(MPM-202) Optoelectronics and Optical Communication System

UNIT-I (Optical Process in Semiconductors)

Lecture-4

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.

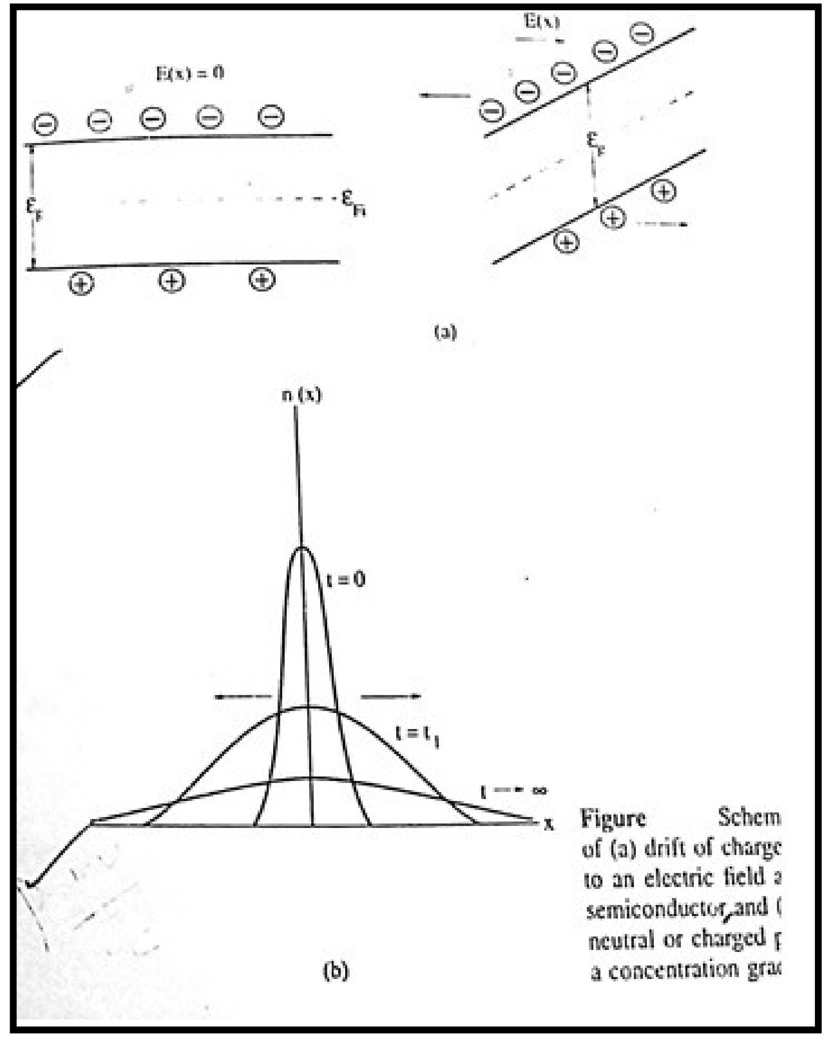


Figure Schem
of (a) drift of charge
to an electric field a
semiconductor, and (
neutral or charged p
a concentration grad

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

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

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-

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

Energy gained from the field

Energy lost due to collision

- Solution of the differential equation leads to

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

Drift Process in Semiconductors

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

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

✓ **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,

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

Drift Process in Semiconductors

- And in the time $\boldsymbol{\tau_C}$ the **current** also **reduces to zero.**

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

$$mean\ v_{Dx} = \mu_e E \tag{6}$$

and

$$J_x = nq\mu_e E \tag{7}$$

❖ If $\boldsymbol{\tau_C}$ is not a function of E, which is usually a valid assumption. It follows that

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

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

$$\boxed{J_{dr} = q(n\mu_e + p\mu_h)\mathbf{E}} \tag{9}$$

and the conductivity is given by

$$\boxed{\sigma = q(n\mu_e + p\mu_h)} \tag{10}$$

- 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

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

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

$$\boldsymbol{P = nk_B T} \qquad \textbf{(12)}$$

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

$$v_{diff} = -\frac{\tau_{Ce}}{m_e^*}\frac{1}{n}\frac{dP}{dx} \tag{13}$$

and taking into account equation (12)

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

Diffusion Process in Semiconductors

- This leads to the well-known equation for diffusion

$$v_{diff} = -\frac{D_e}{n}\frac{dn}{dx} \tag{15}$$

where D_e is the ***diffusion coefficient*** for electrons, given by

$$D_e = -\frac{\tau_{Ce} k_B T}{m_e^*} \tag{16}$$

- The current due to diffusion of electrons is expressed as

$$J_{diff}^{e} = -nqv_{diff} = qD_e\frac{dn}{dx} \tag{17}$$

Diffusion Process in Semiconductors

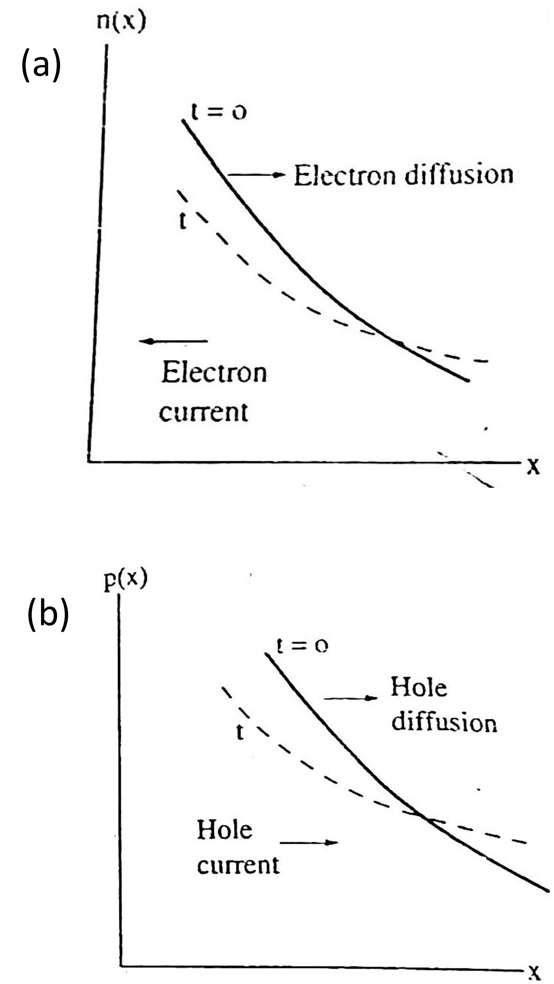
- Similarly for holes

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

where $\boldsymbol{D_h}$ 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



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,

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

Carrier Scattering Phenomena (Temperature Dependence)

- In a very pure crystal, the mobility is limited by high temperatures by carrier lattice, or phonon scattering.

- The lattice vibrations depend on temperature.

- At temperature, T> 0 K, atoms randomly vibrate. These thermal vibrations cause a disruption of the periodic potential function. This resulting in an interaction between carrier and the vibrating lattice atoms.

- Mobility due to lattice or **phonon scattering**, μ_P

$$\boldsymbol{\mu_P \propto T^{-3/2}}$$

- As **temperature decreases**, the **probability of a scattering** event **decreases** and thus, **mobility increases.**

Carrier Scattering Phenomena (Temperature Dependence)

- However, even in sufficiently pure crystals, there are impurities and other electrically active defects.

- As the temperature is lowered, the moves more slowly through the crystal and therefore the probability of collision with such charged or neutral (at very low temperature) impurity centers increase.

- To a first approximation mobility limited by ionized impurity scattering is given by, $\boldsymbol{\mu_I}$

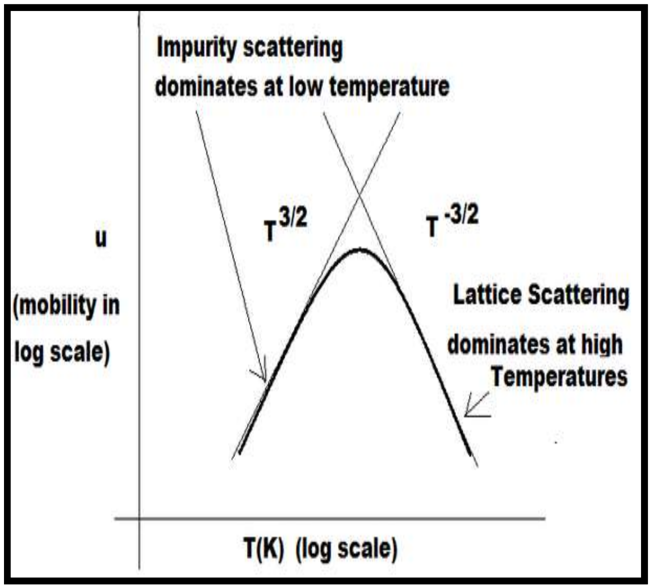
$$\boldsymbol{\mu_I} \propto \boldsymbol{T}^{3/2} \text{ and also } \boldsymbol{\mu_I} \propto \boldsymbol{N_i^{-1}}$$

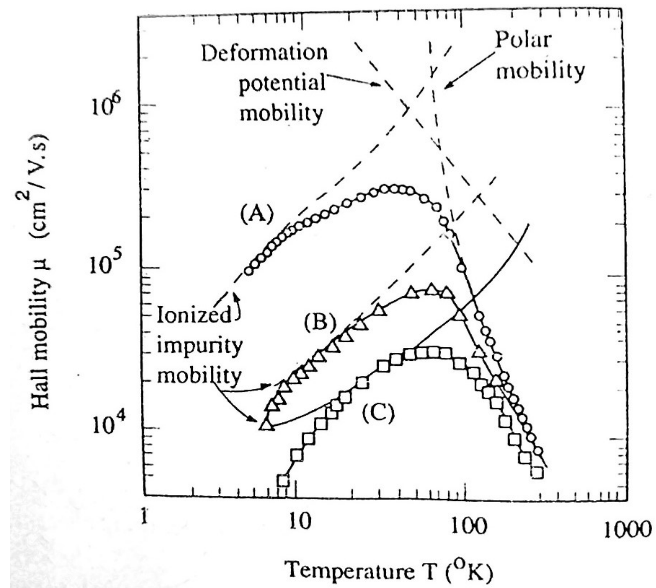
where N_i is the density of impurity centers.

- Thus total mobility as a function of temperature is given by Mattheisen's rule, as

$$\boxed{\frac{1}{\mu} = \frac{1}{\mu_I} + \frac{1}{\mu_P}}$$

Dependence of Carrier Mobility on Temperature

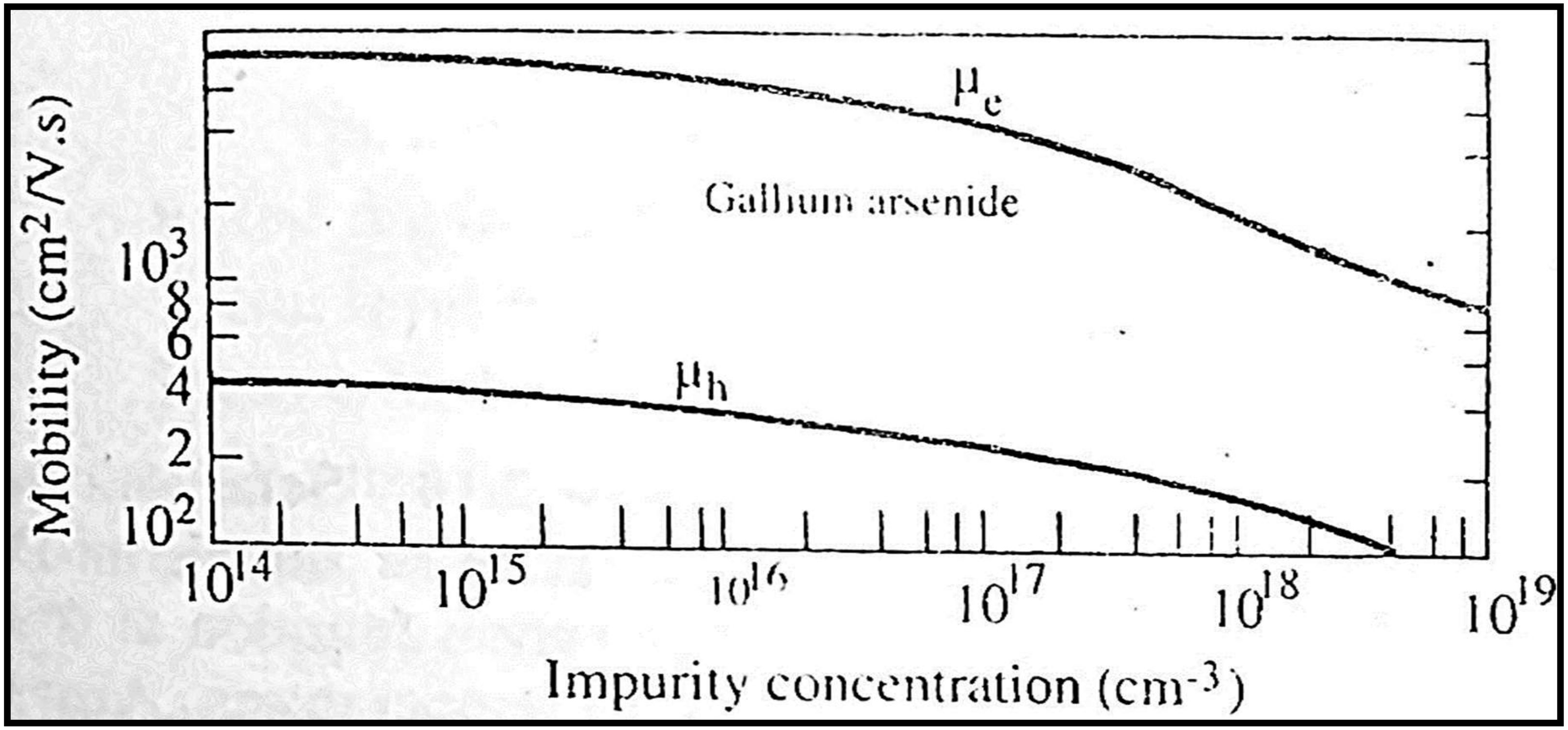




(a) **(b)**

(a) Approximate temperature dependence of mobility in very pure semiconductor sample.
(b) Mobility measured as a function of temperature in a very pure sample of GaAs grown by vapour phase epitaxy

Dependence of Carrier Mobility on Impurity Concentration



Variation of electron and hole mobilities in GaAs as a function of doping level

Carrier Scattering Phenomena (Temperature Dependence)

- In addition to two dominant carrier-scattering mechanisms, there are other sources of scattering in a real crystal.

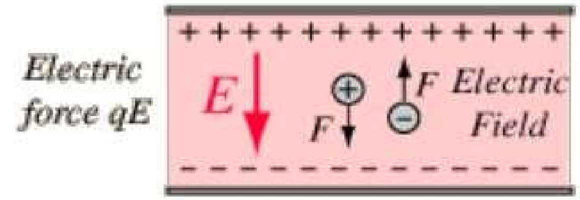
- In particular, in alloy semiconductors there is a dominant effect called *alloy scattering,* which limits the mobility.

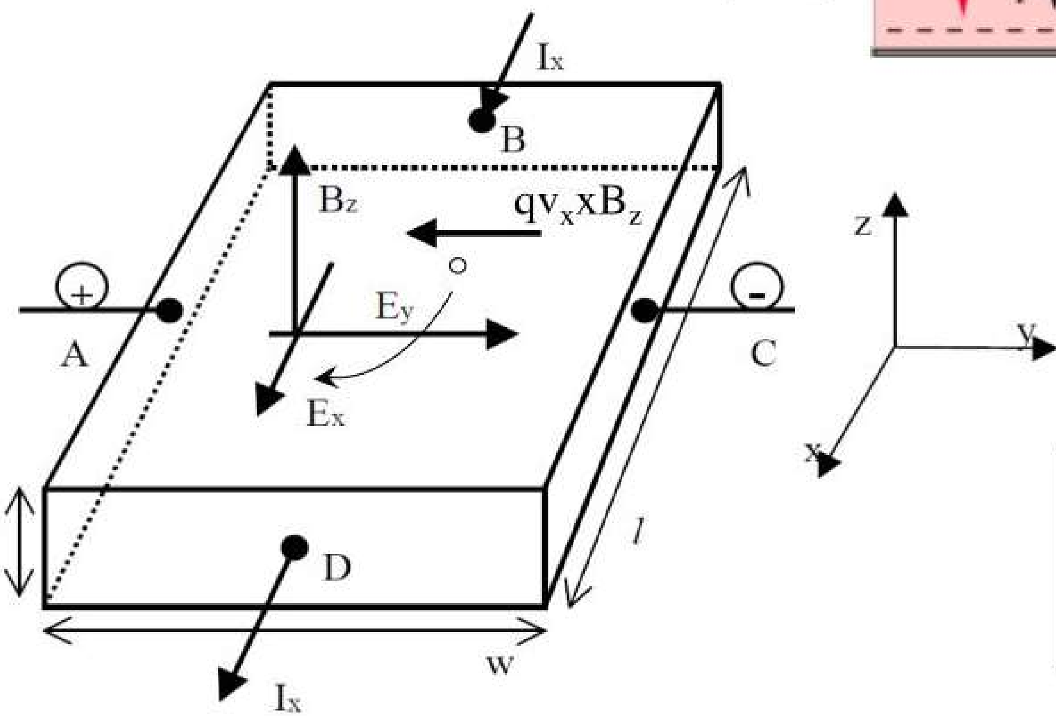
- Alloy scattering rises from the random positioning of the substituting atom species in the relevant sub lattice and the consequent perturbation of the crystal potential.

- The measurement of mobility can be easily done by Hall measurement in which motion of the carriers across the sample is altered by the Lorentz force due to magnetic field.

- This creates Hall voltage in the sample, which can be related to the mobility which is known as Hall mobility.

Hall Measurement





$$\boxed{F_B = qv_x \times B_z}$$

$$qE_y = qv_x \times B_z$$

$$E_y = \frac{1}{qp} J_x B_z$$

$$p = \frac{1}{q}\frac{I_x}{t}\frac{B_z}{V_H}$$

$$\sigma_p = q\mu_p p$$

$$\mu_p = \frac{\sigma_p}{qp}$$

Generation of forces and fields caused by Hall Effect and effect of magnetic field on the movement of holes.


THANK YOU