Engineering Physics (2025)
Course code 25PY101
Module 2 Unit 2: Optoelectronics

Course Instructor:
Dr. Sreekar Guddeti
Assistant Professor in Physics
Department of Science and Humanities
Vignan's Foundation for Science, Technology and Research

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M2U2 Plan

1. p-n junction diode – forward and reverse conditions
2. Solar cell
3. Photo-diode
4. Direct and indirect band gap semiconductors
5. Light Emitting Diode
6. Tunneling diode

M2U2 Plan

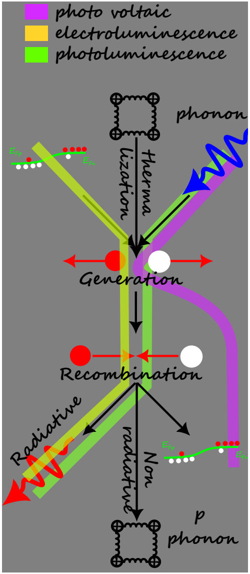
Luminescence

Definition

Luminescence refers to the general property of light emission.

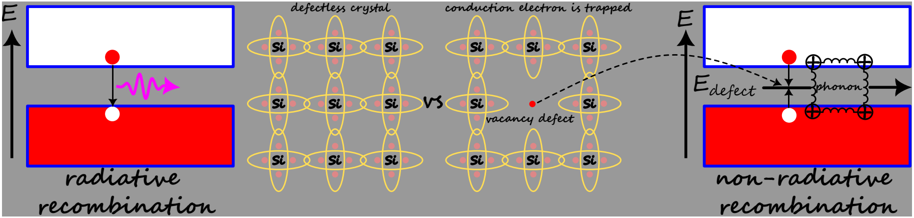
- The previous two opto-electronic devices – solar cell and photo diode – were based on generation of excess carriers. The source of energy for generation was photon.
- The counterpart of generation is recombination.
- Recombination is of two types –
  - radiative recombination – the charge carriers recombine to emit photon
  - non radiative recombination – the charge carriers recombine to emit phonon i.e. heat.
- Here there are two types of radiative recombination –
  - **Photo luminescence** – If the excess charge carriers were generated by photon absorption, the photo emission from the recombination is called photo luminescence
  - **Electro-luminescence** – If the excess charge carriers were generated by current caused by an applied electric field, the photo emission from the recombination is called electro-luminescence.

Transfer of energy



- From the perspective of transfer of energy, the various processes can be understood as
  - Photo voltaic effect – Light → Electrical
  - Photoluminescence – Light → Light
  - Electroluminescence – Electrical → Light
- Processes that end up as light energy are due to **radiative recombination**.
- However, some other processes are also possible, where the energy ends up as heat
  - Photodiode – Light → Electrical → Thermal
  - pn junction at forward bias – Electrical → Thermal
  - pn junction at reverse bias – Thermal → Electrical → Thermal
- Processes that end up as thermal energy are due to **non-radiative recombination**.
- The third opto-electronic device – LED – is

Radiative vs Non radiative recombination

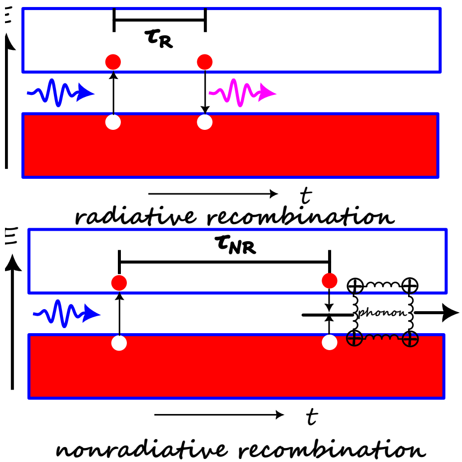


- Defects are imperfections in semiconductor. These are different from impurities.
- Some examples of defects are absence of atom in lattice – vacancy defect or presence of extra atom – interstitial defect
- Defects arise when temperature is increased. These lead to defect levels **within** the forbidden band gap.
- If the crystal is without defects, radiative recombination is preferred and final particle emitted is a **photon**.
- If the crystal is with defects, electron and hole reach the defect level first, then they recombine non radiatively and final particle emitted is a **phonon** or lattice vibration.

Recombination lifetime

Definition

Recombination lifetime is the time period between generation and recombination of charge carriers.



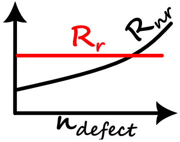
- Consider an electron-hole pair is generated.
- When an electron is in conduction band, its energy has increased. It wants to recombine with a hole to reduce energy.
- The time taken to recombine radiatively τ_r is less than the time taken to recombine non-radiatively τ_{nr} since the defect level lowered the energy of electron.

Recombination rate – Classification of semiconductors

Definition

Recombination rate is defined as the rate at which the excess charge carriers are recombining

- The recombination rate is inversely related to the recombination lifetime.
- In the absence of defects, radiative recombination rate R_r is higher than non-radiative recombination rate R_{nr}.
- However, as the defect density n_{defect} increases, the radiative recombination rate is not affected, but the non-radiative recombination rate increases.

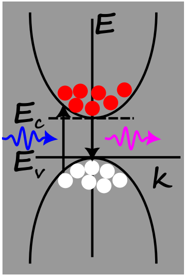


- The bandstructure of the semiconductor also affects the recombination rates. Based on bandstructure the semiconductors classified as –
  - Direct band gap
  - Indirect band gap

Direct band gap semiconductor

Definition

A direct band gap semiconductor is defined as a semiconductor with the top of valence band and bottom of conduction band at the **same** value of wave vector.



- Consider electron moves from E_c to E_v.
- In the radiative recombination process,
  - Energy of electron is transferred to energy of photon.
  - Initial momentum of electron is equal to final momentum.
  - Therefore, both the energy and momentum of the (electron + hole + photon) system is **conserved**.
  - **three** particles are involved

$$\mathrm{e}^- + \mathrm{h}^+ \rightarrow \text{photon}$$

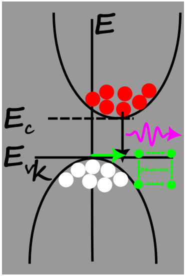
Key Insight

Radiative type of recombination is the dominant mechanism in a direct bandgap semiconductor.

Indirect band gap semiconductor

Definition

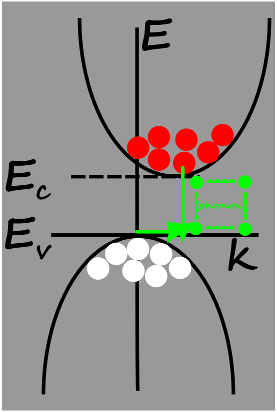
An indirect band gap semiconductor is defined as a semiconductor with the top of valence band and bottom of conduction band at the **different** values of wave vector.



- Consider electron moves from E_c to E_v.
- In the radiative recombination process,
  - Energy of electron is transferred to energy of photon.
  - Initial momentum of electron is not equal to final momentum.
  - Therefore, energy of the (electron + hole + photon) system is **conserved** but the momentum is not conserved.
- To conserve momentum, a **phonon assisted radiative recombination** occurs where difference in momentum is supplied by phonon and **four** particles are involved

$$\mathrm{e}^{-} + \mathrm{h}^{+} \rightarrow \text{photon} + \text{phonon}$$

Indirect band gap semiconductor



- Since the four particle process is difficult to occur, the phonon-assisted radiative recombination is not dominant mechanism.
- Instead the photon emission is avoided and the energy and momentum conservation is satisfied by emission of phonon only.

$$e^- + h^+ \rightarrow \text{phonon}$$

- Emission of phonon leads to rise in temperature of material.

Key Insight

Non-radiative type of recombination is the dominant mechanism in an indirect bandgap semiconductor.

Direct vs indirect bandgap semiconductor

SNo.	Property	Direct	Indirect
1	k at E_C vs k at E_v	equal	unequal
2	Recombination mechanism	Radiative	Non-radiative
3	Particle emitted	Photon	Phonon
4	Periodic table	Compound s.c. like GaAs, InP	Elemental s.c. like Si, Ge
5	Applications	LED, laser diode	transistors, diodes