(MPM-202)
Optoelectronics and Optical Communication System

UNIT-I (Optical Process in Semiconductors)
Lecture-3
by
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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.

Effect of Temperature on Semiconductor's Band gap

As the temperature of a semiconductor is varied, several important effects takes place in the lattice.

- The lattice will expand or contract, and the oscillations of the lattice atoms around their mean positions will increase or decrease.

- The electron lattice interaction also changes with temperature.

- Impurity potentials of shallow donors and acceptors are also affected, although the ionization energy of the impurities remain fairly constant.

- The experimentally observed macroscopic factor is a change in the band gap with temperature.

- The dependence varies in different temperature range and approximately obeys the empirical relation, first proposed by **Varshni .**

Effect of Temperature on Semiconductor's Band gap
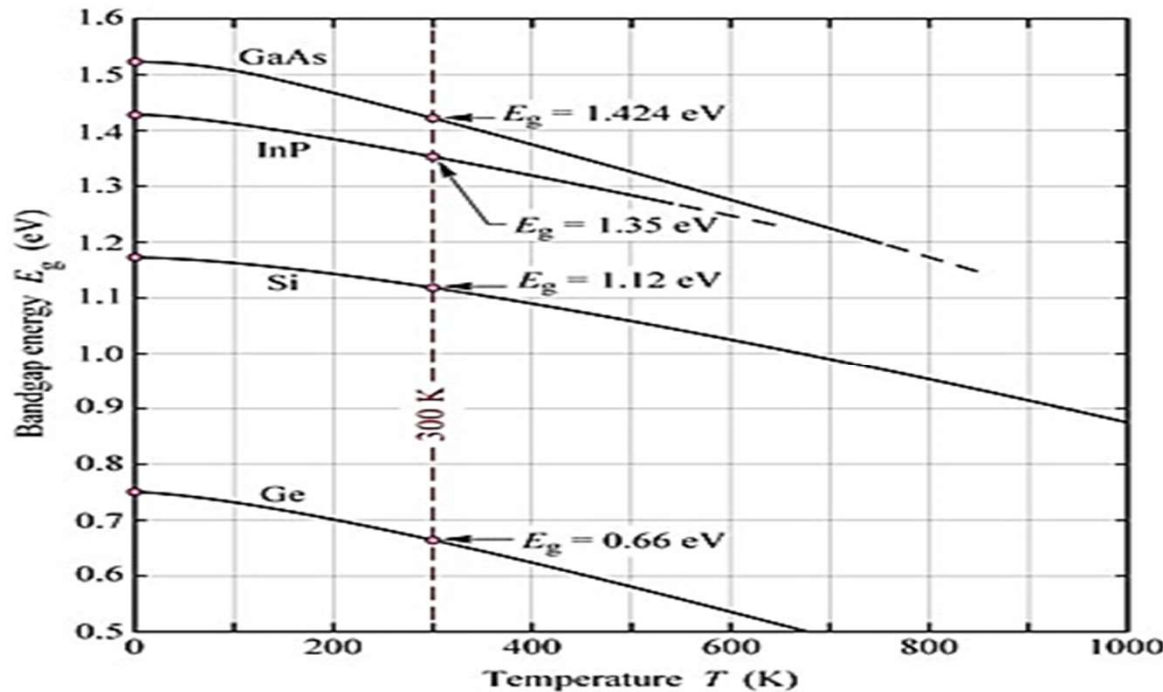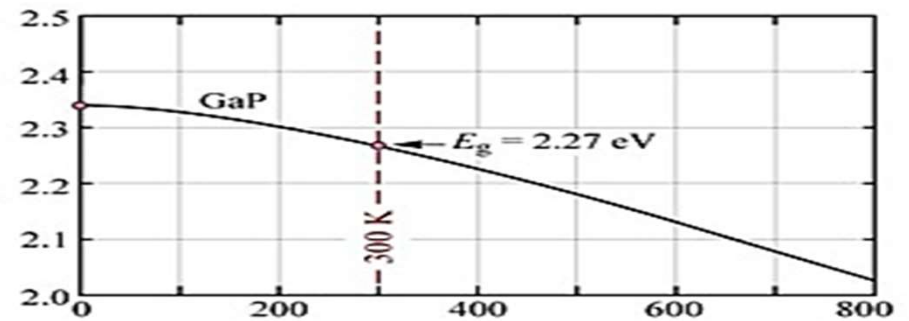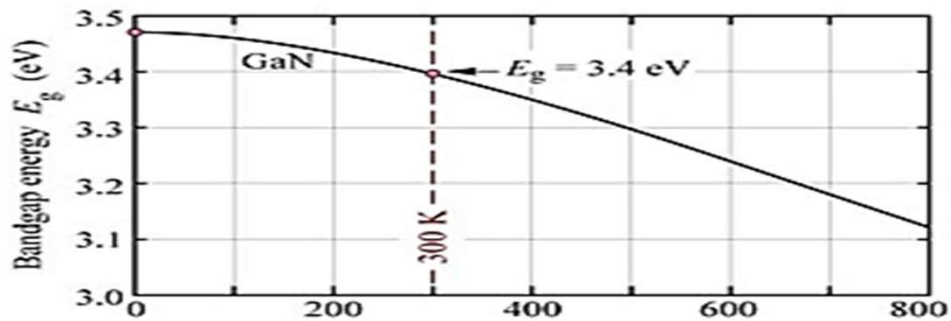
Varshni formula:
$$E_g = E_g(0K) - \frac{\alpha T^2}{T + \beta}$$

	$E_g(0K)$	$\alpha\ (10^{-4}\ \frac{eV}{K})$	β (K)
GaN	3.470	7.70	600
GaP	2.340	6.20	460
GaAs	1.519	5.41	204
InP	1.425	4.50	327
Si	1.170	4.73	636
Ge	0.744	4.77	235

Fundamental bandgap energy of GaN, GaP, GaAs, InP, Si, and Ge as a function of temperature. The bandgap energy is approximated by the Varshni formula which uses the fitting parameters α and β (from data compiled by Ioffe, 2004).

Effect of Pressure on Semiconductor's Band gap

- The built-in biaxial strain is caused by the lattice mismatch between the growing layer and the substrate.

- Compressive hydrostatic presser decreases the interatomic spacing, which results in an increase in the fundamental energy band gap.

- In general, all energy levels in a semiconductor are shifted, and the change can be expressed by the equation

$$\boldsymbol{\varepsilon(P) = \varepsilon(0) - \varepsilon_1 \Delta a}$$

Which denotes a linear change in the energy level with change in lattice constant Δa. The above relation is valid for small value of Δa.

Effect of Pressure on Semiconductor's Band gap

- $\varepsilon(0)$ is the energy level without the application of hydrostatic pressure.
- ε_1 is pressure coefficient or deformation potential.

➤ The change in the energy gap of a semiconductor can then be expressed by the equation-

$$\varepsilon_g(P) = \varepsilon_g(0) \pm (\varepsilon_{1C} + \varepsilon_{1V})\Delta a$$

Where ε_{1C} and ε_{1V} are the respective pressure coefficients for the conduction and valance bands.

➤ Different valleys have different pressure coefficient and some may be even have negative values.

Effect of Pressure on Semiconductor's Band gap

- For example, in GaAs,

i. Γ valley increases in energy at a faster rate than the L valleys, and the X valleys decrease in energy.

ii. The valley pressure coefficients for Γ, L and X valleys is tabulated below-

Valley	Valley pressure coefficients (eV/bar)
Γ	12.6×10^{-6}
L	5.5×10^{-6}
X	-1.5×10^{-6}

Thus the different valleys cross over and after a certain magnitude of hydrostatic pressure GaAs becomes an indirect band gap semiconductor.

Effect of Pressure on Semiconductor's Band gap

- The process of alloying and application of hydrostatic pressure, and equivalent.

- In alloying depending on the relative atomic size, the host lattice can be compressed or dilated.

As the $\Gamma - L$ And $\Gamma - X$ energy separations decrease, due to alloying or hydrostatic pressure, there will be transfer and redistribution of carriers among the direct and indirect minima.

- The mobility and equilibrium carrier concentration will now be average quantities, determined by the parameter of all the bands.

- Since the effective mass and density of state are higher in the X and L minima, the average measured mobility will be lower than that in GaAs.

Effect of Pressure on Semiconductor's Band gap

- The concentration of electron in the Γ - minimum will decrease.

- The distribution of electrons between the different conduction minima can be simply expressed by Boltzmann statistics.

$$\text{The total electron concentration, } n_T = n_\Gamma + n_L + n_X$$

➤ A change in band gap due to hydrostatic pressure cause changes in other properties of the material. For example-

- The intrinsic carrier concentration, depends exponentially on the energy band gap.
- Change in the dielectric constant which indirectly alters the ionization energies of impurity atoms and the binding energy of excitons.

Carrier Scattering

- Mobile electrons and atoms in the Si lattice are always in random thermal motion.
  - Electrons make frequent collisions with the vibrating atoms

    "lattice scattering" or **"phonon scattering"** – increases with increasing T

- Other scattering mechanisms:
  - deflection by ionized impurity atoms
  - deflection due to Columbic force between carriers

    "carrier-carrier scattering" – only significant at high carrier concentrations
- **The net current in any direction is zero, if no E-field is applied.**
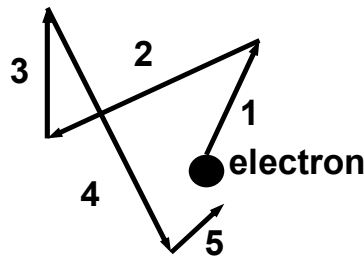
1. Lattice Scattering or Phonon Scattering

- In equilibrium a charged carrier electron or hole, in a semiconductor has thermal velocity $v_{th} = (\frac{3k_BT}{m^*})^{1/2}$ which is derived from its energy distribution.

- When the carriers move in the influence of externally applied bias, or due to concentration gradient, its motion with in the lattice can be greatly restricted by impurities, defect and other imperfections.

- In addition, at any finite temperature, the atoms in the lattice are vibrating about their mean position in the lattice

- The quanta of lattice vibrations are called *phonons,* which are quantum mechanical particles.

- In a diatomic lattice, such as GaP and InP and their derivatives there are *acoustic and optical phonons.*

Lattice Scattering or Phonon Scattering

- The names are associated with their oscillation frequencies.

- In a *monoatomic* lattice such as Si, there are only *acoustic* phonons.

- The probability of finding a phonon of frequency ω, is given by the function-

$$f_{BE}(\omega) = \frac{1}{\left[exp\left(\frac{\hbar\omega}{k_B T}\right) - 1\right]}$$

Which is *Bose-Einstein* distribution function.

- An interesting relation exists between the optical phonon frequencies and the dielectric constant in a crystal.

- **At lower frequencies** in the optical spectrum, such as for infrared light, thee atomic sub lattices respond to the variations caused by the em wave, and the corresponding change of dipole momentum can be accounted for by the static dielectric constant ϵ_s.

Lattice Scattering or Phonon Scattering

- **At higher frequencies**, for example for visible light , the atoms can no longer response to the fast-varying electric field, and thus the high frequency dielectric constant ϵ_∞ is determined by electronic motion alone.

- Usually ϵ_∞ *is smaller than* ϵ_s and the relationship

$$\frac{\omega_{L0}}{\omega_{T0}} = \left(\frac{\epsilon_s}{\epsilon_\infty}\right)^{1/2}$$

was derived by Liddane, Sachs, and Teller.

This equationis therefore known as ***Liddane-Sachs-Teller relationship.***

2. Ionized Ion Scattering

- There are other sources of carrier scattering such as scattering by **charged impurities** and by other defects within the crystal.

In general, anything that perturbs the periodic crystal potential in the lattice, which in turn alters the bandedge potentials, will scatter carriers.

✓ Now we will derive a simple relation between the relaxation time for carrier scattering and resulting mobility of the carriers i.e.

$$\mu_e = -\frac{q\tau_{C_e}}{m_e^*} \ and \ \mu_h = \frac{q\tau_{C_h}}{m_h^*}$$

for electron and hole respectively.

Ionized Ion Scattering

Derivation :

- First we define a scattering cross section $\sigma_s(\theta, \phi)d\Omega$, which the probability that an electron is scattered from $(\theta, \phi) = 0$ to some angle (θ, ϕ) within an **incremental solid angle** $d\Omega$.
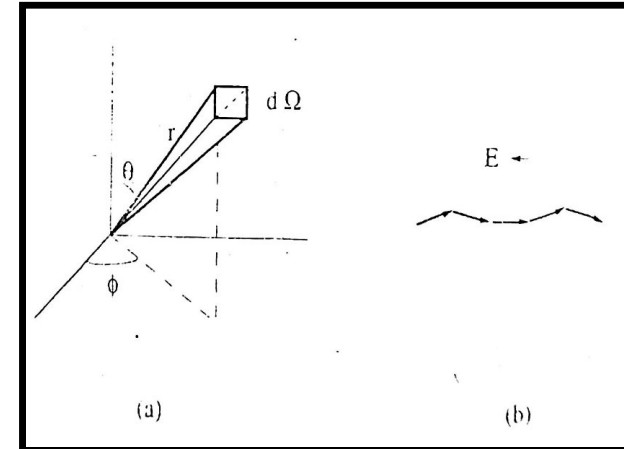
- The total cross section is then
$$\sigma_{st} = \int \sigma_s(\theta, \phi)d\Omega \qquad (1)$$

- We also define a mean free time τ_C between successive collisions such that
$$\tau_C = \frac{l}{v} \qquad (2)$$

Where l is the mean free path and v is the mean velocity.

(a) Scattering geometry in polar coordinates and (b) motion of an electron under the influence of an electric field. The motion is superposition of drift and random motion with thermal velocity. As the field increases, the drift component becomes more dominant.

Ionized Ion Scattering

- Consider n electrons moving with the velocity v in a given direction.

- The **number of collisions, dn ,** in time dt is proportional to n and dt, so that

$$dn = -Cndt \qquad (3)$$

where C is a constant of proportionality. We define

$$C = \frac{1}{\tau_C} \qquad (4)$$

where τ_C is defined as the **relaxation time.**

- Combining equation (3) and (4),

$$\frac{dn}{n} = -\frac{dt}{\tau_C} \qquad (5)$$

which, on integration gives

$$n = n^0 e^{-t/\tau_C} \qquad (6)$$

where $n = n^0$ at t = 0.

Ionized Ion Scattering

- The probability that a electron has not made a collision is

$$\frac{n}{n^0} = e^{-t/\tau_C} \qquad (7)$$

- The mean time between collisions is

$$mean\ t = \frac{1}{\tau_C}\int_0^\infty te^{-t/\tau_C} = \tau_C \qquad (8)$$

- The mean free path can also be defined as

$$\frac{1}{l} = N_{SC}\sigma_{SC} \qquad (9)$$

 where N_{SC} is the density of scattering centers. Therefore from equation (2),

$$\tau_C = \frac{1}{N_{SC}\sigma_{SC}v} \qquad (10)$$

- Now, consider an electron under the influence of an electric field and suffering collisions as depicted in previous figure.

Ionized Ion Scattering

- At time t = 0, its velocity is v_0 and velocity v at time t, when it suffers collision, is given by

$$v = v_0 - \frac{qEt}{m_e^*} \qquad (11)$$

  where E is the applied field.

- This equation must be averaged over all time knowing that $\frac{1}{\tau_C} e^{-t/\tau_C}$ is the probability that a collision will occur after t seconds. Thus, the time-averaged velocity is given by

$$mean\ v = mean\ v_0 - \frac{qE}{\tau_C m_e^*} \int_0^\infty t e^{-t/\tau_C} dt$$

$$= mean\ v_0 - \frac{qE\tau_C}{m_e^*} \qquad (12)$$

- If the collisions are truly random, $mean\ v_0$ =0 and the mean drift velocity is given by

$$mean\ v = mean\ v_D = - \frac{qE\tau_C}{m_e^*} \qquad (13)$$

Ionized Ion Scattering

✓ **The magnitude of the mean drift velocity per unit field is defined as 'mobility',** such that

✓ For electrons,

$$\mu_e = \frac{mean\ v_D}{E} = \frac{-q\tau_{C_e}}{m_e^*} \qquad (14)$$

and for holes,

$$\mu_h = \frac{mean\ v_D}{E} = \frac{q\tau_{C_h}}{m_h^*} \qquad (15)$$

Therefore, through the effective masses, the carrier mobilities depend on the dispersion (E-k) curve