# Physics of Semiconductor: Lecture # Lec 3


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# Today's agenda

- Types of Semiconductors
- Carrier concentration in intrinsic semiconductors
  - Concentration of electrons
  - Concentration of holes
- Fermi level and its variation with temperature
- Intrinsic carrier concentration
- Intrinsic conductivity & Determination of bandgap of semiconductor

# What you will learn today



At the end of this session you should be able to

- State the different types of semiconductors
- Define intrinsic semiconductors
- Derive the expression for electron/hole density in a intrinsic semiconductor

# Semiconductor

- ✓ The electrical conductivity of a pure semiconductor, known as intrinsic conductivity, is significantly low and is drastically influenced by temperature.
- ✓ As such pure semiconductors cannot be used in device fabrication.
- ✓ Through the technique of doping, the conductivity of a semiconductor can be increased in magnitude to a desired value and can be made independent of temperature in a certain temperature interval.
- ✓ Doped semiconductors are known as extrinsic semiconductors.
- ✓ The remarkable feature of extrinsic semiconductors is that current is transported in them by two different charge carriers, electrons and holes; and through two different processes, drift and diffusion.
- ✓ Extrinsic semiconductors are widely used in fabrication of solid-state devices.
- ✓ An understanding of the mechanism of conduction in intrinsic and extrinsic semiconductors helps us understand the working of solid-state devices

# Types of semiconductor

## SEMICONDUCTOR

**Intrinsic** | **Extrinsic**

- ✓ **Chemically pure semiconductors are known as intrinsic semiconductors.**
- ✓ **A semiconductor is considered to be pure when there is less than one impurity atom in a billion host atoms.**

In a real crystal, the concentration of atoms N is given by

$$N = \frac{N_A \rho}{M} \qquad (30.1)$$

where $N_A$ is the Avogadro number, ρ the density and $M$ the atomic weight of the material.

Using the data for silicon into equ. (30.1), we obtain

$$N = \frac{\left(6.02\times10^{26}\ \text{atoms/k.mol}\right)\left(2330\ \text{kg/m}^3\right)}{28.09\ \text{kg / k.mol}}$$

or

$$N = 5 \times 10^{28}\ \text{atoms/m}^3 \qquad (30.2)$$

The valence and conduction bands of silicon crystal contain 2N energy levels each. Therefore, the number of energy levels in each band is $10^{29}$ levels/m$^3$. In other words, there are $2\times10^{29}$ states/m$^3$. The number of valence electrons available in the silicon crystal is $4N = 2\times10^{29}$ electrons/m$^3$. These electrons occupy the valence band and leave the conduction band vacant.

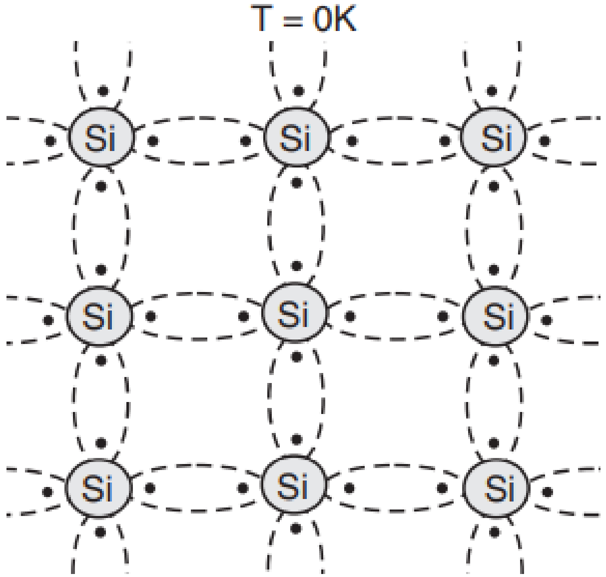
# Intrinsic semiconductor



**At 0K an Intrinsic Semiconductor Behaves as a Perfect Insulator**

At 0K and temperatures close to 0K, all valence electrons are locked in covalent bonds (Fig. 30.2 a) and spend most of the time between neighbouring atoms. Since all the valence electrons are engaged in covalent bonds, the bonds are complete. The energy available at 0K is not sufficient to break the covalent bonds.

**Therefore, there are no free electrons within the material at absolute zero. Consequently, the semiconductor at 0K cannot conduct electricity and acts as a perfect insulator**

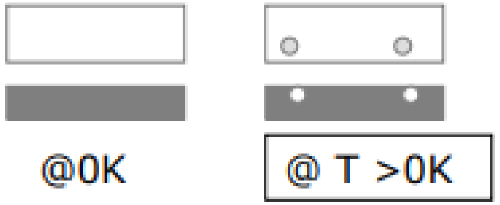


# Intrinsic semiconductor



Pure semiconductors characterized by

- conductivity at higher temperatures due to thermally (electrically/ optically) generated electron-hole pairs



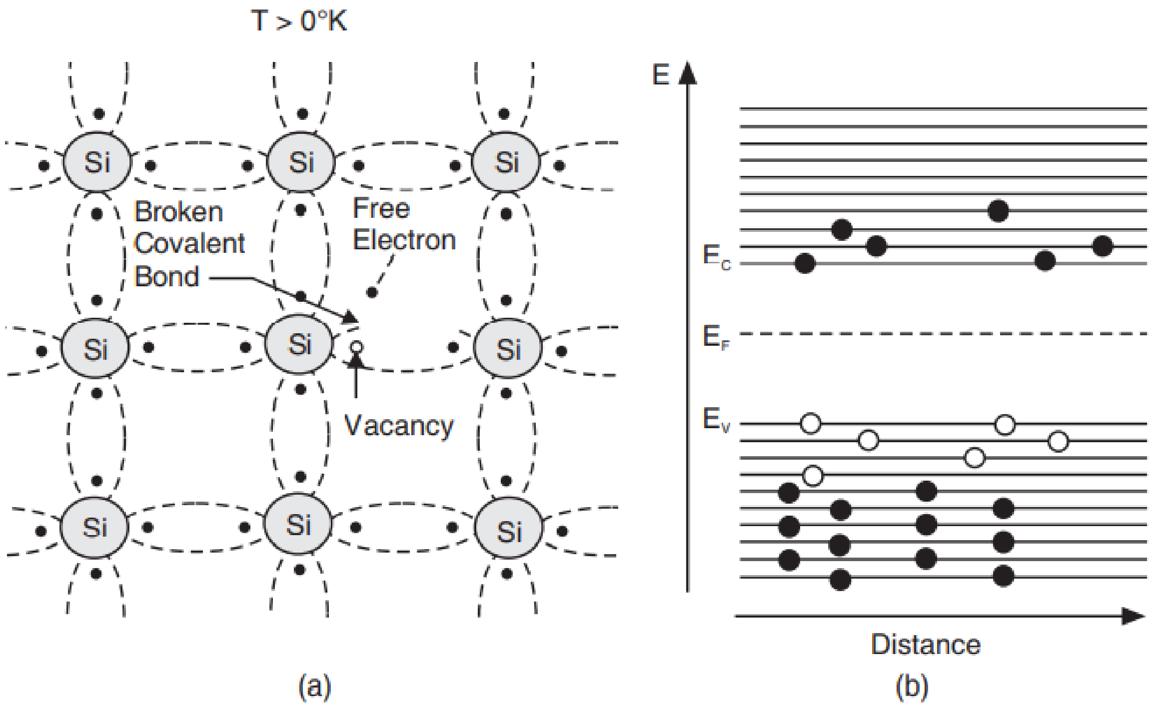

At temperatures above absolute zero, the finite thermal energy causes each atom in the crystal to vibrate about its mean position.

When the vibrations become violent, some of the electrons acquire sufficient energy and break away from covalent bonds.

Whenever a covalent bond is ruptured by thermal energy, a valence electron becomes free.

The higher the temperature, the more covalent bonds are broken.

The electrons liberated from bonds move randomly in the void spaces between the atoms in the crystal.




If an electric field is applied, these free electrons cause electrical conduction.

# Intrinsic semiconductor

- From the energy band point of view, it means that some of the electrons in the valence band convert part of their thermal energy into potential energy.
- Those electrons which acquire energy equal to or in excess of the band gap energy are excited to the conduction band.
- Thus, the band gap energy is the minimum amount of energy required to excite an electron from valence band to conduction band.
- The number of electrons excited to the conduction band depends on the amount of thermal energy received by the crystal.
- For example, the concentration of broken bonds in a silicon crystal at 300K is $1.5\times10^{16}$ /$m^3$.
- Thus, there are $1.5\times10^{16}$ electrons/$m^3$ in the conduction band at 300K.
- In fact, the conduction band can accommodate $2\times10^{29}$ electrons/$m^3$ and hence it is partially filled.

# Intrinsic semiconductor

- When an electron from the valence band jumps to the conduction band, an empty state (quantum vacancy) arises in the valence band.
- In silicon crystal at 300K, $1.5\times10^{16}$ vacant states/$m^3$ appear in the valence band, which are very small in number compared to the number of electrons remained in the band.
- Thus, now both the bands are partially filled.
- The electrons in the conduction band and the electrons in the valence band can be excited to upper vacant levels within the respective bands.
- Therefore, if an electric field is applied, these electrons can move into higher vacant levels and current flows in the crystal at ordinary temperatures.
- The motion of valence electrons in the valence band is customarily described in terms of a fictitious particle called hole which is bequeathed with a positive charge +e and a mass $m_h$ equal to that of an electron.
- In pure semiconductors all available charge carriers, electrons and holes, arise due to thermally ruptured bonds and these thermally generated electron-hole pairs cause electrical conduction.
- Thermal generation is an intrinsic process.

# Intrinsic semiconductor

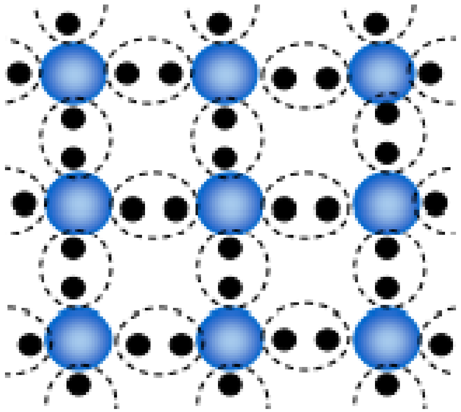
**Definition: An intrinsic semiconductor is a semiconductor crystal in which electrical conduction arises due to thermally excited electrons and holes**

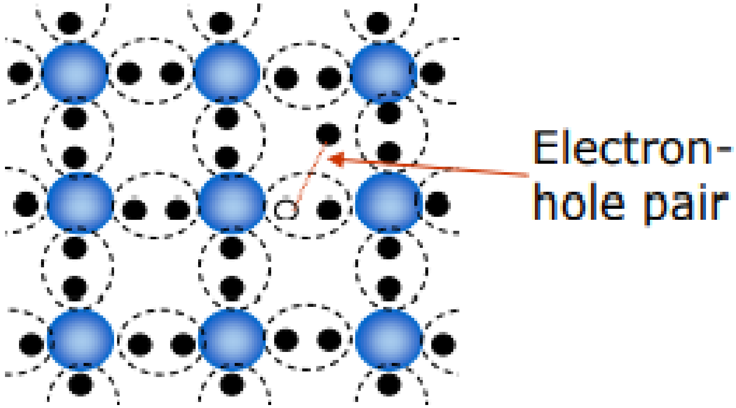
no. density of electrons, n = no. density of holes, p

$$\boxed{n = p = n_i}$$

*(Purity - <1 impurity in 1 billion host atoms)*

Could be elemental (eg: Si, Ge ) or compound (GaAs, InP, CdTe)





# Bandgap

- The band gap energy $E_g$ is the minimum amount of energy required for breaking a covalent bond.
- It is the minimum amount of energy required to excite an electron from valence band to conduction band.
- Also, it is the minimum amount of energy required to convert a bound electron into a free electron.
- The energy required to break a covalent bond in a germanium crystal is about 0.72 eV at 300K and that in silicon is 1.12 eV

# Concept of hole

Helps to differentiate 2 types of electron motions possible in a semiconductor above 0K.

- Motion of high energy "free" electrons in the conduction band

  Where "free" implies not involved in any covalent bonds –sees constant potential.

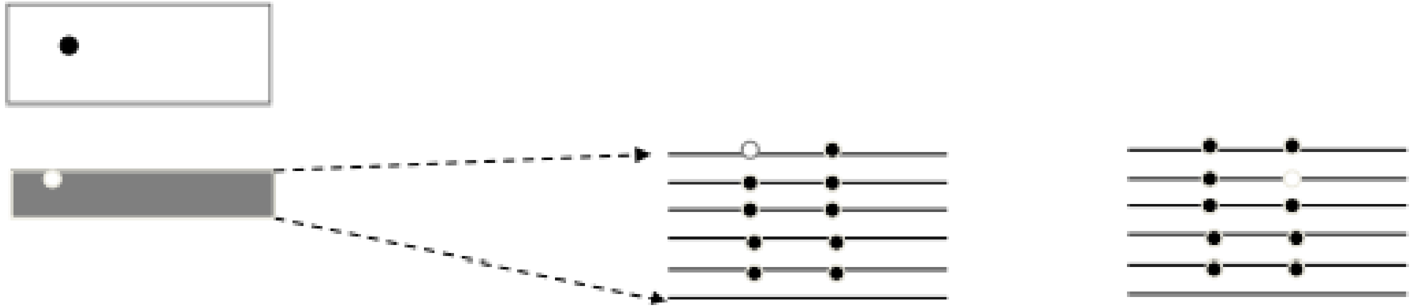
-Motion of Electron

- Motion of low energy electrons in the valence band

  (an electron at lower energy level undergoes transition to upper vacant level within the valence band-sees periodic potential)

- Motion of Hole

Motion of large no. of electrons in one direction is equivalent to motion of single hole (vacancy) in the opposite direction



# Generation and recombination

In semiconductors a single event of covalent bond breaking leads to the generation of two charge carriers, an electron in the conduction band and a hole in the valence band (Fig. 30.3). The electron and hole are produced simultaneously as a pair and the process is called **electron-hole pair generation**. The process may be represented as

$$\text{Covalent bond} + \text{Thermal energy} \xrightarrow{\text{Rupture}} (\text{Electron} + \text{Hole})\ \text{pair}$$

In the process of generation, a covalent bond is broken and a bound electron is transformed into a free electron. Thermal energy is one of the agents which causes pair generation. Another agent is optical illumination. At any temperature $T$, the number of electrons generated would be equal to the number of holes produced. If $n$ denotes the concentration of electrons in the conduction band and $p$ is the concentration of holes in the valence band, then

$$n = p \tag{30.7}$$

# Generation and recombination

It is likely that the electron in conduction band may lose its energy due to collision with other particles in the lattice and fall into the valence band (Fig. 30.6). When a free electron falls into valence band, it merges with a hole. This process is called *recombination*. When a recombination event occurs, the free electron enters a ruptured covalent bond and re-bridges it.

$$\text{Electron} + \text{Hole} \rightarrow \text{Covalent bond} + \text{Energy}\uparrow$$

- **Therefore, recombination means that a free electron transforms into a valence electron and that a ruptured covalent bond is re-bridged.**
- **In the process the electron hole pair disappears, and energy is released.**
- **The released energy is mainly in the form of thermal energy.**

# Intrinsic semiconductor- carrier concentration

- **With an increase in temperature covalent bonds are broken in an intrinsic semiconductor and electron-hole pairs are generated.**

- **We expect that a large number of electrons can be found in the conduction band and similarly, a large number of holes in the valence band.**

- **As electrons and holes are charged particles, they are together are called charge carriers.**

- **Carrier concentration is the number of electrons in the conduction band per unit volume (n) and the number of holes in the valence band per unit volume (p) of the material.**

- **Carrier concentration is also known as the density of charge carriers.**

- **We would like to calculate the electron concentration, n, in the conduction band and the hole concentration, p, in the valence band.**

# Intrinsic semiconductor- Calculation of electron density

## 30.8.1 Calculation of Electron Density

Let $dn$ be the number of electrons whose energy lies in the energy interval $E$ and $E + dE$ in the conduction band. Then,

$$dn = Z(E)f(E)dE \tag{30.20}$$

where $Z(E)\,dE$ is the density of states in the energy interval $E$ and $E + dE$ and $f(E)$ probability that a state of energy is occupied by an electron.

The electron density in the conduction band is given by integrating the above equation between the limits $E_C$ and $\infty$. $E_C$ is the energy corresponding to the bottom edge of the conduction band and $\infty$ the energy corresponding to the top edge of the conduction band. As the probability of electrons occupying upper levels of conduction band $f(E)$ readily approaches zero for higher energies, the upper limit, namely the top of conduction band is taken as $\infty$. Thus,

$$n = \int_{E_C}^{\infty} Z(E)\,f(E)\,dE \tag{30.21}$$

The density of states in the conduction band is given by

# Intrinsic semiconductor- Calculation of electron density

$$Z(E)dE = \frac{4\pi}{h^3}\left(2m_e^*\right)^{3/2} E^{1/2}dE \quad \text{for } E > E_C. \tag{30.22}$$

The bottom edge of the conduction band $E_C$ corresponds to the potential energy of an electron at rest. Therefore, $(E - E_C)$ will be the kinetic energy of the conduction electron at higher energy levels. Hence, equ. (30.22) is to be modified as follows.

$$Z(E)dE = \frac{4\pi}{h^3}\left(2m_e^*\right)^{3/2}\left(E - E_C\right)^{1/2} dE \tag{30.23}$$

The probability of an electron occupying an energy level is given by

$$f(E) = \frac{1}{1+\exp\left[\left(E-E_F\right)/kT\right]}$$

When the number of particles is very small compared to the available energy levels, the probability of an energy state being occupied by more than one electron is very small. Such a situation is valid when $(E - E_F) >> 3kT$. Under this circumstance, the number of available states in the conduction band is far larger than the number of electrons in the band. Then, Fermi-Dirac function can be approximated to Boltzmann function,

$$f(E) = \exp[-(E - E_F)/kT]. \tag{30.24}$$

# Intrinsic semiconductor- Calculation of electron density

Using the equations (30.23) and (30.24) into (30.21), we obtain

$$\therefore \quad n = \frac{4\pi}{h^3}\left(2m_e^*\right)^{3/2}\int_{E_C}^{\infty}(E-E_C)^{1/2}e^{-(E-E_F)/kT}dE \qquad (30.25)$$

or

$$n = \frac{4\pi}{h^3}\left(2m_e^*\right)^{3/2}e^{(E_F-E_C)/kT}\int_{E_C}^{\infty}(E-E_C)^{1/2}e^{-(E-E_C)/kT}dE \qquad (30.26)$$

The integral in eq. (30.26) is of the standard form which has a solution of the following form.

$$\int_0^{\infty}x^{1/2}e^{-ax}dx = \frac{\sqrt{\pi}}{2a\sqrt{a}}$$

where $a = 1/kT$ and $x = (E - E_C)$.

$$\therefore \quad n = \frac{4\pi}{h^3}\left(2m_e^*\right)^{3/2}e^{(E_F-E_C)/kT}\left[\frac{\sqrt{\pi}}{2}(kT)^{3/2}\right] \qquad (30.27)$$

Rearranging the terms, we get

$$n = 2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{3/2}e^{-(E_C-E_F)/kT} \qquad (30.28)$$

# Intrinsic semiconductor- Calculation of electron density

The above equation is the expression for the **electron concentration** in the conduction band of an intrinsic semiconductor.

Designating
$$N_C = 2\left[\frac{2\pi m_e^* kT}{h^2}\right]^{3/2} \quad (30.29)$$

in the above equation, we obtain
$$n = N_C e^{-(E_C - E_F)/kT} \quad (30.30)$$

$N_C$ is a temperature dependent material constant known as the **effective density of states** in the conduction band. In silicon at 300 K, $N_C = 2.8 \times 10^{25}/\text{m}^3$.

**The importance of the relation (30.30) is that it relates the equilibrium electron concentration to a single variable, namely the Fermi level $E_F$. Therefore, electron concentration is specified, if $E_F$ is specified**

# Summary

Types of semiconductors

(i) Intrinsic (Elemental & Compound)
(ii) Extrinsic

Intrinsic semiconductors are pure semiconductors characterized by completely filled valence shell at 0K ,with conductivity at higher temperatures due to thermally or optically generated electron-hole pairs .($n=p=n_i$)

Conductivity in semiconductors is due to both holes (electrons in valence band) and electrons (in conduction band)

Electron density available for conduction, $\boxed{n = N_c\, e^{-(E_c - E_F)/kT}}$