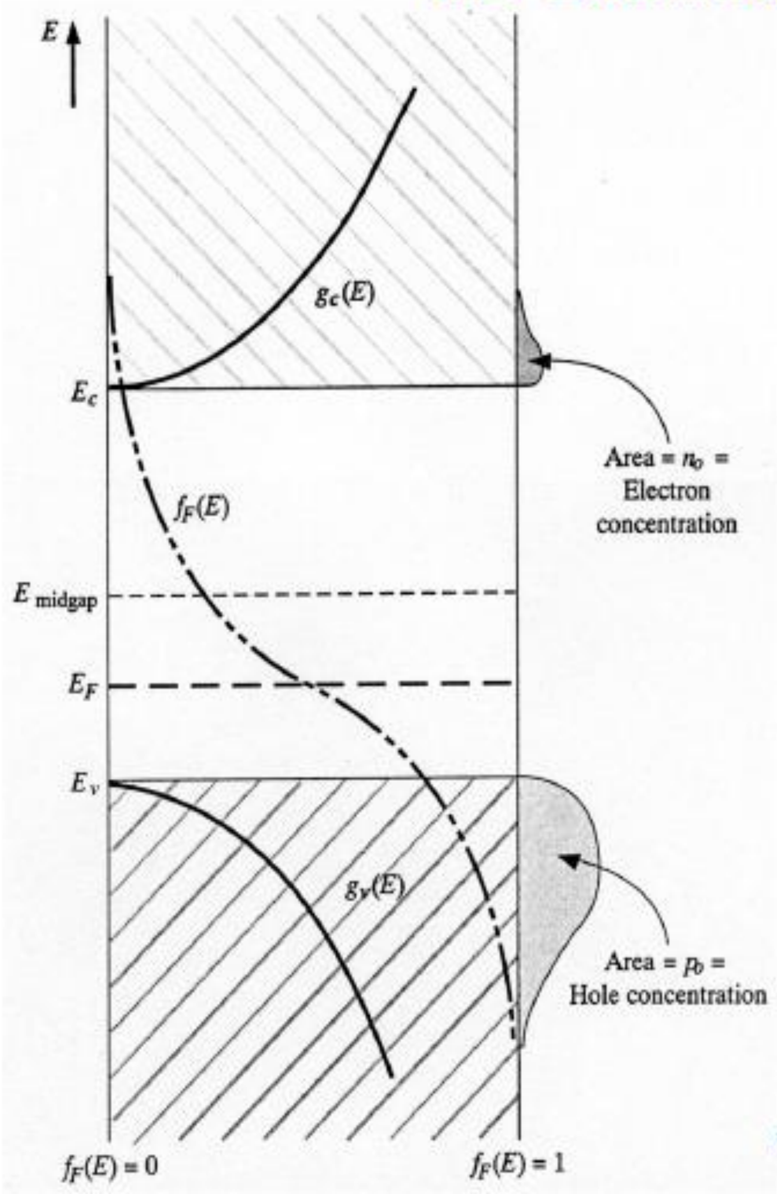
Acceptor Atoms and Energy Levels



The holes can move through the crystal to generate a current, while the negatively charged boron atoms are fixed in the crystal. The group III atom accepts an electron from the valence band and so is referred to as **an acceptor impurity atom**. The acceptor atoms can generate holes in the valence band without generating electrons in the conduction band. This type of semiconductor materials is referred to as **a p-type semiconductor**.

An extrinsic semiconductor will have either a preponderance of electrons (n-type) or a preponderance of holes (p-type).

Equilibrium Distribution of Electrons and Holes in the Extrinsic Semiconductor



In general, when $E_F < E_{midgap}$, the density of electrons is smaller than that of holes, and the semiconductor is **p-type**.

$$\boxed{\begin{aligned} n_0 &= N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right] \\ p_0 &= N_v \exp\left[\frac{-(E_F - E_v)}{kT}\right] \end{aligned}}$$

The above are **general equations for n_0 and p_0 in terms of the Fermi energy**. The values of n_0 and p_0 will change with the Fermi energy, E_F.

Hole Drift Current Density

The drift current density due to holes is:

$$J_{\mathrm{p|drf}} = (ep)v_{\mathrm{dp}}$$

The equation of motion for a hole in the presence of an electric field is:

$$F = m_{\mathrm{p}}^{*}a = eE$$

If the electric field is constant, then we expect the velocity to increase linearly with time. **However, charged particles in semiconductors are involved in collisions with ionized impurity atoms and with thermally vibrating lattice atoms. When the collision happens, the charged particle loses most or all of its energy.** It will begin to accelerate and gain energy until it is again involved in a scattering process. **Throughout this process, the particle will gain an average drift velocity, which, for low electric fields, is directly proportional to the electric field.**

$$v_{\mathrm{dp}} = \mu_{\mathrm{p}}E \qquad \textbf{Then} \qquad \boxed{J_{\mathrm{p|drf}} = (ep)v_{\mathrm{dp}} = e\mu_{\mathrm{p}}pE}$$

Electron Drift Current Density

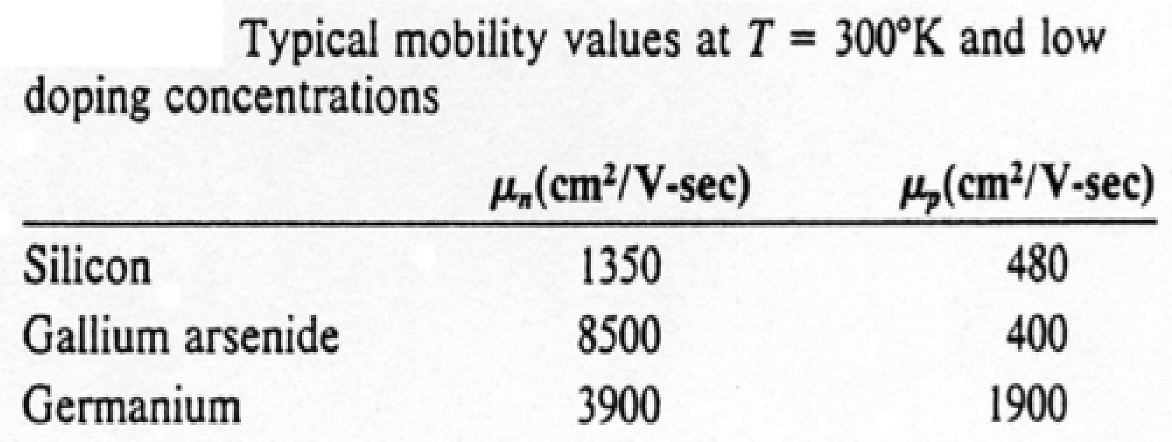
The same discussion holds for electrons:

$$J_{\mathrm{n|drf}} = (-en)v_{\mathrm{dn}} \qquad v_{\mathrm{dn}} = -\mu_{\mathrm{n}} E$$

$$\boxed{J_{\mathrm{n|drf}} = (-en)(-\mu_{\mathrm{n}} E) = e\mu_{\mathrm{n}} n E}$$

The conventional drift current due to electrons is also in the same direction as the applied electric field even though the electron movement is in the opposite direction.

Electron and hole mobilities are functions of temperature and doping concentrations.



Typical mobility values at T = 300°K and low doping concentrations

	μ_n(cm^2/V-sec)	μ_p(cm^2/V-sec)
Silicon	1350	480
Gallium arsenide	8500	400
Germanium	3900	1900

Total Drift Current Density

The total drift current density is the sum of the individual electron and hole drift current densities:

$$J_{\mathrm{drf}} = e(\mu_{\mathrm{n}} n + \mu_{\mathrm{p}} p)E$$

Calculate the drift current density of a Ge sample at $T = 300$ K with $N_{\mathrm{d}} = 0$, $N_{\mathrm{a}} = 10^{16}$ cm^{-3}, $n_{\mathrm{i}} = 2.4 \times 10^{13}$ cm^{-3}, $\mu_{\mathrm{n}} = 3900$ cm^2/(V·s), and $\mu_{\mathrm{p}} = 1900$ cm^2/(V·s) under an applied electric field of $E = 50$ V/cm.

The semiconductor is p-type:

$$p = \frac{N_{\mathrm{a}} - N_{\mathrm{d}}}{2} + \sqrt{\left(\frac{N_{\mathrm{a}} - N_{\mathrm{d}}}{2}\right)^2 + n_{\mathrm{i}}^2} = 10^{16}\mathrm{cm}^{-3}$$

$$n = \frac{n_{\mathrm{i}}^2}{p} = \frac{(2.4 \times 10^{13})^2}{10^{16}} = 5.76 \times 10^{10}\mathrm{cm}^{-3}$$

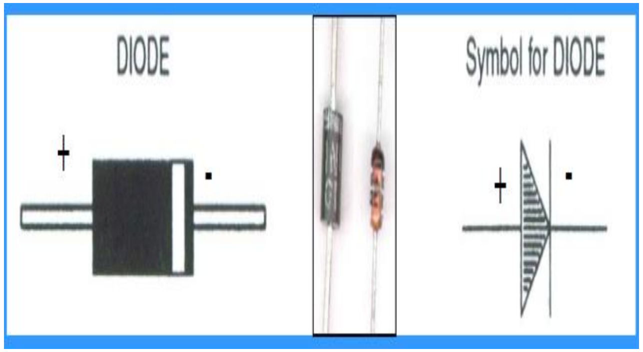
The drift current will be due primarily to the majority carrier in an extrinsic semiconductor.

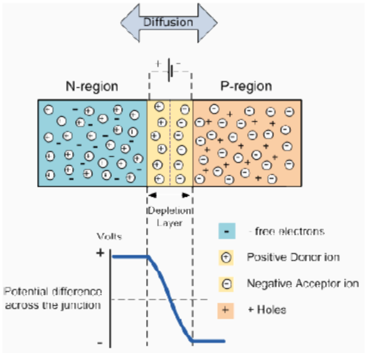
$$J_{\mathrm{drf}} = e(\mu_{\mathrm{n}} n + \mu_{\mathrm{p}} p)E \approx e\mu_{\mathrm{p}} pE$$

$$J_{\mathrm{drf}} = (1.602 \times 10^{-19})(1900)(10^{16})(50) = 152\mathrm{A/cm}^2$$

Diode

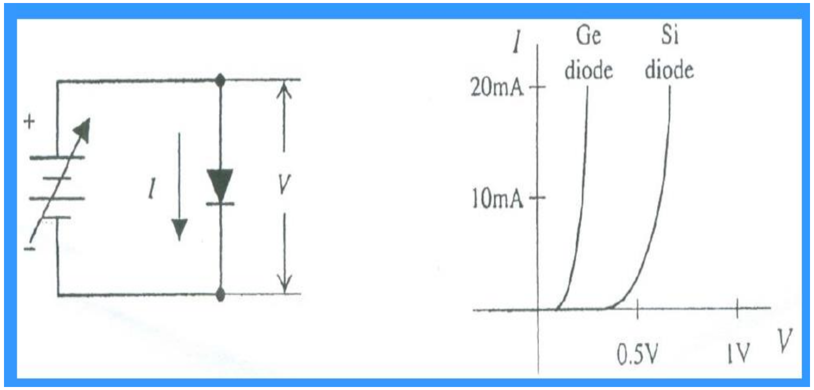
- A diode is a 2 lead semiconductor that acts as a one way gate to electron flow.
  - ✓ Diode allows current to pass in only one direction.
- A pn-junction diode is formed by joining together n-type and p-type silicon.
- In practice, as the n-type Si crystal is being grown, the process is abruptly altered to grow p-type Si crystal. Finally, a glass or plastic coating is placed around the joined crystal.
- The p-side is called anode and the n-side is called cathode.
- When the anode and cathode of a pn-junction diode are connected to external voltage such that the potential at anode is higher than the potential at cathode, the diode is said to be forward biased.
  - ✓ In a forward-biased diode current is allowed to flow through the device.
- When potential at anode is smaller than the potential at cathode, the diode is said to be reverse biased. In a reverse-biased diode current is blocked.

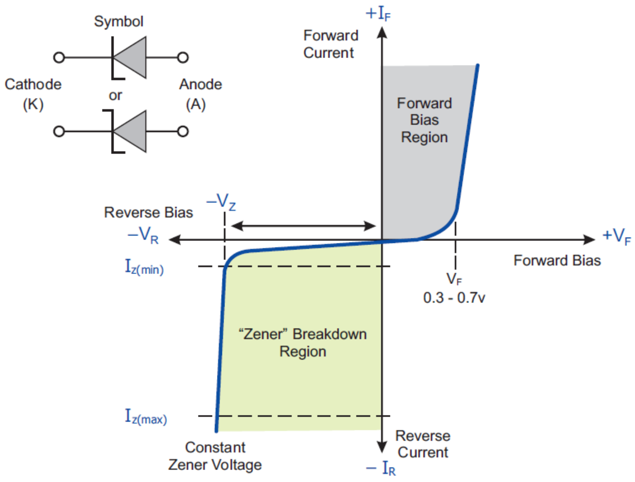




Diode: How it Works

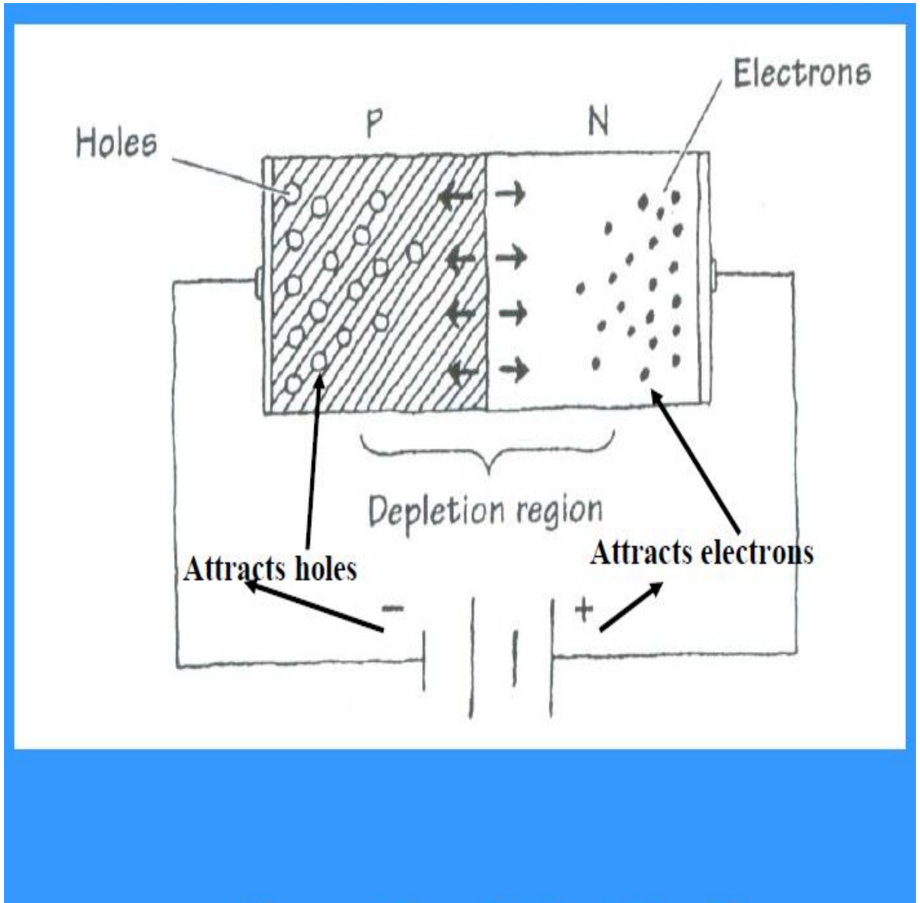
- A diode’s one-way gate feature does not work all the time.
- Typically for silicon diodes, an applied voltage of 0.6V or greater is needed, otherwise, the diode will not conduct.
- This feature is useful in forming a voltage-sensitive switch.
- I-V characteristics for silicon and germanium diodes is shown below





Diode: How it doesn’t Works

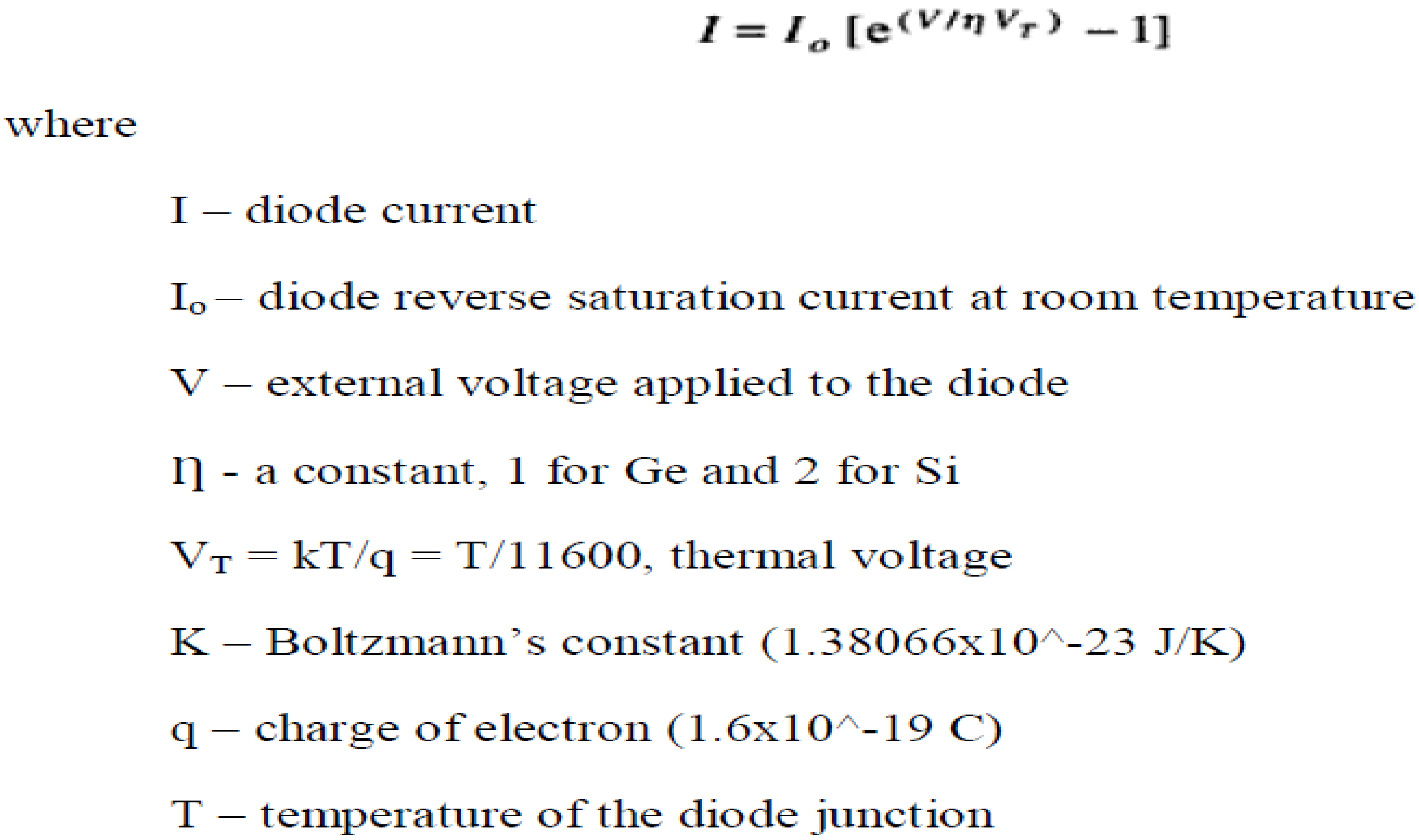
- When a diode is connected to a battery as shown, holes in the inside are forced to the left while electrons in the p-side are forced to the right.
- This results in an empty zone around the pn- junction that is free of charge carries creating a ***depletion region***.
- This depletion region acts as an insulator preventing current from flowing through the diode.
- When a diode is arranged in this way, it is said to be **reverse biased.**



Reverse-biased (“closed door”)

Diode current equations

DIODE CURRENT EQUATION The diode current equation relating the voltage V and current I is given by



$$I = I_o\,[e^{(V/\eta V_T)} - 1]$$

where

I – diode current

I_o – diode reverse saturation current at room temperature

V – external voltage applied to the diode

η - a constant, 1 for Ge and 2 for Si

$V_T = kT/q = T/11600$, thermal voltage

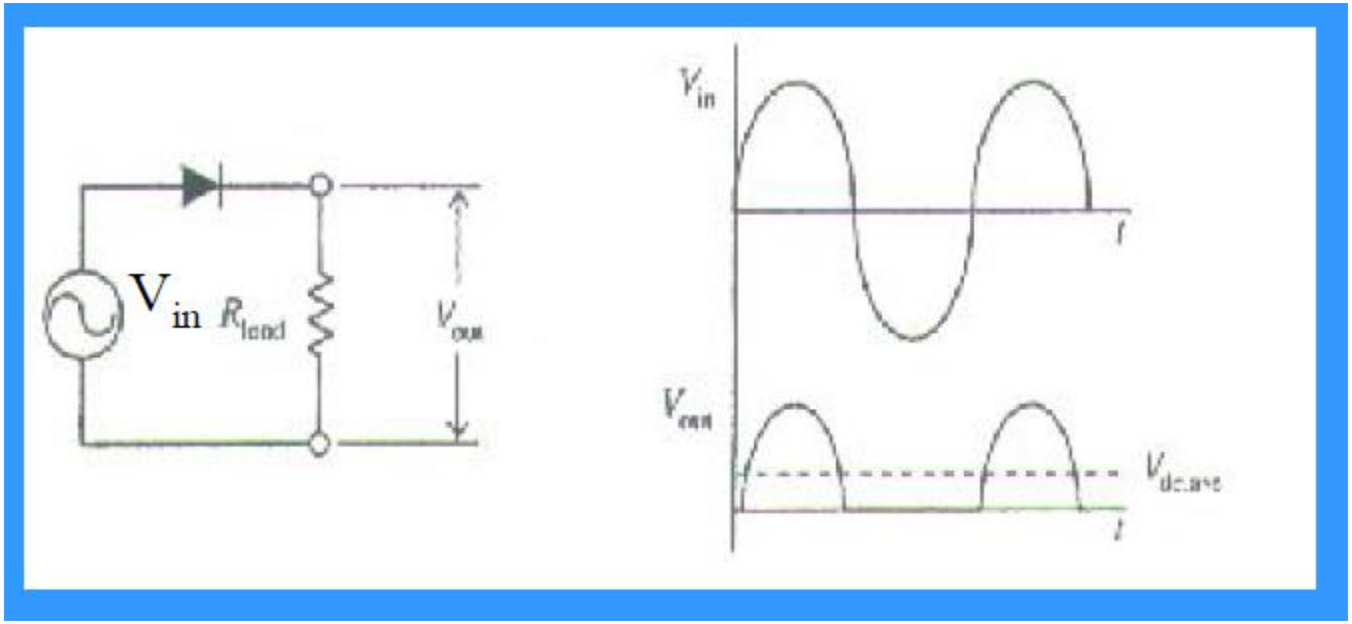
K – Boltzmann's constant (1.38066x10^-23 J/K)

q – charge of electron (1.6x10^-19 C)

T – temperature of the diode junction

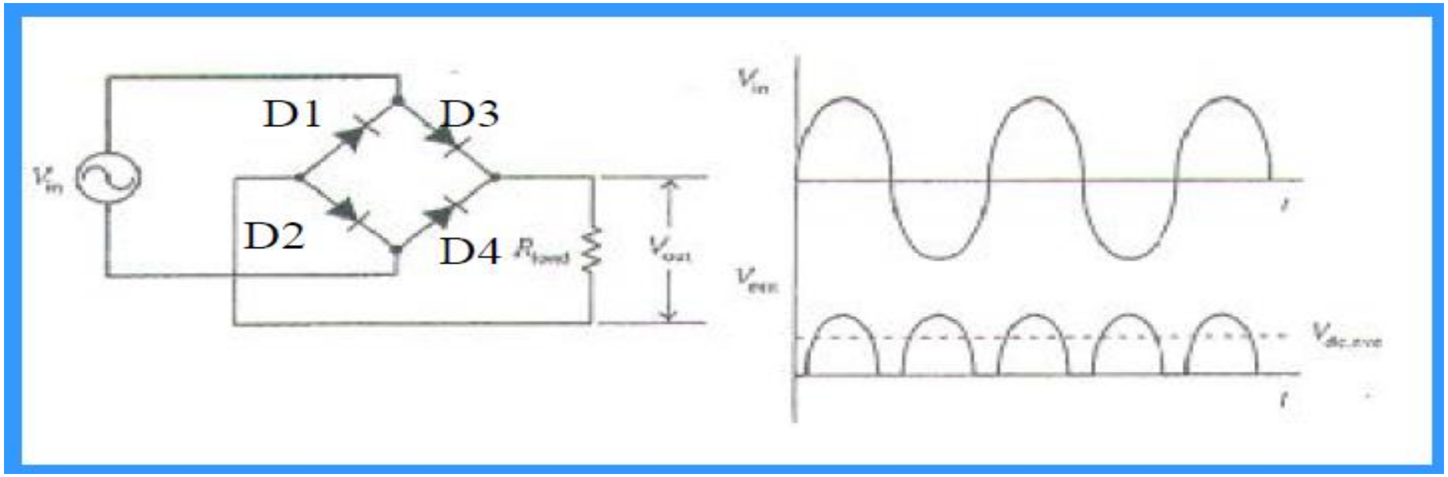
Diode Applications —Half Wave Rectifier

- Diode converts ac input voltage to a pulsed dc output voltage.
- Whenever the ac input becomes negative at diode’s anode, the diode blocks current flow.
- Output voltage become zero.
- Diode introduces a 0.6V drop so o/p peak is 0.6V smaller than the i/p peak.
  - ✓ The output frequency is same as the input frequency.



Diode Applications —Full wave rectifier

- A full-wave rectifier does not block negative swings in the input voltage, rather it transforms them into positive swings at the output
- To gain an understanding of device operation, follow current flow through pairs of diodes in the bridge circuit.
- It is easily seen that one pair (D3-Rout-D2) allows current flow during the positive half cycle of V_{in} while the other pair (D4-Rout-D1) allows current flow during the negative half cycle of V_{in}.
- Output voltage peak is 1.2V below the input voltage peak.
  - ✓ The output frequency is twice the input frequency.



Zener Diode

- A specially designed silicon diode which is optimized to operate in the breakdown region is known as as zener diode

❖ Characteristics of Zener Diode

(i) Its characteristics are similar to an ordinary diode with the exception that it has a sharp (or distinct) breakdown voltage called zener voltage V_Z .

(ii) It can be operated in any of the three region i.e. forward, eakage or breakdown. But usually it is operated in the breakdown region as shown in fig. below

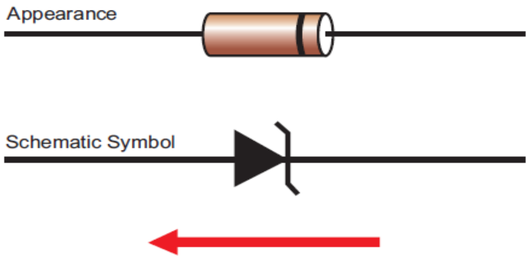
(iii) The voltage is almost constant (vz) over the operating region.

(iv) Usually, the value of vz at particular test current Izr is specified in the data sheet.

(v) During operation it will not burn as long as the external circuit limits the current flowing through it below the burn out value i.e I_Z (the maximum rated zener current).

❖ Application

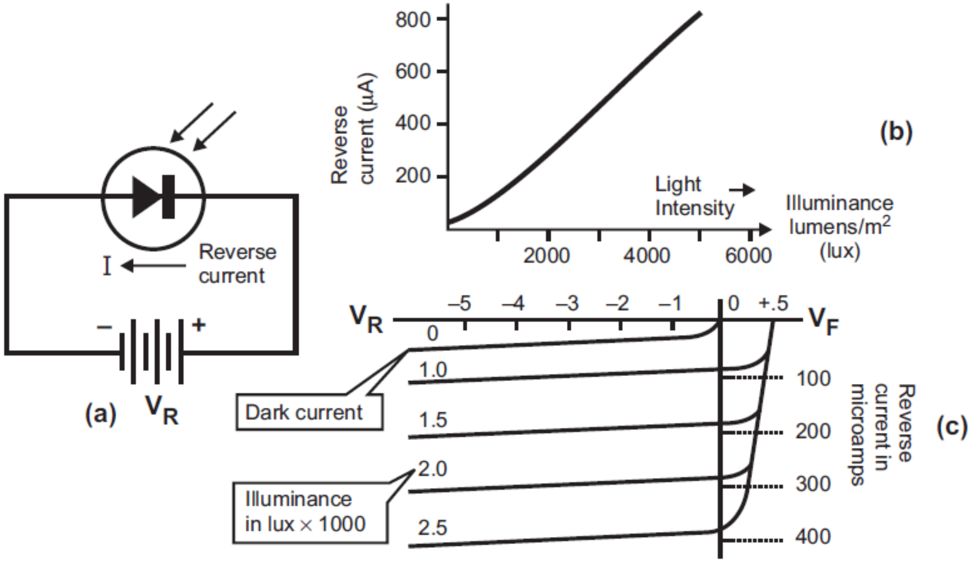
(i) Meter Protection
(ii) Voltage Regulator
(iii) Wave Shaping Circuit



Backwards Current Flow Too, but only Past the “Zener” Breakdown Voltage

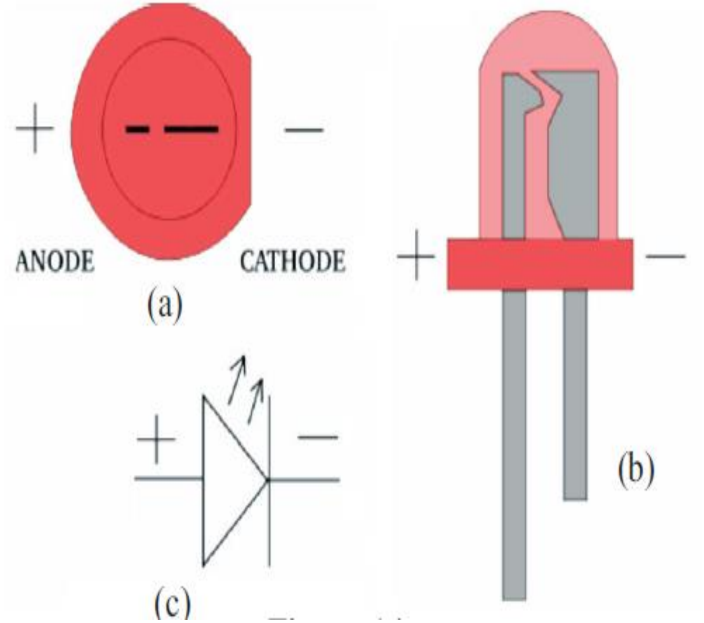
Photo Diode

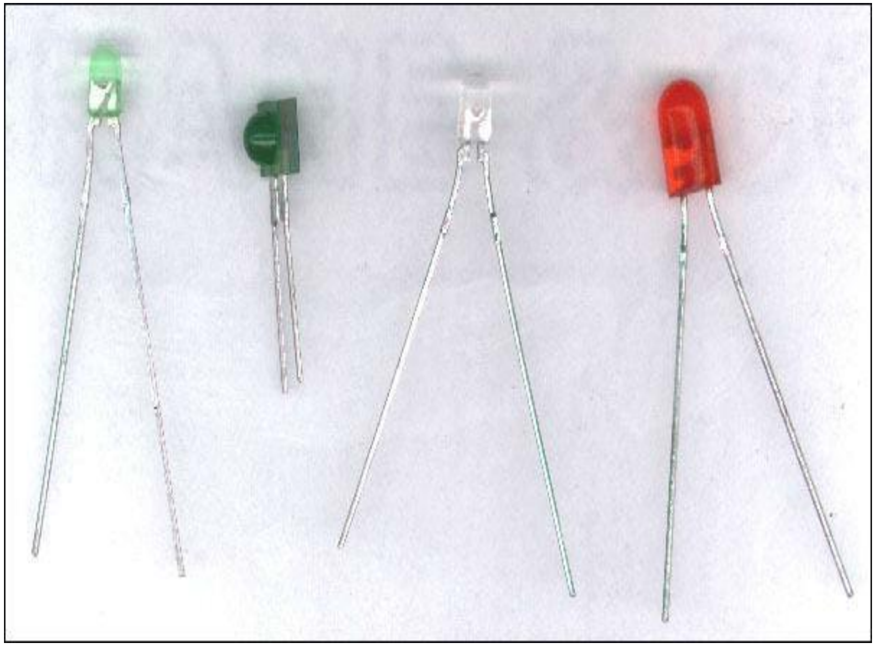
- When a diode is reverse biased a minute current flows in the diode due to minority carriers. These carriers exist because of thermal energy which dislodge the valence electrons from their orbits producing free electrons and holes in the process.
- When light energy falls on a pn junction, it also imparts energy to dislodge valence electron. In other words the amount of light striking on the junction can control the reverse current in a diode.
- A diode that is optimised for its sensitivity to light is known as photo diode



Light Emitting Diode

- When a diode is forward biased the potential barrier is lowered.
- The conduction band free electrons from n- region cross the barrier and enter the p-region, as these electrons enter the p- region they fall into the holes lying in the valence band. Hence they fall from a higher energy level to a lower energy level in the process they radiate energy.
- The LED are different. These are made of gallium arsenide phosphide (GaAsP) and gallium phosphide (GaP). In LED the energy is radiated in the form of light and hence they glow.





Thank you