Fiber Optics Communications

Week 9 Optical Detectors

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Topics of Previous Lecture (Week-8)

Optical Modulators

- Direct and External Optical Modulation Techniques
- External Modulators Important Parameters
- Electro-Optic Modulators

Materials

- ✓ Pockels
- ✓ Kerr

Configurations

- ✓ Transversal
- ✓ Longitudinal

- Mach-Zehnder Amplitude Modulator
- Electro-Absorption Optical Modulators

Week-9: Lecture Learning Outcomes

1. Explain the fundamental role of optical detectors in converting light signals into electrical signals.
2. Identify common types of optical detectors and their applications in communication systems
3. Describe the working principle of semiconductor photodiodes
4. Identify commonly used materials for photodiodes (e.g., silicon, InGaAs, Ge) and their spectral response ranges.
5. Explain the structure and operation of PIN photodiodes
6. Describe the avalanche multiplication effect and its role in APDs
7. Compare APDs with PIN photodiodes in terms of gain, noise, and sensitivity
8. Identify key noise sources affecting photodetector performance, including shot noise and dark current.

Week-9: Optical Detectors

Outline

- Introduction to Optical Detectors
- Semiconductor Photodiodes
- Photodiode Materials Choices
- PIN Photodiodes
- Avalanche Photodiodes (APD)
- Noise Sources in Photodetectors

Introduction to Optical Detectors

- The optical detector or photodetector serves as the front-end device at the receiver in an optical communication systems
- Its role is to convert the received optical signal in to electrical domain to recover the information signal
- There are many types of optical detectors such as [1]:
    - **Phototransistors**
    - **Photo multipliers**
    - **Pyroelectric photodetectors**
    - **Semiconductor photodetectors or photodiodes**

Semiconductor Photodiodes

- Among various types of optical detectors, **semiconductor photodetectors or Photodiodes** are most suitable for optical communication due to their:
    - **Small size**
    - **High sensitivity**
    - **Fast response time (High Bandwidth)**
- Photodetectors operate by generating **electron–hole pairs** through light **absorption** and collecting the resulting charge carriers
- Upon light absorption, photogenerated electrons and holes stay in the material, leading to increased electrical conductivity
- Transport of photogenerated electrons and holes as a result of an applied electric field produces an electric current

Photon Assisted Electron-Hole Generation

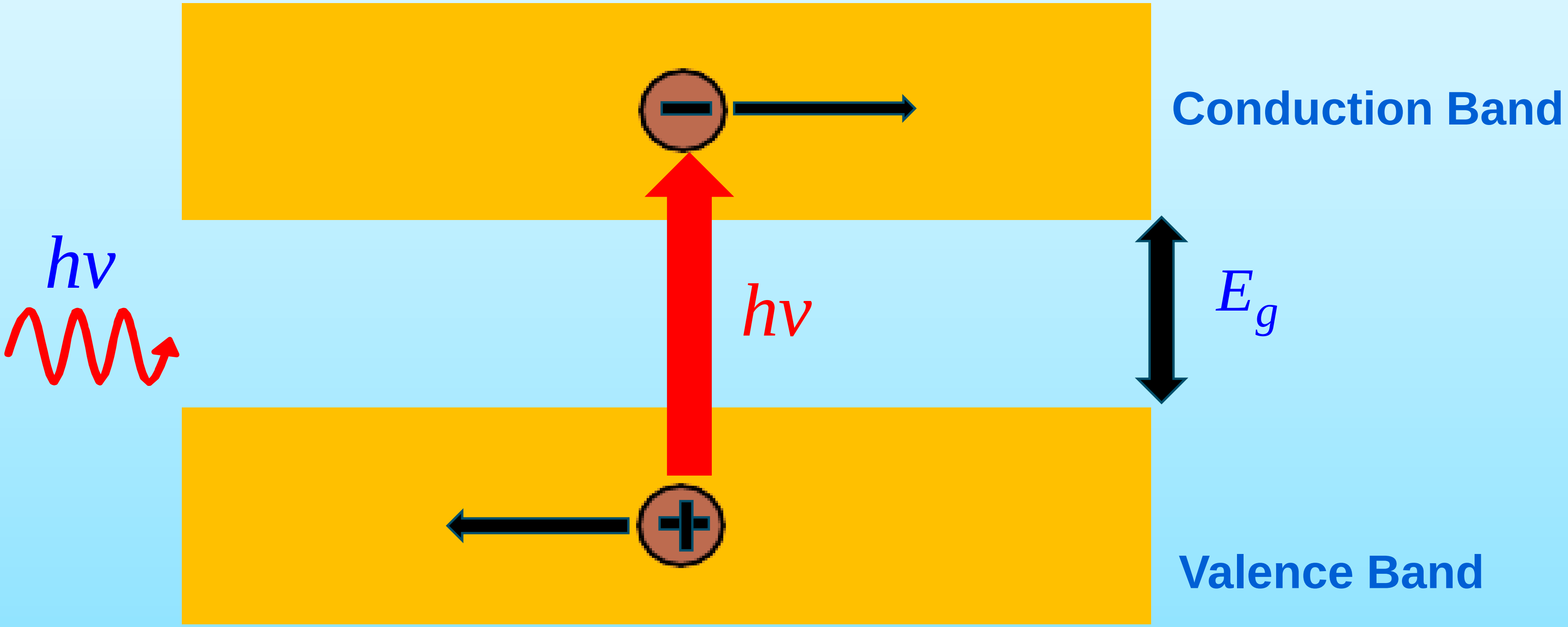


Figure 1: Electron-Hole Generation

Absorption Threshold

- The energy of the photon which empings on the photodetector should be greater than or equal to the band gap energy to achieve electron-hole pair generation [2]:

$$hv = \frac{hc}{\lambda} \geq E_g \qquad (1)$$

- From Eq (1), we have:

$$\lambda \leq \frac{1.24\ \mu\text{m}}{E_g\ \text{eV}} \qquad (2)$$

- Threshold wavelength (λ_{th}), the longest photon wavelength capable of producing an electron–hole pair is given by:

$$\lambda_{th} = \frac{1.24\ \mu\text{m}}{E_g\ \text{eV}} \qquad (3)$$

Direct and Indirect Optical detector Materials

- In fiber optic communication, the photon energy emitted by the optical source at the transmitter must be larger than the energy gap of the optical detector at the receiver.
- Hence, the emitted photon wavelength at the transmitter must be lower than the threshold wavelength (λ_{th})
- Direct and Indirect band gap materials can be used to realize photodiodes:

Example:

- ❖ **Direct Band gap:** InGaAs, GaAs, InP
- ❖ **Indirect Band gap:** Si, Ge

- Direct band gap materials are much preferable since they have higher **absorption coefficient** and **smaller absorption volume**

Absorption Coefficient

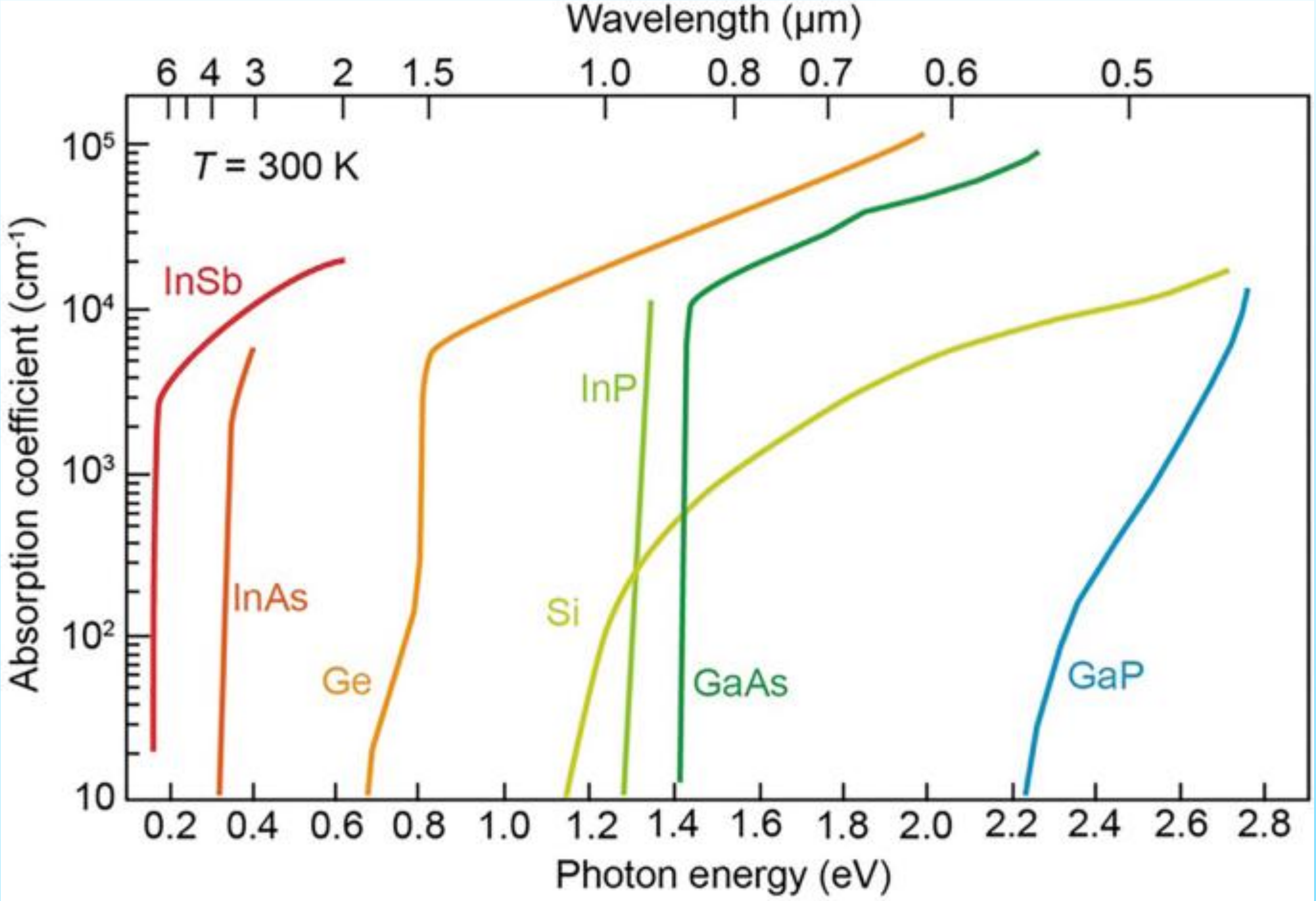


Figure 2: Absorption coefficient vs Photon energy

Source: P. Sutter, “Introduction to Semiconductors: From Materials to Devices,” Springer, 2025. https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-3-031-86006-5_8/MediaObjects/541857_1_En_8_Figa_HTML.png

Absorption Coefficient

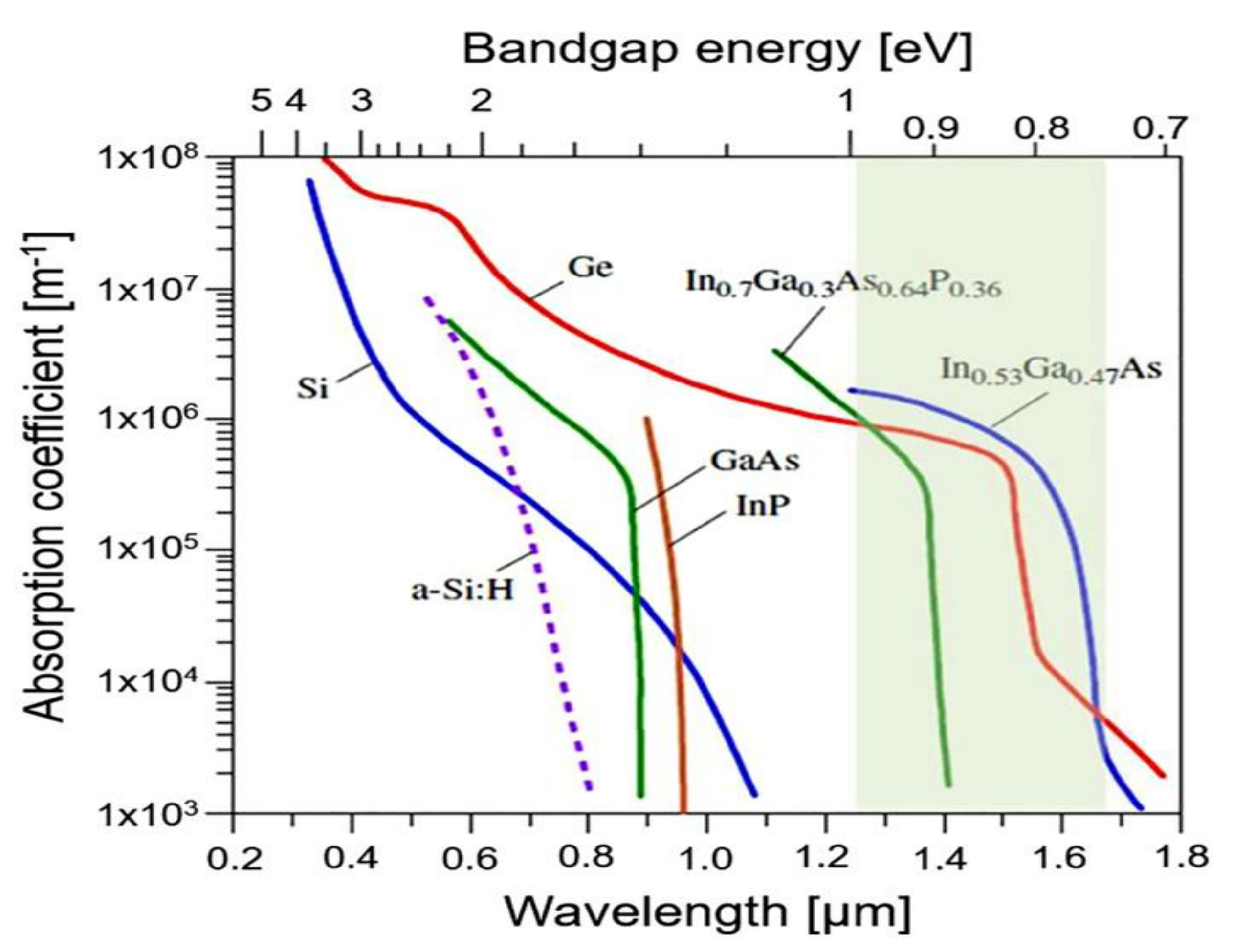


Figure 3: Absorption coefficient vs Photon wavelength

Source: D. Benedikovič, L. Virot, G. Aubin, L. Vivien, et al., “Silicon-germanium receivers for short-wave-infrared optoelectronics and communications: High-speed silicon-germanium receivers,” Nanophotonics, Dec. 2020. https://www.researchgate.net/publication/347445172/figure/fig1/AS:11431281121978686@1677156627848/Absorption-coefficient-as-a-function-of-the-wavelength-and-bandgap-energy-for-several_W640.jpg

Photodiode Materials Choices

- The photodiode material should have a bandgap energy slightly lower than the photon energy of the system’s longest operating wavelength.
- While choosing the material it is important to ensures a high absorption coefficient for good response while minimizing thermally generated carriers to achieve low dark current

Materials for long-haul Optical communication, 1550nm	Materials for short-haul Optical communication, 800nm
❖ **Direct:** InGaAs, InGaAsp, AlGaSb ❖ **Indirect:** Ge	❖ **Direct:** GaAs, AlGaAs ❖ **Indirect:** Ge, Si

Types Photodiodes

- The two primary optical detectors used in optical fiber communication systems are
  - **Semiconductor-based PIN photodiodes**
  - **Avalanche photodiodes (APDs).**
- These devices are suitable for fiber optic communication because of their:
  - compact size compatible with optical fiber
  - High sensitivity at operational wavelengths
  - fast response times that enable precise signal detection

PIN Photodiodes

PIN Photodiodes

- The PIN photodiode is the basic optical detector for application of fiber optics communications
- The device structure features p-type and n-type regions separated by a lightly n-doped intrinsic (i) layer.
- Electron-hole pairs are generated within the intrinsic depletion region.

Feature of PIN Photodiodes
❖ Has no internal gain (offers unity gain)
❖ Low shot noise and dark current
❖ RC circuit and transit time of carrier limits the device bandwidth
❖ Suitable for high-speed fiber optic communication beyond 10 Gb/s

PIN Photodiodes Operation

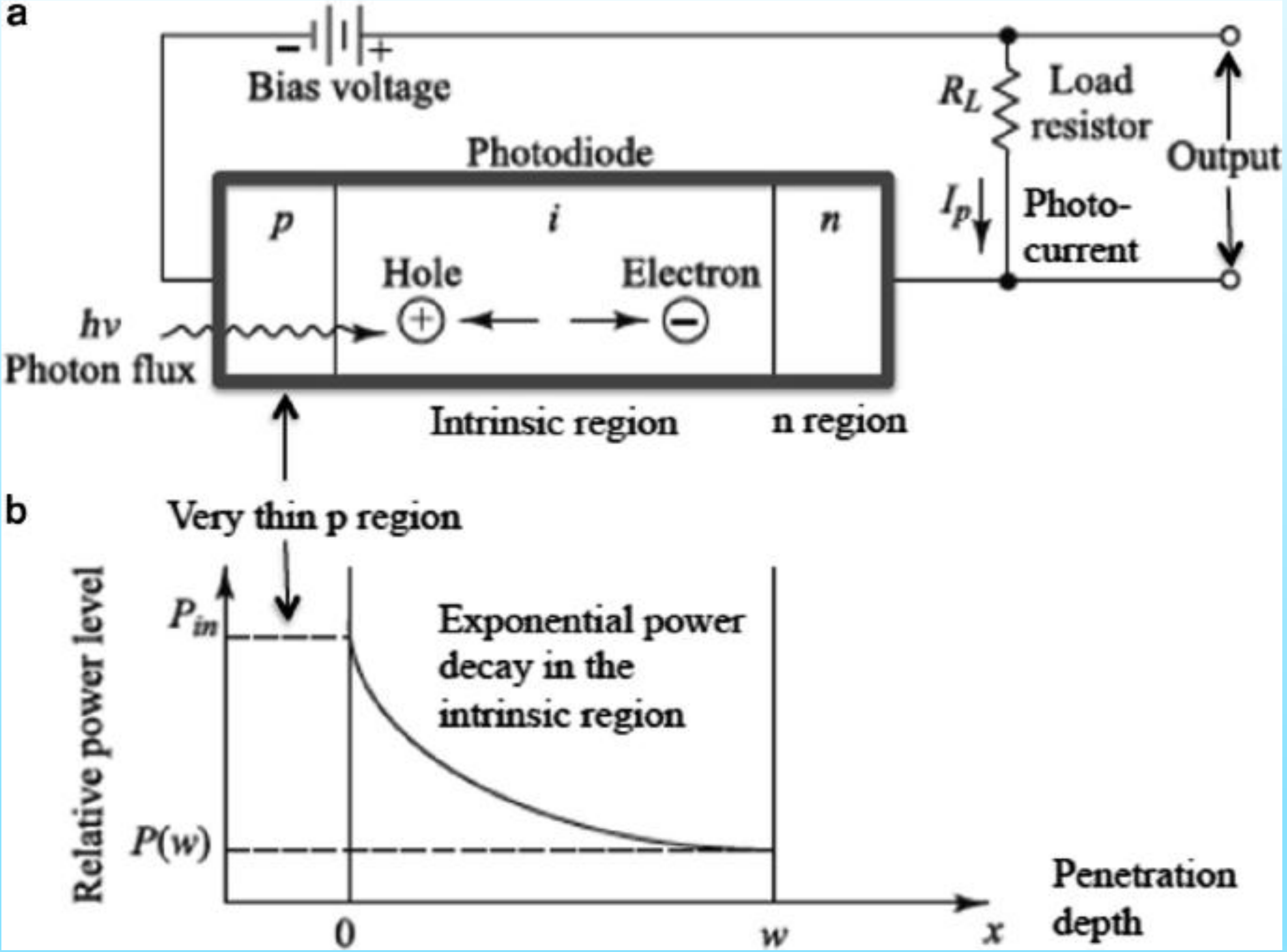


Figure 4: (a) PIN photodiode operation in reverse bias mode (b) power decay in the depletion region

Source: G. Keiser, Fiber Optic Communications, Springer, Singapore, 2021. https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-981-33-4665-9_6/MediaObjects/495048_1_En_6_Fig1_HTML.png

PIN Photodiodes Operation

- Under reverse bias conditions, the majority charge carriers in both the n and p regions move away from the junction
- Therefore, majority carriers do not contribute to electric current flow
- When light is incident on the PIN diode, most of the energy is absorbed by the intrinsic (depletion) region and many electron-hole pairs will be generated
- Free electrons generated in the intrinsic region drift toward the n-side, while the holes move toward the p-side.
- The movement of free electrons and holes between regions results in the flow of electric current called **Photo Current**

PIN Photodiodes Energy Band Diagram

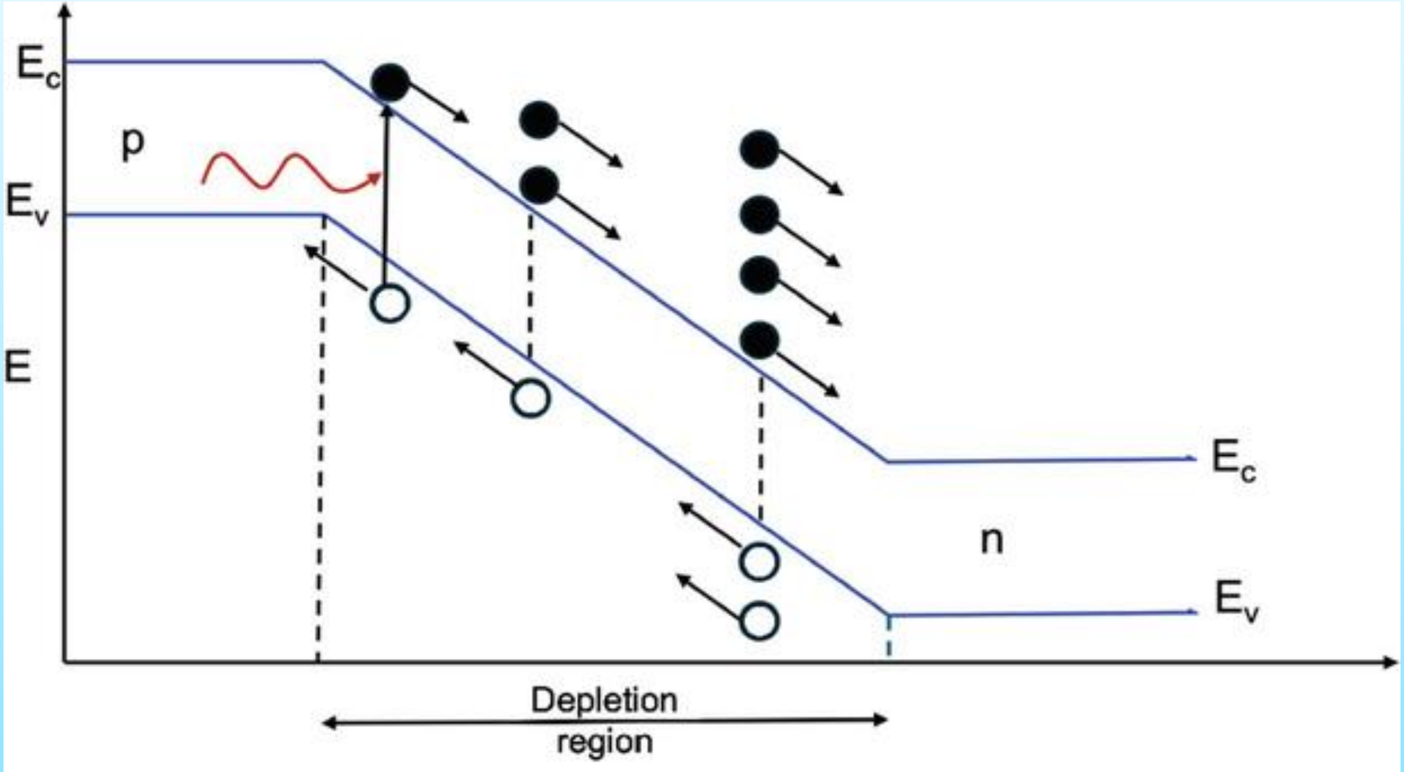
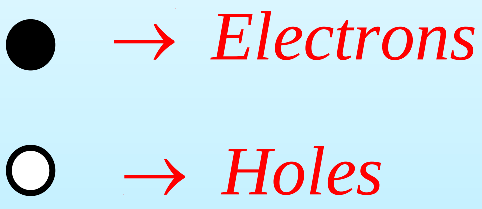


Figure 5: PIN photodiode energy band

Source: M. A. G. Abushagur, "Applied Photonics: An Introduction for Physicists and Engineers," Springer, 2025. https://media.springernature.com/lw685/springer-static/image/chp%3A10.1007%2F978-3-031-86457-5_13/MediaObjects/609428_1_En_13_Fig13_HTML.png



Absorbed Optical Power

- The optical power absorbed ($P_{abs}(x)$) in the depletion region is given by:

$$P_{abs}(x) = P_0 - P(x) = P_0(1 - e^{-\alpha x}) \qquad (4)$$

$l = 0$ $\qquad$ $l = x$

Incident Light power $\quad P_0$

$P(l) = P(x) = P_0 e^{-\alpha x}$ $\quad$ Optical power at point x

$$P_{abs}(x) = P_0 - P(x) = P_0(1 - e^{-\alpha x})$$

Absorbed optical power in length x

Photocurrent

- If we consider the entrance face reflection coefficient R_f :

$$P_{abs}(x) = P_0(1 - R_f) - P(x) = P_0(1 - e^{-\alpha x})(1 - R_f) \quad (5)$$

Transmitted Light power In to depletion region

$l = 0$

$P_0(1 - R_f)$

$l = x$

$P(l) = P(x) = P_0(1 - R_f)e^{-\alpha x}$

Optical power at point x

$$P_{abs}(x) = P_0(1 - R_f) - P(x) = P_0(1 - e^{-\alpha x})(1 - R_f)$$

Absorbed optical power in length x

Photocurrent

- The photocurrent (I_p) resulted from the optical signal absorption is given by:

$$I_p = q\left(\frac{P_{abs}}{h\nu}\right) = \frac{q}{h\nu}(P_0(1-e^{-\alpha x})(1-R_f)) \qquad (6)$$

This term in parathesis is related to the number of photons absorbed or the number of photo- generated electrons

Where:

q Is the charge of electron

- The photon to electron conversion efficiency of the device measures its efficiency

Quantum Efficiency and Responsivity

- **Quantum efficiency** (η)**:** is a measure of how effectively a device converts incident photons into electrons, representing the ratio of signal electrons to incident photons

$$\eta = \frac{number\ \ Photo-genertaed\ \ electrons}{number\ \ incident\ \ photons} = \frac{I_p / q}{P_0 / h\nu} \qquad (7)$$

- **Responsivity** $(\Re)$ **:** It quantifies the photodetector's efficiency of converting the incident optical power in to photocurrent.

$$\Re = \frac{I_p}{P_0} = \frac{\eta q}{h\nu} \quad [A/W] \qquad (8)$$

Avalanche Photodiodes (APD)

Avalanche Photodiode (APD)

- **APD** multiply the number of photogenerated electrons internally
- APD can offer higher output current compared to PIN for the same illumination level
- However, compared to PIN It has also:
  - Less speed
  - High noise
- The structure of APD is composed of two regions:
  - **Carrier Generation (Photon Absorption) Region :** Primary photo-current generated in this region
  - **Carrier Multiplication Region:** internal gain or multiplication of carriers takes place in this region

Avalanche Photodiode (APD)

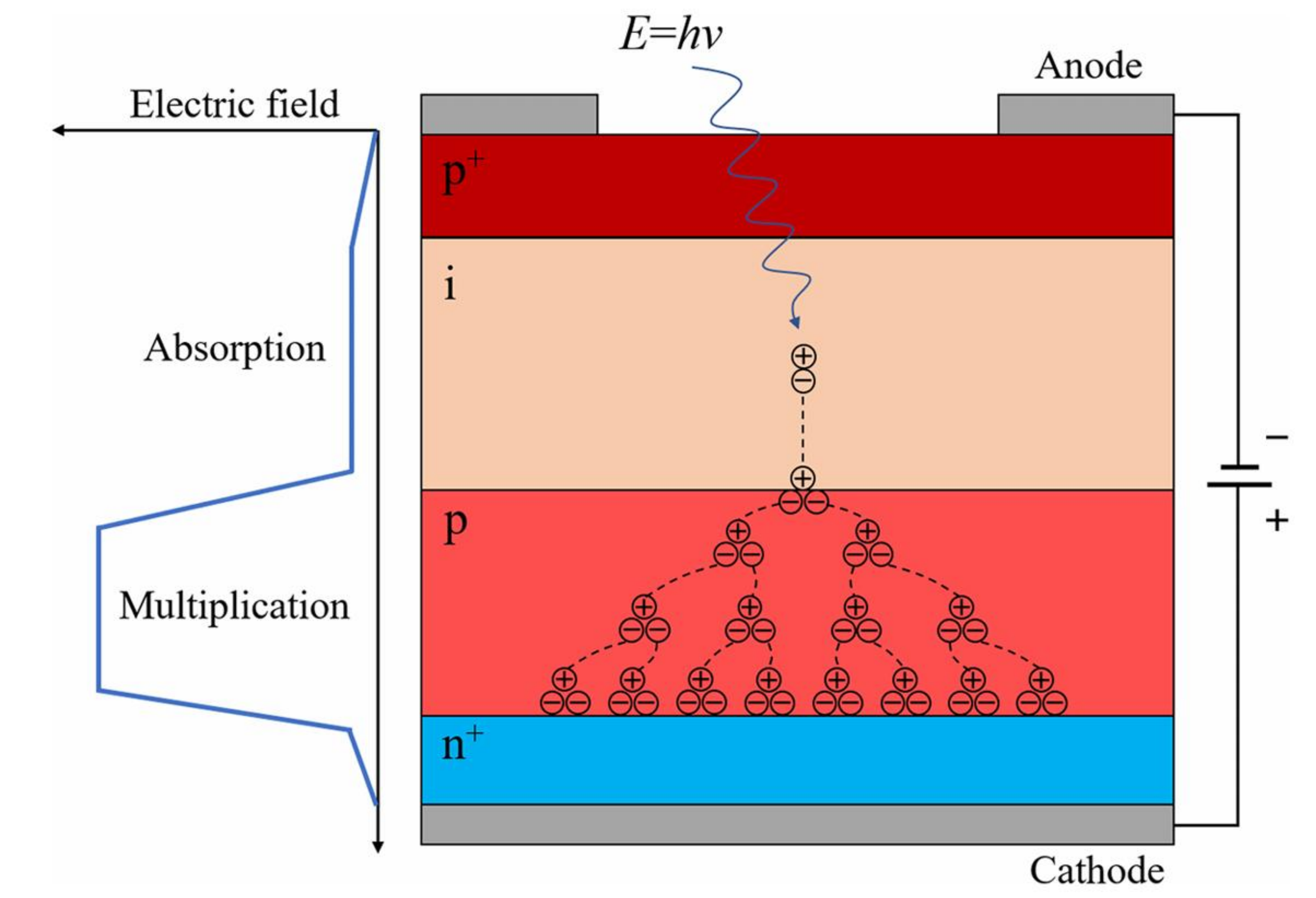


Figure 6: Avalanche photodiode

Source: B. Wang and J. Mu, “High-speed Si-Ge avalanche photodiodes,” Photon iX, Springer, vol. 3, no. 8, Mar. 2022. https://www.researchgate.net/publication/359456660/figure/fig1/AS:1137575326687239@1648230501830/Avalanche-photodiode-operating-principle-The-left-part-is-the-electric-field-profile-of.png

Avalanche Photodiode (APD)

- The photogenerated carriers generated in the absorption region must traverse through a high field multiplication region for **carrier multiplication.**
- In multiplication region, the photo-generated electrons obtains kinetic energy and accelerated by the high field and collide with electrons in the valence band.
- The valance band electron will obtain enough energy from the cloison to make them selves **free electrons,** and the process is called **Impact Ionization**
- The newly created free electrons will results in more ionization and create more free elections and the process is called **Avalanche Effect.**

Current Gain and Responsivity of APD

- The current gain or multiplication factor (M) of APD is given by:

$$M = \frac{I_M}{I_p} \qquad (9)$$

Where:

I_M Is average value of the total multiplied output current

I_p Is the primary photocurrent

- The responsivity of APD $(\Re_{APD})$ is given by:

$$\Re_{APD} = \frac{I_M}{P_0} = M\frac{I_p}{P_0} = M\frac{\eta q}{h\nu} = M\Re \qquad (10)$$

Where:

$\Re$ Is the unity gain responsivity

Noise Sources in Photodetectors

Noise Sources in Photodetectors

- The major noises associated with optical detectors are::
  - **Quantum (Shot) Noise:** arises from the statistical nature of photo-generated carriers creation and collection
  - **Dark Current:** electric current that flows through the photodiode circuitry even in the absence of incident light and dark current is two types:
    - **Bulk Dark Current:** due to thermally generated carriers
    - **Surface Dark Current:** due to surface defect and bias voltage
- APD has more noise compared to PIN due to multiplication of dark current.

Summary

- **Suitable types of optical Detectors for fiber optics communication:**
  - ✓ Semiconductor Optical Detectors
- **Semiconductor Optical Detector:**
  - ✓ **PIN photodiode:** Highs speed, has no internal gain
  - ✓ **Avalanche Photodiode:** high sensitivity, has internal gain
- **Materials for long-haul Optical communication, 1550nm:**
  - ✓ **Direct bandgap:** InGaAs, InGaAsp, AlGaSb
  - ✓ **Indirect bandgap:** Ge
- **Materials for short-haul Optical communication, 800nm:**
  - ✓ **Direct bandgap:** GaAs, AlGaAs
  - ✓ **Indirect bandgap:** Ge, Si
- **Noise Sources:** Quantum (shot noise)**,** dark current

References

[1] Gerd Keiser, *“Fiber Optic Communications”,* Springer, Pp.241, 2021.

[2] Giovanni Ghione,*‘’ Semiconductor Devices for High-Speed Optoelectronics”,*
CAMBRIDGE UNIVERSITY PRESS, Pp.161, 2009.

Thank You !