(MPM-202)
Optoelectronics and Optical Communication System

UNIT-I (Optical Process in Semiconductors)

Lecture-8

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.

Electron-Hole Pair Recombination Rate

- All the processes occur at the same time in a material but at different rates.

- If we have device with **low field and non-degenerate** semiconductor then the recombination-generation mechanism **at room temperature** that dominates is-

1. **Band-to- Band Transition**
2. **R-G Center Transition**

- For example,
- In a **direct** band gap semiconductor, **band-to-band** transitions dominate.
- In **indirect** band gap semiconductors, **R-G center** transitions dominate.

Electron-Hole Pair Recombination Rate

- In general, the total recombination rate is given by the sum of recombination rate due to all the processes-

$$R = B_1 np + B_2 np + B_3 np + \ldots\ldots\ldots\ldots$$

- Not all of them will dominate so one can simplify the expression by looking at only the dominating recombination mechanism.

- **There are two special cases in device physics-**

1. **Low Level Injection**
2. **High Level Injection or Excitation**

Electron-Hole Pair Recombination Rate

Case I- Low Level Injection :

Let in equilibrium we have the equilibrium concentration of electrons and holes is $\boldsymbol{n_0}$ & $\boldsymbol{p_0}$ and $\boldsymbol{n_i}$ be the intrinsic carrier concentration then-

$$\boldsymbol{n_0 p_0 = n_i^2} \qquad \textbf{(1)}$$

Now, we create excess electrons and holes such that new carrier concentration be-

$$\boldsymbol{n = n_0 + \Delta n \; ; p = p_0 + \Delta p} \qquad \textbf{(2)}$$

Where $\boldsymbol{\Delta n \; and \; \Delta p}$ are the excess number of electrons and holes generated respectively.

Electron-Hole Pair Recombination Rate

- At t = 0, in optical and thermal generation,

$$\Delta n_0 = \Delta p_0 \, ; \, \Delta n = \Delta p \qquad \textbf{(3)}$$

- Low level injection means the excess carrier generated at any time must be much smaller than the majority carrier concentration of semiconductor.

$$\Delta p, \Delta n \ll n_0 \qquad \textbf{for n-type} \qquad \textbf{(4)}$$

$$\Delta p, \Delta n \ll p_0 \qquad \textbf{for p-type} \qquad \textbf{(5)}$$

Electron-Hole Pair Recombination Rate

- Now we want to see how the carrier concentration is changing with time at any time 't'-

$$\frac{dn}{dt} = \frac{dp}{dt} = \underbrace{BnP}_{\text{Recombination Rate}} - \underbrace{G_{th}}_{\text{Thermal Generation Rate (B } n_0 p_0\text{)}} \qquad (6)$$

the carrier concentration at any time 't' is-

$$\frac{d(n_0 + \Delta n)}{dt} = B(n_0 + \Delta n)(p_0 + \Delta p) - Bn_0 p_0 \qquad (7)$$

Electron-Hole Pair Recombination Rate

$$\frac{d(n_0 + \Delta n)}{dt} = B(n_0 + \Delta n)(p_0 + \Delta p) - Bn_0p_0$$

$$\frac{d(\Delta n)}{dt} = B(n_0p_0 + p_0\Delta n + n_0\Delta p + \Delta n\Delta p) - Bn_0p_0 \qquad \textbf{(8)}$$

$\Delta n\Delta p$ is negligible at low level injection

$$\frac{d(\Delta n)}{dt} = B(p_0\Delta n + n_0\Delta p) \qquad \textbf{(9)}$$

Since $\Delta n = \Delta p$

Electron-Hole Pair Recombination Rate

$$\frac{d(\Delta n)}{dt} = B\Delta n(p_0 + n_0) \quad (10)$$

At t=0 , $\Delta n = \Delta n_0$, therefore after solving above equation we get the equation for change in excess carrier concentration at any time t-

$$\boxed{\Delta n = \Delta n_0 e^{-\frac{t}{\tau}}} \quad (11)$$

Where $'\tau'$ is the ***'carrier life time'*** which is defined as

$$\boxed{\tau = \frac{1}{B(n_0 + p_0)}} \quad (12)$$

Electron-Hole Pair Recombination Rate

- From equation 10 and 12 we get, the recombination rate R is given by-

$$\boxed{R = \frac{dn}{dt} = \frac{d(\Delta n)}{dt} = B\Delta n(p_0 + n_0) = \frac{\Delta n}{\tau}} \qquad \textbf{(13)}$$

$$\text{Since } \tau = \frac{1}{B(n_0+p_0)}$$

- In a **n-type device** majority carrier concentration is n_0 so, $\tau = \frac{1}{B(n_0)}$ **(14)**
- In a **p-type device** majority carrier concentration is p_0 so, $\tau = \frac{1}{B(p_0)}$ **(15)**

Electron-Hole Pair Recombination Rate

- For a single recombination process

$$R = \frac{\Delta n}{\tau}$$

- If more processes of recombination are involved then the recombination rate is given by-

$$\boxed{R = \frac{\Delta n}{\tau_1} + \frac{\Delta n}{\tau_2} + \frac{\Delta n}{\tau_3} + \ldots\ldots\ldots\ldots} \qquad \textbf{(16)}$$

- **This expression of recombination is for low level injecction**

Electron-Hole Pair Recombination Rate

Case I- High Level Injection :

The excess carrier generated in this case is very much larger than the total equilibrium concentration of electrons an holes-

$$\Delta n \gg n_0 + p_0 \qquad (17)$$

Simillar to low level injection eq (8) is given by-

$$\frac{d(\Delta n)}{dt} = B(n_0 p_0 + p_0 \Delta n + n_0 \Delta p + \Delta n \Delta p) - B n_0 p_0 \qquad (18)$$

Here, in this case $n_0 p_0$ is negligible as compared to other and $\Delta n = \Delta p$.

Electron-Hole Pair Recombination Rate

$$\frac{d(\Delta n)}{dt} = B\left(\Delta n(p_0 + n_0) + \Delta n^2\right) \tag{19}$$

After solving this gives change in carrier concentration,

$$\boxed{\Delta n(t) = \frac{1}{(Bt + \Delta n^{-1})}} \tag{20}$$

Thus, the rate of recombination **at high level injection** is given by-

$$\boxed{R = -\frac{dn}{dt} = -\frac{B}{\left(Bt + \Delta n_0^{-1}\right)^2}} \tag{21}$$

Summary Recombination Rate

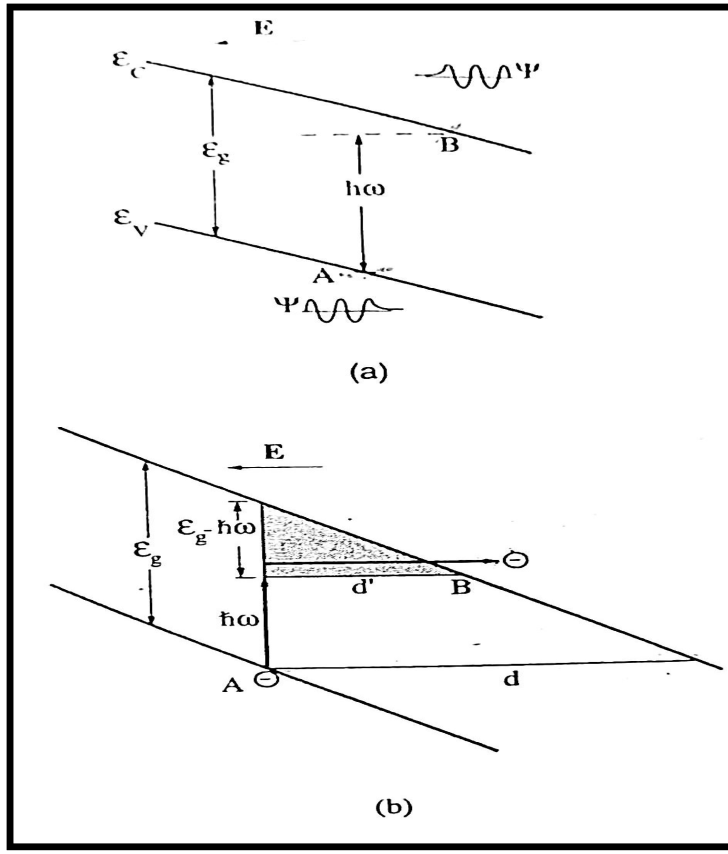
<u>Case I- Low Level Injection</u>	<u>Case II- High Level Injection</u>
$\Delta n(t) = \Delta n_0 e^{-\frac{t}{\tau}}$	$\Delta n(t) = \frac{1}{(Bt + \Delta n^{-1})}$
$\tau = \frac{1}{B(n_0 + p_0)}$	$R = -\frac{dn}{dt} = -\frac{B}{\left(Bt + \Delta n_0^{-1}\right)^2}$
$R = \frac{dn}{dt} == B\Delta n\left(p_0 + n_0\right) = \frac{\Delta n}{\tau}$	

Effect of Electric Field on Absorption: FRANZ-KELDYSH AND STARK EFFECTS

- The change in absorption in a semiconductor in the presence of strong electric field is the ***Franz-Keldysh effect,*** which results in the **absorption of photons with energy less than the band gap** of the semiconductor.

- The energy bands of semiconductor in the presence of electric field E and with an incident photon of energy $\hbar\omega < \varepsilon_g$ are shown in figure (a) and (b).

- In figure (a) shows **the bending of bands due to applied electric field** and (b) shows **the absorption of photon with $\hbar\omega < \varepsilon_g$ due to carrier tunneling** (Franz-Keldysh effect).



Franz-Keldysh Effect

- The classical turning points are marked as A and B, the electron wave functions change from oscillatory to decaying behaviour.

- Thus electron in the energy gap is described by an **exponentially decaying** function $\boldsymbol{u_k e^{jkx}}$, where k is imaginary.

- With **increase of electric field**, the distance **AB decreases** and **the overlap** of the wave functions within the gap **increases.**

- In the **absence of a photon**, the valance electron has to tunnel through a triangular barrier of height ε_g and thickness d, given by

$$\boldsymbol{d = \frac{\varepsilon_g}{qE}}$$

Franz-Keldysh Effect

- With the assistance of an absorbed photon of energy $\hbar\omega < \varepsilon_g$, it is evident that the tunnelling barrier thickness is reduced to

$$d' = \frac{(\varepsilon_g - \hbar\omega)}{qE}$$

And the overlap of the wave function increases further and the valance electron can easily tunnel to the conduction band.

- **The net result is that a photon of energy $\hbar\omega < \varepsilon_g$ is absorbed.**

- **In this case, the transverse component of the momentum is conserved.**

- **The Franz-Keldysh effect is therefore, inessence, photon assisted tunnelling.**

Franz-Keldysh Effect

➢ The electric field dependent absorption coefficient is given by-

$$\alpha = K(E')^{1/2}(8\beta)^{-1}exp\left(-\frac{4}{3}\beta^{3/2}\right)$$

Here, $E' = \left(\frac{q^2E^2\hbar^2}{2m_r^*}\right)^{1/3}$, $\beta = \frac{\varepsilon_g - \hbar\omega}{E'}$ and **K** is a material dependent parameter and has value of $5 \times 10^4\ cm^{-1}\ (eV)^{-1/2}$ in **GaAs.**

➢ The exponential term is the tunnelling probability of an electron through a triangular barrier of height $(\varepsilon_g - \hbar\omega)$ and can be obtained from the well known **Wentzel-Kramers-Brillouin (WKB) approximation**.

Franz-Keldysh Effect

- The other factors are related to the upward transition of an electron due to photon absorption.

- Substituting appropriate values for the different parameters, it is seen that in GaAs $\boldsymbol{\alpha = 4\ cm^{-1}}$ at a photon energy of $\boldsymbol{\varepsilon_g - 20\ meV}$ with electric field **E ~ 10^4 V/cm.**

- This value of absorption coefficient is much smaller than the value of α at the band edge at zero field.

- Therefore, Franz-Keldysh effect will be small unless $\boldsymbol{E \geq 10^5\ V/cm.}$

Stark Effect

- The ***Stark effect*** refers to the **change in atomic energy upon the application of an electric field.**

- The electric field affects the higher order, or outer, orbits of the precessing electrons so that the center of gravity of the elliptical orbit and the focus are displaced to each other and linearly aligned in the direction of the electric field.

- As a result, there is splitting of the energy of the outer 2s or 2p states, and the energy shift is simply given by $\boldsymbol{\Delta\varepsilon = qdE}$, where $\boldsymbol{d}$ is the eccentricity of the orbit. This is ***linear Stark effect.***

- The effect of electric field on ground state orbits also leads to an energy shift of the state, and that is the ***quadratic or second-order Stark effect.***


THANK YOU