Module 6 : PHYSICS OF SEMICONDUCTOR DEVICES

Lecture 35 : Photoconductivity

Objectives

In this course you will learn the following

- Photoconductivity.
- Diffusion and drift.
- Einstein relations.

Photoconductivity

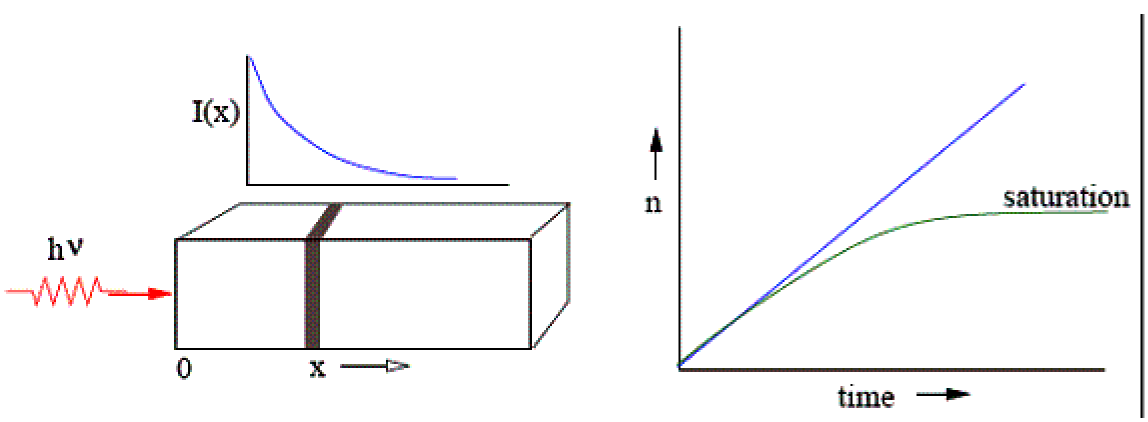
A consequence of small band gap (Δ) in semiconductors is that it is possible to generate additional carriers by illuminating a sample of semiconductor by a light of frequency greater than Δ/h. This leads to an increased conductivity in the sample and the phenomenon is known as **photoconductivity** . The effect is not very pronounced at high temperatures except when the illumination is by an intense beam of light. At low temperatures, illumination results in excitation of localized carriers to conduction or valence band.

Consider a thin slab of semiconductor which is illuminated by a beam of light propagating along the direction of its length (x-direction). Let I be the radiation intensity (in watts/m ^{2}) at a position x from one end of the semiconductor. If $\alpha =$ absorption coefficient per unit length, the power absorbed per unit length is αI . The change in the intensity with distance along the sample length is given by

$$\frac{dI}{dx} = -\alpha I$$

which has solution

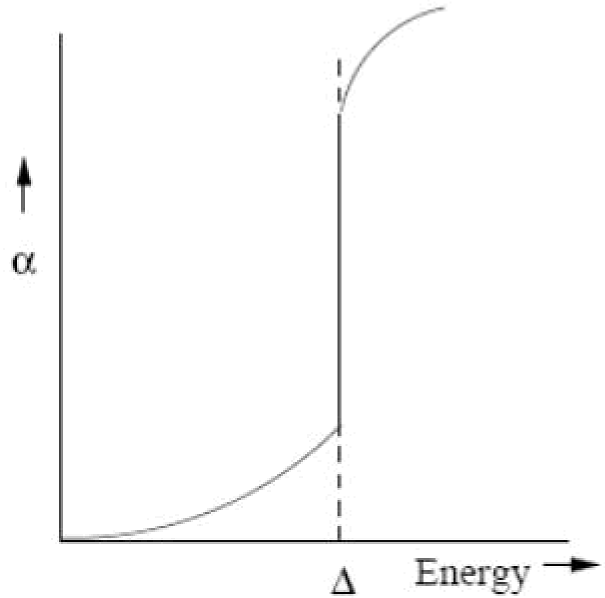
$$I = I_0 e^{-\alpha x}$$



If we define η as the *quantum efficiency* , i.e. the fraction of absorbed photons that produce electron-hole pairs, the number of pairs produced per unit time is given by

$$\Delta n = \Delta p = \frac{\eta \alpha I}{h\nu}$$

In principle, the process of illumination will lead to a continued increase in the number of carriers as the amount of energy absorbed (and hence Δn and Δp) will increase linearly with time. However, the excited pairs have a finite life time ($\sim 10^{-7}$ to 10^{-2} s). This results in recombination of the pairs. The relevant life time is that of minority carriers as a pair is required in the process. Recombination ensures that the number of excess carriers does not increase indefinitely but saturates.



Consider an n-type semiconductor. If the recombination life time for the minority carriers is τ_p, the rate of change of carrier concentration is given by

$$\frac{d}{dt}(\Delta p) = \frac{\eta \alpha I}{h\nu} - \frac{\Delta p}{\tau_p}$$

Under steady state condition $d\delta p/dt = 0$, which gives

$$\delta p = \frac{\eta \alpha I_p \tau_p}{h\nu} = \Delta n$$

This excess hole density leads to an additional conductivity

$$\Delta\sigma = q\delta n\mu_e + q\Delta p\mu_h$$

Diffusion

Diffusion is the process by which particles move from a region of higher concentration to a region of lower concentration. If the process is left undisturbed, it would result in uniform density of particles in the medium. The following points are to be noted about diffusion **:**

- Diffusive motion takes place because of random thermal motion.
- Diffusion takes place irrespective of whether the particles are charged or not.
- Diffusion of particles takes place along the concentration gradient, i.e. from a region of higher concentration to that of lower concentration.

If the particles of the medium are charged carriers, like electrons and holes in a semiconductor, the diffusion along the concentration gradient results in a current, known as **diffusion current.** Unlike the **drift current** , the diffusion current depends on gradient of concentration rather than on the concentration itself. If the carriers are electrons, the diffusion current is proportional to ∇n, where n is the electron density.

Likewise, the hole diffusion current is proportional to ∇p.

Consider the diffusive motion of holes in one dimension. If $p(x)$ is the concentration at x, and $dp/dx > 0$, i.e., if the concentration is increasing where E_F^i is the intrinsic Fermi level and E_F is the Fermi level in the presence of acceptor impurities (we have dropped the redundant superscript p). Thus

$$\nabla p = \frac{p_i}{kT} e^{(E_F^i - E_F)/kT} (\nabla E_F^i - \nabla E_F)$$
$$= \frac{p}{kT} (\nabla E_F^i - \nabla E_F)$$

Fermi level in a material remains uniform inside a material, i.e. $\nabla E_F = 0$ Thus

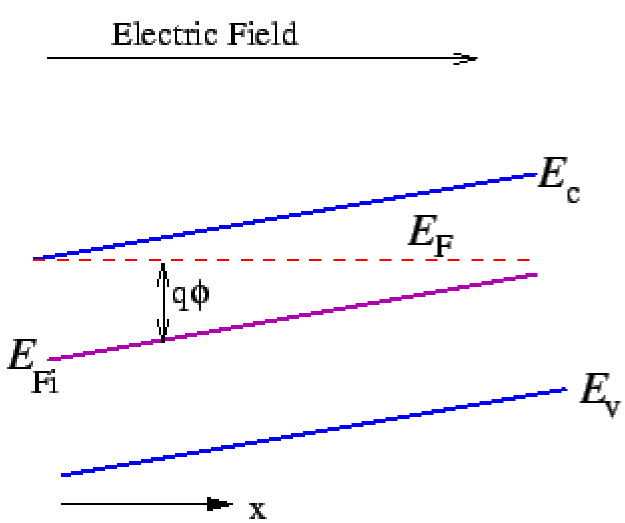
$$\nabla p = \frac{p}{kT} \nabla E_F^i (B)$$

Thus diffusion takes place when there exists an intrinsic Fermi level gradient. In order to evaluate the gradient of E_F^i, consider the valence band. The kinetic energy of the holes is the difference between the energy of the top of the valence band and the total energy of the holes. Thus the energy at the top of the valence band is the potential energy of the holes. Similarly, the energy at the bottom of the conduction band is the potential energy of the electrons. As the intrinsic Fermi energy depends on these two energy levels, temperature and other constants, the change in the electron or hole energy is also given by the difference between the intrinsic Fermi energy E_F^i and the (uniform) Fermi energy E_F,

$$q\phi = (E_F - E_F^i)$$

The electric field, $E(x)$ is then given by

$$E_x = -\frac{d\phi}{dx} = \frac{1}{q} \frac{dE_F^i}{dx} (C)$$



Assume *quasi-charge neutrality* for which the concentration of holes is equal to the concentration of acceptors, $p \simeq N_a$. Using one dimensional form of (B),

$$\frac{dE_F^i}{dx} = \frac{kT}{p}\frac{dp}{dx} \simeq \frac{kT}{N_a}\frac{dN_a}{dx}$$

which gives

$$E(x) = \frac{kT}{q}\frac{1}{N_a}\frac{dN_a}{dx}$$

Substituting the above in (A) and cancelling common terms, we get

$$\frac{D_p}{\mu_h} = \frac{kT}{q}$$

A similar relation can be established for electrons. The relations

$$\boxed{\frac{D_p}{\mu_h} = \frac{D_n}{\mu_e} = \frac{kT}{q}}$$

Are known as bf Einstein relations between mobility and diffusion constant.

Example 12

Electron concentration in a semiconductor varies linearly from a value 1×10^{24} per m ^{3} to 6×10^{23} per m ^{3} over a distance of 0.1 cm. If the diffusion constant is 0.025 m ^{2}/s, find the diffusion current density in the sample.

Solution

$$\frac{dn}{dx} = \frac{10^{24} - 6 \times 10^{23}}{0.001} = 4 \times 10^{26} \ \mathrm{m}^{-4}$$

Thus the diffusion current density

$$j = eD_n\frac{dn}{dx}$$

$$= 1.6 \times 10^{-19} \times 0.025 \times 4 \times 10^{26}$$

$$= 1.6 \times 10^{6} \ \mathrm{A/m^2}$$

Exercise 1

An n- type semiconductor has a graded impurity concentration along the x-axis given by $N_d = 10^{22} - 10^{24}x$ per m ^{3}. Find the electric field at $x = 0$ at room temperature

(Ans. 2.6 V)

Exercise 2

i)For the semiconductor in the above exercise, calculate the diffusion coefficient at 300 K if the electron mobility is 1500 cm ^{2}/V-s. (ii) Calculate the diffusion current density. Explain the direction of diffusion current.(Ans. (i) $3.9 \times 10^{-3}\ \mathrm{m}^2/s$ (ii) 624 A/m ^{2})

(Hint : Use Einstein relation to find D_n)

Recap

In this course you have learnt the following

- As the band gap in semiconductors is less than the energy of optical photons, carriers can move across the gap when light is incident on semiconductor. This is known as photoconductivity.
- When there is a gradient of concentration, charge carriers move from a region of higher concentration to that of lower concentration. The process is known as diffusion.
- Einstein relations provide connectivity between mobility of carriers and temperature for diffusive motion.