

Optoelectronics Devices & Circuits (MEC-166)



UNIT-I

By

Dr. POOJA LOHIA

Department of Electronics & Communication

Madan Mohan Malaviya University of Technology, Gorakhpur

SYLLABUS

Madan Mohan Malaviya University of Technology, Gorakhpur-273 010, India

M. Tech. (Digital Systems) Syllabus



MEC-166	Optoelectronics Devices & Circuits	
Topics Covered		
UNIT-I		
Elements and compound Semiconductor, Electronic Properties of semiconductor, Carrier effective masses and band structure, effect of temperature and pressure on bandgap, Carrier scattering phenomena, conductance processes in semiconductor, bulk and surface recombination phenomena.		9
UNIT-II		
Optical Properties of semiconductor, EHP formation and recombination, absorption in semiconductor, Effect of electric field on absorption, absorption in quantum wells, radiation in semiconductor, Deep level transitions, Augur recombination's.		9
UNIT-III		
Junction theory, Schottky barrier and ohmic contacts, semiconductor heterojunctions, LEDs, Photo Detectors, Solar cells.		9
UNIT-IV		
Optoelectronics modulation and switching devices: Analog and Digital modulation, Franz-Keldysh and stark effects modulators, Electro-optic modulators. Optoelectronics Integrated Circuits (OEICs): Need for hybrid and monolithic integration, OEIC transmitters and receivers.		9
Textbooks		
1.	Semiconductor optoelectronic Devices By <u>Pallab Bhattacharya</u> , Prentice Hall Publications.	
2.	Physics of Semiconductor Devices, By S.M. Sze, Wiley Publication.	

Key Points

- ❖ Introduction to Optoelectronics Devices
- ❖ Energy bands in solids, E-k diagram
- ❖ Elemental and Compound Semiconductor
- ❖ Semiconductor optoelectronic materials
- ❖ Carrier effective mass
- ❖ Effect of Temperature and Pressure on bandgap
- ❖ Carrier scattering
- ❖ Effect of scattering on mobility of carriers
- ❖ Conductance process in semiconductor
- ❖ Bulk and surface recombination phenomena

Semiconductor Statistics

- Free carriers, electrons, and holes are essential for the operation of semiconductor devices.
- These free carriers are introduced by doping process.
- Depending upon the temperature of the crystal the carrier are distributed in energy in the dopant energy level and the respective bands.
- The number of carriers at any energy level will depend on the no. of available states at that energy and the energy distribution of the carrier.
- The two important functions that determine carrier distribution in semiconductor are:
 - The energy distribution function
 - The density of states function

Density of State

The density of state describes the number of states that are available in a system and is essential for determining the carrier concentrations and energy distributions of carrier within the semiconductor.

The expression for density of state is given by-

$$D_n(E) = \left(\frac{1}{2\pi^2} \right) \left(\frac{2m_e}{\hbar^2} \right)^{3/2} (E - E_C)^{1/2}$$

- The **number of carriers** that can contribute to the conduction process is a function of the number of available energy or quantum states since, by the **Pauli exclusion principle**, only one electron can occupy a given quantum state.
- After **splitting of energy levels** the band of **allowed and forbidden energies forms**.
- The **band of allowed energy** is actually made up of **discrete energy levels**.

We must determine the density of these allowed energy states as a function of energy in order to calculate the electron and hole concentrations.

Fermi-Dirac distribution and the Fermi-level

Density of states tells us how many states exist at a given energy E . The Fermi function $f(E)$ specifies how many of the existing states at the energy E will be filled with electrons. The function $f(E)$ specifies, under equilibrium conditions, the probability that an available state at an energy E will be occupied by an electron. It is a probability distribution function.

$$f(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$

E = The energy of states or level

E_F = Fermi energy or Fermi level

k = Boltzmann constant = 1.38×10^{-23} J/K
= 8.6×10^{-5} eV/K

T = absolute temperature in K

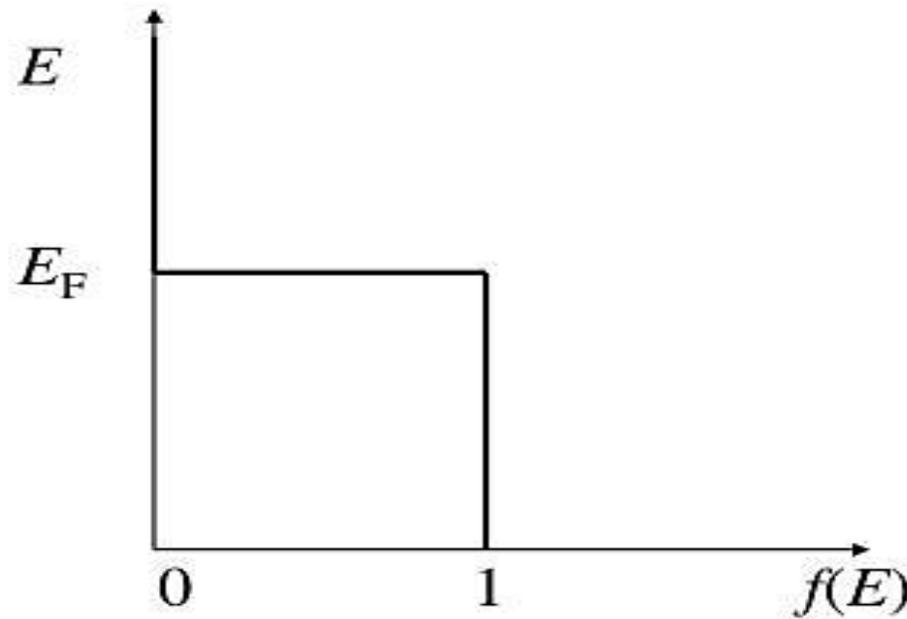
FERMI-DIRAC DISTRIBUTION

Condition-I

Fermi-Dirac distribution: **Consider $T \rightarrow 0$ K**

$$\text{For } E > E_F : \quad f(E > E_F) = \frac{1}{1 + \exp(+\infty)} = 0$$

$$\text{For } E < E_F : \quad f(E < E_F) = \frac{1}{1 + \exp(-\infty)} = 1$$



FERMI-DIRAC DISTRIBUTION

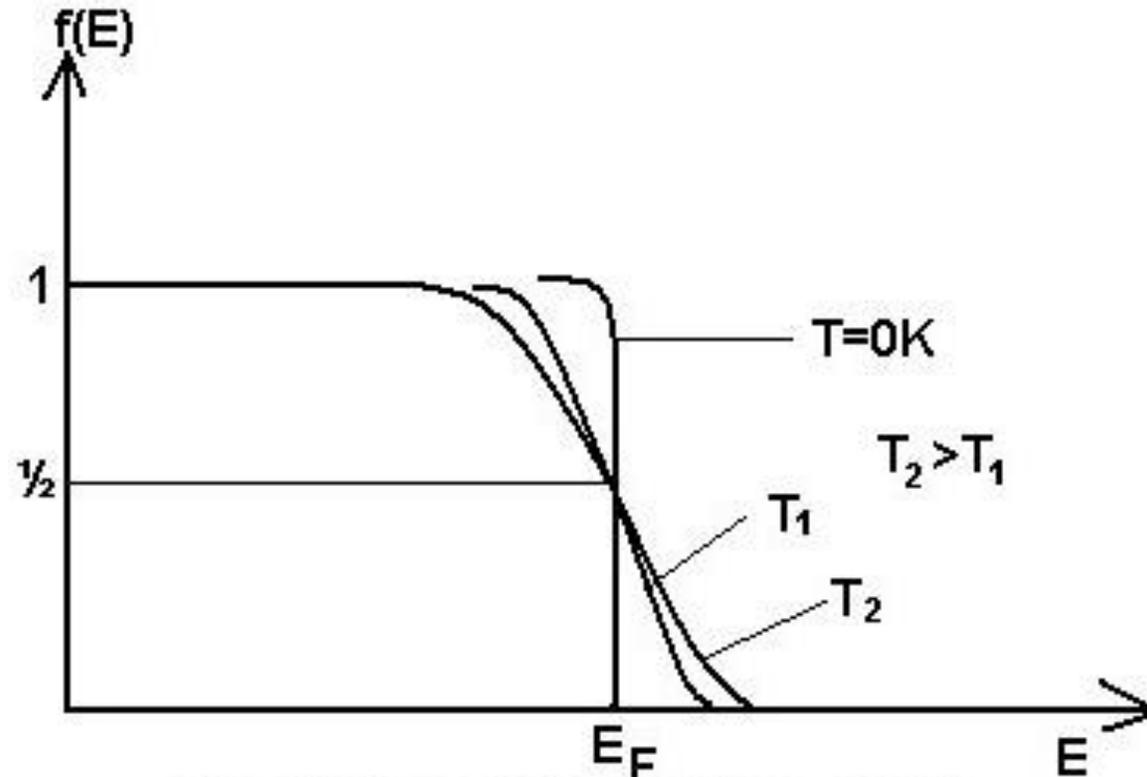
CONDITION I:

- First it is seen that the maximum value of function is unity.
- Therefore the probability of occupation of an energy level can never exceed unity, or not more than one electron can occupy the same quantum states.

CONDITION II:

- At $E=E_F$ the value of the function goes from unit to zero at 0°K .
 - At any temperature T , $F(E)=1/2$ at $E=E_F$.
- Thus, the fermi energy can be defined as the energy level up to which all level occupied and above which all levels are empty at 0°K .
- At any temperature $T > 0^\circ\text{K}$ the probability of occupation at the fermi level is $1/2$.

Temperature Dependence of Fermi Distribution Function



- **Fig:1.6:** Schematic representation of fermi Dirac distribution function at 0° K and higher Temperatures.
- Indicates the lowering of fermi energy E_F with increase of temperature.

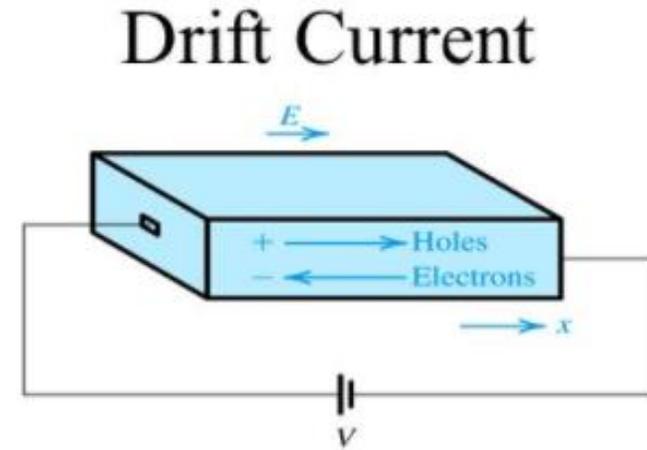
Conduction Processes in Semiconductors

- 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 process in Semiconductors

- Conduction process in semiconductor takes place by the following process:
- Drift current
- Diffusion current

Drift current:



The drift current arises due to the force applied by an externally applied electric field (E) on the charge carriers. Therefore the resulting current is known as drift current and corresponding density is known as drift current density (J_D).

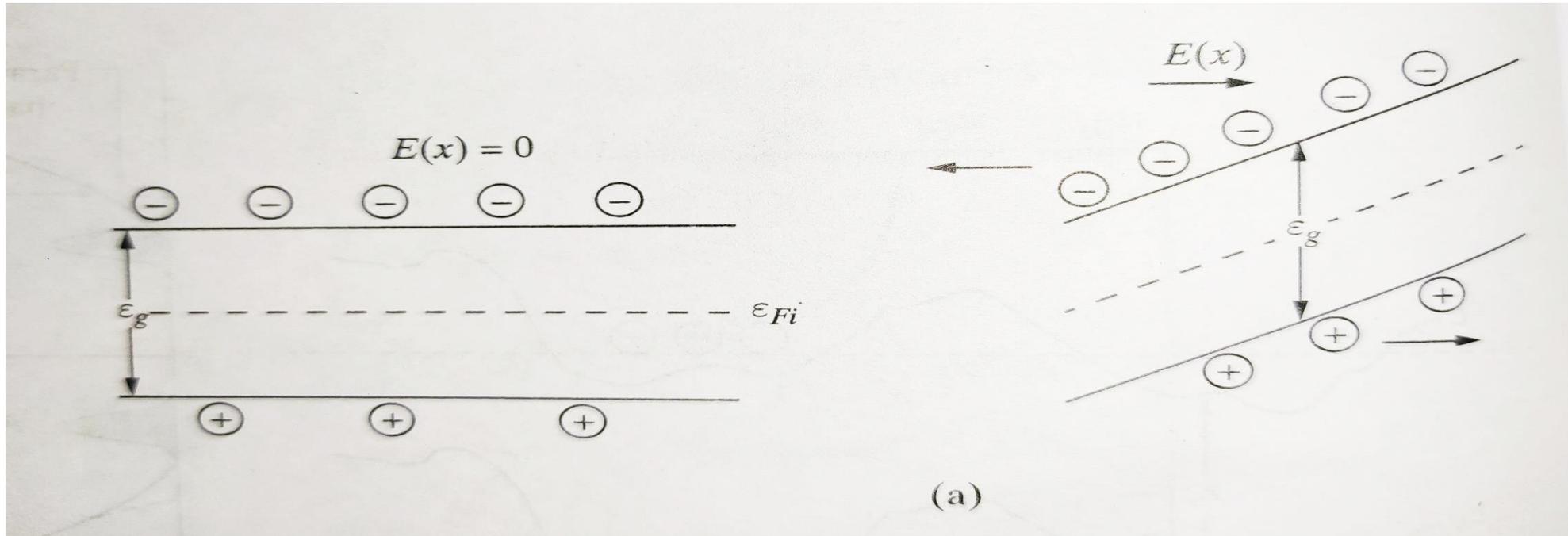


Fig: Drift of carries due to external field

- It can be noted from the figure the bending of bands and motion of electrons are in opposite directions.

Diffusion current:

- **Diffusion arises from a nonuniform density of carriers electrons and holes.**
- The carriers will diffuse from a region of high density to low density and the process is identical for natural and charged particles.

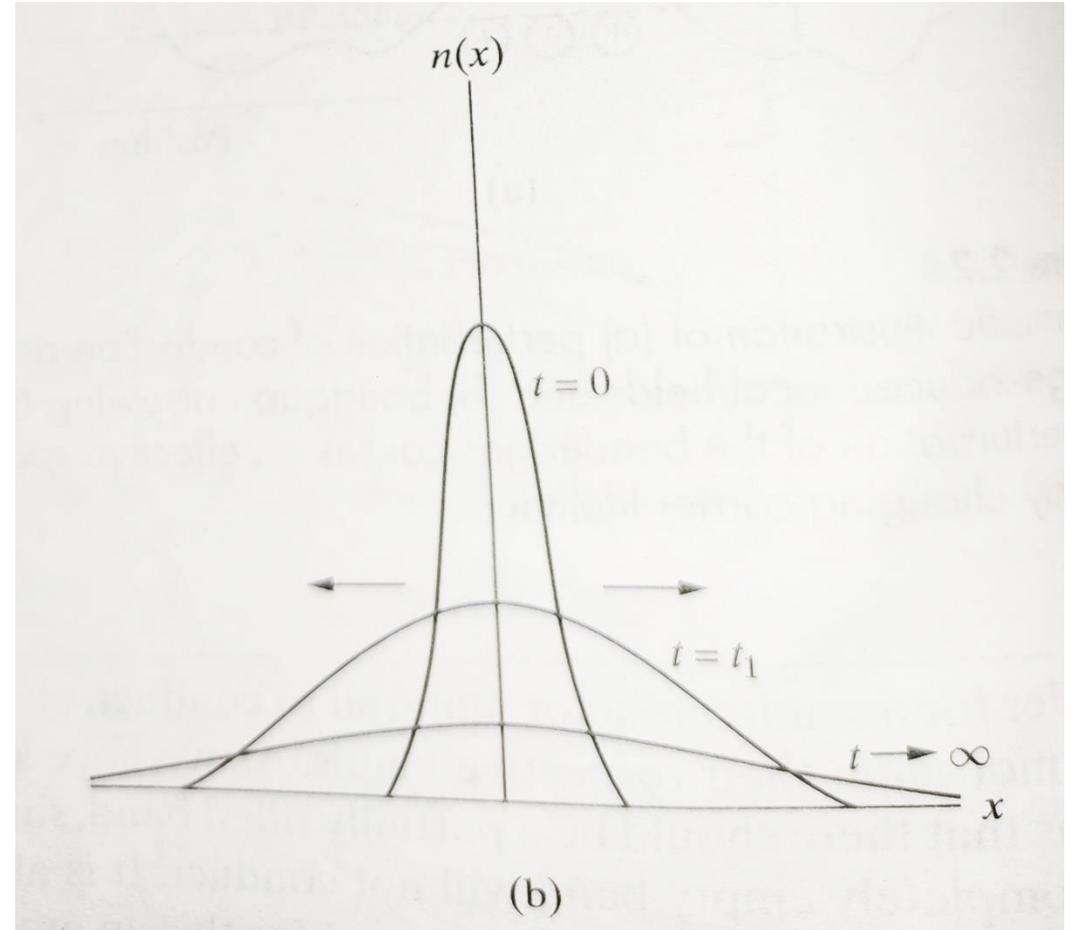


Fig: Diffusion of charge particle due to concentration gradient

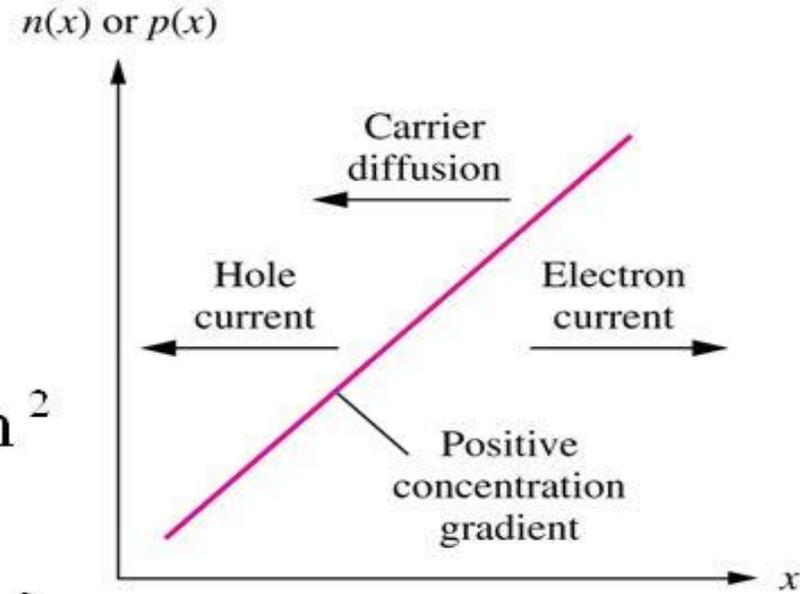
Diffusion Current (cont.)

- Carriers move toward regions of lower concentration, so diffusion current densities are proportional to the **negative** of the carrier gradient.

$$j_p^{diff} = (+q)D_p \left(-\frac{\partial p}{\partial x} \right) = -qD_p \frac{\partial p}{\partial x} \quad \text{A/cm}^2$$

$$j_n^{diff} = (-q)D_n \left(-\frac{\partial n}{\partial x} \right) = +qD_n \frac{\partial n}{\partial x} \quad \text{A/cm}^2$$

Diffusion current density equations



Diffusion currents in the presence of a concentration gradient.

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

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

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

- Let the average time between collisions be τ_C , then the average rate of change of momentum due to collision is mv_D/τ_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

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

Drift Process in Semiconductors

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

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

- ✓ 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,

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

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

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

and

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

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

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

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

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

and the conductivity is given by

$$\sigma = q(n\mu_e + p\mu_h) \quad (10)$$

- 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

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

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

$$P = nk_B T \quad (12)$$

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

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

and taking into account equation (12)

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

Diffusion Process in Semiconductors

- This leads to the well-known equation for diffusion

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

where D_e is the diffusion coefficient for electrons, given by

$$D_e = \frac{\tau_{ce} k_B T}{m_e^*} \quad (16)$$

- The current due to diffusion of electrons is expressed as

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

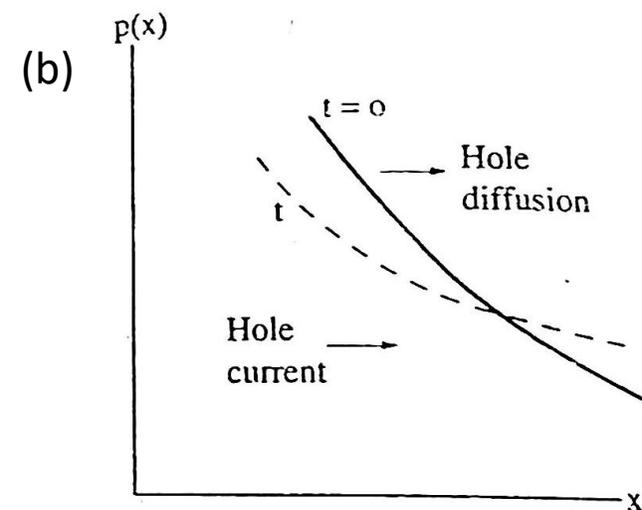
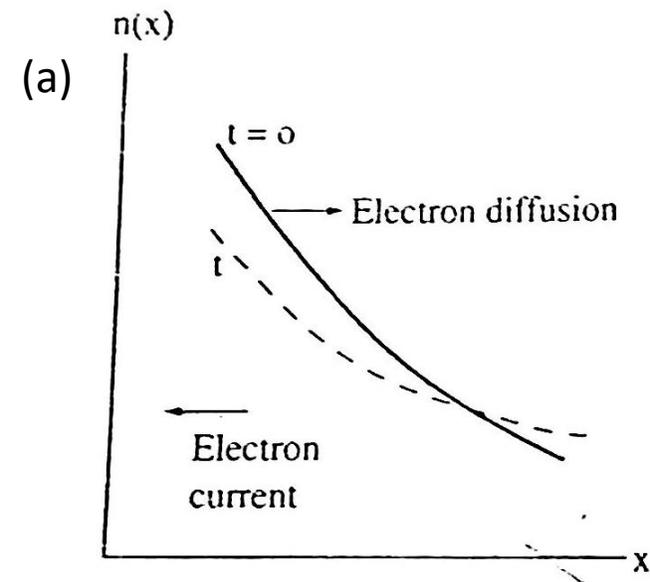
Diffusion Process in Semiconductors

- Similarly for holes

$$J_{diff}^h = -qD_h \frac{dp}{dx} \quad (18)$$

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



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

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

Similarly,

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

Einstein Relation & Total Current Density

From which

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

This is known as the *Einstein relation*. At room temperature $D/\mu = 26 \text{ mV}$.

- 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

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

(24)

THANK YOU

