UESTC 3002: Electronic Devices

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Lecture 10

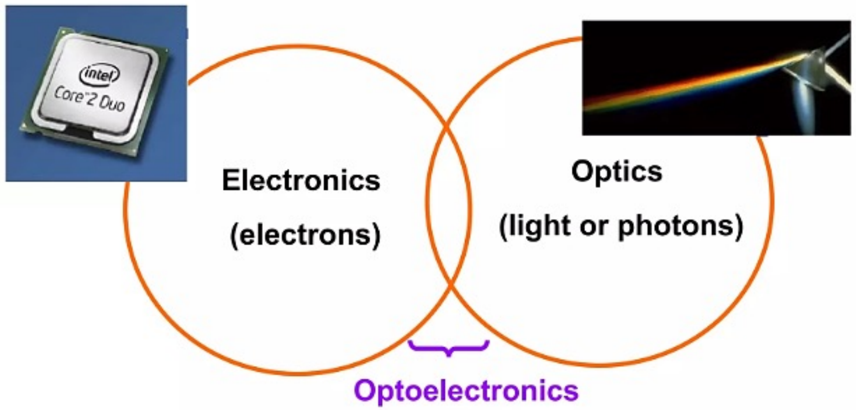
In This Lecture

Optoelectronic Devices

Optoelectronic Devices

Definition

- **Optoelectronic:** functions involving the interaction of photons with semiconductors.
- **Optoelectronics Devices:** devices that detect photons and those that emit photons.
- **Photoconductors:** are devices or materials that exhibit photoconductivity. Photoconductivity refers to the change in electrical conductivity of a material when exposed to light.

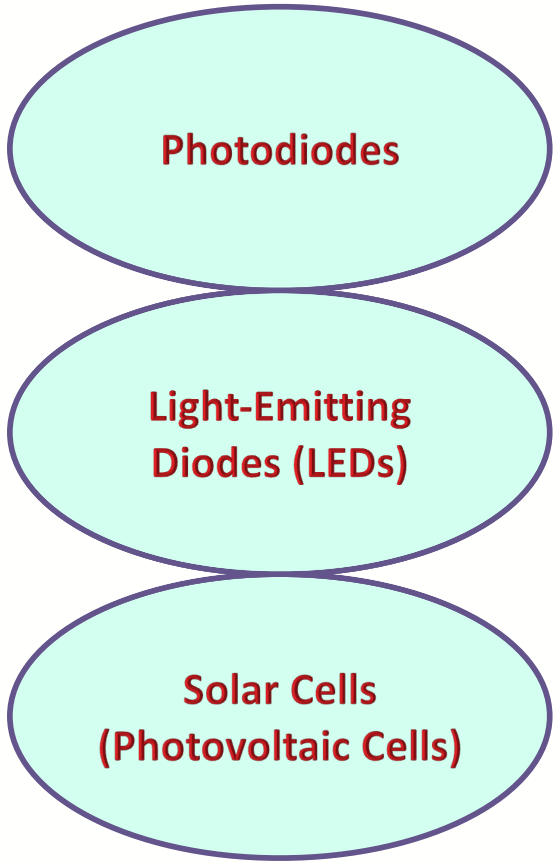


Optoelectronic Devices

Types of Optoelectronic Devices

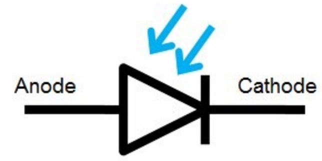
There is a wide variety of very interesting and useful device functions involving the interaction of photons with semiconductors:

- Devices that convert optical energy into electrical energy include photodiodes and solar cells.
- Emitters of photons include incoherent sources such as light-emitting diodes (LEDs) and coherent sources in the form of lasers.



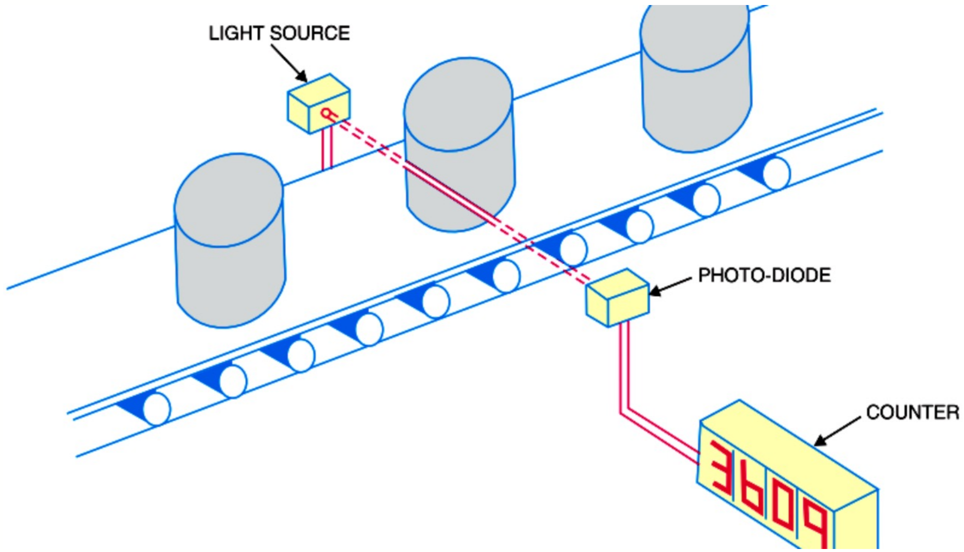
Optoelectronic Devices

Photodiodes



Photodiode symbol

- **Photodiodes:** Two-terminal devices designed to respond to photon absorption.
- Some photodiodes have extremely high sensitivity and response speed.
- Since modern electronics often involves optical as well as electrical signals, photodiodes serve important functions as electronic devices.



Optoelectronic Devices (Photodiodes)

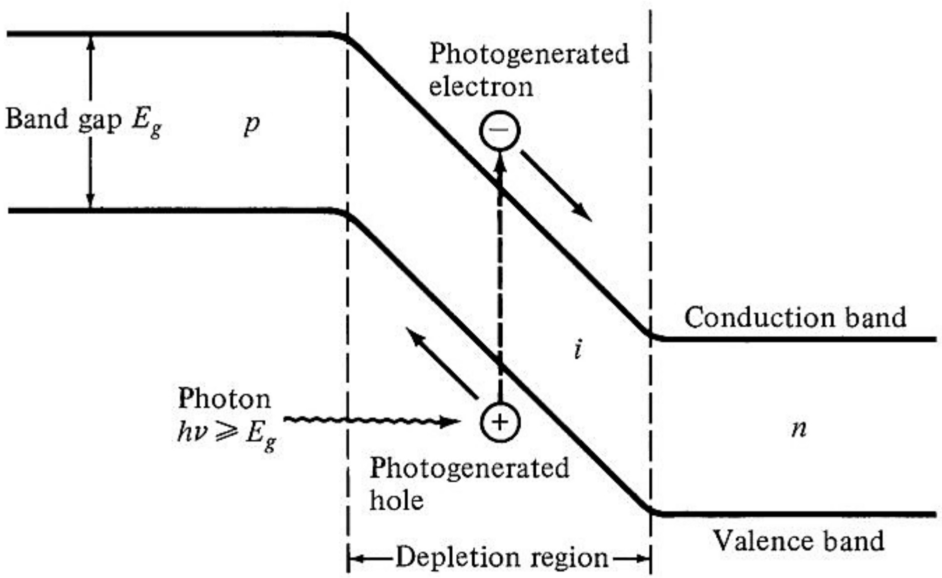
Energy Band Diagram

Unbiased Photodiode:

- In the absence of external bias voltage, a photodiode typically has a built-in potential due to the difference in energy levels between the p-type and n-type semiconductor materials.

Incident Light:

- When photons from incident light strike the photodiode, they may be absorbed by the semiconductor material.

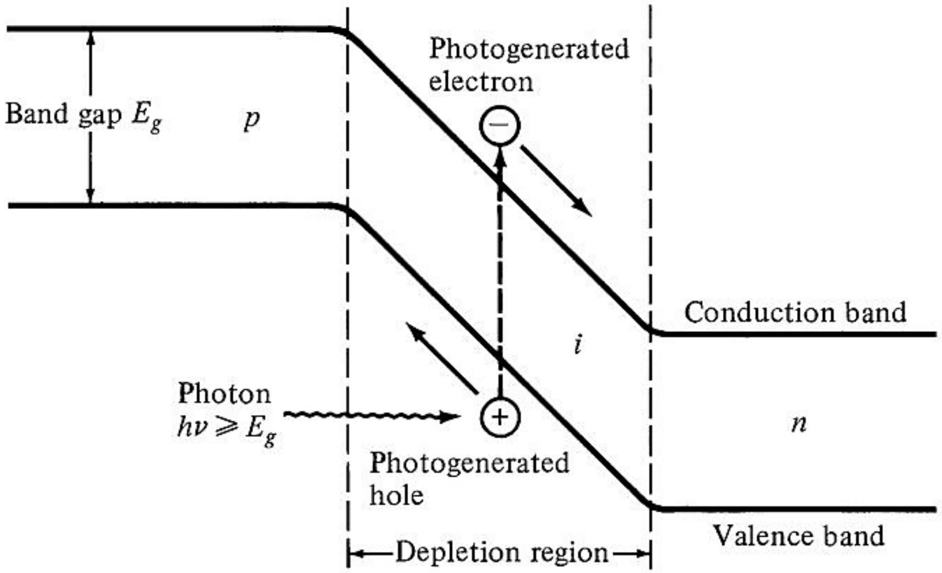


Optoelectronic Devices (Photodiodes)

Energy Band Diagram

Electron-Hole Pair Generation:

- If the energy of a photon is greater than the bandgap energy of the semiconductor material, it can generate an electron-hole pair.
- Electrons move to the n-type region, and holes move to the p-type region.

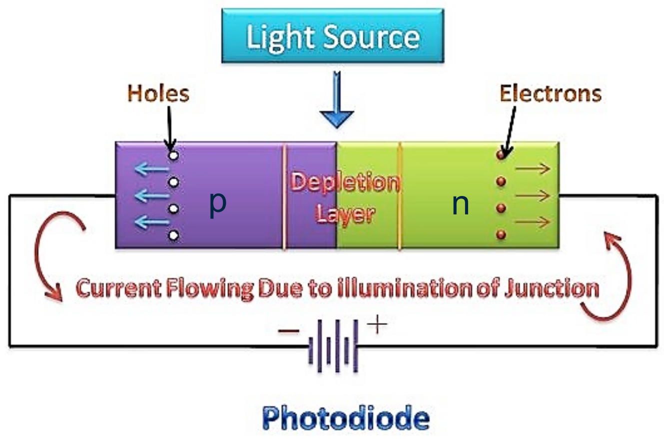


Optoelectronic Devices (Photodiodes)

External Bias Applied

Under Reverse Bias:

- If an external voltage is applied in reverse bias (negative voltage applied to the p-type and positive voltage applied to the n-type), it increases the width of the depletion region.
- This reverse bias helps to sweep the generated electrons and holes away from the junction, reducing the recombination of charge carriers.



Current Flow:

- The electrons and holes, separated by the electric field in the depletion region, contribute to the photocurrent.

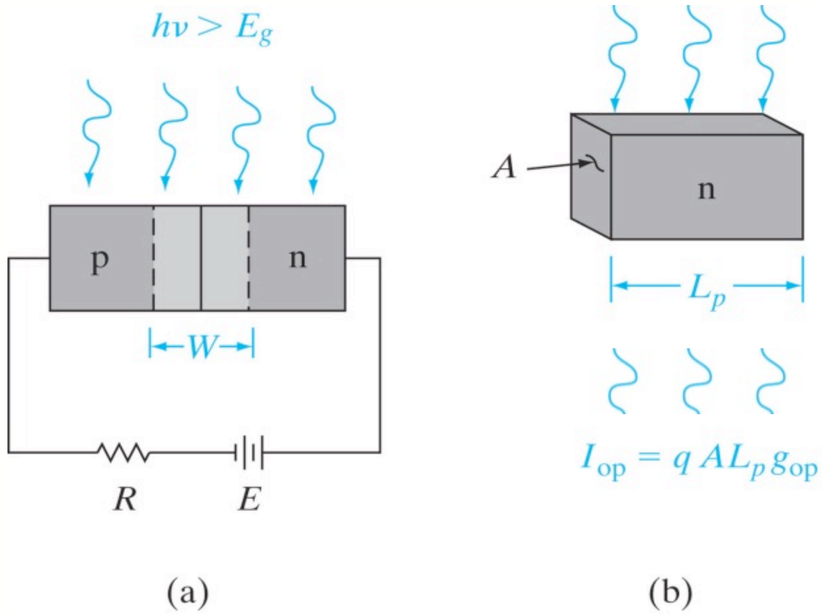
Optoelectronic Devices (Photodiodes)

Current and Voltage in an Illuminated Junction

The resulting current due to the collection of optically generated carriers by the junction is

$$I_{op} = qAg_{op}(L_p + L_n + W)$$

g_{op}: the optical generation rate $\left({}^{EHP}/_{cm^3-s}\right)$
A : the cross-sectional area of the junction.
q : the elementary charge $1.6\times10^{-19}\ Coulombs$.
L_p : the diffusion length for holes.
L_n : the diffusion length for electrons.
W : the width of the depletion region.



Optical generation of carriers in a p-n junction: (a) absorption of light by the device; (b) current Iop resulting from EHP generation within a diffusion length of the junction on the n side;

Optoelectronic Devices (Photodiodes)

Example

Consider a photodetector with the following parameters:

- Cross-sectional area of the junction: 2 cm^2
- Diffusion length for holes: 4 μm
- Diffusion length for electrons: 4 μm
- Width of the depletion region: 1 μm

➢ Calculate the current generated optically, given a generation rate of electron-hole pairs of 8×10^{19} EHP/cm^3-s.

Optoelectronic Devices (Photodiodes)

Total Reverse Current with Illumination

If we call the thermally generated current (I_{th}), we can add the optical generation (I_{op}) to find the total reverse current with illumination:

$$I = I_{th}\left(e^{qV/kT} - 1\right) - I_{op}$$

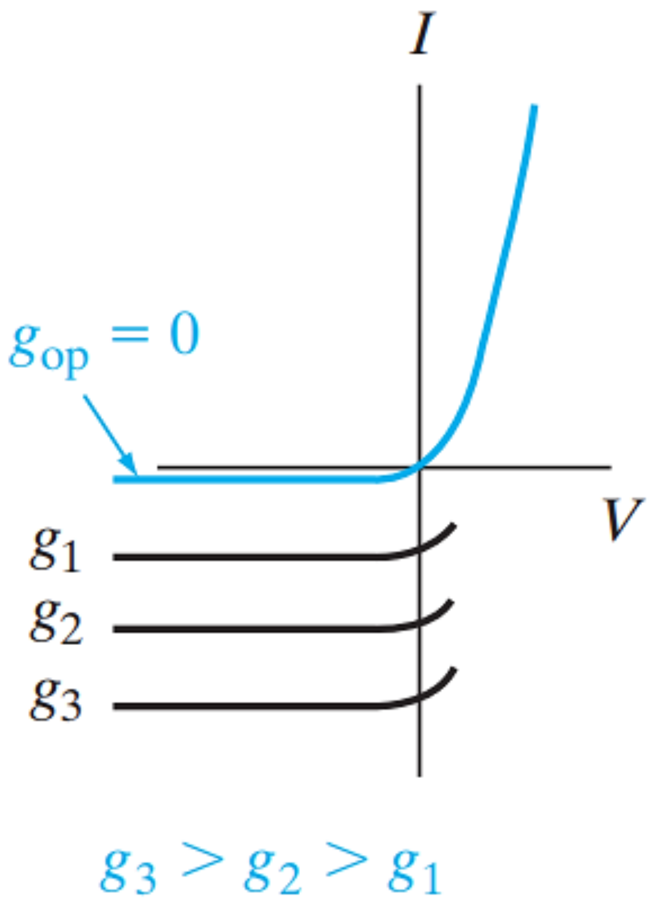
where,
V is the applied voltage.
k is Boltzmann's constant ($1.38\times10^{-23}\,J/K$).
T is the temperature in Kelvin

This equation can be considered in two parts—the current described by the usual diode equation and the current due to optical generation.

Optoelectronic Devices (Photodiodes)

Current-Voltage (I-V) Curve

The I–V curve is lowered by an amount proportional to the generation rate.



Optoelectronic Devices (Photodiodes)

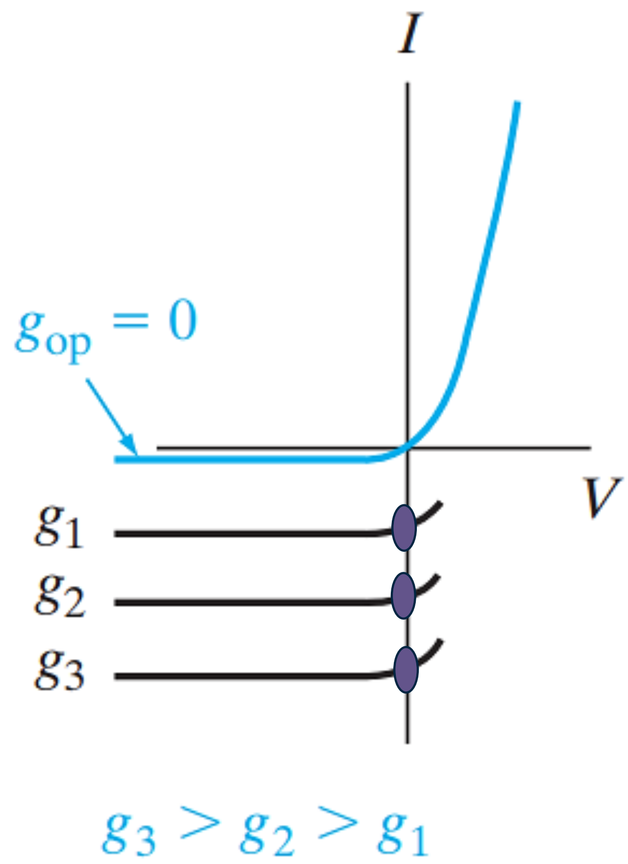
Short Circuit Current

- Short Circuit: when the device is short circuited ($V = 0$), the diode terms from the equation of total reverse current illumination cancel, as expected.

$$I = I_{th}\left(\cancel{e^{qV/kT}} - 1\right) - I_{op}$$

- However, there is a short-circuit current:

$$I = -I_{op}.$$



Optoelectronic Devices (Photodiodes)

Open Circuit Voltage

- Open Circuit: when there is an open circuit across the device, $I = 0$ and the voltage $V = V_{oc}$ is

$$V_{oc} = \frac{kT}{q} \ln\left[\frac{I_{op}}{I_{th}} + 1\right]$$

Where
I_{op} is the optically generated current
I_{th} is thermally generated current

Optoelectronic Devices (Photodiodes)

Example

Consider a photodetector with the following parameters:

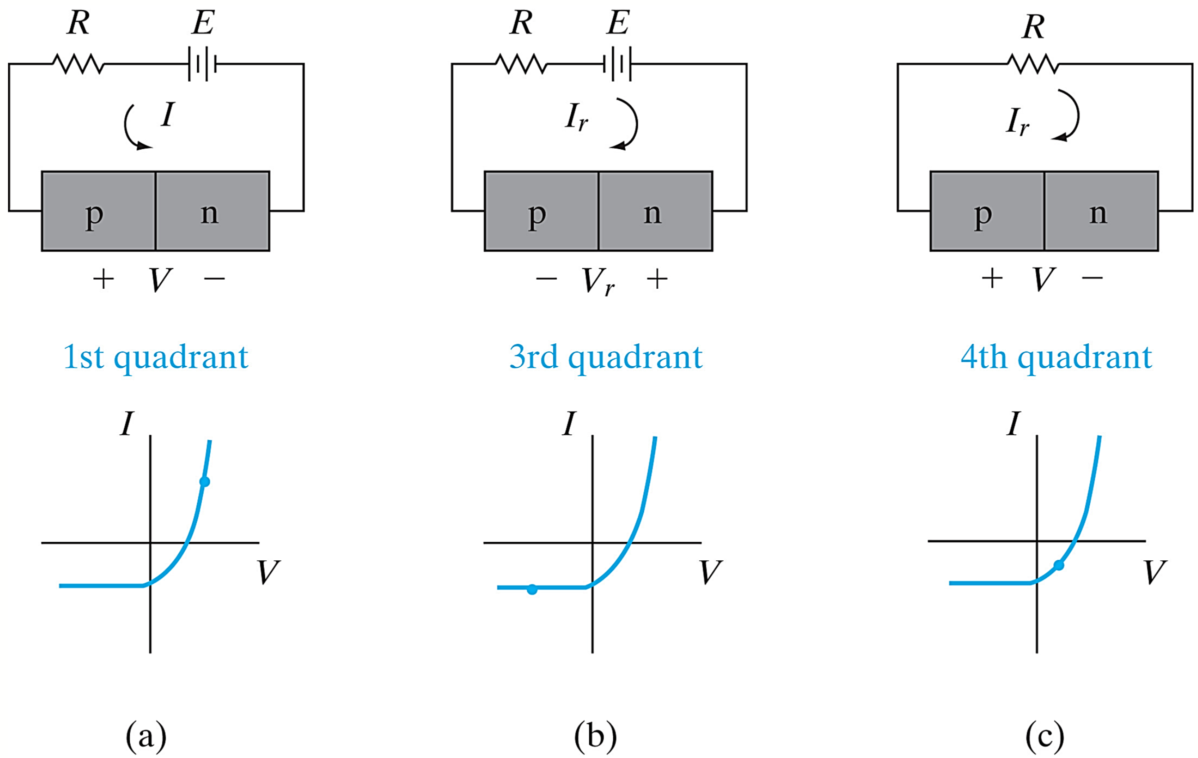
- Cross-sectional area of the junction: 2 cm^2
- Diffusion length for holes: 4 μm
- Diffusion length for electrons: 4 μm
- Width of the depletion region: 1 μm
- A generation rate of electron-hole pairs of $8{\times}10^{19}$ EHP/cm^3-s.
- The absolute temperature (T): 300 K

➢ An open circuit is established across this device. Determine the corresponding open-circuit voltage, considering that the thermally generated current is 15 nA.

Optoelectronic Devices (Photodiodes)

I–V characteristic

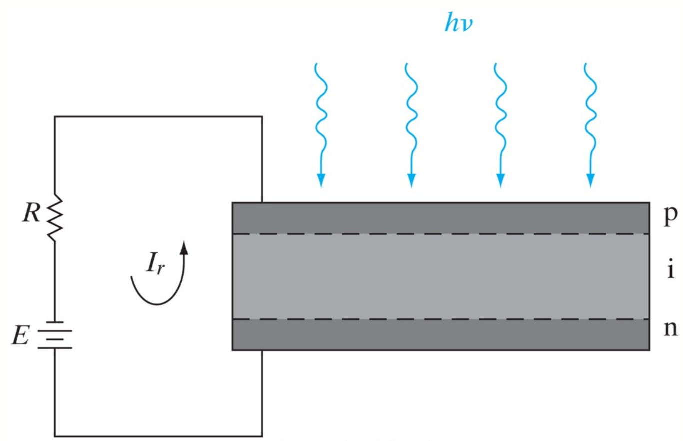
- Depending on the intended application, the photodiode can be operated in either the third or fourth quarters of its I–V characteristic.
- In (a) and (b), power is delivered to the device by the external circuit;
- In (c) the device delivers power to the load.



Optoelectronic Devices (Photodiodes)

Photodiodes

- When the photodiode is operated in the third quadrant of its I–V characteristic, the current is essentially independent of voltage but is proportional to the optical generation rate.
- In most optical detection applications, the detector's speed of response is critical.
- The appropriate width for width of the depletion (W) is chosen as a compromise between sensitivity and speed of response.
- One convenient method of controlling the width of the depletion region is to build a p-i-n photodiode.



Optoelectronic Devices (Photodiodes)

Types of Photodiodes (1/3)

- Photodiodes come in various types and configurations, each designed for specific applications based on factors such as sensitivity and speed of response. Three common types of photodiodes are as follows:

1- PN Photodiode

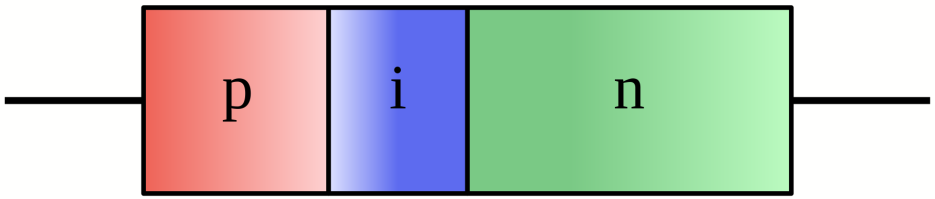
- The most basic type of photodiode, consisting of a p-n junction.
- It operates in reverse bias mode to generate photocurrent when exposed to light.
- They are versatile and used in many general-purpose applications.

Optoelectronic Devices (Photodiodes)

Types of Photodiodes (2/3)

2- PIN Photodiode

- PIN (p-type, intrinsic, n-type) photodiodes have an intrinsic (i) layer between the p and n layers.
- PIN diodes have low dark current means very low electric current flows through the diode when no photons enter the diode.
- They are capable of detecting light over a broader wavelength range.
- PIN photodiodes are often used as photoreactor in high-speed and low-noise applications.



Optoelectronic Devices (Photodiodes)

Types of Photodiodes (3/3)

3- Avalanche Photodiode (APD)

- APDs are designed for extremely high sensitivity.
- They incorporate avalanche multiplication, where carriers generated by incident photons trigger an avalanche effect, resulting in higher photocurrent.
- APDs are used in low-light-level detection, such as in astronomy, fiber-optic telecommunication and LIDAR (Light Detection and Ranging) systems.

Optoelectronic Devices (Photodiodes)

Responsivity

The primary equation that governs the operation of a photodiode is the relationship between the generated photocurrent (I_{op}), incident light power (P), and the photodiode's responsivity (R):

$$\text{Responsivity } (R) = \frac{I_{op}}{P}$$

$$I_{op} = P \times R$$

Where:

- I_{op} is the photocurrent generated by the photodiode (in amperes, A).
- P is the incident optical power (in watts, W).
- R is the responsivity of the photodiode (in amperes per watt, A/W).

Optoelectronic Devices (Photodiodes)

Example

Consider a photodetector with the following parameters:

- Cross-sectional area of the junction: 2 cm^2
- Diffusion length for holes: 4 μm
- Diffusion length for electrons: 4 μm
- Width of the depletion region: 1 μm
- A generation rate of electron-hole pairs of 8×10^{19} EHP/cm^3-s.

➢ Determine the responsivity of the photodetector with the provided incident light power of 5 mW.

Optoelectronic Devices (Photodiodes)

Responsivity

The responsivity also can vary with wavelength, so it's often specified as a function of wavelength $R(\lambda)$:

$$\mathrm{R}(\lambda) = \eta \frac{q}{hf} \approx \eta \frac{\lambda_{(\mu m)}}{1.23985}$$

Where:

- η is the quantum efficiency.
- $R(\lambda)$ is the responsivity of the photodiode at a specific wavelength λ (in A/W).
- q is the electron charge,
- f is the frequency of the optical signal,
- h is Planck's constant.

Optoelectronic Devices (Photodiodes)

Example

You are working with a photodetector that has the following parameters:

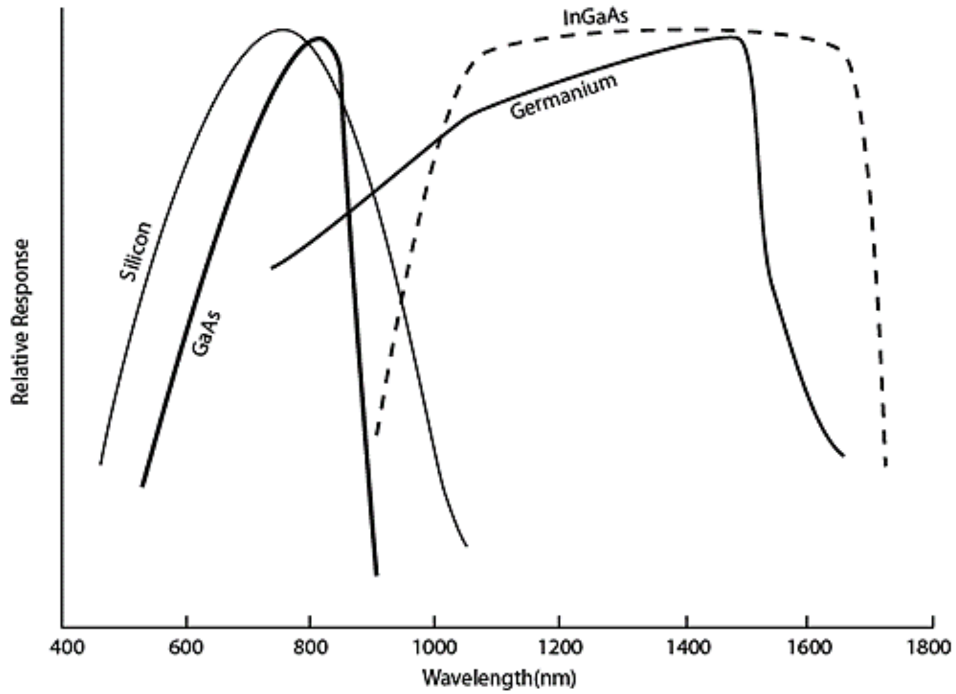
- Quantum efficiency (η): 0.85
- Charge of an electron (q): 1.6×10^{-19} C
- Planck's constant (h): 6.626×10^{-34} J.S
- Frequency of incident light (f): 4.5×10^{14}

Calculate the spectral responsivity of the photodetector for the given parameters.

Optoelectronic Devices (Photodiodes)

Responsivity (Typical Photodetector Characteristic)

Photodetector	Wavelength (nm)	Responsivity (A/W)
Silicon PN	550-850	0.41-0.7
Silicon PIN	850-950	0.6-0.8
InGaAs PIN	1310-1550	0.85
InGaAs APD	1310-1550	0.80
Germanium	1000-1500	0.70



Optoelectronic Devices (Photodiodes)

Quantum Efficiency

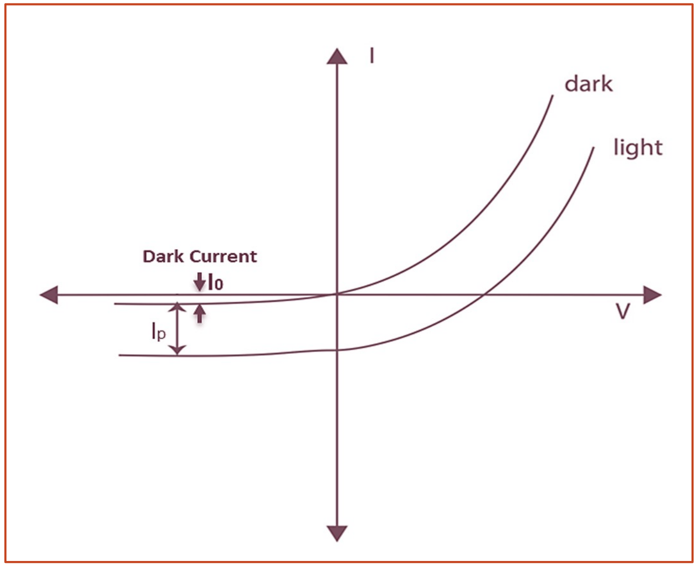
Another important measure for a photodetector is the external quantum efficiency.

In a photodiode (or some other photodetector), the quantum efficiency can be defined as the fraction of incident photons which contribute to the external photocurrent.

$$\eta = \frac{Number\ of\ electron/holes\ genetrated}{Number\ of\ incident\ photons}$$

Optoelectronic Devices (Photodiodes)

Dark Current



- In the reverse bias region (negative voltage applied), the photodiode's dark current is plotted.
- Dark current is the small current that flows through the photodiode when there is no incident light.
- The dark current is slightly increased as the reverse bias voltage increases.

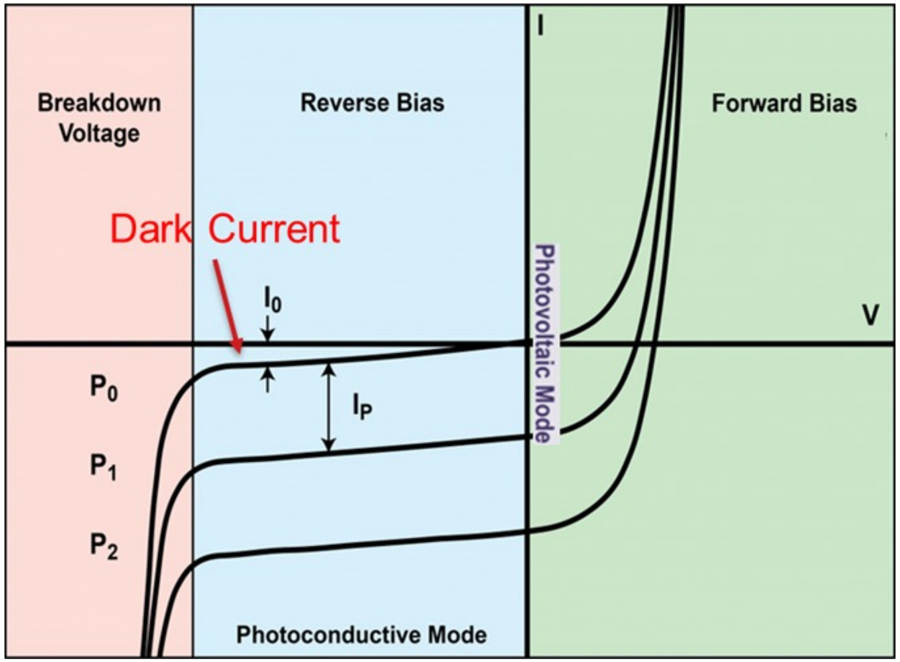
- The dark current is affected by the photodiode material, temperatures (thermal generation) and the size of the active area.
- Silicon devices generally produce lower dark current compared to germanium devices.

Optoelectronic Devices (Photodiodes)

Photodiode Operating Modes

A photodiode can be operated in one of two modes:

- Photoconductive (reverse bias)
- Photovoltaic (zero-bias).

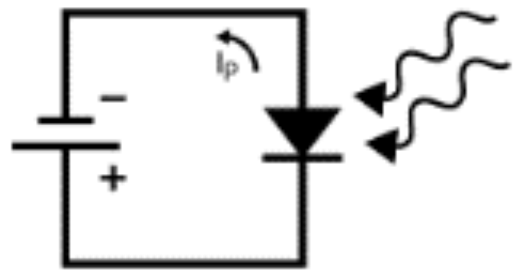


Mode selection depends upon the application's speed requirements and the amount of tolerable dark current (leakage current).

Optoelectronic Devices (Photodiodes)

Photoconductive

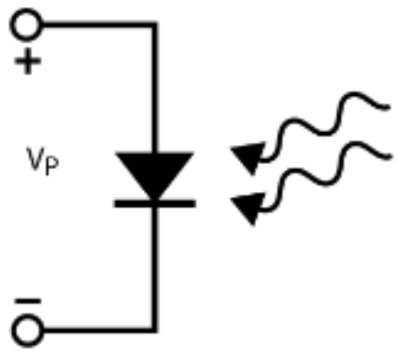
- In photoconductive mode, an external reverse bias is applied, which is the basis for our high-speed optical communication.
- The current measured through the circuit indicates illumination of the device; the measured output current is linearly proportional to the input optical power.
- Operating under these conditions does tend to produce a larger dark current, but this can be limited based upon the photodiode material.



Optoelectronic Devices (Photodiodes)

Photovoltaic

- In photovoltaic mode the photodiode is zero biased.
- The flow of current out of the device is restricted and a voltage builds up.
- This mode of operation exploits the photovoltaic effect, which is the basis for solar cells
- The amount of dark current is kept at a minimum when operating in photovoltaic mode.



Optoelectronic Devices (Photodiodes)

Hints and Sample Questions

Optoelectronic Devices (Photodiodes)

1: What are the three types of photodiodes? Explain briefly.

2: Explain the responsivity definition with interacted parameters in the photodiode.

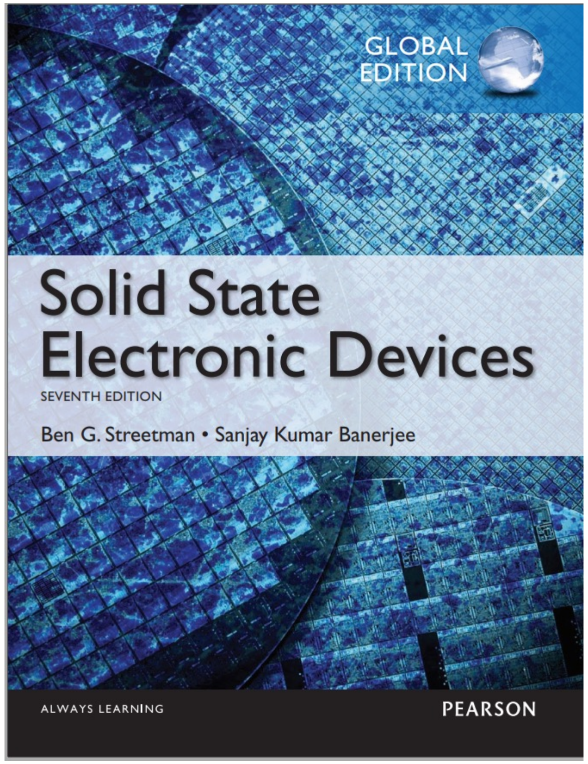
3: Describe the main parts involved in the formulation of total reverse current with illumination.

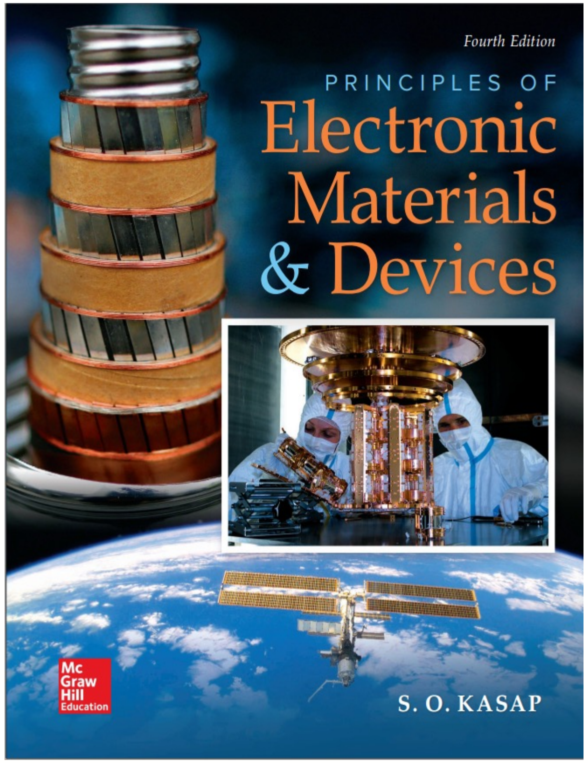
4: Describe the main parts involved in the formulation of open circuit voltage in the photodiode.

5: Explain quadrants of the I-V curve involved in photodiodes operations.

6. Describe the Quantum Efficiency definition including the formulation.

Optoelectronic Devices (Photodiodes)





In The Next Lecture

Optoelectronic Devices

(Light-Emitting Diode)