2021

Chapter Two

Transport Phenomena in Semiconductor

Chapter Two: Transport Phenomena in Semiconductor.

2.1 Electrical Connectivity

In semiconductor, the conduction band electron and valence band hole participate in electrical conduction. To obtain expression for electrical conductivity consider an intrinsic semiconductor bar which is connected to external battery as shown in Fig. 2.1.

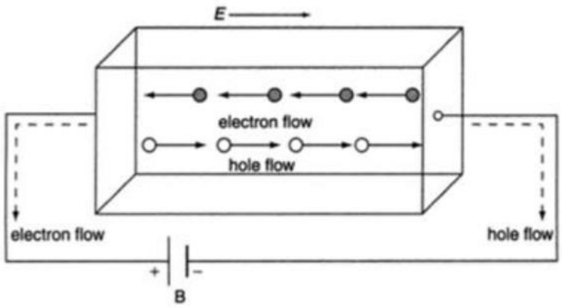


Fig. 2.1 Semiconductor bar connected to the battery.

The electric field exist along x direction. The field accelerate electrons (conduction electrons) along negative x direction. They starts moving with a constant velocity called **Drift velocity (v_d)** .

The drift velocity produced per unit electric field is called **mobility (μ)** , Thus :

$$\mu = v_d \ / \ \mathcal{E}$$

or

$$v_d = \mu \, \mathcal{E} \qquad \text{......(2.1)}$$

The unit of mobility (μ) is (m^2/volt.sec).

- **Drift Current Density (J_d):**

Drift current is the electric current, or movement of charge carriers, which is due to the applied electric field. When an electric field is applied across a semiconductor material, a current is produced due to the flow of charge carriers.

In order to find the current density of electrons, let the concentration of electrons are 'n', charge is 'e' and drift velocity is 'v_d' , then :

$$J_d = n\, e\, v_d \qquad \text{......(2.2)}$$

Substituting eqn. (2.1) of drift velocity in eqn. (2.2), we can write:

$$J_d = n\, e\, \mu\, \mathcal{E} \qquad \text{......(2.3)}$$

Also the drift current density (J_d) is the amount of current per unit area:

$$J_d = I/A \qquad \text{......(2.4)}$$

Where :
I : the current passing through the semiconductor.
A : is across-section area in (meter).

- **Conductivity (σ) :**

Conductivity is a measure of its ability to conduct electricity. Calculated as the ratio of the current density in the material to the electric field which causes the flow of current (Ohms law).

From Ohms law :

$$J_d = \sigma\, \mathcal{E} \qquad \text{.....(2.5)}$$

From eqn. (2.3) and eqn. (2.5), we can write:

$$J_d = \sigma\, \mathcal{E} = n\, e\, \mu\, \mathcal{E}$$

Then :

$$\sigma = n\, e\, \mu \qquad \text{......(2.6)}$$

The unit of conductivity (σ) is Siemens per meter (S/m).

The **conductivity (σ)** is inversed proportional to the **Resistivity (ρ)** :

$\sigma \;\alpha\; 1/\rho$

Example:

A silicon crystal having a cross-sectional area of 0.001cm^2 and a length of 10^{-3}cm is connected at it`s ends with 10v battery at temperature 300^oK, when the current is 100mA. Find the resistivity and the conductivity?

Solution:

$$J = \sigma E \Rightarrow \sigma = \frac{J}{E} = \frac{I/A}{V/L} = \frac{100\times10^{-2}/0.001\times10^{-4}}{10/(10^{-3}\times10^{-2})} = 10\,(\Omega.m)^{-1}$$

$$\rho = \frac{1}{\sigma} = \frac{1}{10} = 0.1(\Omega.m)$$

Example:

1μA current passing through an intrinsic silicon bar has 3mm length and 50$\times$ 100 μm^2 cross-section. The resistivity of the bar is 2.3 $\times$ 10^5 Ω.cm at 300^oK. find the voltage across the bar?

Solution:

$J = \sigma E$, $J = I / A$, $\sigma = 1/\rho$

$I / A = (1/\rho) * E$

$E = (I * \rho) / A$

$= (1 * 10^{-6} * 2.3 * 10^5 * 10^{-2}) / (50 * 10^{-6} * 100 * 10^{-6})$

$= 4.6 * 10^5$ V / m .

$V = E * L$

$= 4.6 * 10^5 * 3 * 10^{-3} = 1380$ V .

Example:

Given (1.8×10^{-8} Ω.m) is the resistively for a copper bar with length (2cm). The applied voltage on this bar is (10 V) and the conduction electron density is (8.5×10^{28} m^{-3}). Find the mobility and drift velocity?

Solution:

$\sigma = ne\mu = 1/\rho \Rightarrow \mu = 1/ne\rho$

$\mu = 1/(8.5\times10^{28}\times1.6\times10^{-19}\times1.8\times10^{-8}) = 4.08\times10^{-3}\ m^2/V.s$

2.2 Intrinsic Semiconductor and Extrinsic Semiconductor

The semiconductor is divided into two types:

2.2.1 Intrinsic (pure) semiconductor

The pure form of the semiconductor is known as the Intrinsic semiconductor. The conductivity of this type becomes zero at room temperature.

In a **pure (intrinsic) semiconductor** the number of holes is equal to the number of free electrons. Thermal agitation continues to produce new hole-electron pairs, whereas other hole-electron pairs disappear as a result of recombination. The hole concentration *p* must equal the electron concentration *n*, so that

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

where: n_i is called the intrinsic concentration.

example:

$$Ge_{32}: \underbrace{1S^2}_{n=1}\ \underbrace{2S^2\ 2P^6}_{n=2}\ \underbrace{3S^2\ 3P^6\ 3d^{10}}_{n=3}\ \underbrace{4S^2\ 4P^2}_{n=4}$$

الغلاف الاخير
يحتوي على الكترونات التكافؤ

Germanium (Ge) is the most important semiconductor used in electronic devices. The crystal structure of Ge is shown in Fig. 2.2

عند درجة حرارة 0 سيليزي:

جميع الالكترونات في حزمة التكافؤ مكونة اواصر تساهمية ولاتوجد الكترونات حرة فتعتبر بذلك المادة عازلة.

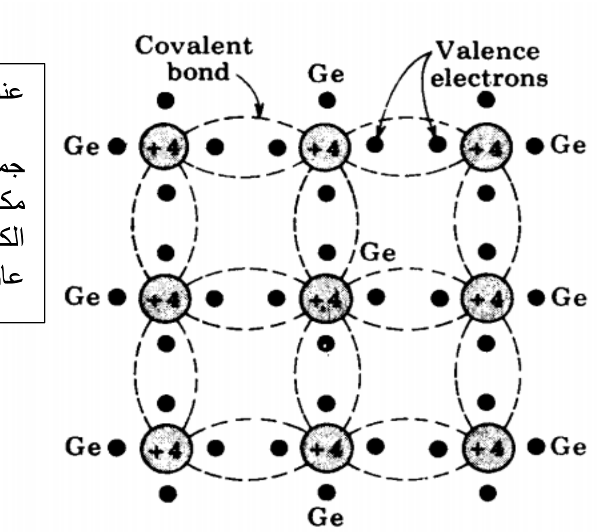


Fig. 2.2 Crystal structure of Germanium.

At Zero temperature the ideal structure of Fig.2.2 is approached, and the crystal behaves as an **insulator**, since no free carriers of electricity are available.

At room temperature (22 C), some of the covalent bonds will be broken because of the thermal energy supplied to the crystal, and **conduction is made possible**. This situation is illustrated in Fig.2.3.

عند درجة حرارة الغرفه تقريبا 22C:

تنكسر بعض الاواصر التساهمية وتتحرر الالكترونات الى حزمة التوصيل مولدة فجوات مكانها في حزمة التكافؤ.

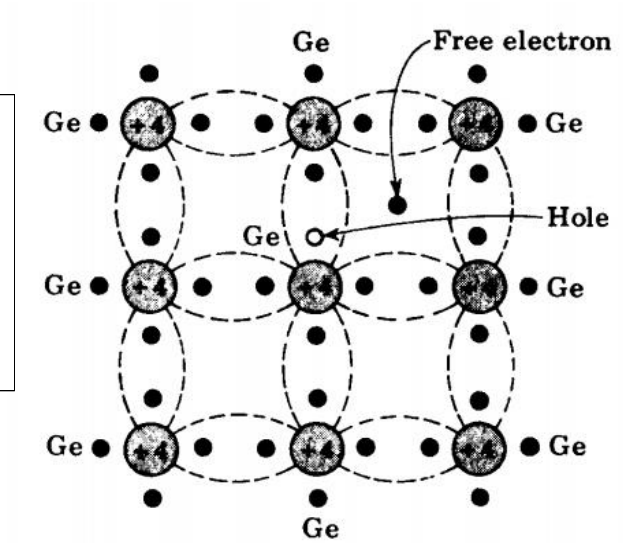
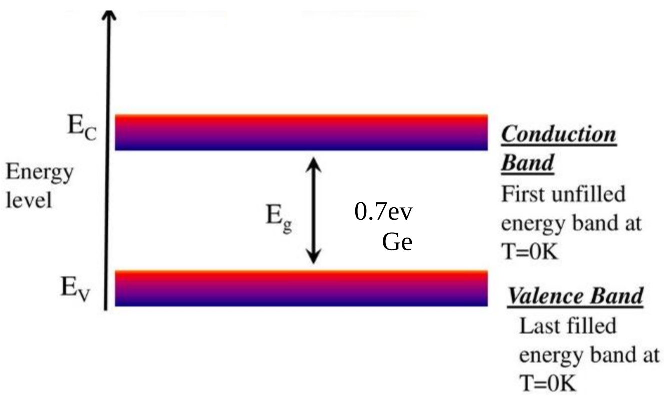


Fig. 2.3 Germanium crystal with a broken covalent bond.

The absence of the electron in the covalent bond is represent by the small circle in Fig.2.3, and such an incomplete covalent bond is called a **hole**. The importance of the hole is that it may serve as a carrier of electricity comparable in effectiveness with the free electron.

The energy required to break such a covalent bond is about **0.7 eV for Germanium at room temperature** as in figure below.



2.2.2 Extrinsic semiconductor

The semiconductor in which intentionally impurities is added for making it conductive is known as the Extrinsic semiconductor. The conductivity of this type is very less conductive at room temperature.

An intrinsic semiconductor is capable to conduct a little current even at room temperature, but it is not useful for the preparation of various electronic devices. Thus, to make it conductive a small amount of suitable impurity is added to the material.

2.3 Doping

The process by which an impurity is added to a semiconductor is known as **Doping**. The amount and type of impurity which is to be added to the material have to be closely controlled during the preparation of extrinsic semiconductor.

Generally, one impurity atom is added to 10^8 atoms of a semiconductor.

The purpose of adding impurity in the semiconductor crystal is to increase the conductivity by raising the number of free electrons or holes.

Depending upon the type of impurity added, the extrinsic semiconductor may be classified as:

1- n-type semiconductor.

2- p-type semiconductor.

2.3.1 n-type semiconductor

When a small amount of **Pentavalent impurity** is added to a pure semiconductor providing a large number of free electrons in it, the extrinsic semiconductor thus formed is known as n-type semiconductor. The conduction in the n-type semiconductor is because of the free electrons denoted by the pentavalent impurity atoms.

The addition of pentavalent impurities (such as arsenic (As), antimony (Sb) and phosphorus (P)) provides a large number of free electrons in the semiconductor crystal. Such impurities which produce n-type semiconductors are known as **Donor Impurities**.

They are called a donor impurity because each atom of them donates one free electron crystal.

example: crystal lattice with a germanium atom doped by antimony (sb) atom.

$$Ge_{32}: \underbrace{1s^2}_{n=1}, \underbrace{2s^2\ 2p^6}_{n=2}, \underbrace{3s^2\ 3p^6\ 3d^{10}}_{n=3}, \underbrace{4s^2\ 4p^2}_{n=4}$$

الغلاف الاخير

يحتوي على الكترونات التكافؤ

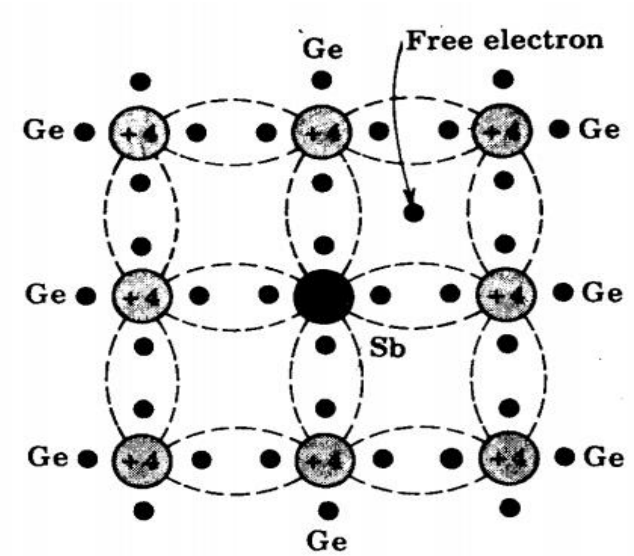


Fig. 2.4 Crystal lattice with a Germanium atom displaced by a pentavalent impurity atom (sb).

When donor impurites (sb) are added to the intrinsic semiconductor, allowable energy levels are introduced as very samll distance below the conduction band, as is shown in Fig. 2.5. In the case of **Germanium, the**

distance of the new discrete allowable energy level is only 0.01 eV (0.05 eV in Silicon) below the conduction band, and therefore at room temperature almost all the "fifth" electrons of the donor material are raised into the conduction band.

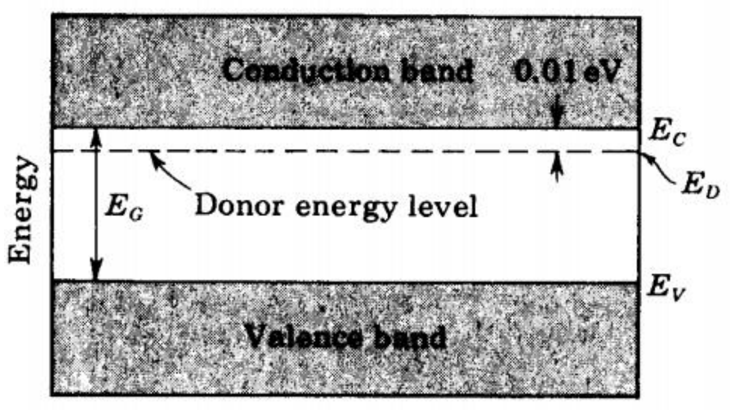
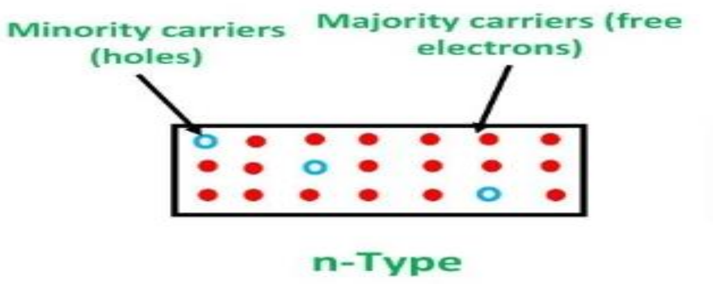


Fig. 2.5 Energy band diagram of n-type semiconductor.

2.3.1.1 Majority and Minority Carriers in an n-type Semiconductor

In an n-type semiconductor, the electrons are the **majority** carriers whereas, the holes are the **minority** carriers as shown in figure below:



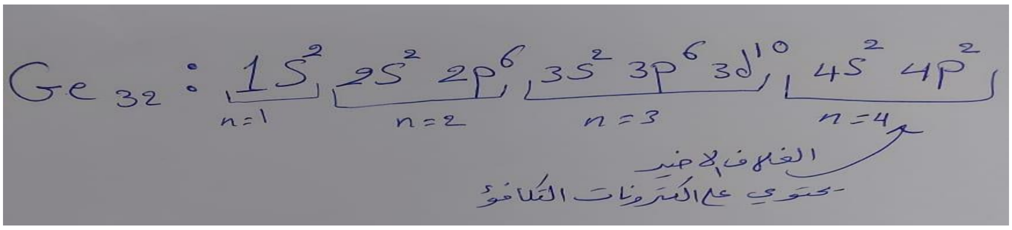
An n-type semiconductor contains a large number of free electrons and a few numbers of holes. This means the electron provided by pentavalent impurity added and share of electron-hole pairs. Therefore, in n-type semiconductor, most of the current conduction is due to the free electrons available in the semiconductor. So, in this type:

n >> p

2.3.2 p-type semiconductor

The extrinsic p-type semiconductor is formed when a trivalent impurity is added to a pure semiconductor in a small amount, and as result, a large number of holes are created in it. A large number of holes are provided in the semiconductor material by the addition of trivalent impurities like boron (B) , gallium (GA) and indium (I). such types of impurities which produce p-type semiconductor are known as an **Acceptor Impurities** because each atom of them create one hole which can accept one electron.

example: crystal lattice with a germanium atom doped by indium atom



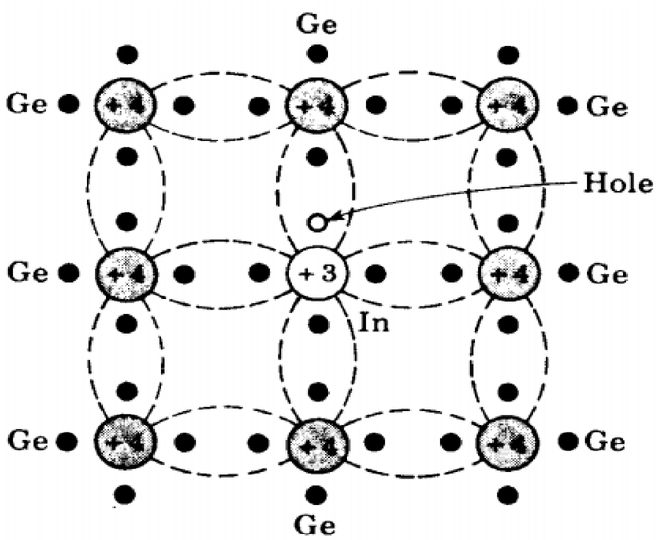


Fig. 2.6 Crystal lattice with a Germanium atom displaced by an atom of trivalent impurity.

In Fig. 2.6, indium (In) atom is added to germanium crystal therefore only three of the covalent bonds can be filled, and the vacancy that exists in the fourth bond constitutes a hole.

When acceptor impurities are added to the intrinsic semiconductor, they produce an allowable discrete energy level which is just above the valence band, as shown in Fig. 2.7. Since a very small amount of energy is required for an electron to leave the valence band and occupy the acceptor energy level, it follows that the holes generated in the valence band by these electrons constitute the largest number of carriers in the semiconductor material.

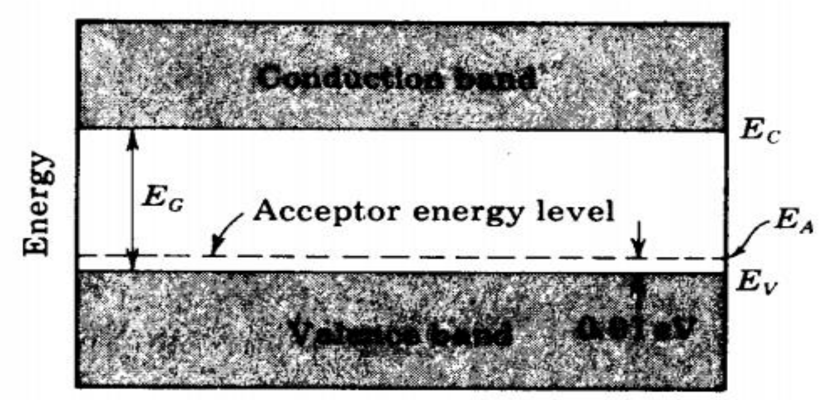
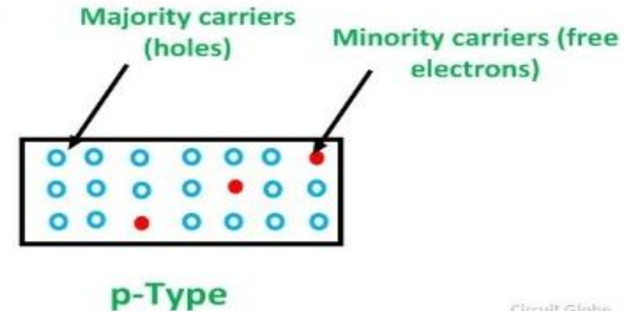


Fig. 2.7 Energy band diagram of p-type semiconductor.

2.3.1.1 Majority and Minority Carriers in an p-type Semiconductor

In the p-type semiconductor material, the holes are the **majority** carriers whereas, the electrons are the **minority** carriers as shown in figure below:



In the p-type semiconductor, the holes are in the majority as compared to electrons, and the conduction takes place because of the very few electrons which are present in the minority. So, in this type:

p >> n

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2.4 Mass Action Low

In electronics and semiconductor physics, the law of mass action is a relation about the concentrations of free electrons and electron holes under thermal equilibrium. It states that, under thermal equilibrium, the product of the free electron concentration n and the free hole concentration p is equal to a constant square of intrinsic carrier concentration n_i^2 . This relationship is called the *mass action low* and is given by:

$$n \times p = n_i^2 \qquad for\ intrinsic\ semiconductor \qquad \ldots\ldots\ldots..(2.7)$$

In **n-type semiconductor,** the density of electrons is approximatly equal to the density of donor atoms.

$n = N_D$ majority carriers (electrons) ……. (2.8)

Where N_D : concentration of Donor atoms.

So, eqn. (2.7) for this type can be written as:

$$N_D \times p = n_i^2 \qquad \dots\dots\dots (2.9)$$

Similarly, for **p-type semiconductor**:

$$p = N_A \qquad mijority\ carriers\ (holes)$$

N_A : concentration of Acceptor atoms.

The mass action low for this type can be written as:

$$n \times N_A = n_i^2 \qquad \dots\dots.(2.10)$$

2.5 Electrical Properties in Semiconductors

A fundemental difference between a metal and a semiconductor is that the former is unipolar (conducte current by means of charges (electrons) of one sign only), whereas a semiconductor is bipolar (contains two charge carrying "particles" of opposite sign).

2.5.1 Electrical Conduction in Intrinsic Semiconductors

Conductivity one carrier is negative (the free electron), of mobility μ_n , and the other is positive (the hole), of mobility μ_p. These particles move in opposite directions in an electric field Ɛ, but since they are of opposite sign, the current of each is in the same direction.

$\sigma = n\, e\, \mu$ for Conduction

$\sigma_i = \sigma_n + \sigma_p$ for Intrinsic Semiconductor

$= n\, e\, \mu_n + p\, e\, \mu_p$

$\because n = p = n_i$

$\therefore \sigma_i = n_i\, e\, (\mu_n + \mu_p)$

2.5.2 Electrical Conduction in Extrinsic Semiconductors

In **n-type Semiconductor** , the semiconductor is doped by impurities has N_D oncentration ($n \gg p$) and ($n = N_D$) then the conductivity is:

$\sigma_{(n)} = \sigma_n + \sigma_p$

$= N_D\, e\, \mu_n + p\, e\, \mu_p$ ……(2.11)

In **p-type Semiconductor** , the semiconductor is doped by impurities has N_A oncentration ($p \gg n$) ($p = N_A$) then the conductivity will be:

$\sigma_{(p)} = \sigma_n + \sigma_p$

$= n\, e\, \mu_n + N_A\, e\, \mu_p$ ……(2.12)

Example :

Pure germanium has $4 \times 10^{22}\, atom/cm^3$ *doped by indium atoms, the impurity is add to the extent of* ***1*** *part in* 10^8 *germanium atoms, if the intrinsic concentration of germanium* $2.5 \times 10^{13} cm^{-3}$*, note that* $\mu_n = 3800 \frac{cm^2}{v.s}$ *and* $\mu_p = 1800 \frac{cm^2}{v.s}$.

1) *Find the conductivity and the resistivity before the doping?*
2) *Find the conductivity and the resistivity after the doping?*
3) *What you conclude from 1 and 2?*

Sol:

1) $\sigma_i = \sigma_n + \sigma_p$

$$\sigma_i = ne\mu_n + pe\mu_p$$

$\because$ *the semiconductor is intrinsic* $\longrightarrow \quad n = p = n_i$

$$\sigma_i = n_i \times e(\mu_n + \mu_p)$$

$$\sigma_i = 2.5 \times 10^{13} \times 1.6 \times 10^{-19}\ (3800 + 1800) = 0.0224\ s/cm$$

$$\rho_i = \frac{1}{\sigma_i} = \frac{1}{0.0224} = 44.64\, \Omega.cm$$

2) *Doping with Indium means adding acceptor atoms:*

$$\therefore N_A = \frac{4 \times 10^{22}}{10^8} = 4 \times 10^{14} cm^{-3}$$

$$n \times p = n_i^2 \quad \longrightarrow \quad n \times N_A = n_i^2 \quad \longrightarrow \quad n = \frac{n_i^2}{N_A}$$

$$n = \frac{(2.5 \times 10^{13})^2}{4 \times 10^{14}} = 1.56 \times 10^{12} cm^{-3}$$

$$\sigma_{(p)} = \sigma_n + \sigma_p$$

$$\sigma_{(p)} = ne\mu_n + N_A e\mu_p$$

$$\sigma_{(p)} = 1.6 \times 10^{-19}(1.56 \times 10^{12} \times 3800 + 4 \times 10^{14} \times 1800)$$

$$= 0.116\, s/cm$$

$$\rho = \frac{1}{\sigma_{(p)}} = \frac{1}{0.116} = 8.62\, \Omega.cm$$

3) $\frac{0.116}{0.0224} = 5.18$

It can be observed that the conductivity of Germanium increases by more than ***5*** *time after doping.*

Example:

Pure silicon doped by Antimony (Sb) has concentration equal to $2 \times 10^{10}\, atoms/cm^3$, *until* $\boldsymbol{N_D - N_A \gg 2n_i}$. *Find the conductivities* $(\sigma_n, \sigma_p$ *and* $\sigma)$ *and the resistivity* ρ *of the silicon? note that* $\mu_n = 1260 \frac{cm^2}{v.s}$ *and* $\mu_p = 460 \frac{cm^2}{v.s}$.

Sol:

The doping by Antimony mean doping by donor atoms:

$$\mathrm{N_D} = 2 \times 10^{15}\, \mathrm{atoms/cm^3}$$

$$\therefore\ 2 \times 10^{10} - 0 \gg 2\mathrm{n_i}$$

$$\mathrm{n_i} = 10^{10}\, \mathrm{atoms/cm^3}$$

$$\mathrm{n \times p = n_i^2} \quad \longrightarrow \quad \mathrm{p \times N_D = n_i^2} \quad \longrightarrow \quad \mathrm{p} = \frac{\mathrm{n_i^2}}{\mathrm{N_D}}$$

$$\mathrm{p} = \frac{(10^{10})^2}{2 \times 10^{10}} = 5 \times 10^9 \text{ atoms/cm}^3$$

$$\sigma_\mathrm{n} = \mathrm{N_D} e \mu_\mathrm{n}$$

$$\sigma_\mathrm{n} = 2 \times 10^{10} \times 1.6 \times 10^{-19} \times 1260 = 0.403 \ \mathrm{s/cm}$$

$$\sigma_\mathrm{p} = \mathrm{p} e \mu_\mathrm{p}$$

$$\sigma_\mathrm{p} = 5 \times 10^{9} \times 1.6 \times 10^{-19} \times 460 = 368 \times 10^{-14} \ \mathrm{s/cm}$$

$$\sigma_{(n)} = \sigma_\mathrm{n} + \sigma_\mathrm{p}$$

$$\therefore \sigma_{(n)} = 0.403 \ \mathrm{s/cm}$$

$$\rho = \frac{1}{\sigma_{(n)}} = \frac{1}{0.403} = 2.48 \ \Omega.\mathrm{cm}$$

2.6 Diffusion Current Density (J_{diff}) in Semiconductor

It is possible to have a nonuniform concentration of particles in a semiconductor. As indicated in Fig. 2.8, the concentration p of holes varies with distance x in the semiconductor, and there exists a concentration gradient $\frac{dp}{dx}$ in the density of carriers. The existence of a gradient implies that if an imaginary surface (shown dashed) is drown in the semiconductor, the density of holes immediately on one side of the surface is larger than the density on the other side. The holes are in a random motion as a result of their thermal energy. Accordingly, holes will continue to move back and forth across this surface. We may then expect that, in a given time interval, more holes will cross the surface from the side of greater concentration to the side of smaller concentration than in the reverse direction. This net transport of holes across the surface constitutes a current in the positive x direction. It should be noted that this net transport of charge is not the result of mutual repulsion among charges of like sign, but is simply the result of a statistical phenomenon. This diffusion is exactly analogous to that which occurs in a neutral gas if a concentration gradient exists in the gaseous container. The diffusion hole current density J_p (ampere per square meter) is proportional to the concentration gradient, and is given by:

$$J_{p\,diff} = -eD_p \frac{dp}{dx} \qquad \ldots\ldots(2.13)$$

Where :

$$D_p = \frac{k\,T}{e}\,\mu_p$$

$$V_T = \frac{k\,T}{e} = \frac{T}{11600}$$

Where k is the Boltzmann constant in joules per degree Kelvin.

$k = 1.38 * 10^{-23}$ (J / K) , $k = 8.617 * 10^{-5}$ eV/K .

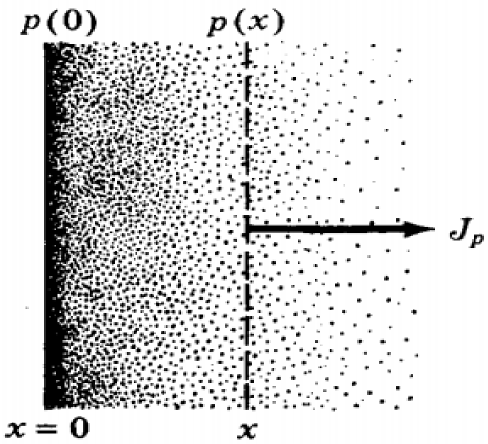

Fig. 2.8 A non-uniform concentration p(x) results in a diffusion current J_{pdiff}.

Where D_p (square meters per second) is called the diffusion constant for holes. Since p in Fig. 2.8 decreases with increasing x, then dp/dx is negative and the minus sign in eqn. (2.13) is needed, so that J_p will be positive in the positive x direction.

A similar equation exists for **diffusion electron current density** [p is replaced by **n**, and the minus sign is replaced by a **plus sign** in eqn.(2.13)] `and is given by:

$$J_{n\,diff} = eD_n \frac{dn}{dx} \qquad \text{… … (2.14)}$$

Where :

$$D_n = \frac{k\,T}{e}\,\mu_n$$

$$V_T = \frac{k\,T}{e} = \frac{T}{11600}$$

Example:

The relationship of changing the density of electrons along the x-axis is given as [$10^{28}\exp(-10^{-6}x)$]. Find the diffusion current density at (x=0) and (x=10^{-5} m) if the mobility of electron is (4 x10^{-3} m^2/V.s) at T=300^0 K? e = 1.6x10^{-19}C , K = 1.38x10^{-23}J/K.

Solution :

$$J_{n\,diff} = eD_n \frac{dn}{dx}$$

$$D_n = \frac{k\,T}{e}\,\mu_n = \frac{(1.38\times10^{-23})\times300\times(4\times10^{-3})}{1.6\times10^{-19}}$$

$$= 1.035\times10^{-4}\,m^2/sec$$

$$J_{n\,diff} = 1.035\times10^{-4}\times1.6\times10^{-19}\times[-10^{-28}\times10^{-6}\times\exp(-10^{-6}x)]$$

1- at x = 0 :

$J_{n\,diff}$ =-16.56 A/m^2.

2- at x = 10^{-5} :

$$J_{n\,diff} = 1.035 \times 10^{-4} \times 1.6 \times 10^{-19} \times [-10^{-28} \times 10^{-6} \times \exp(-10^{-11})]$$

Example:

If the density of electron decrease linearly on x-axis for a metal from $(8 \times 10^{29} m^{-3})$ *to* $(6 \times 10^{25} m^{-3})$ *during the distance from x=0 to x=15mm. Find the diffusion current density at temperature 290*^oK*, if the electron mobility is* $0.004 \frac{m^2}{v.s}$ *?* e = 1.6x10^{-19}C , K = 1.38x10^{-23}J/K.

Solution:

$$J_{n\,diff} = eD_n \frac{dn}{dx}$$

$$\frac{dn}{dx} = \frac{n_2 - n_1}{x_2 - x_1} = \frac{6 \times 10^{25} - 8 \times 10^{29}}{15 \times 10^{-3} - 0} = 5.53 \times 10^{31}$$

$$J_{n\,diff} = e \frac{k\,T}{e} \mu_n \times \frac{dn}{dx}$$

$$= 1.38 \times 10^{-23} \times 290 \times 0.004 \times 5.53 \times 10^{31}$$

$$= 8.53 \times 10^{8}\ A/m^2.$$

Example:

If the electron concentration increase along the x-axis of a conductor as shown in equation below:

$$\mathbf{n = 10^{28} + 5 \times 10^{30}x + 4 \times 10^{33}x^2}$$

and $D_n = 1.2 \times 10^{-4}\ m^2/s$, *Find the diffusion current density at* **x = 5mm** *?*

Solution:

$$n = 10^{28} + 5 \times 10^{30}x + 4 \times 10^{33}x^2$$

$$\frac{dn}{dx} = 5 \times 10^{30} + 8 \times 10^{33}x$$

$$\frac{dn}{dx} = 5 \times 10^{30} + 8 \times 10^{33} \times 5 \times 10^{-3} = 45 \times 10^{30} \ \ (at\ x = 5mm)$$

$$J_{n\ diff} = eD\frac{dn}{dx} = 1.6 \times 10^{-19} \times 1.2 \times 10^{-4} \times 45 \times 10^{30} = 8.64 \times 10^{8}\ A/m^2$$