

Lecture-2

Conduction Phenomenon in Semiconductors

Property	Ge	Si
Atomic Number	32	14
Atomic Weight	72.6	28.1
Density, g/cm^3	5.32	2.33
Dielectric Constant (relative)	16	12
Atoms/ cm^3	4.4×10^{22}	5.0×10^{22}
E_{GO} , eV, at 0 K	0.785	1.21
E_{GO} , eV, at 300 K	0.72	1.1
n_i at 300 K, cm^{-3}	2.5×10^{13}	1.5×10^{10}
Intrinsic resistivity at 300 K, $\Omega - cm$	45	230,000
μ_n , $cm^2/V - s$ at 300 K	3,800	1,300
μ_p , $cm^2/V - s$ at 300 K	1,800	500
D_n , $cm^2/s = \mu_n V_T$	99	34
D_p , $cm^2/s = \mu_p V_T$	47	13

Table 1: Properties of Germanium and Silicon

1. **Intrinsic Semiconductors:** Silicon, Germanium, and Gallium Arsenide are the three most widely used semiconductors. Because of the predominance of silicon devices, we confine our discussion to it. The crystal structure of silicon consists of a regular repetition in three dimensions of a unit cell having the form of a tetrahedron with an atom at each vertex. A two-dimensional symbolic representation of this structure is illustrated in figure-1. Silicon has a total of 14 electrons in its atomic structure, four of which are valence electrons, so that the atom is tetravalent. The inert ionic core of the silicon atom has a charge of +4 measured in units of electronic charge. The binding forces between neighboring atoms result from the fact that each valence electron of a silicon atom is shared by one of its four nearest neighbors. This covalent bond is represented in figure-1 by the two lines which join each ion to each of its neighbors. The valence electrons serve to bind one atom to the next and this results in these electrons being tightly bound to the nucleus. Hence, in spite of the availability of four valence electrons, the crystal has low conductivity.

Hole: At very low temperature (say, $0 K^o$) the ideal structure is shown in the figure-1 and the crystal behaves as an insulator, since no free carriers of electricity are available. At a very low temperature (say, $0 K^o$) the ideal structure shown in figure-1 is approached, and the crystal behaves as an insulator.

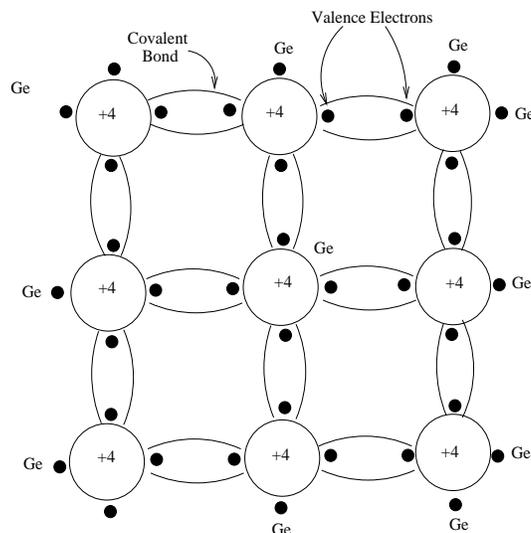


Figure 1: Crystal Structure of germanium, in two dimensions

Since no free carriers electricity are available. At room temperature, however, some of the covalent bonds will be broken because of the thermal energy supplied to the crystal, and conduction is made possible. Here an electron, which usually forms part of a covalent bond, is pictured as being dislodged and is thus free to wander in a random fashion throughout the crystal. The energy E_G required to break such a covalent bond is about 1.1 eV for silicon at room temperature. The absence of the electron in the covalent bond is represented by the small circle in figure-2 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. Contribution of hole to the conductivity is explained as follows: When the bond is incomplete, hole exists. An electron moving from a bond to fill a hole leaves a hole in its initial position. Hence we say that hole effectively moves in the direction opposite to that of electron. This phenomenon is illustrated in the figure-3.

The crystal structure displayed in figure-2 assumes a pure sample of germanium; that is, the sample contains no foreign atoms. Such pure crystals are called **intrinsic semiconductors**. Breaking of a covalent bond results in both a free electron and a hole. Consequently, the hole concentration p and electron concentration n must be equal and hence we have

$$n = p = n_i \quad (1)$$

where n_i is called *intrinsic concentration*.

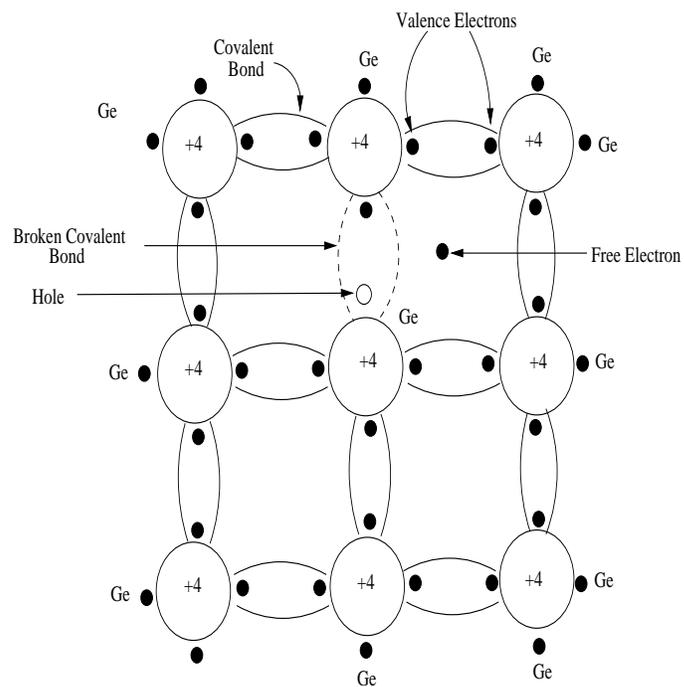


Figure 2: Germanium Crystal with a broken covalent bond

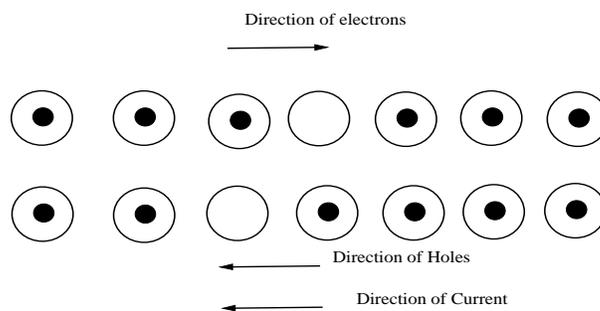


Figure 3: The mechanism by which a hole contributes to the conductivity

Q: An intrinsic silicon bar is 3mm long has a rectangular cross section $50 \times 100 \mu\text{m}$. At 300 K , determine the electric field intensity in the bar and the voltage across the bar when a steady current of $1 \mu\text{A}$ is measured.

A: The field intensity can be obtained from the current density and conductivity as

$$\varepsilon = \frac{J}{A} = \frac{I}{A} \times \frac{1}{\sigma} = \frac{I}{A} \rho$$

using the value of ρ given in table-1, we obtain

$$\begin{aligned} \varepsilon &= \frac{10^{-6}}{50 \times 10^{-6} \times 100 \times 10^{-6}} \times 2.3 \times 10^5 \times 10^{-2} \\ &\Rightarrow \varepsilon = 4.6 \times 10^5 \text{ V/m} \end{aligned}$$

Therefore the voltage across the bar is

$$V_{bar} = \varepsilon L = 4.6 \times 10^5 \times 3 \times 10^{-3} = 1380 \text{ V}$$

2. **Extrinsic Semiconductors:** If, to a intrinsic silicon or germanium, there is added a small percentage of trivalent or prevalent atoms, a *doped, impure,* or *extrinsic* semiconductor is formed. The usual level of doping is in the range of 1 impurity atom for 10^6 to 10^8 silicon atoms.

(a) n-type Semiconductor: Figure-4, depicts the crystal structure obtained when silicon is doped in the pentavalent impurity. Four of five valence electrons occupy covalent bonds, and fifth will be nominally unbounded and will be available as a carrier of current. The energy required to detach the fifth electron from the atom is of the order of only 0.05 eV for silicon. Suitable pentavalent impurities are antimony, phosphorus, and arsenic. Such impurities donate excess electron carriers and are referred to as *donor, or n-type, impurities.*

If intrinsic semiconductor material is doped with n-type impurities, not only does the number of electrons increase, but the number of holes decreases below that which would be available in the intrinsic semiconductor. The number of holes decreases because the larger number of electrons present causes the rate of recombination of electrons with holes to increase. Consequently, the dominant carriers are the negative electrons and doping with donors results in an n-type semiconductor.

(b) p-type Semiconductor: Boron, gallium, and indium are trivalent atoms which, when added to intrinsic semiconductors, provide electrons to fill only three covalent bonds. The vacancy that exists in the fourth bond constitutes a hole as illustrated in figure-5. This type of impurity makes

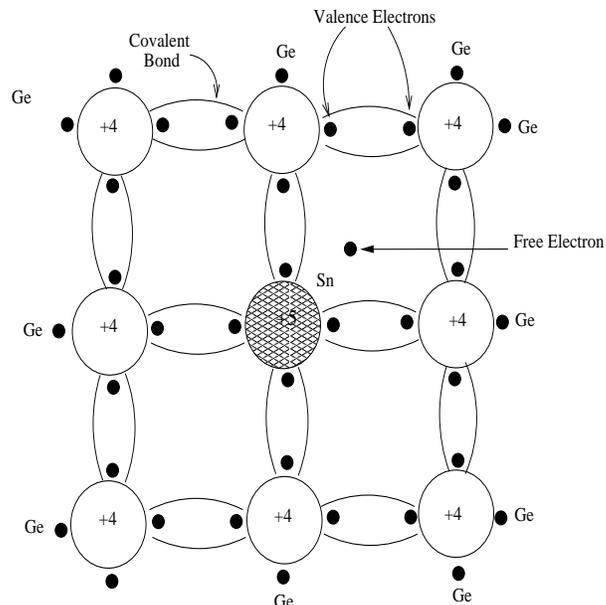


Figure 4: Germanium atom displaced by the pentavalent atom

positive carriers available because it creates holes which can accept electrons. Thus trivalent impurities are called acceptors and form p-type semiconductors in which holes are the predominant carrier.

3. **Mass Action Law:** We noted previously that the addition of n-type impurities causes the number of holes to decrease. Similarly, doping with p-type impurities decreases the concentration of free electrons below that in the intrinsic semiconductor. A theoretical analysis leads to the result that, under thermal equilibrium, the product of the free negative and positive concentrations is a constant independent of the amount of donor and acceptor impurity doping. This relationship is called the *mass-action law* and is given by

$$np = n_i^2 \quad (2)$$

4. **Charge Densities in Semiconductor:** Let N_D be the concentration of donor atoms and N_A the concentration of acceptor atoms. Since these impurities are practically all ionized, they produce positive-ion and negative-ion densities of N_D and N_A , respectively. To maintain the electric neutrality of the crystal, the total positive charge density must equal the concentration of negative charges as expressed in below equation,

$$N_D + p = N_A + n \quad (3)$$

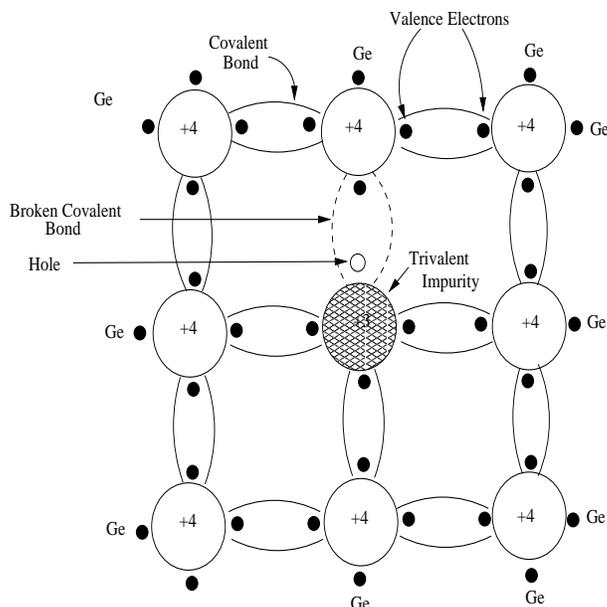


Figure 5: Germanium atom displaced by the trivalent atom

Let us now consider an n-type material having $N_A = 0$. Since the number of electrons is much greater than the number of holes in an n-type semiconductor ($n > p$), eqn.(3) reduces to

$$N_D \approx n \quad (4)$$

In an n-type material the free-electron concentration is approximately equal to the density of donor atoms. The concentration of holes in the n-type semiconductor is obtained by substituting eqn.(4) in eqn.(2). Thus

$$p_n = \frac{n_i^2}{N_D} \quad (5)$$

where p_n is the concentration of holes in the n-type semiconductor. Similarly, in a p-type semiconductor, with $N_D = 0$, we have

$$N_A \approx p \quad (6)$$

$$n_p = \frac{n_i^2}{N_A} \quad (7)$$

where n_p is the concentration of electrons in the p-type semiconductor.

5. Electrical Properties of Semiconductors:

- (a) Conductivity: In the case of extrinsic semiconductor the current density is the sum of densities due to electrons and hole. Let μ_n and μ_p are the mobilities of electrons and holes respectively. Then using the eqn.(30) in Lecture notes-1, the total current density is given by J

$$J = (n\mu_n + p\mu_p)q\varepsilon = \sigma\varepsilon \quad (8)$$

where n = concentration of free-electrons, p =concentration of holes, σ =conductivity. Hence

$$\sigma = (n\mu_n + p\mu_p)q \quad (9)$$

For a pure semiconductor, $n = p = n_i$ is the intrinsic concentration, the above eqns., reduces as

$$J = n_i(\mu_n + \mu_p)q\varepsilon = \sigma\varepsilon \quad (10)$$

where

$$\sigma = n_i(\mu_n + \mu_p)q \quad (11)$$

Q: An n-type silicon sample is 3 mm long and has a rectangular cross section $50 \times 100 \mu m$. The donor concentration at 300 K is $5 \times 10^{14} cm^{-3}$ and corresponds to 1 impurity atom for 10^8 silicon atoms. A steady current of $1 \mu A$ exists in bar. Determine the electron hole concentrations, the conductivity, and the voltage across the bar.

A: From the eqns.(4) and (5), and using the values of n_i and μ_n in the table-1, we obtain

$$n = N_D = 5 \times 10^{14} cm^{-3}$$

and

$$p = \frac{(1.45 \times 10^{10})^2}{5 \times 10^{14}} = 4.2 \times 10^5 cm^{-3}$$

As $n \gg p$, only electron concentration need to be considered in the eqn.(8), so that the conductivity is

$$\sigma = qn\mu_n = 1.6 \times 10^{-19} \times 5 \times 10^{14} \times 1.5 \times 10^3 = 0.12(\Omega - cm)^{-1}$$

The voltage across the bar, obtained as

$$V_{bar} = \frac{IL}{A\sigma} = \frac{10^{-6}(0.3)}{(5 \times 10^{-3})(10^{-2}) \times 0.12} = 0.05 V$$

- (b) Dependence of Intrinsic Concentration on Temperature: With increasing

temperature, the density of hole-electron pairs increases and, correspondingly, the conductivity increases. It is found that the intrinsic concentration n_i varies with T as

$$n_i^2 = A_0 T^3 e^{-\frac{E_{G0}}{kT}} \quad (12)$$

where E_{G0} is the energy gap at $0^\circ K$ in eV as given in Table-1, k is the Boltzmann constant in $eV/^\circ K$, and A_0 is a constant dependent on temperature.

- (c) Energy Gap: The forbidden energy gap E_G in a semiconductor depends upon temperature, and it is found that,

$$E_G = 1.21 - 3.6 \times 10^{-4}T \text{ for Silicon} \quad (13)$$

and at room temperature ($300^\circ K$), $E_G = 1.1 \text{ eV}$ and similarly for germanium,

$$E_G = 0.785 - 2.23 \times 10^{-4}T \quad (14)$$

and hence at room temperature, $E_G = 0.72 \text{ eV}$

- (d) Mobility: This parameter μ varies as T^{-m} over a temperature range of 100 to $400^\circ K$. For silicon, $m = 2.5$ (2.7) for electrons (holes), and for germanium, $m = 1.66$ (2.33) for electrons (holes). The mobility is also found to be a function of electric field intensity and remains constant only if $\varepsilon < 10^3 \text{ V/cm}$ in n-type silicon. For $10^3 < \varepsilon < 10^4 \text{ V/cm}$, μ_n varies approximately as $\varepsilon^{-1/2}$. For higher fields, μ_n is inversely proportional to ε and the carrier speed approaches the constant value of 10^7 cm/s .

6. **Conductivity Modulation**: From the eqn.(11), we see that the conductivity of the semiconductor is proportional to the concentration of free carriers, σ may be increased by increasing n or p . The two most important methods for varying n or p are to change the temperature or to illuminate the semiconductor and thereby generate new hole-electron pairs.

- (a) Thermistor: The conductivity of germanium (silicon) is found from eqn.(12) to increase approximately 6(8) percent per degree increase in temperature. Such a large change in conductivity with temperature places a limitation upon the use of semiconductor devices in some circuits. On the other hand, for some applications it is exactly this property of semiconductors that is used to advantage. A semiconductor used in this manner is called a *thermistor*. Such devices are used in thermometry, microwave-frequency power, as a thermal relay, and in control devices actuated by changes in temperature.

- (b) Photoconductors: If radiation falls upon a semiconductor, its conductivity increases. This photoconductive effect is explained as follows: Radiant energy supplied to the semiconductor ionizes covalent bonds; that is, these bonds are broken, and hole-electron pairs in excess of those generated thermally are created. These increased current carriers decrease the resistance of the material, and hence such a device is called a *photoresistor*, or *photoconductor*. The minimum energy of photon required for intrinsic excitation is the forbidden-gap energy E_G (eV) of the semiconductor material. The wavelength λ_c of a photon whose energy corresponds to E_G is given with $E_2 - E_1 = E_G$. If λ_c is expressed in microns and E_G in electron volts, then

$$\lambda_c = \frac{1.24}{E_G} \quad (15)$$

7. **Diffusion**: In addition to conduction current, the transport of charges in a semiconductor may be accounted for by a mechanism called diffusion, not ordinarily encountered in metals. Figure-6, shows the concentration p of holes varies with distance x in the semiconductor, and hence there exists a concentration gradient dp/dx . This implies that if we draw a vertical line across, the density of the carriers on the left side is greater than that of the right side. Hence due to this gradient there will be net transport of the charge in the positive direction of x -axis. The diffusion current density J_p is proportional to the concentration gradient, and is given by,

$$J_p = -qD_p \frac{dp}{dx} \quad (16)$$

where D_p (square meters per second) is called the *diffusion constant* for holes. Since p in the figure-6 decreases with increasing x , then dp/dx is negative (since the slope is negative). The minus sign in the eqn.(16) is needed so that J_p is positive in the positive X direction. Similarly the diffusion current-density with p replaced by n , and minus sign replaced by plus sign, we get J_n .

- (a) Einstein Relationship: The relationship between the diffusion current density (D) and mobility (μ) is given by the Einstein equation,

$$\frac{D_n}{\mu_n} = \frac{D_p}{\mu_p} = V_T \quad (17)$$

where V_T is the “volt-equivalent of temperature,” defined by

$$V_T = \frac{\bar{k}T}{q} = \frac{T}{11,600} \quad (18)$$

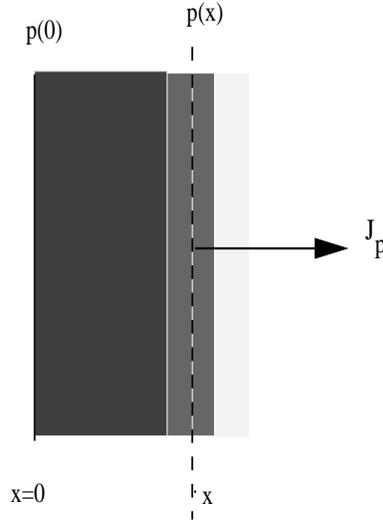


Figure 6: A nonuniform concentration $p(x)$ results in a diffusion current J_p

where \bar{k}^1 . At room temperature ($300^\circ K$), $V_T = 0.026V$.

8. **Total Current:** Now the total current density is given by sum of diffusion current and conduction current. Thus the eqn.(8) is given by

$$J = J_n + J_p \quad (19)$$

where J_n and J_p are given by the following two equations,

$$J_n = q\mu_n n \varepsilon + qD_n \frac{dn}{dx} \quad (20)$$

$$J_p = q\mu_p p \varepsilon - qD_p \frac{dp}{dx} \quad (21)$$

9. **Continuity Equation:** The concentrations of carriers in semiconductor material will vary with time. In general, the carrier concentration in the body of semiconductor is function of both time and distance. We now derive the differential equation, which governs this relationship. This is called the continuity equation, which is based on the fact that charge can neither be created nor destroyed.

Consider the infinitesimal element of volume of area A and length dx as shown

¹ $\bar{k} = 1.6 \times 10^{-19} k$ is the Boltzmann constant in $J/^\circ K$, where k is in $eV/^\circ K$

in the figure-7. Let p be the average hole concentration (m^{-3}). Assume that the hole current I_p is a function of one-dimension say x . As indicated in the figure-7, let the current entering the volume at x is I_p at time t and leaving at $x + dx$ is $I_p + dI_p$ at the same time t .

$$I_p = \text{current entering at } x \text{ at time } t \quad (22)$$

$$I_p + dI_p = \text{current leaving at } x + dx \text{ at the same time } t \quad (23)$$

\Rightarrow there must be ' dI_p ' of more coulombs per second ($C/s = A$) leaving the

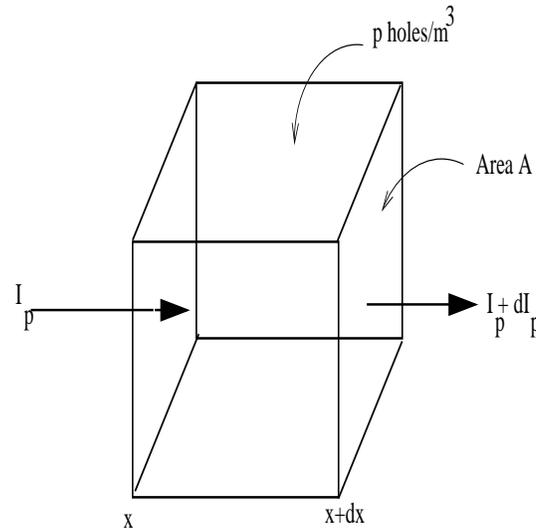


Figure 7: Law of Conservation of Charge

volume than entering it. (if $dI_p > 0$)

Hence *decrease* in number of coulombs per second within the volume is dI_p .

From the definition of current we have,

$$I_p = \frac{N_p q}{t} \quad (24)$$

$$\Rightarrow \frac{dI_p}{q} = \frac{dN_p}{t} \quad (25)$$

= decrease in the number of holes per second

where N_p represents the number of holes in the infinitesimal volume $A dx$, thus we have hole concentration present in the volume as $dp = \frac{dN_p}{A dx}$.

From the eqn.(25), we can *decrease* in the hole concentration (number of hole per unit volume) per second, due to the current dI_p by dividing both sides of

the eqn(25) with Adx

$$\begin{aligned} \Rightarrow \frac{1}{Adx} \frac{dI_p}{q} &= \frac{1}{Adx} \frac{dN_p}{t} \\ &= \left(\frac{dN_p}{Adx} \right) \left(\frac{1}{t} \right) \\ &= \frac{dp}{t} \end{aligned} \quad (26)$$

= decrease in the hole concentration per second

$$\begin{aligned} \Rightarrow \frac{dp}{t} &= \frac{1}{q} \frac{dI_p}{dx} \\ &= \frac{1}{q} \frac{dJ_p}{dx} \end{aligned} \quad (27)$$

Let p_0 represents the hole concentration present under thermal equilibrium and τ_p be the average time the hole will exist before it recombines. This is called *mean lifetime* of the hole (respectively for electron).

Thus the equation,

$$g = \frac{p_0}{\tau_p} \quad (28)$$

= increase in the hole concentration per second

$$\frac{p}{\tau_p} = \text{decrease in hole concentration per second due to} \quad (29)$$

recombination

Finally as we know that charge can neither be created nor destroyed, the increase in the concentration of holes per second is given by

$$\frac{dp}{dt} = \left(\begin{array}{c} \text{increase in hole} \\ \text{concentration/second} \end{array} \right) - \left(\begin{array}{c} \text{decrease in hole} \\ \text{concentration/second} \end{array} \right) \quad (30)$$

Therefore substituting the eqns.(26), (27), (28) and (29) in the eqn.(30) we get,

$$\frac{dp}{dt} = \left(\frac{p_0}{\tau_p} \right) - \left(\frac{p}{\tau_p} - \frac{1}{qA} \frac{dI_p}{dx} \right) \quad (31)$$

$$= \frac{p_0 - p}{\tau_p} - \frac{1}{q} \frac{dJ_p}{dx} \quad (32)$$

More precisely as p is a function of both x and t the derivatives in the above

equation become partial derivatives, thus we have

$$\frac{\partial p}{\partial t} = \frac{p_0 - p}{\tau_p} - \frac{1}{q} \frac{\partial J_p}{\partial x} \quad (33)$$

The eqn.(33) is called the *law of conservation of charge* or the *continuity equation* for charge. This law applies equally well for electrons, and the corresponding equation is obtained by replacing p with n in the eqn.(33).

10. **Injected Minority-Carrier Charge:** Consider the physical situation pictured in figure-8(a). A long semiconductor bar is doped uniformly with donor atoms so that the concentration $n = N_D$ is independent of position. Radiation falls upon the end of the bar at $x = 0$. Some of the photons are captured by the bound electrons in the covalent bonds are broken and hole-electron pairs are generated. Let us investigate how the steady-state minority-carrier concentration p varies with the distance x into the specimen.

We shall make the reasonable assumption that the injected minority concentration is very small compared with the doping level; that is, $p' \ll n$, where p' is the concentration of holes when the specimen is radiated to light source. The statement that the minority concentration is much smaller than the majority concentration is called the *low-level injection* condition. Since the drift current is proportional to the concentration [eqn.(8)] and since $p = p' + p_0 \ll n$, we shall neglect the hole drift current (but not the electron drift current) and shall assume that I_p is due entirely to diffusion. This assumption is justified at the end of this section. The controlling differential equation for p can be derived as follows,

In the continuity eqn.(32) if $dp/dt = 0$, i.e., for steady state, then it becomes,

$$\Rightarrow \frac{1}{q} \frac{dJ_p}{dx} = \frac{p_0 - p}{\tau_p} \quad (34)$$

substituting eqn.(16), in above we have,

$$\begin{aligned} \frac{1}{q} \frac{d}{dx} \left(-qD_p \frac{dp}{dx} \right) &= \frac{p_0 - p}{\tau_p} \\ \Rightarrow -D_p \frac{d^2p}{dx^2} &= \frac{p_0 - p}{\tau_p} \\ \Rightarrow \frac{d^2p}{dx^2} &= \frac{p - p_0}{\tau_p D_p} \end{aligned} \quad (35)$$

Let us define “diffusion length” for holes L_p as

$$L_p = (D_p \tau_p)^{\frac{1}{2}} \quad (36)$$

Substituting eqn.(36) in eqn.(35) we have

$$\frac{d^2 p}{dx^2} = \frac{p - p_0}{L_p^2} \quad (37)$$

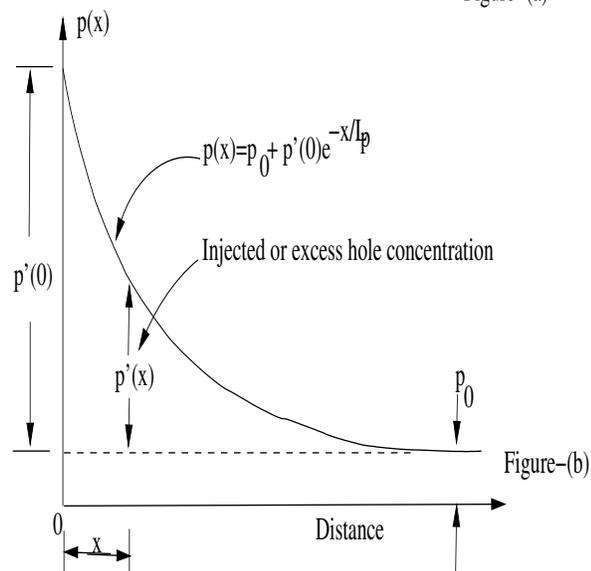
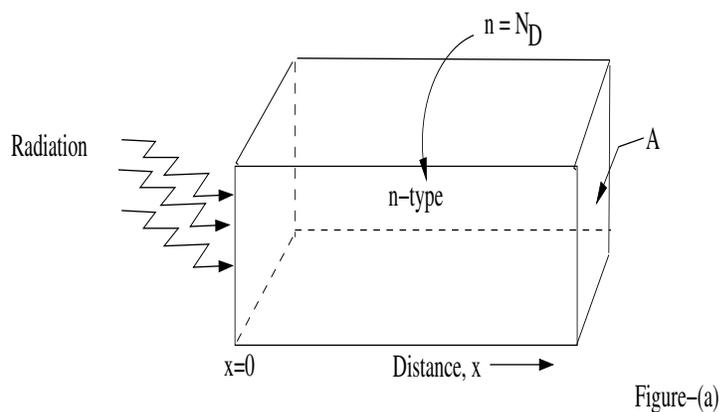


Figure 8: Law of Conservation of Charge

Having obtained the second order differential equation, we can now obtain the

solution² of $p(x)$ this by solving this equation. This is done as follows,

$$\begin{aligned} \Rightarrow \frac{d^2 p}{dx^2} - \frac{p}{L_p^2} &= -\frac{p_0}{L_p^2} \\ \Rightarrow \left(D^2 - \frac{1}{L_p^2} \right) p &= -\frac{p_0}{L_p^2} \end{aligned} \quad (38)$$

where

$$D^2 = \frac{d^2}{dx^2}$$

and

$$\left(D^2 - \frac{1}{L_p^2} \right)$$

is called axillary equation (A.E) Therefore the solution of $p(x)$ is given by

$$p(x) = \left(\begin{array}{c} \text{Complementary} \\ \text{function (C.F)} \end{array} \right) + \left(\begin{array}{c} \text{Particular} \\ \text{solution (P.S)} \end{array} \right) \quad (39)$$

C.F is obtained by equating A.E to zero, and thus we have,

$$\begin{aligned} \Rightarrow \left(D^2 - \frac{1}{L_p^2} \right) &= 0 \\ \Rightarrow D &= \pm \frac{1}{L_p} \\ \Rightarrow \text{C.F} &= c_1 e^{-x/L_p} + c_2 e^{x/L_p} \end{aligned} \quad (40)$$

where c_1, c_2 are constants, which can be obtained from the initial conditions. The particular solution is given by,

$$\text{P.S} = \frac{-\frac{p_0}{L_p^2} e^0}{D^2 - \frac{1}{L_p^2}}$$

substituting $D = 0$ in the above equation we have,

$$\Rightarrow \text{P.S} = p_0 \quad (41)$$

²For more details on solving the ordinary second order nonhomogeneous differential equations, please refer to page-101, Chapter-2, of “*Advanced Engineering Mathematics*”, Erwin Kreyszig, 8th edition

Substituting eqn.(40) and (41) in eqn.(39), we get

$$p(x) = c_1 e^{-x/L_p} + c_2 e^{x/L_p} + p_0 \quad (42)$$

In the above equation, as the $\lim_{x \rightarrow \infty}$, the second term of $p(x)$ approaches to infinity, making $p(x) \rightarrow \infty$, which is impractical. Hence, c_2 must be equal to zero. Therefore eqn.(42) becomes,

$$p(x) = c_1 e^{-x/L_p} + p_0 \quad (43)$$

Observing the above equation at $x = 0$ we get $c_1 = p(0) - p_0$. Thus we have,

$$p(x) = p_0 + \{p(0) - p_0\} e^{-x/L_p} \quad (44)$$

(a) Diffusion Currents: In the diffusion current equation $I_p(x) = A J_p(x)$, substituting eqn.(16) we get,

$$\begin{aligned} I_p &= A \left(-q D_p \frac{dp}{dx} \right) \\ \Rightarrow I_p(x) &= A \left(-q D_p \frac{d}{dx} \left(p_0 + \{p(0) - p_0\} e^{-x/L_p} \right) \right) \\ \Rightarrow I_p(x) &= A \left(-q D_p \{p(0) - p_0\} e^{-x/L_p} \left(\frac{-1}{L_p} \right) \right) \\ \Rightarrow I_p(x) &= \frac{A q D_p}{L_p} \{p(0) - p_0\} e^{-x/L_p} \end{aligned} \quad (45)$$

where I_p is the minority hole diffusion current. Let $I_n(x)$ be the majority electron diffusion current in the specimen, then we have

$$I_n(x) = A \left(q D_n \frac{dn}{dx} \right) \quad (46)$$

Assuming the change in the majority carriers equals to the change in the minority carriers at low-level injection. Thus we have,

$$n - n_0 = p - p_0 \quad (47)$$

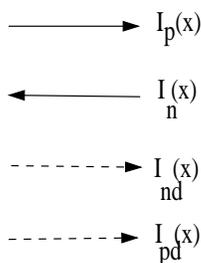
Differentiating both sides with respect to x we have,

$$\frac{dn}{dx} = \frac{dp}{dx} \quad (48)$$

substituting this in eqn.(46), we get

$$\begin{aligned}
 I_n(x) &= AqD_n \frac{dp}{dx} \\
 &= AqD_n \left(\frac{-1}{AqD_p} I_p(x) \right) \text{ by sub. eqn.(16)} \\
 \Rightarrow I_n(x) &= -\frac{D_n}{D_p} I_p(x) \tag{49}
 \end{aligned}$$

- (b) Drift Current: Since the specimen taken is an open circuited bar, the sum of all currents must be equal to zero, (i.e sum of hole and electron currents). Thus we have



where 'd' stand for drift current

Figure 9: Direction of diffusion and drift currents in the specimen

$$I_p(x) + I_{pd}(x) + I_{nd}(x) + I_n(x) = 0 \tag{50}$$

Let us assume that $I_{pd}(x)$ is very small and hence can be neglected ($I_{pd}(x) \approx 0$). However we will justify the assumption, by the end of this section. Substituting eqn.(49), in eqn.(50) we get, electron drift current as

$$I_{nd}(x) = \left(\frac{D_n}{D_p} - 1 \right) I_p \tag{51}$$

Thus must exist an electric field ε in the bar, in order for the drift current to exist. This electric field is created by the injected carriers. From the eqns.(30) of lecture notes-1, we have,

$$\begin{aligned}
 I_{nd} &= (nq\mu_n\varepsilon)A \\
 &= \left(\frac{D_n}{D_p} - 1 \right) I_p \text{ from eqn.(51)}
 \end{aligned}$$

$$\Rightarrow \varepsilon = \frac{1}{nq\mu_n A} \left(\frac{D_n}{D_p} - 1 \right) I_p \quad (52)$$

Let us now verify the assumption. The hole drift current is given by,

$$\begin{aligned} I_{pd} &= Aqp\mu_p\varepsilon \\ &= \frac{p}{n} \frac{\mu_p}{\mu_n} \left(\frac{D_n}{D_p} - 1 \right) I_p \end{aligned} \quad (53)$$

since $p \ll n$, then $I_{pd} \ll I_p$. The hole drift current is negligible compared with hole diffusion current, thus justifying the assumption that the injected minority-carrier current, under low-level injection is essentially a diffusion current.