(MPM-202)
Optoelectronics and Optical Communication System

UNIT-I (Optical Process in Semiconductors)

Lecture-5

by

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SYLLABUS

MPC-202 OPTOELECTRONICS AND OPTICAL COMMUNICATION SYSTEM Credits 4 (3-1-0)

UNIT I: Optical process in semiconductors

Optoelectronic properties of semiconductor: effect of temperature and pressure on bandgap, carrier scattering phenomena, conductance processes in semiconductor, bulk and surface recombination phenomena, optical properties of semiconductor, EHP formation and recombination, absorption in semiconductors, effect of electric field on absorption.

UNIT II: Optical sources and detectors

An overview of optical sources (Semiconductor Laser and LEDs), Optical Detectors: Type of photo detectors, characteristics of photo detectors, noise in photo detectors, photo transistors and photo conductors.

UNIT III: Optical fiber

Structure of optical wave guide, light propagation in optical fiber, ray and wave theory, modes of optical fiber, step and graded index fibers, transmission characteristics of optical fibers, signal degradation in optical fibers; attenuation, dispersion and pulse broadening in different types of optical fibres.

UNIT IV: Fiber components and optoelectronic modulation

Fiber components: Fibre alignments and joint loss, fiber splices, fiber connectors, optical fiber communication, components of an optical fiber communication system, modulation formats, digital and analog optical communication systems, analysis and performance of optical receivers, optoelectronic modulation.

Conduction Processes in Semiconductors

- In order for a semiconductor material to conduct following conditions are required-

- Electrons and holes must be in motion in their respective band.
- There should be partially filled band.
- Carrier motion should be a net direction and for this an external force is needed.

Conduction Processes in Semiconductors

- Since the electrons and holes are charged particles, an **externally applied electric field** can move carriers in a band in the direction of the electric field. Such motion is called ***'drift'*** as shown in figure.

- The bending of bands and the motion of electrons and holes in opposite direction occurs.

- Electrons and holes, like neutral particles, acquire directional motion **due to a concentration gradient**, and such motion is termed ***'diffusion'*** as shown in figure.

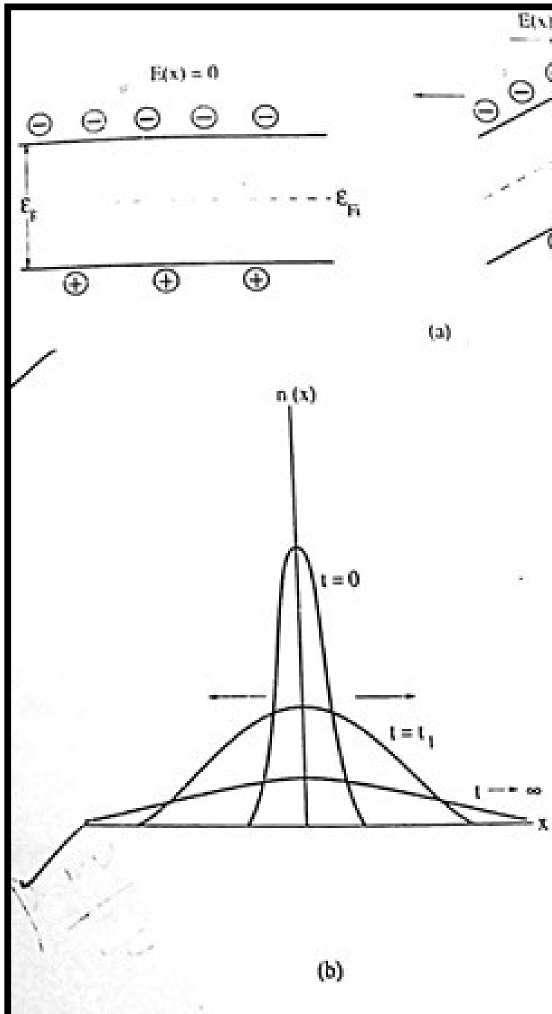


Figure Schem of (a) drift of charge to an electric field a semiconductor, and (neutral or charged p a concentration grad

Drift Process in Semiconductors

- Drift process in semiconductor arises due to force |qE| applied by an externally applied electric field E on charge carriers.

- The current due to electron in conduction band is given by

$$\begin{aligned} \boldsymbol{J_{dr}} &= -\boldsymbol{nqv} \\ &= -\,\boldsymbol{\sigma E}\ (\boldsymbol{A/cm^2}) \end{aligned} \quad \textbf{(1)}$$

which is essentially Ohm's law. Here $\boldsymbol{\sigma}$ is the conductivity of the sample, **E** is the applied electric field, and $\boldsymbol{v} = \boldsymbol{v_D}$ is the average scattering-limited drift velocity of the electrons.

- Let the average time between collisions be $\boldsymbol{\tau_C}$, then the average rate of change of momentum due to collision is $\boldsymbol{mv_D/\tau_C}$.

Drift Process in Semiconductors

- The equation of motion of an electron subject to an electric field in the x-direction is then given by-

$$-qE = m_e^* \frac{dv_{Dx}}{dt} + m_e^* \frac{v_{Dx}}{\tau_C} \quad (2)$$

Energy gained from the field

Energy lost due to collision

- Solution of the differential equation leads to

$$v_{Dx} = -\frac{q\tau_C E}{m_e^*}\left(1 - e^{-t/\tau_C}\right) \quad (3)$$

Drift Process in Semiconductors

- From eq.(1), the current density is given by

$$J_{dr} = -\frac{n\,q^2\tau_C E}{m_e^*}\left(1 - e^{-t/\tau_C}\right) \quad (4)$$

✓ **Equation (3) and (4) indicate that v_{Dx} and J_{dr} rise exponentially with time to a constant value in a time comparable to τ_C, which is defined as *relaxation time*.**

✓ **Physically, it is the time taken by the system to relax back to thermal equilibrium after the field is switched off to zero.**

- Thus,

$$v_{Dx} = v_{D0}\left(e^{-t/\tau_C}\right) \quad (5)$$

Drift Process in Semiconductors

- And in the time τ_C the **current** also **reduces to zero.**

- The ***steady-state*** values of velocity and current are given by

$$mean\ v_{Dx} = \mu_e E \qquad (6)$$

and

$$J_x = nq\mu_e E \qquad (7)$$

❖ If τ_C is not a function of E, which is usually a valid assumption. It follows that

$$\sigma = nq\mu_e = \frac{n\, q^2 \tau_C}{m_e^*} \quad (ohm.cm)^{-1} \qquad (8)$$

The equation derived above are equally valid for hole transport in the valance band

Drift Process in Semiconductors

- The total current density due to drift of electrons and holes is given by

$$\boldsymbol{J_{dr} = q(n\mu_e + p\mu_h)\mathbf{E}} \quad \textbf{(9)}$$

and the conductivity is given by

$$\boldsymbol{\sigma = q(n\mu_e + p\mu_h)} \quad \textbf{(10)}$$

- For doped semiconductors in which the impurity levels are fully ionized, n and p are replaced by N_D and N_A , respectively.

Diffusion Process in Semiconductors

- Diffusion arises **from a non uniform density of carriers** – electrons and holes.
- In the absence of any other processes such as drift, the carriers will diffuse from a region of high density to a region of low density.
- The force of diffusion acting on each electron is given by

$$F_{diff} = -\frac{1}{n}\frac{dP}{dx} \qquad \textbf{(11)}$$

where the negative sign signifies that the carriers move in a direction opposite to the concentration gradient. Here

$$P = nk_BT \qquad \textbf{(12)}$$

Diffusion Process in Semiconductors

- P is the force per unit area acting on the distribution of electrons.
- But the motion of carriers by diffusion is limited by collisions and scattering. Thus, F_{diff} is equivalent to the force exerted by an electric field
- The velocity due to diffusion is therefore given by

$$v_{diff} = -\frac{\tau_{Ce}}{m_e^*}\frac{1}{n}\frac{dP}{dx} \qquad \textbf{(13)}$$

and taking into account equation (12)

$$v_{diff} = -\frac{\tau_{Ce} k_B T}{m_e^*}\frac{1}{n}\frac{dn}{dx} \qquad \textbf{(14)}$$

Diffusion Process in Semiconductors

- This leads to the well-known equation for diffusion

$$\boldsymbol{v_{diff} = -\frac{D_e}{n}\frac{dn}{dx}} \quad \textbf{(15)}$$

where $\boldsymbol{D_e}$ is the ***diffusion coefficient*** for electrons, given by

$$\boldsymbol{D_e = -\frac{\tau_{Ce} k_B T}{m_e^*}} \quad \textbf{(16)}$$

- The current due to diffusion of electrons is expressed as

$$\boldsymbol{J_{diff}^{e} = -nqv_{diff} = qD_e\frac{dn}{dx}} \quad \textbf{(17)}$$

Diffusion Process in Semiconductors

- Similarly for holes

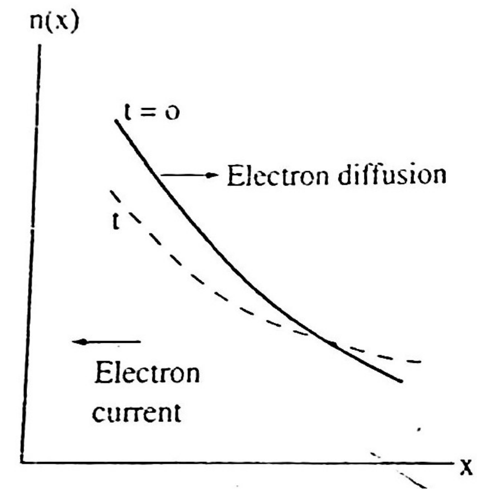
$$J^h_{diff} = -qD_h \frac{dp}{dx} \qquad \textbf{(18)}$$

where D_h is the diffusion coefficient for holes.

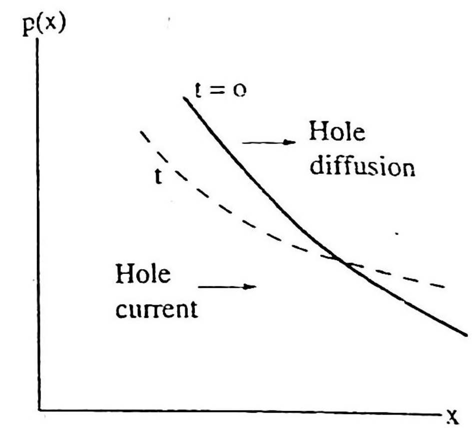
- The **positive and negative signs** in equation (17) and (18) signify the **direction of current** with respect to the concentration gradient.

- The figure illustrated here shows diffusion of (a) electrons and (b) holes due to concentration gradient and the corresponding current directions

(a)



(b)



Diffusion Process in Semiconductors

- Thus, **for electrons** having **positive concentration gradient** the **diffusion velocity** is in the **negative x direction** and **diffusion current** is in the **positive x direction**.

- **For holes** having a **positive concentration gradient**, the **hole diffusion velocity** and **diffusion current** are both in the **negative x direction**.

- Since $\boldsymbol{\mu_e} = \frac{mean\ v_D}{E} = \frac{-q\tau_{C_e}}{m_e^*}$ hence from eq. (16), the diffusion constant for electrons can also be expressed as

$$D_e = -\frac{\mu_e k_B T}{q} \quad (cm^2/s) \tag{19}$$

Similarly,

$$D_h = -\frac{\mu_h k_B T}{q} \quad (cm^2/s) \tag{20}$$

Einstein Relation & Total Current Density

From which

$$\left|\frac{D_{e(h)}}{\mu_{e(h)}}\right| = \frac{k_B T}{q} \quad (21)$$

This is known as the ***Einstein relation***. At room temperature D/ μ = 26 mV.

- If an electric field is present in addition to a concentration gradient in a semiconductor, the total current density for electrons and holes are given by

$$J_e = qn\mu_e E + qD_e \frac{dn}{dx} \quad (22)$$

$$J_h = qp\mu_h E - qD_h \frac{dp}{dx} \quad (23)$$

in which first term arises from drift and second from diffusion.

Total Current Density in Semiconductors

The total current density is the sum of the contributions due to electrons and holes

$$J(x) = J_e(x) + J_h(x) \tag{24}$$

Introduction : Bulk and Surface Recombination Phenomena

- In a semiconductor carriers are generated by intrinsic photo excitation or by injection across a forward bias p-n junction.

- Since the density of majority carriers are not usually affected, these are termed **minority-carrier generation process.**

- The *excess* minority carrier, after living a mean life, generally recombines with a majority carrier and the pair is dissipated.

- In a n-type semiconductor, net rate of recombination of holes is

$$R = \frac{1}{\tau_h}(p - p_0) \qquad \textbf{(25)}$$

where τ_h is the **hole life time** and p *and* p_0 are the **non equilibrium** and **equilibrium hole concentrations.**

Introduction : Bulk and Surface Recombination Phenomena

- The recombination can be radiative or nonradiative.
- In this section we will study non radiative recombination, in which phonon is usually emitted.

Recombination-Generation via Defects or Levels in the Band gap

- In band to band downward transition their is a small probability of emission of phonons, in which recombination becomes non radiative.

- Such nonradiative recombination take place more likely via levels with in the band gap of the semiconductor as shown in figure given below-

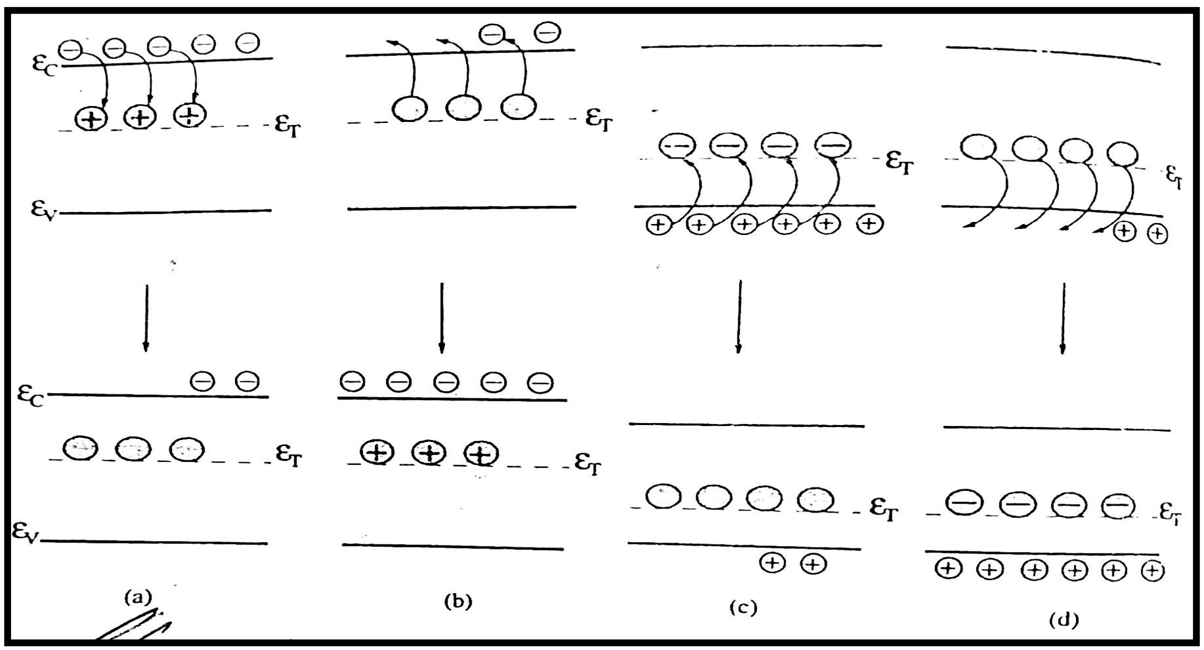


Illustration of (a) electron capture, (b) electron emission, (c) hole capture, and (d) hole emission. The deep levels in (a) and (b) are electron traps and those in (c) and (d) are hole traps

Recombination-Generation via Defects or Levels in the Band gap

- Deep levels initially act as carrier recombination or trapping centers and adversely affect device performance.

- Deep levels can be produced by a variety of defects that include substitution and interstitial impurity atom, lattice vacancies or complex defects formed by a combination of two types of defects.

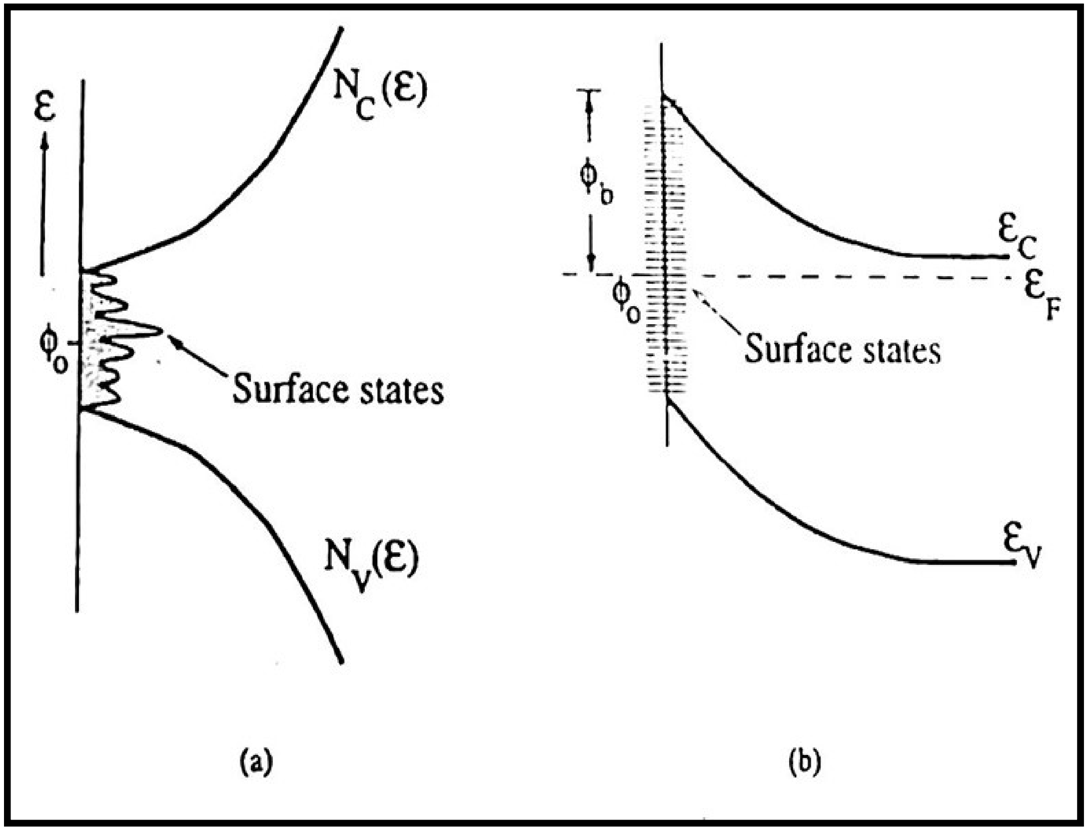
- The probability of the involvement of a phonon is very high in such transitions, which make them non radiative.

Surface Recombination

- All the bulk properties of a semiconductor come to an abrupt halt at a surface.
- The surface usually consists of ***dangling bonds*** or bonds that are satisfied by atoms other than the host atoms in the bulk.
- A common element is oxygen, and therefore a native oxide is quickly formed on a semiconductor surface.
- The dangling bonds and bonding with foreign atoms give rise to a high density of defects at the surface of a semiconductor.
- As a result, there is a distribution of defect states in the band gap at the surface as shown in following figure-

Surface Recombination

Fig. (a) Distribution of surface states in the band gap of a semiconductor and (b) band-bending caused by Fermi level pinning at the surface. $\boldsymbol{\Phi_0}$ is called the ***neutral level.*** In (b) the acceptor like surface states are occupied with electrons above $\boldsymbol{\Phi_0}$ and the surface has a net negative charge, which balances the positive charge in the depletion layer of the n-type semiconductor.



Surface Recombination

- The Fermi level is **pinned** by the overall charge state at the surface rather than by charge neutrality in the bulk.

- Due to the **large density** of such **surface states**, there is an **enhanced recombination** at the surface of the semiconductor.

- The **surface state density** N_{ST} is usually characterized by a delta function at the surface as shown in figure.

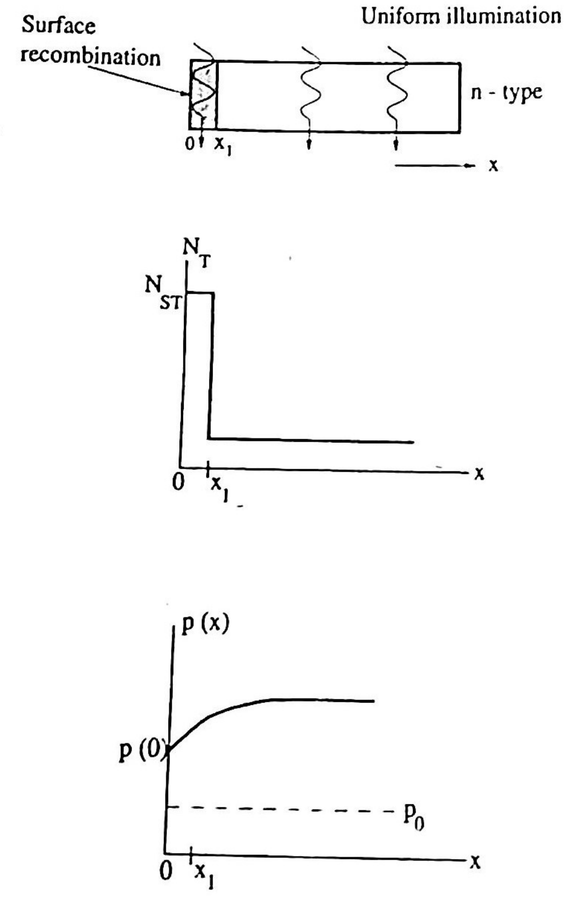


Figure – Enhanced surface recombination and resulting distribution of excess minority carriers in the presence of surface states.

Surface Recombination

- When **light falls** on such a surface, most of it can **recombine at the surface** even before reaching the bulk .

- This is extremely detrimental to the operation of most optoelectronic devices, and **special treatment of the semiconductor surface** is usually necessary.

- Due to the density of recombination centers at the surface, the resulting distribution of excess minority carriers in the semiconductor is as shown in previous figure.

- It is assumed that the surface-state density N_{ST} then the ***surface recombination velocity*** is given by-

$$s_R = s_h v_{th} N_{ST}$$

Where s_h is hole trap and v_{th} is thermal velocity.

Minimizing Surface Recombination

- Surface recombination can be minimized either by passivating the surface with a dielectric such a silicon dioxide or silicon nitride or by having a lattice matched heterojunction at the free surface.

- In both cases the wider band gap material on top of the free surface not only minimizes surface recombination but also serves as a window layer so that in a device such as a detector or solar cell light can be absorbed in the active region of interest.

Conclusion

- To conclude this session following point may be noted that-

Bulk and surface nonradiative recombination are extremely detrimental to the operation of optoelectronic devices. These centers, sometimes called *"killer centers"*, provide a nonradiative shunt path through which the excess carriers are dissipated.


THANK YOU