

# Fiber Optics Communications

**Week 6**

**Optical Sources**

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# Topics of Previous Lecture (Week-5)

- Introduction to Fiber Optics Non-Linear Effect
- Types Nonlinear Effects in Optical Fibers
- Origin of Nonlinear Effects
- Stimulated Raman Scattering (SRS)
- Stimulated Brillouin Scattering (SBS)
- Self-Phase Modulation (SPM)
- Cross-Phase Modulation (XPM)
- Four-Wave Mixing (FWM)

# Week-6: Lecture Learning Outcomes

1. Describe the role of optical sources in fiber optic communication systems
2. Identify the main types of optical sources for fiber optics communications
3. Explain the fundamental properties of semiconductors
4. Distinguish between intrinsic and extrinsic semiconductors
5. Explain the operation of a pn-junction under forward and reverse bias
6. Understand optical source rate equation and relate carrier injection and recombination processes to optical emission
7. Explain why direct bandgap materials are suitable for optical emission
8. Describe the working principle of an LED
9. Explain the principle of stimulated emission and population inversion in laser operation

# Week-6: Optical Sources

## Outline

- Introduction to Optical Sources
- Basic Concepts of Semiconductor Physics
- Reverse and forward biased pn junction semiconductor materials
- Direct and indirect bandgap materials
- Light-Emitting Diodes
- Laser diodes

# Introduction to Optical Sources

- An optical transmitter converts electrical signal into optical signal, which is launched into the fiber
- Optical source is the major component in an optical transmitter which converts the signal from electrical to optical domain.
- The two main and widely used semiconductor light sources for fiber optic communication are [1]:

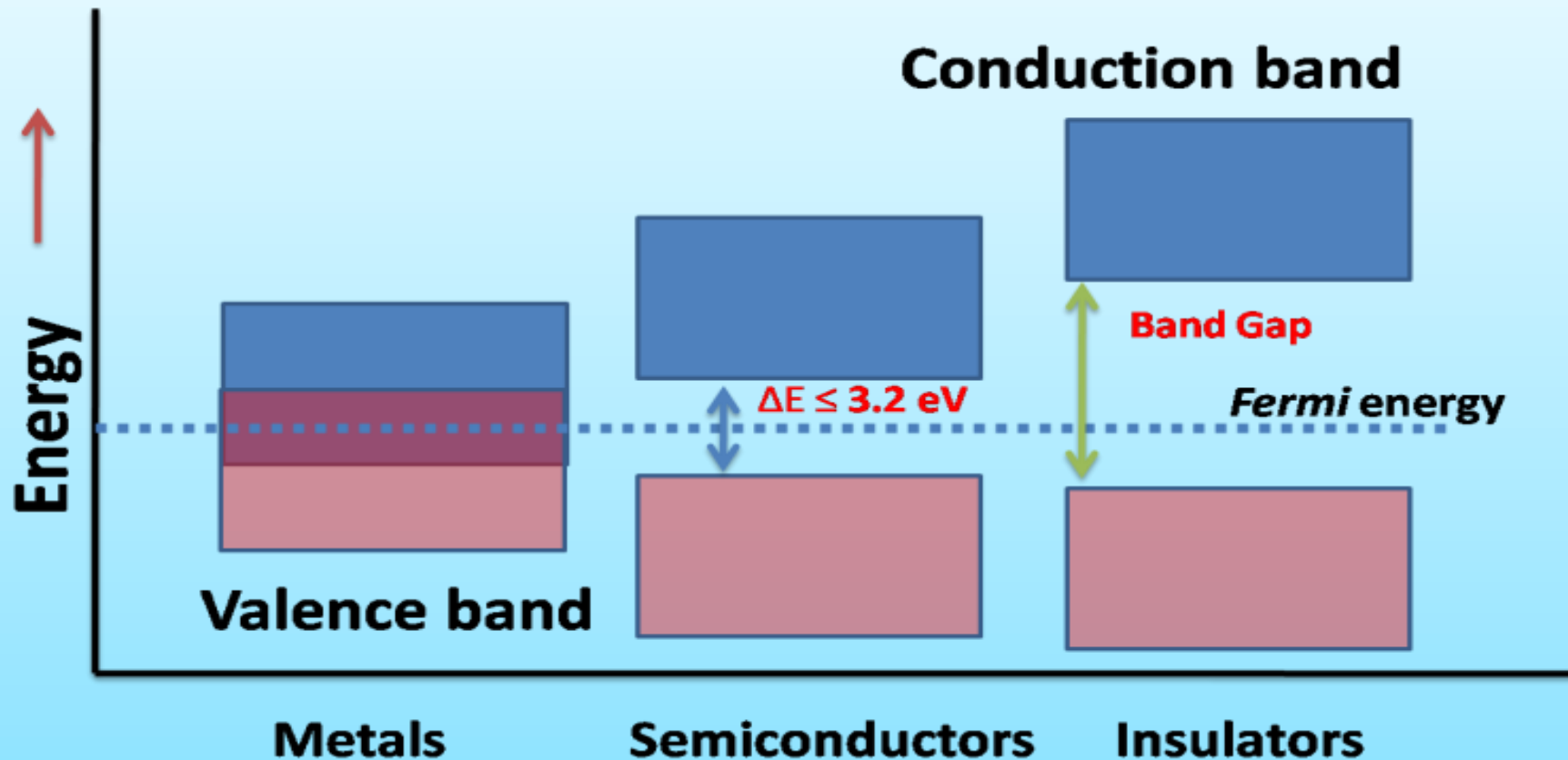
- **LED** (Light Emitting Diode)
- **LASER** (Light Amplification by Stimulated Emission of Radiation)

- Key semiconductor fundamentals for light sources operation are bandgap energy, electron-hole recombination, photon emission, and photon absorption

# Basic Concepts of Semiconductor Physics

- Semiconductors conduction properties lie between metals and insulators
- In semiconductor material, the outer-shell electrons makes covalent bonds with its neighboring atoms in a crystal.
- Such outer-shell electrons are called **valence electrons**.
- The conduction properties of a semiconductor can be interpreted with the aid of the energy-band diagrams
- Energy-band contains Valence band, Conduction band, and Energy gap (Forbidden band)
- In semiconductors, the valence band is completely filled and the conduction band is empty at low temperature ( $T=0$  K) [2]
- The valence band is the lowest allowed energy band for electrons with energy  $E_v$
- The conduction band is the next higher range of allowed energy levels for electrons, with  $E_c$  as its lowest level

# Basic Concepts of Semiconductor Physics



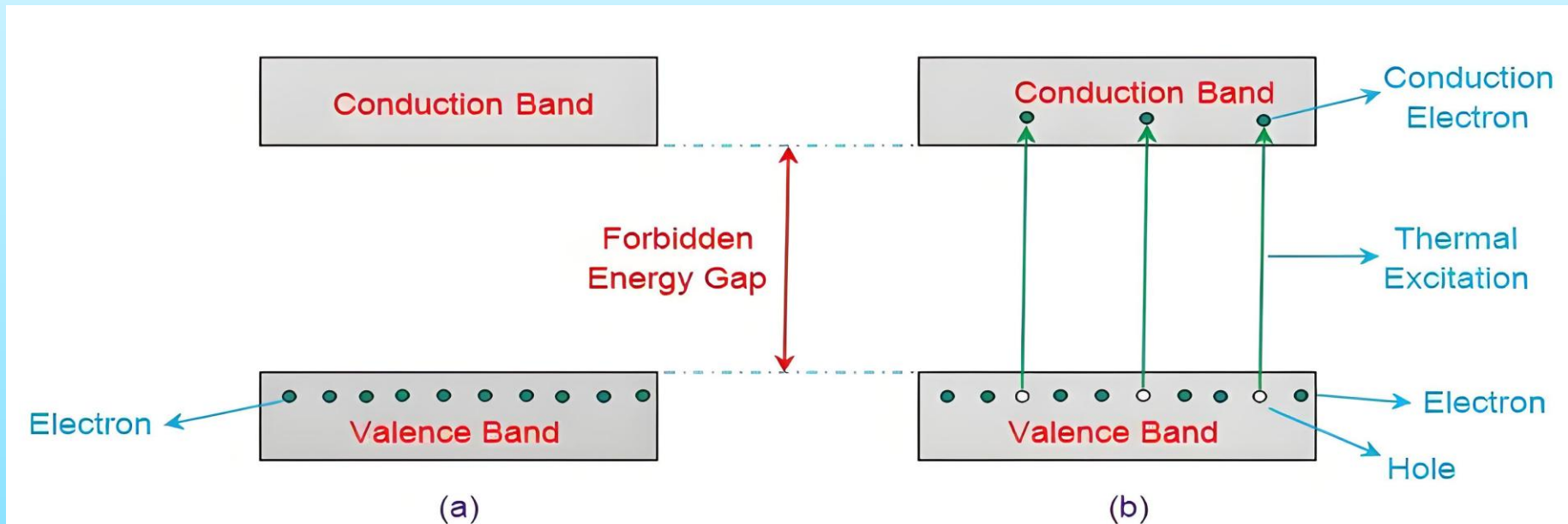
**Figure 1:** Energy band of metals, semiconductors, and insulators

**Source:** H. Takabe, "Theoretical Model of Dense Plasmas," in *The Physics of Laser Plasmas and Applications*, Vol. 2, Springer, 2024, pp. 353–395.

[https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-3-031-45473-8\\_8/MediaObjects/486398\\_1\\_En\\_8\\_Fig5\\_HTML.png?as=webp](https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-3-031-45473-8_8/MediaObjects/486398_1_En_8_Fig5_HTML.png?as=webp)

# Basic Concepts of Semiconductor Physics

- In a pure intrinsic semiconductor crystal at low temperatures, the valence band is full of electrons while the conduction band is empty.
- Raising the temperature thermally excites some electrons across the bandgap.



**Figure 2** Energy Band Diagram of Intrinsic Semiconductor at (a) 0K (b) Temperature > 0K

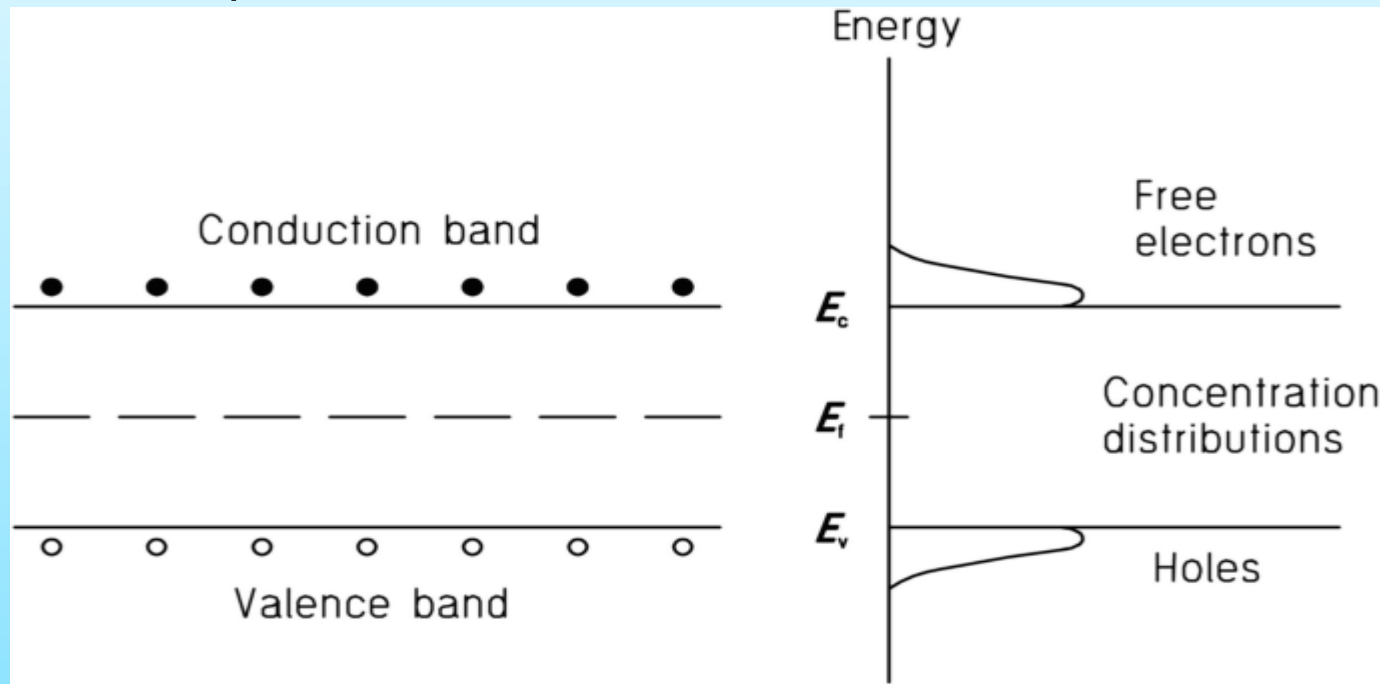
## Figure 2: Thermal excitation of electrons

**Source:** "What is Intrinsic Semiconductor?," IEE-Business.

<https://oss.iwone.cn/img/ueditor/202408/1724719879853.jpeg>

# Basic Concepts of Semiconductor Physics

- This excitation creates a concentration  $n$  of free electrons in the conduction band and an equal concentration  $p$  of holes in the valence band.



**Figure 3:** Carrier density in intrinsic semiconductor

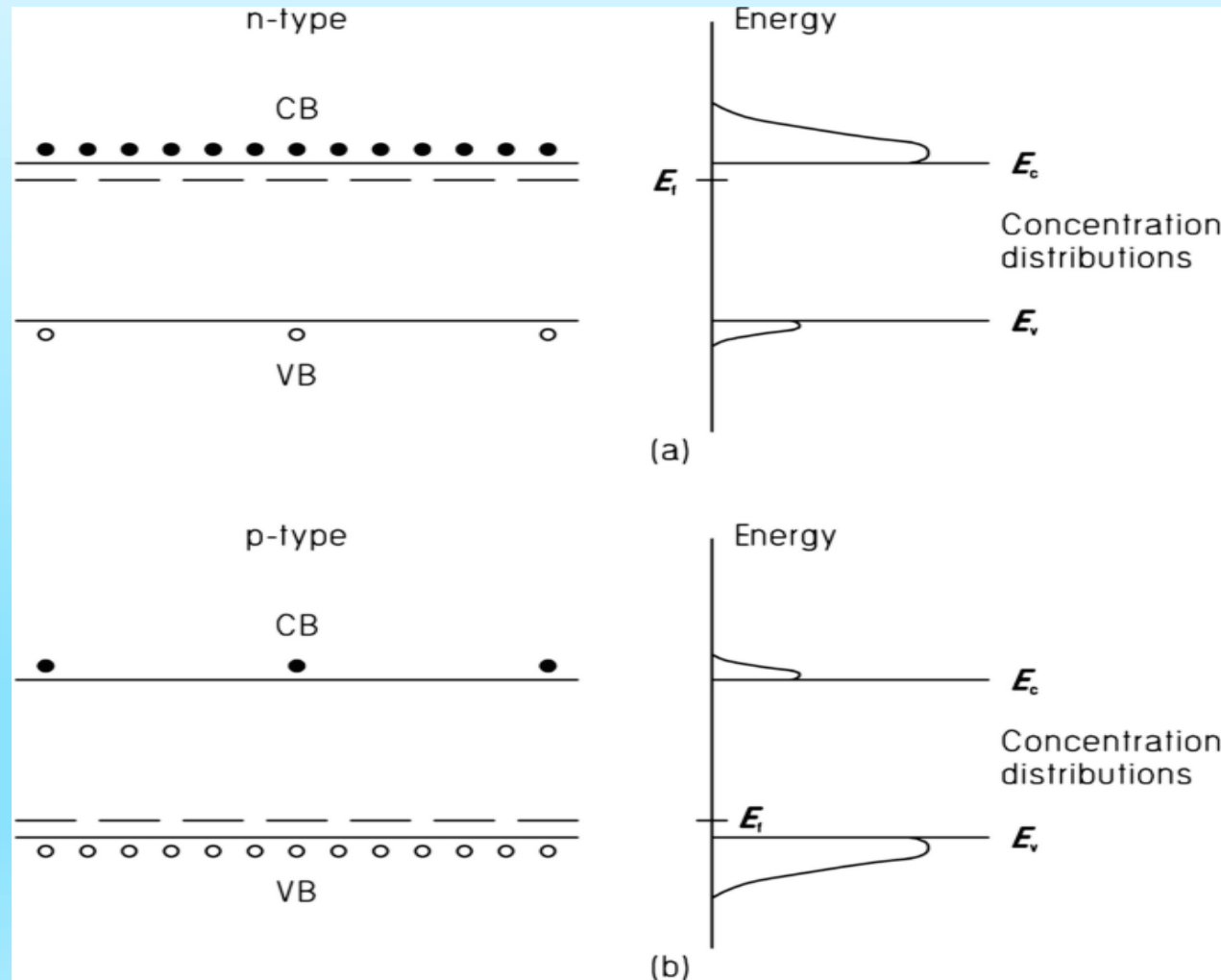
**Source:** M. Sibley, "Optical Transmitters," in Optical Communications, Springer, Cham, 2020, ch. 3. [https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-3-030-34359-0\\_3/MediaObjects/345080\\_3\\_En\\_3\\_Fig1\\_HTML.png](https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-3-030-34359-0_3/MediaObjects/345080_3_En_3_Fig1_HTML.png)

# Basic Concepts of Semiconductor Physics

- Adding small amounts of group V elements (e.g., P, As, Sb) and group III (e.g., Al, Ga, In) to Si is called **Doping**.
- Doping greatly increases conduction, producing an **Extrinsic Semiconductor**.
- If Si doped with group V elements, four outer electrons form covalent bonds with Si, leaving one loosely bound electron for conduction just below the conduction band called **Donnor Level**
- When group V elements are used as a dopant the doped material is called **n-type material**.
- When Si is doped with group III elements, three of Si's outer electrons form covalent bonds with the dopant, an unoccupied level created just above the valence band called **acceptor level**.

# Basic Concepts of Semiconductor Physics

- Conduction occurs when electrons are excited from the valence band to this acceptor level
- This type of material is called **p-type material**

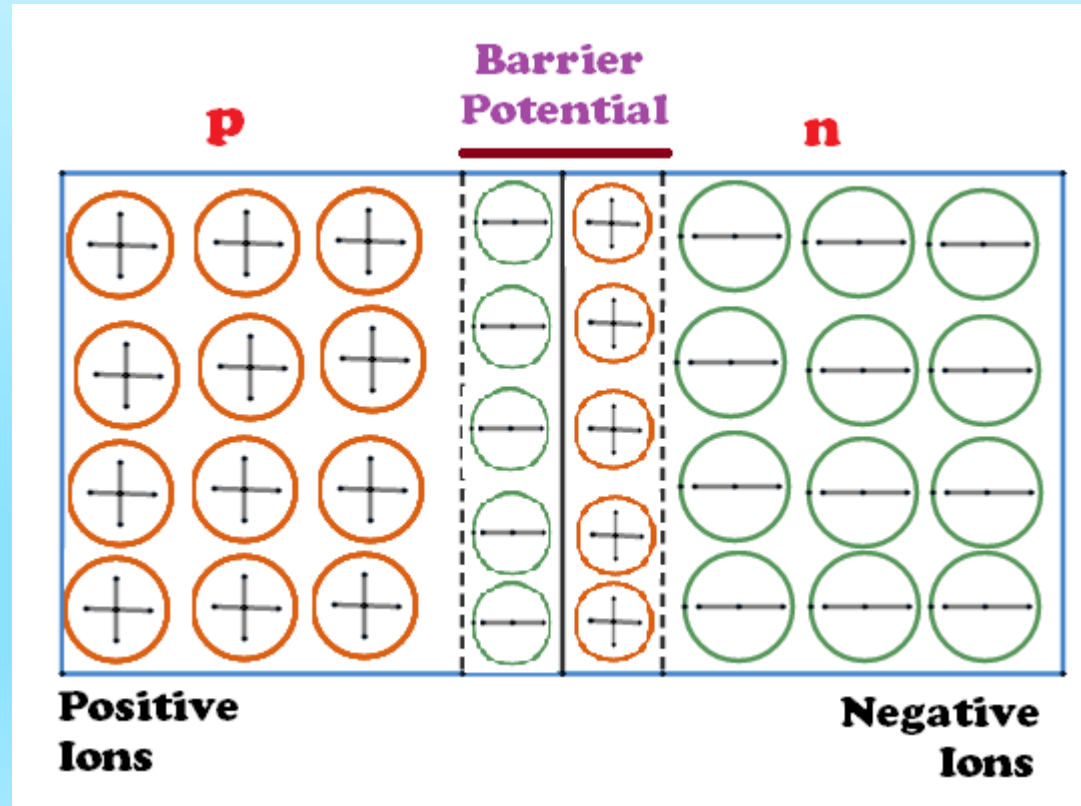


**Figure 4:** Carrier density in p-type and n-type materials

**Source:** M. Sibley, "Optical Transmitters," in *Optical Communications*, Springer, Cham, 2020, ch. 3. [https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-3-030-34359-0\\_3/MediaObjects/345080\\_3\\_En\\_3\\_Fig2\\_HTML.png](https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-3-030-34359-0_3/MediaObjects/345080_3_En_3_Fig2_HTML.png)

# pn Junction

- Doped n-type or p-type semiconductors alone act as conductors.
- To create devices, both types should be combined in a single crystal, forming a pn junction
- When pn junction created, Electron diffusion across a pn junction creates a barrier potential (electric field) in the depletion region.

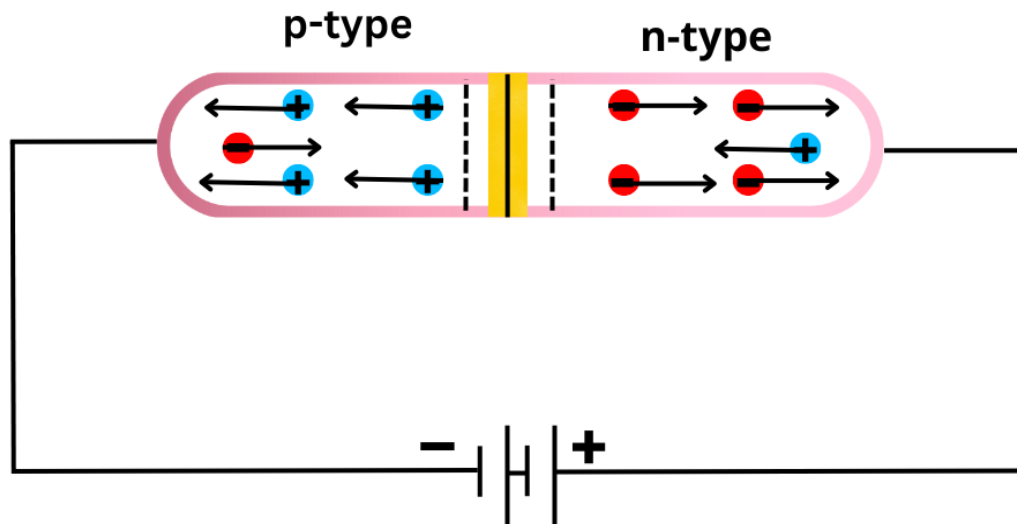


**Figure 5:** unbiased pn junction

**Source:** "When a p-n junction is reverse biased," Vedantu.  
<https://cmds-test.vedantu.com/prod/question-sets/50d04375-f0e8-4409-bc3b-f06c63f71d253354744616380252319.png>

# Reverse Biased pn Junction

- Connecting a battery with its positive terminal to the n-type and negative to the p-type material makes the pn **junction reverse-biased**.
- This will create widened depletion region and increased barrier potential which prevents the majority carrier diffusion at the junction.

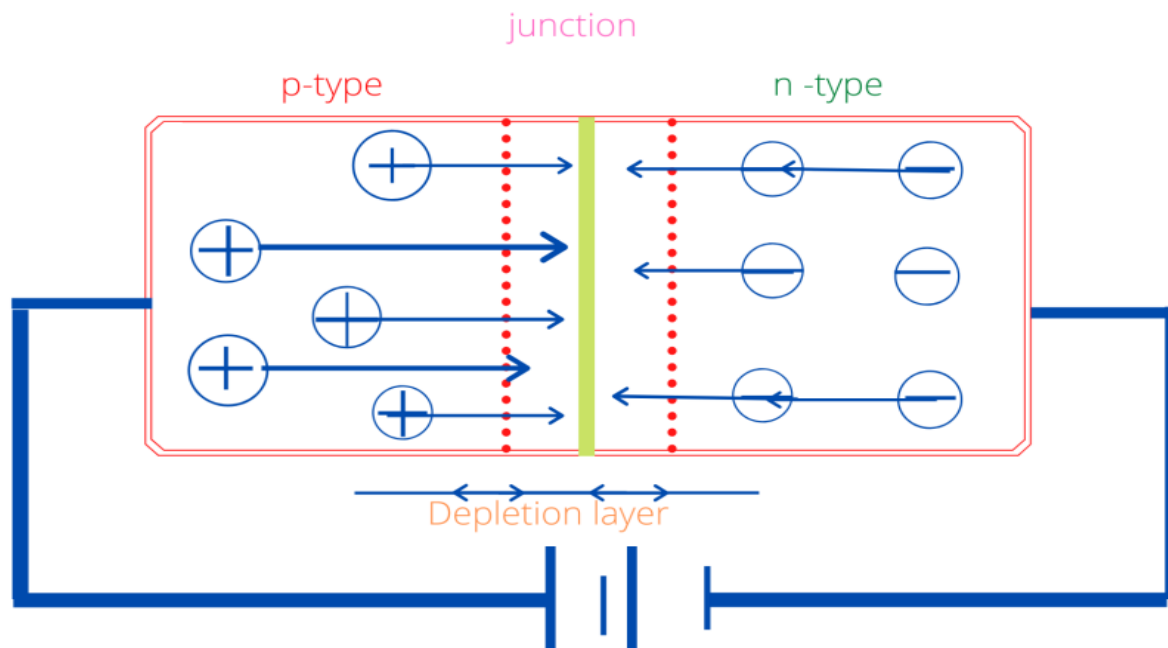


**Figure 6:** Reverse biased pn junction

**Source:** "PN junction diode forward and reverse bias," PhysicsWave, Feb. 1, 2023. <https://i0.wp.com/physicswave.com/wp-content/uploads/2023/02/pn-junction-diode-reverse-bias-circuit-diagram.png?w=1350&ssl=1>

# Forward Biased pn Junction

- Connecting a battery with its positive terminal to the p-type and negative terminal to the n-type material makes the pn **junction forward-biased**.
- This will create narrowed depletion region and decreased barrier potential which permits the majority carrier diffusion at the junction.

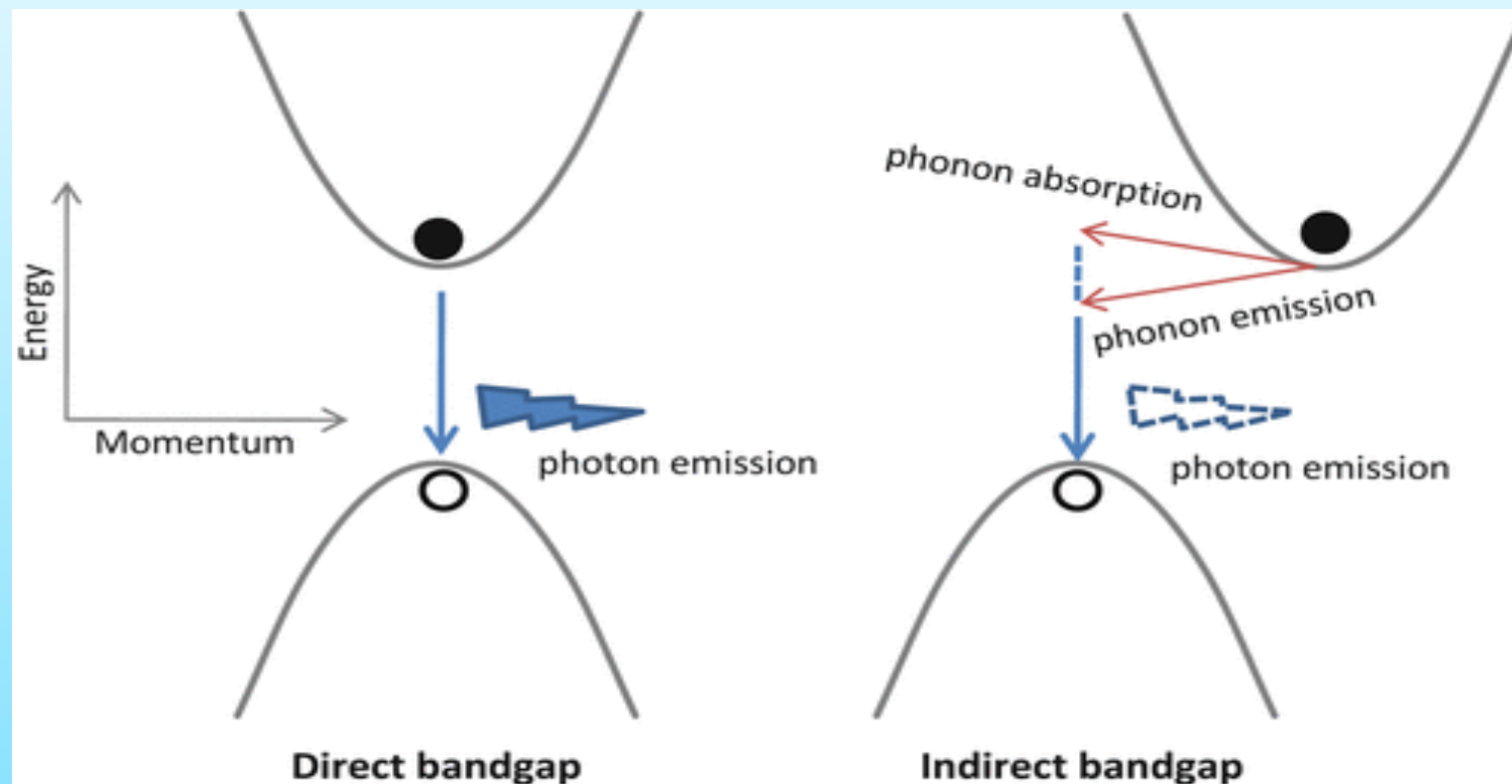


**Figure 7:** Forward biased pn junction

**Source:** "PN junction diode forward and reverse bias," PhysicsWave, Feb. 1, 2023. <https://i0.wp.com/physicswave.com/wp-content/uploads/2020/05/pn-junction.png?resize=1024%2C576&ssl=1>

# Direct and Indirect Band Gap Materials

- Direct band gap materials are preferable for optical source compared to indirect band gap materials



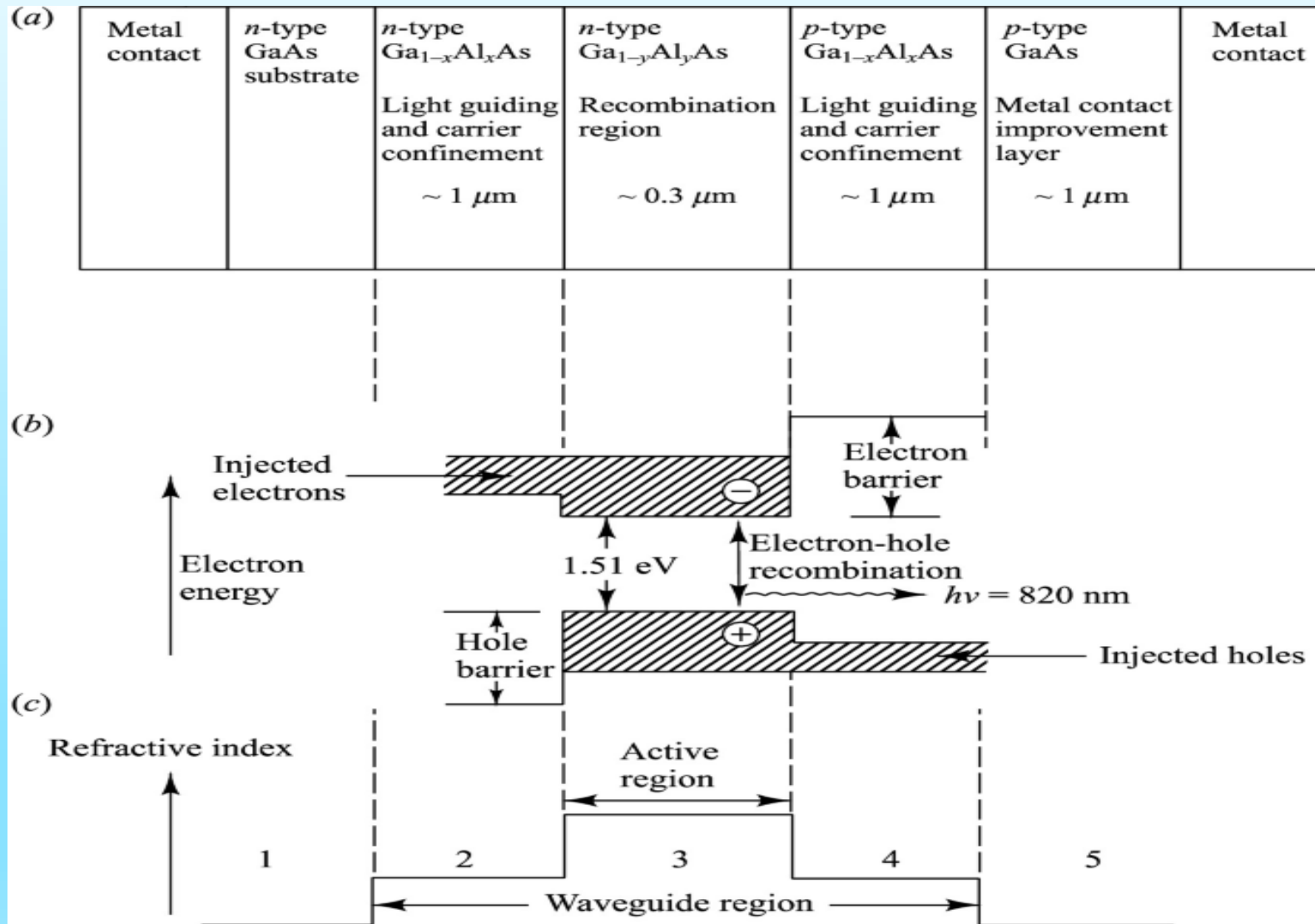
**Figure 8:** Photon emission in direct and indirect band gap materials

**Source:** M. R. Krames, "Light-emitting diodes: Fundamentals," in Handbook of Visual Display Technology, Springer, 2015. [https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-3-642-35947-7\\_75-2/MediaObjects/150079\\_0\\_En\\_75-2\\_Fig2\\_HTML.gif](https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-3-642-35947-7_75-2/MediaObjects/150079_0_En_75-2_Fig2_HTML.gif)

# Light-Emitting Diodes (LEDs)

- LEDs are usually the best choice for optical communications requiring data rate 100-200 Mb/s with multimode fiber.
- To achieve high radiance and efficiency in LEDs, it require confining charge carriers and photons to the pn junction's active region, where radiative recombination occurs.
- Carrier confinement enhances radiative recombination in the active region, leading to high quantum efficiency
- Optical confinement is important to prevent absorption of the emitted radiation.
- double-heterostructure (or heterojunction) configuration is widely used to achieve better carrier and optical confinement
- The material discontinuity arising in the heterojunction leads to important electronic and optical properties, such as confinement of carriers of radiation [3]

# Light-Emitting Diodes (LEDs)



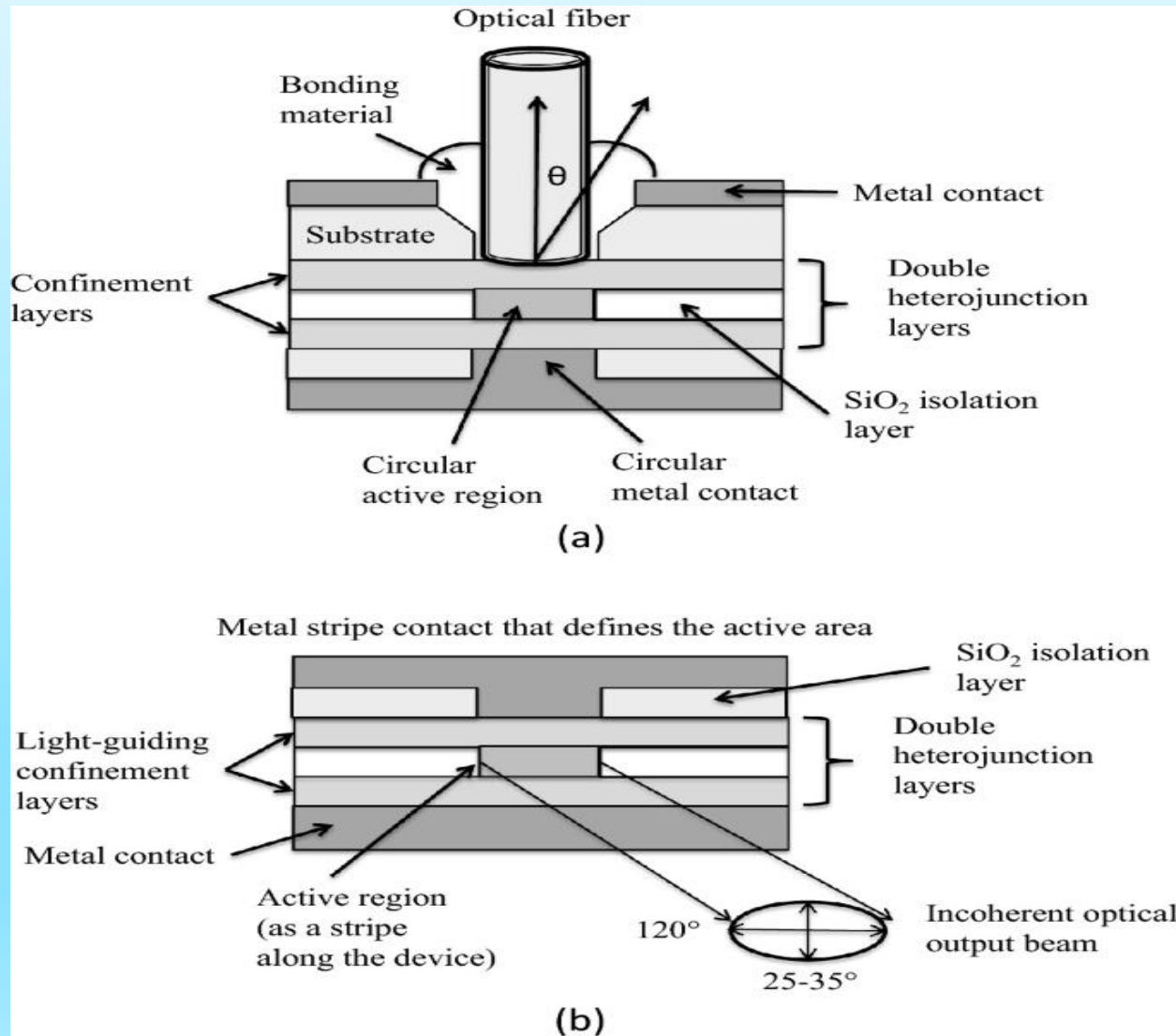
**Figure 9:** Photon and carrier confinement in heterojunction

**Source:** G. Keiser, "Light Sources for Fiber Links," in Fiber Optic Communications, Springer, Singapore, 2021, ch. 4.

[https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-981-33-4665-9\\_4/MediaObjects/495048\\_1\\_En\\_4\\_Fig8\\_HTML.png](https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-981-33-4665-9_4/MediaObjects/495048_1_En_4_Fig8_HTML.png)

# Light-Emitting Diodes (LEDs)

- The two common LED configurations for fiber optics are surface and edge emitting LEDs.

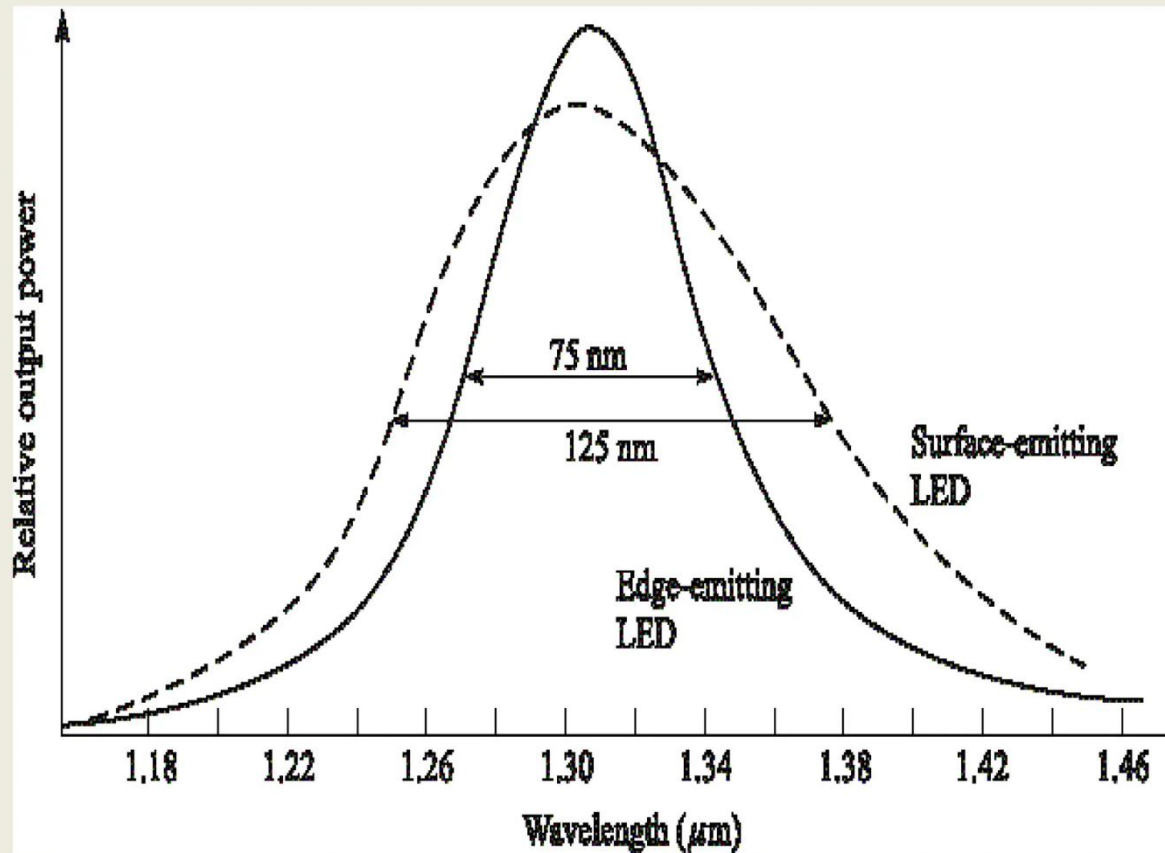


**Figure 10:** (a) surface emitting LED  
(b) edge emitting LED

**Source:** G. Keiser, "Light Sources for Fiber Links," in Fiber Optic Communications, Springer, Singapore, 2021, ch. 4.  
[https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-981-19-3482-7\\_4/MediaObjects/315971\\_2\\_En\\_4\\_Fig7\\_HTML.png](https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-981-19-3482-7_4/MediaObjects/315971_2_En_4_Fig7_HTML.png)

# Light-Emitting Diodes (LEDs)

## LED spectral patterns



**Figure 11:** Spectral width of surface and edge emitting LEDs

**Source:** "UNIT 5 Optical Communications," B.Tech ECE IV Year I Sem, MWOC, Slideshare, Dec. 7, 2023.

<https://image.slidesharecdn.com/unit5mwoc-231207052656-65b66ceb/75/B-Tech-ECE-IV-Year-I-Sem-MWOC-UNIT-5-Optical-CommunicationsUNIT-5-MWOC-pptx-33-2048.jpg>

# Rate equations of LEDs

- Without external carrier injection, excess carrier density decreases exponentially through electron-hole recombination as:

$$n = n_0 e^{-\frac{t}{\tau}} \quad (1)$$

## Where:

$n$  Is the excess carrier density

$n_0$  Is initial injected excess electron density

$\tau$  Is carrier lifetime

- Bulk recombination rate (R)=Radiative recombination rate + nonradiative recombination rate is given by:

$$R = \frac{\partial n}{\partial t} = \frac{\partial}{\partial t} \left( n_0 e^{-\frac{t}{\tau}} \right) = -\frac{n_0}{\tau} e^{-\frac{t}{\tau}} = -\frac{n}{\tau} \quad (2)$$

# Rate equations of LEDs

- With an external supplied current density of  $J$  is applied, the rate equation for the electron-hole recombination is becomes:

$$\frac{\partial n}{\partial t} = \frac{J}{qd} - \frac{n}{\tau} \quad (3)$$

**Where:**

$q$  Is the charge of electron

$d$  Is the thickness of recombination region

- In equilibrium condition  $\frac{\partial n}{\partial t}$  becomes zero and we will have;

$$n = \frac{J\tau}{qd} \quad (4)$$

# Internal Quantum Efficiency of LED

- The internal quantum efficiency in the active region is the fraction of the electron-hole pairs that recombine radiatively.
- If the radiative recombination rate is  $R_r$  and the nonradiative recombination rate is  $R_{nr}$ , the internal quantum efficiency  $\eta_i$  becomes:

$$\eta_i = \frac{R_r}{R_r + R_{nr}} = \frac{\frac{n}{\tau_r}}{\frac{n}{\tau_r} + \frac{n}{\tau_{nr}}} = \frac{\tau_{nr}}{\tau_{nr} + \tau_r} = \frac{1}{1 + \frac{\tau_r}{\tau_{nr}}} \quad (5)$$

**Where:**

$\tau_r$  Is the radiative recombination life time

$\tau_{nr}$  Is the non-radiative recombination life time

# Optical Power of LED

- Optical power generated internally  $P_{\text{int}}$  in the active region in the LED is given by:

$$P_{\text{int}} = \eta_{\text{int}} \frac{I}{q} h\nu = \eta_{\text{int}} \frac{hcI}{\lambda} \quad (6)$$

**Where:**

$I$  Is the Injected current to active region

$q$  Is the charge of electron

$\nu$  Is frequency of the generated photons

$\lambda$  Is wavelength of the generated photons

$c$  Is speed of light in the vacuum

# Optical Power of LED

- The emitted optical power from LED depends on  $P_{int}$  and external quantum efficiency  $\eta_{ext}$  :

$$P_{ext} = P_{int}\eta_{ext} \quad (7)$$

- The external quantum efficiency is the ratio of emitted photons from the LED to the total photons generated internally
- The external quantum efficiency depends on the reflection effects at the surface of the LED.
- Only light within the critical angle  $\varphi_c$  cone at the material interface escapes the LED.

$$\varphi_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \quad (8)$$

**Where:**

$n_1$  Refractive index of the semiconductor material

$n_2$  Refractive index of the outside material

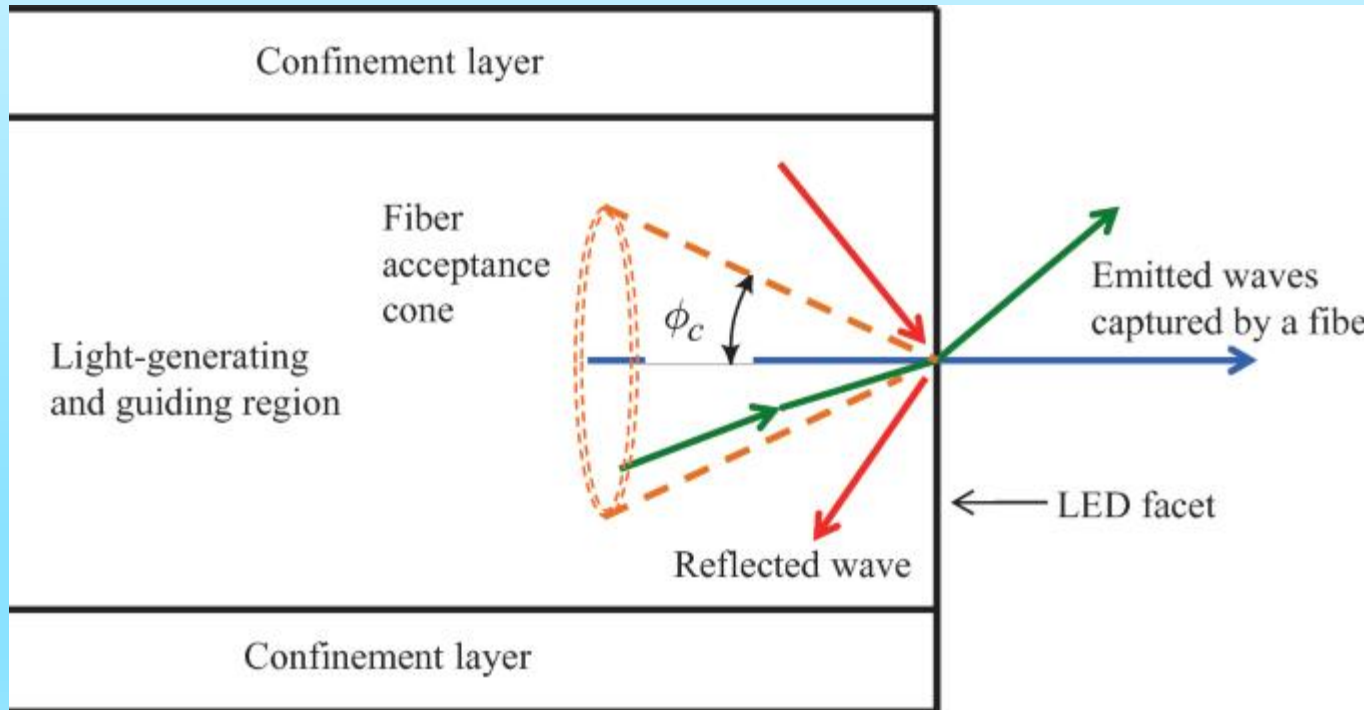
# Optical Power of LED

- The external quantum efficiency  $\eta_{ext}$  can be written as :

$$\eta_{ext} = \frac{1}{4\pi} \left( \int_0^{\phi_c} T(\varphi)(2\pi \sin \varphi) d\varphi \right) \quad (9)$$

**Where:**

$T(\varphi)$ : is Fresnel transmission coefficient



**Figure 12:** light emitted from LED

**Source:** G. Keiser, "Fiber Optic Communications," Springer, Singapore, 2021, ch. 4.

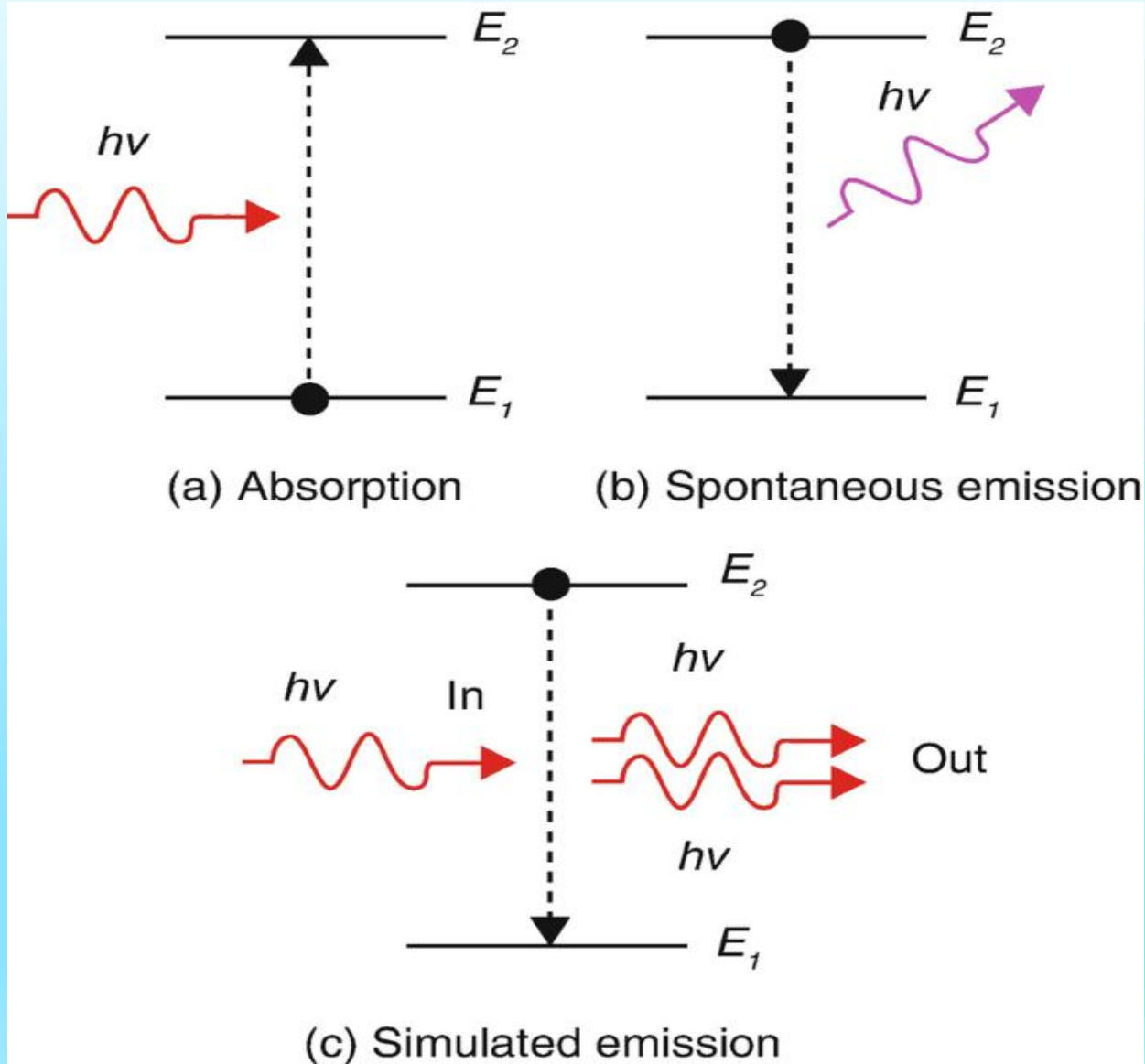
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# Laser Diodes

- Lasers vary in size from microscopic to room-scale, with different lasing medium such as gas, liquid, solid-state crystals, or semiconductors.
- In optical fiber communication systems, semiconductor laser diodes are the primary sources.
- Laser operation is the result of three key processes:

- **Photon Absorption**
- **Spontaneous Emission**
- **Stimulated Emission**

# Laser Diodes



**Figure 13:** (a) Photon absorption (b) Spontaneous emission (c) Stimulated emission

**Source:** M. Sibley, "Optical Transmitters," Springer, Cham, 2021, ch. 5. [https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-3-031-45473-8\\_5/MediaObjects/486398\\_1\\_En\\_5\\_Fig10\\_HTML.png](https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-3-031-45473-8_5/MediaObjects/486398_1_En_5_Fig10_HTML.png)

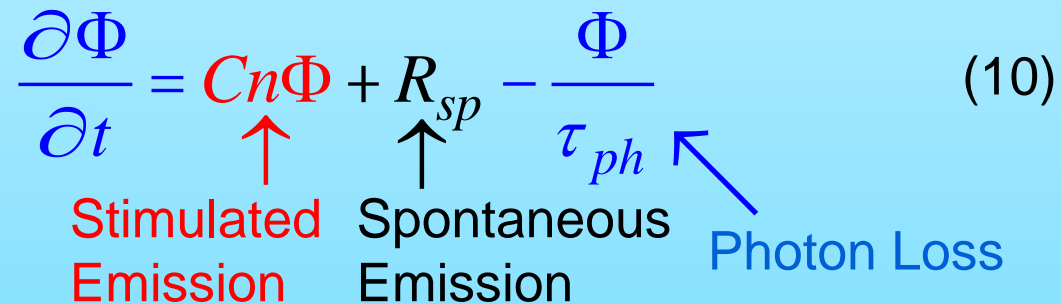
# Laser Diodes

- In thermal equilibrium the density of excited electrons is very small most photons incident on the system will be absorbed
- The **stimulated emission** is significantly negligible and optical emission is mainly by the virtue of the **spontaneous emission**
- **Population Inversion:** Condition in which excited states outnumber ground states, allowing stimulated emission to exceed absorption.
- Population inversion is created through externally induced excitation processes, called pumping techniques
- In a semiconductor laser, population inversion is accomplished by injecting electrons into the material using external source.
- When the injected current reaches above threshold (  $I_{th}$  ), the laser will develop internal gain through stimulated emission

# Laser Diode Rate Equations

- The optical output power vs. diode drive current relationship is analyzed using rate equations that describe photon–electron interactions in the active region
- The total carrier population is influenced by carrier injection, spontaneous recombination, and stimulated emission.
- For a pn junction with a confinement depth  $d$ , the rate equation which governs the number of photons ( $\Phi$ ) is :

$$\frac{\partial \Phi}{\partial t} = Cn\Phi + R_{sp} - \frac{\Phi}{\tau_{ph}} \quad (10)$$

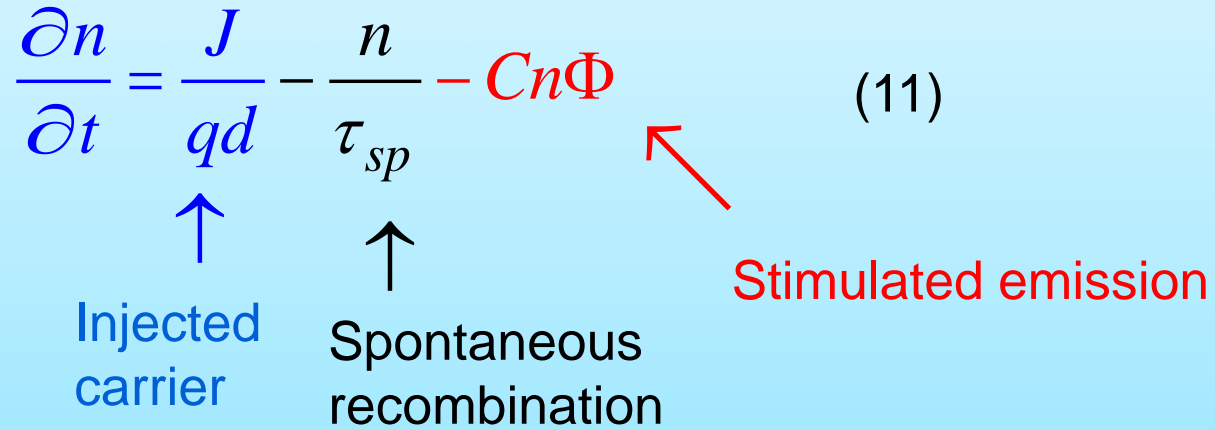
  
Stimulated Emission      Spontaneous Emission      Photon Loss

- $C$  is a coefficient describing the strength of the optical absorption and emission interaction and  $\tau_{ph}$  is the photon lifetime

# Laser Diode Rate Equations

- For a pn junction with a confinement depth  $d$ , the rate equation which governs the number of electrons ( $n$ ) is also given by:

$$\frac{\partial n}{\partial t} = \frac{J}{qd} - \frac{n}{\tau_{sp}} - Cn\Phi \quad (11)$$



Injected carrier      Spontaneous recombination      Stimulated emission

**Where:**

$J$  Is injected current density

$\tau_{sp}$  Is spontaneous recombination lifetime

# Laser Diode Rate Equations

- In the steady-state condition at the lasing threshold ( $n = n_{th}$ ,  $J = J_{th}$ ), the rate equations for electrons become:

$$0 = \frac{J_{th}}{qd} - \frac{n_{th}}{\tau_{sp}} - Cn_{th}\Phi \quad (12)$$

- In Eq (12) the last term is negligible:

$$Cn_{th}\Phi \approx 0, \text{ for } n \leq n_{th} \quad (13)$$

- From Eq (12) and Eq (13), we have:

$$J_{th} = qd \frac{n_{th}}{\tau_{sp}} \quad (14)$$

# Laser Diode Rate Equations

- Steady-state Photon density ( $\Phi_s$ ) for above threshold condition ( $n > n_{th}$ ,  $J > J_{th}$ ):

$$\Phi_s = \frac{\tau_{sp}}{qd} (J - J_{th}) + R_{sp} \tau_{ph} \quad (15)$$

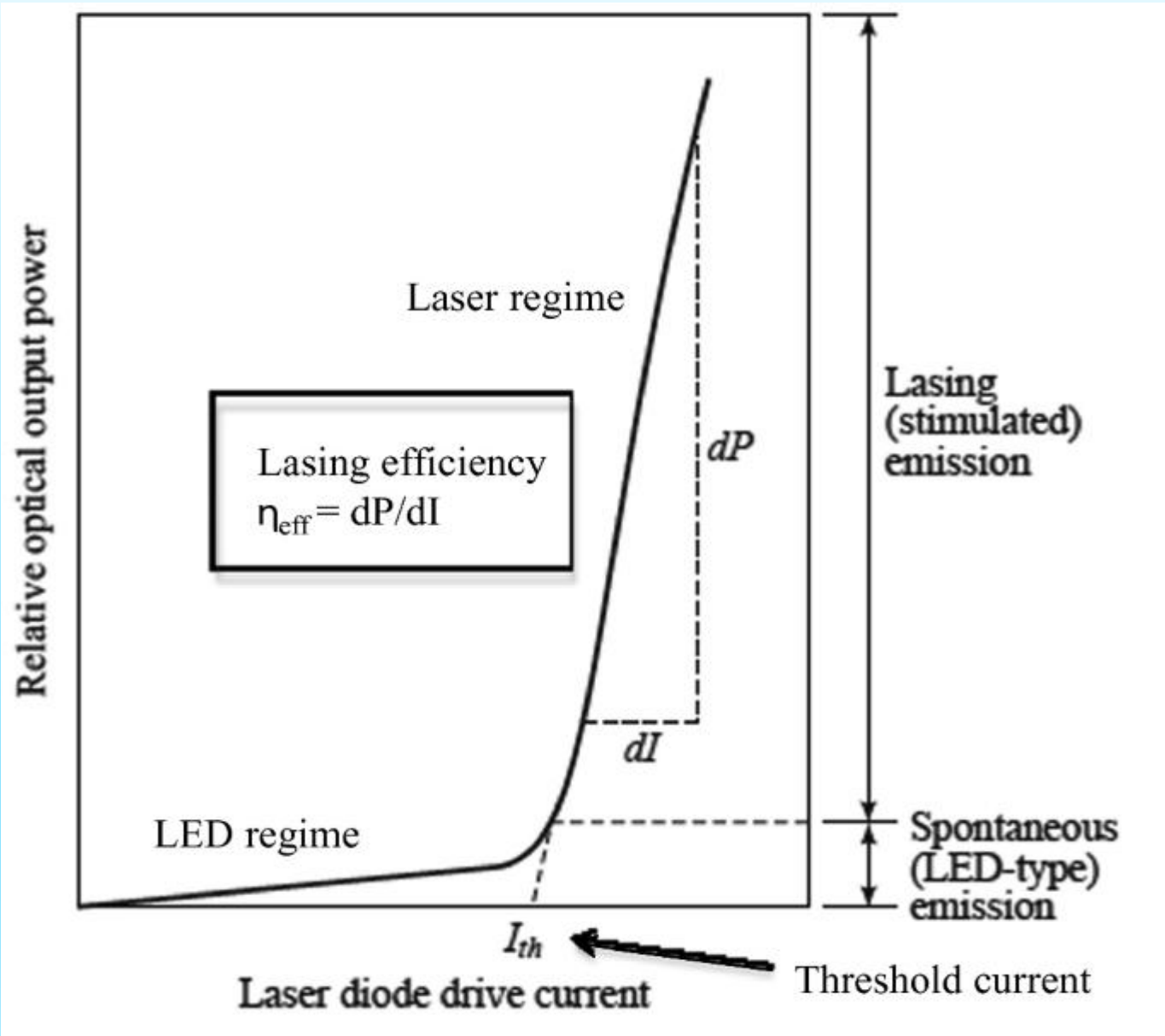


Contribution of Stimulated  
Emission



Contribution of Spontaneous  
Emission

# Laser Diode Rate Equations



**Figure 14:** Laser output power and drive current relation

**Source:** G. Keiser, "Fiber Optic Communications," Springer, Singapore, 2021, ch. 4.  
[https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-981-33-4665-9\\_4/MediaObjects/495048\\_1\\_En\\_4\\_Fig21\\_HTML.png](https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-981-33-4665-9_4/MediaObjects/495048_1_En_4_Fig21_HTML.png)

# Laser Diode Quantum Efficiency

- $\eta_i$  The internal quantum efficiency is not precisely defined in laser diodes, measurements typically show  $\eta_i \approx 0.6\text{--}0.7$  at room temperature.
- Experimentally, the external quantum efficiency ( $\eta_{ext}$ ) is obtained from the linear region of Figure (14) , the optical power (P) vs. drive current (I) curve, yielding:

$$\eta_{ext} = \frac{q}{E_g} \left( \frac{\partial P}{\partial I} \right) \quad (16)$$

**Where:**

$E_g$  Is the bandgap energy in electron volts

# Summary

- **Suitable types of optical sources for fiber optics communication:**
  - ✓ LED and Semiconductor laser
- **Semiconductors:**
  - ✓ **Conductivity:** between conductors and insulators
  - ✓ **Types:** Intrinsic and extrinsic semiconductors
  - ✓ **Electro-optic properties:** determined by band structure and doping
- **Direct and Indirect Bandgap Materials:**
  - ✓ **Direct bandgap:** electrons can recombine with holes directly → efficient photon emission.
  - ✓ **Indirect bandgap:** requires phonon assistance
- **Light-Emitting Diodes (LEDs):** Broad spectral width, moderate output power
- **Laser Diodes:** Require population inversion, stimulated emission is dominant  
applicable for high-speed communication

# References

- [1] Gerd Keiser, *“Fiber Optic Communications”*, Springer, Pp.147, 2021.
- [2] A. Coldren, W. Corzine, and L. Masanovic, *“Diode Lasers and Photonic Integrated Circuits,”* John Wiley & Sons, 2<sup>nd</sup> ed., pp.7, 2012.
- [3] Giovanni Ghione, *“ Semiconductor Devices for High-Speed Optoelectronics”*, CAMBRIDGE UNIVERSITY PRESS, Pp.24, 2009.



**Thank You !**