NANYANG TECHNOLOGICAL UNIVERSITY

EE2003 Semiconductor Fundamentals
(Part III)

Photodetectors

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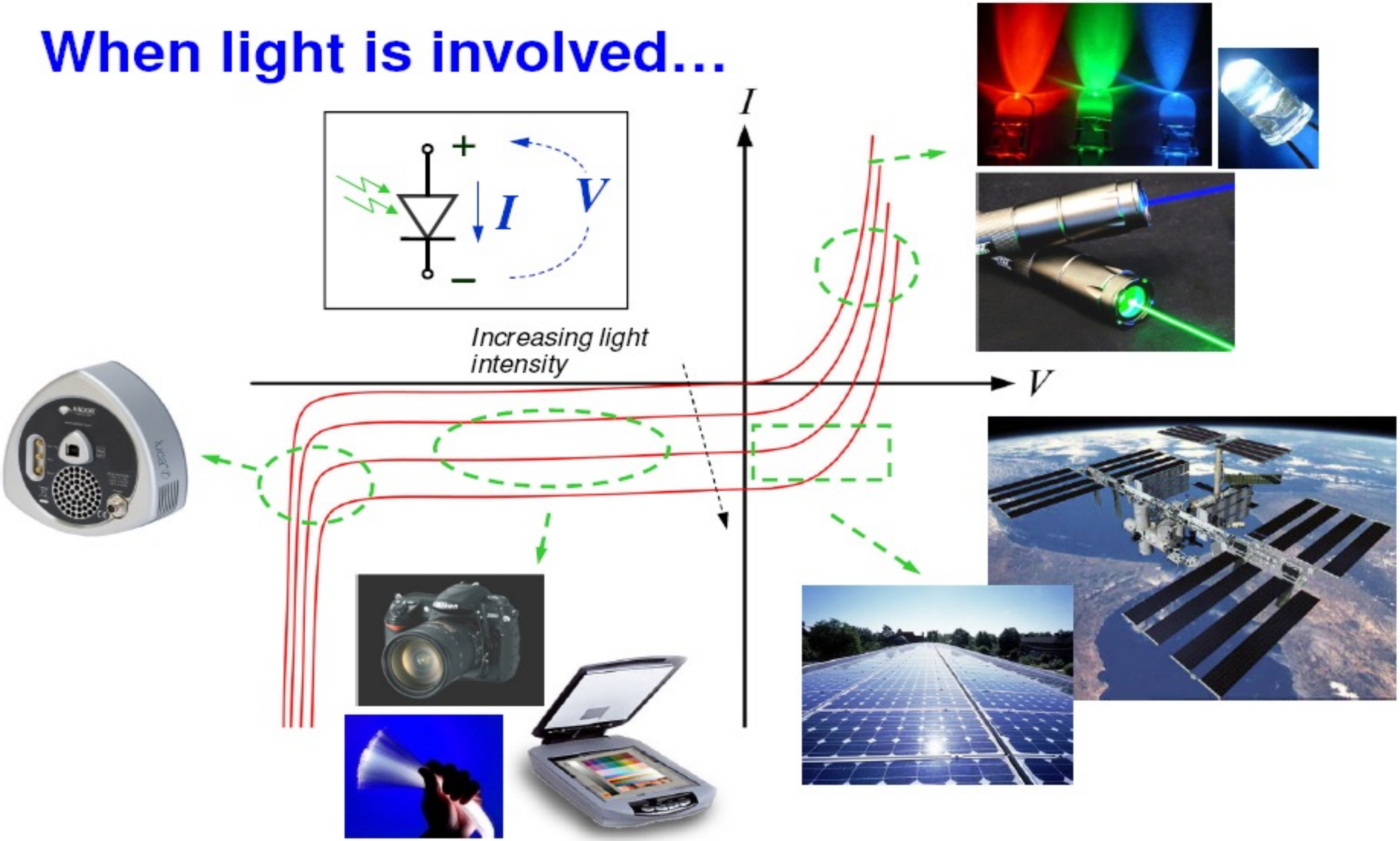
Photodetectors

(Lectures 8 - 9)

When light is involved…



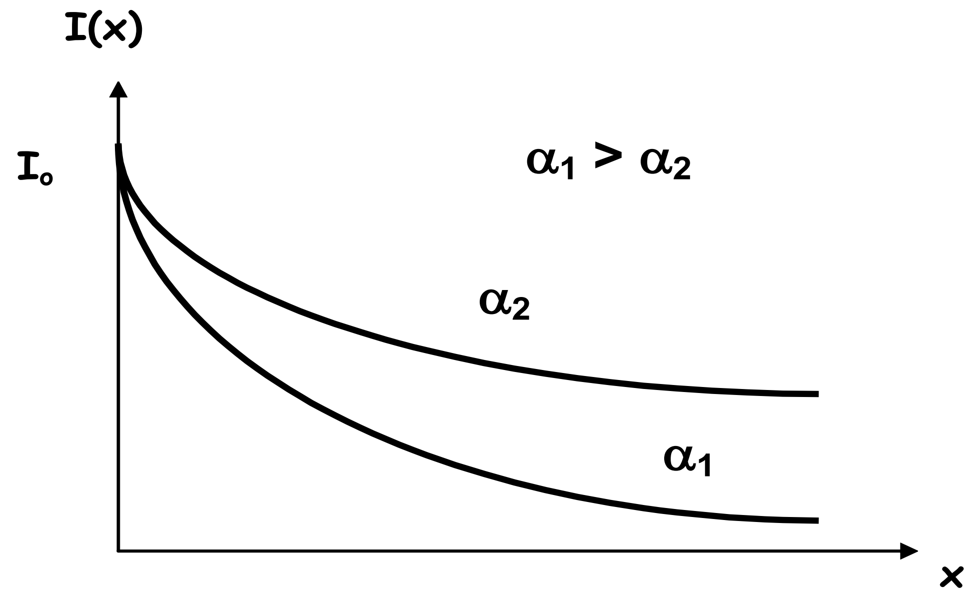
Objectives:

- You will learn different types of photodetectors, the difference and similarity.
- You will learn key parameters that determine the performance of photodetectors.
- You will learn the current-voltage characteristics of photodiodes and solar cells.
- You will learn how photodiodes and solar cells are related to pn junctions.

Outlines

Absorption of photons results in an exponential decrease of the irradiance with distance.

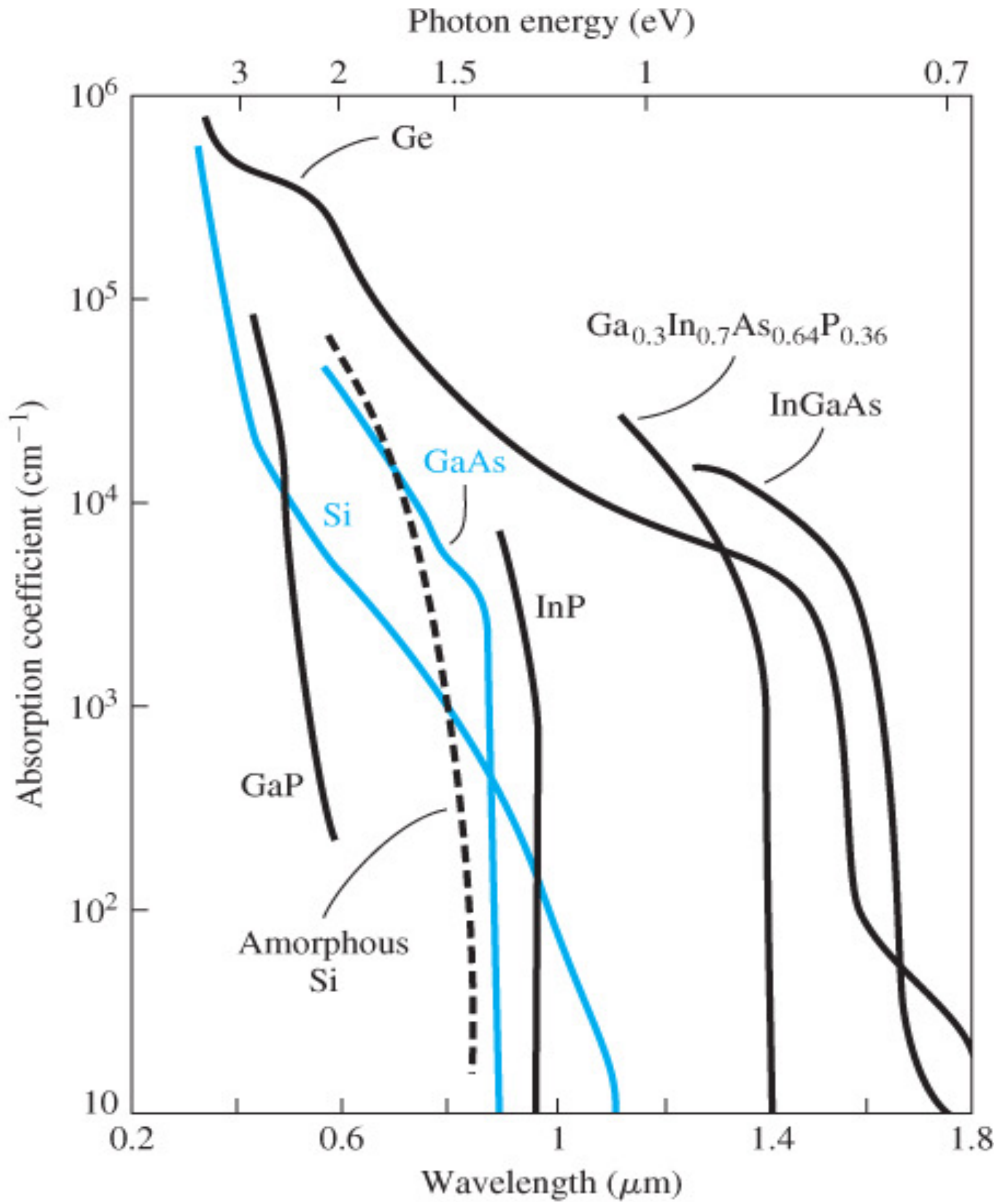
Larger α (absorption coefficient) implies a faster decrease in the irradiance and hence more photon absorption.



Absorption coefficient in the semiconductor is a very strong function of photon energy and bandgap energy.

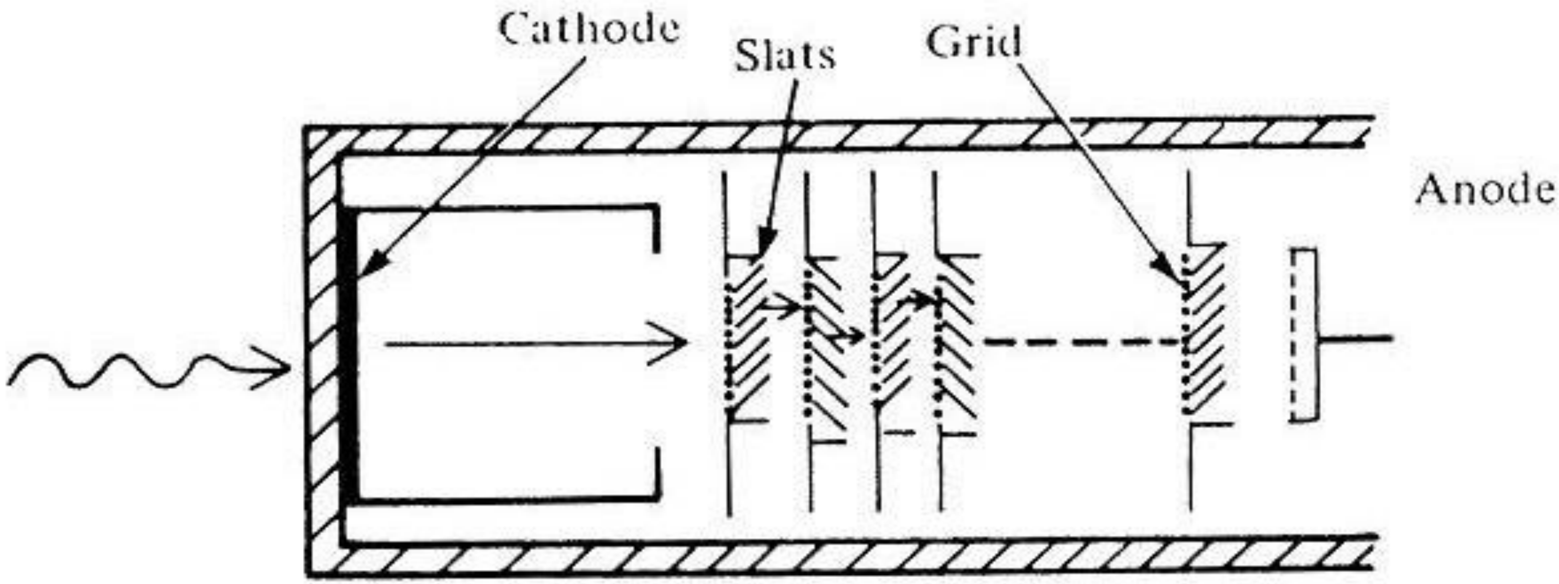
For photons with **hf < E_g**, α is very small due to negligible absorption.

For **hf > E_g**, absorption of light is stronger. It leads to the creation of **EHPs**.



Absorption coefficient as a function of wavelength for several semiconductors

3.1 Photomultipliers (PMTs)



(a)

- e⁻ are emitted from the photocathode when the PMT is illuminated.
- These e⁻ (photoelectrons) are accelerated towards a series of electrodes which are maintained at successively higher potentials with respect to the cathode.

- On striking an electrode surface, each e^- causes the emission of several secondary e^- which are in turn accelerated towards the next electrode and continue the multiplication process.

- If on average, δ secondary e^- are emitted at each electrode surface for each incident e^-, and if there are N dynodes overall, then the total current amplification factor between the cathode and anode is:

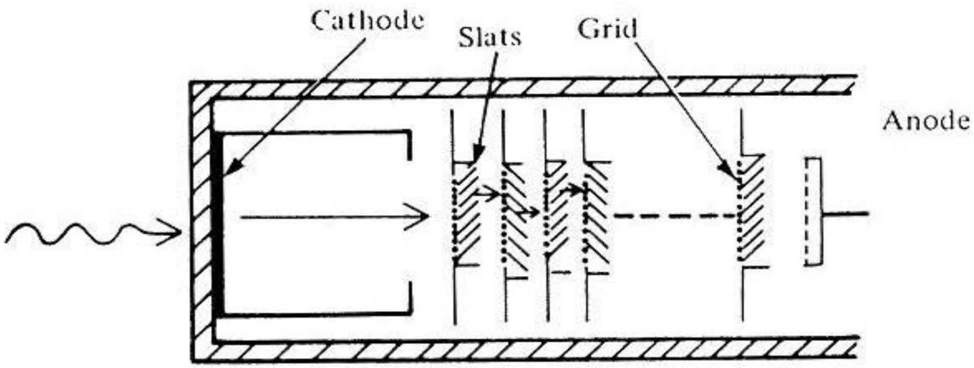
PMTs usually have high gain

$$G = \delta^N$$

e.g. $\delta = 5, \quad N = 9$

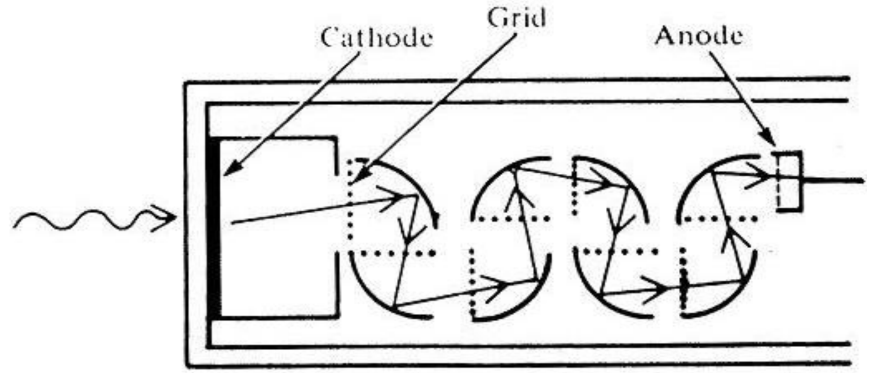
$\therefore \; G = 2 \times 10^6$

Popular PMT configurations are:



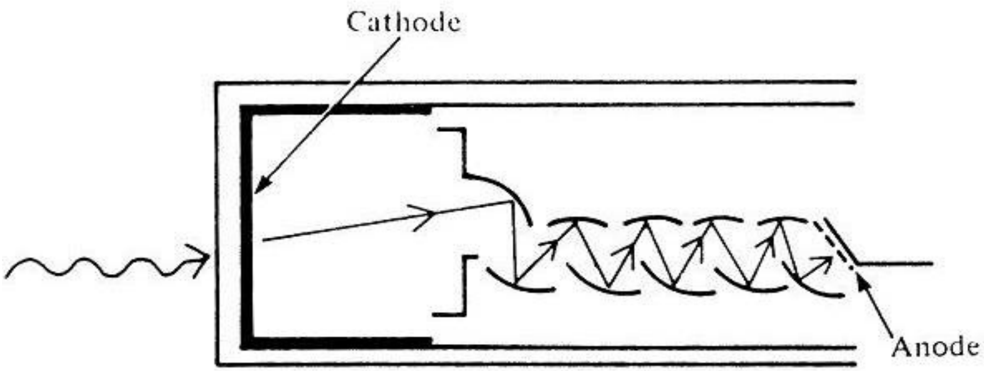
(a)

Venetian blind



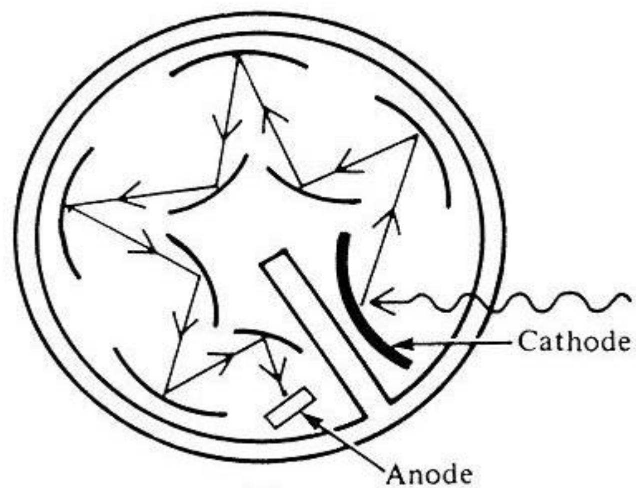
(b)

Box and grid



(c)

Linear focused



(d)

Circular focused

- Thickness of the photocathode is critical.
  - If too thick, few photons will penetrate to the e^- emitting surface.
  - If too thin, few photons will be absorbed.

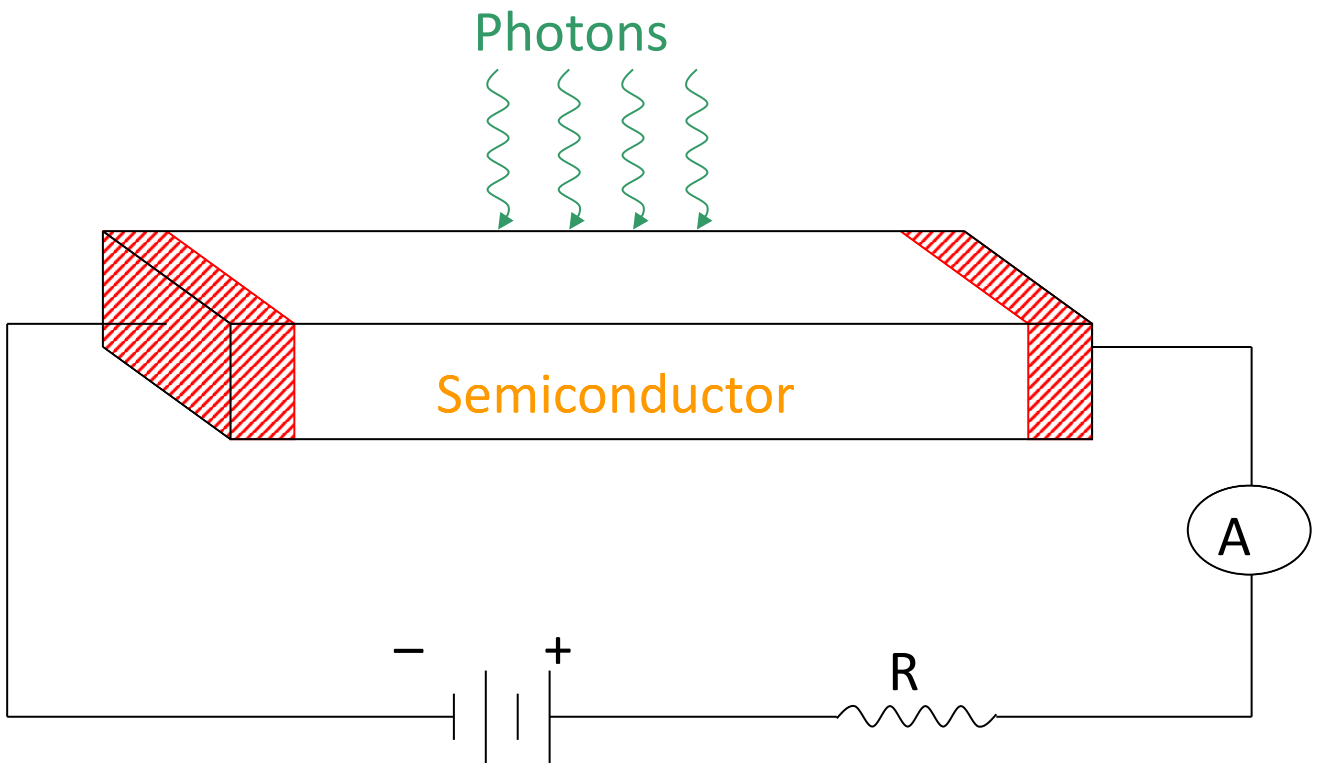
- The Venetian blind, and box and grid type are compact, inexpensive and suitable for large area cathodes. These two types have little focusing capability.

- The linear focused and circular focused types provide some degree of focusing by careful shaping and positioning of the dynodes.

- In general, the focused types have higher e^- collection efficiencies.

3.2 Photoconductive Detectors

One way of detecting the level of light is to use the change of conductivity which occurs when light frees extra carriers (electrons).



Simple photoconductor

- A photoconductor is a uniform piece of material, usually an intrinsic, n-type or p-type semiconductor whose conductivity is changed by optical generation of charges (holes and electrons).

- Photons incident on the semiconductor produce charge carriers which move (drift) in the semiconductor under the application of an electric field.

- In an n-type material for example, (1) the e^- from the donor levels can be excited into the conduction band, thus creating additional e^-, hence changing the conductivity.

- Electrons can also (2) be excited from the valence band into the conduction band, generating e^{-}–h^{+} pairs.

- In any case, the additional charges created by the photons change the conductivity of the photoconductor.

- This appears as a change in the current in the external circuit.

- The output current is linearly dependent on the intensity of the incident radiation.

- At room temperature, the impurity levels may be fully ionized, causing a drop in detector sensitivity. That is, the ratio of the change of the excess carriers over the total carriers is small.

- To prevent this, and to increase the sensitivity of the system, the detector is usually cooled (typically to –200^{o}C) during operation.

Example: HCT photoconductor detector

HCT: Mercury (Hg) Cadmium Telluride

- Mercury Cadmium Telluride (HCT) is narrow direct bandgap II-VI alloy semiconductor with a tunable bandgap (achieved by changing the alloy compositions).

- Such property makes it suitable for near-infrared (λ ~ 1 μm) to long-wave infrared (λ ~ 100 μm) applications.

- HCT is the only common material that can detect infrared radiation in both of the transparent atmospheric windows (3-5 μm) and (8-10 μm).

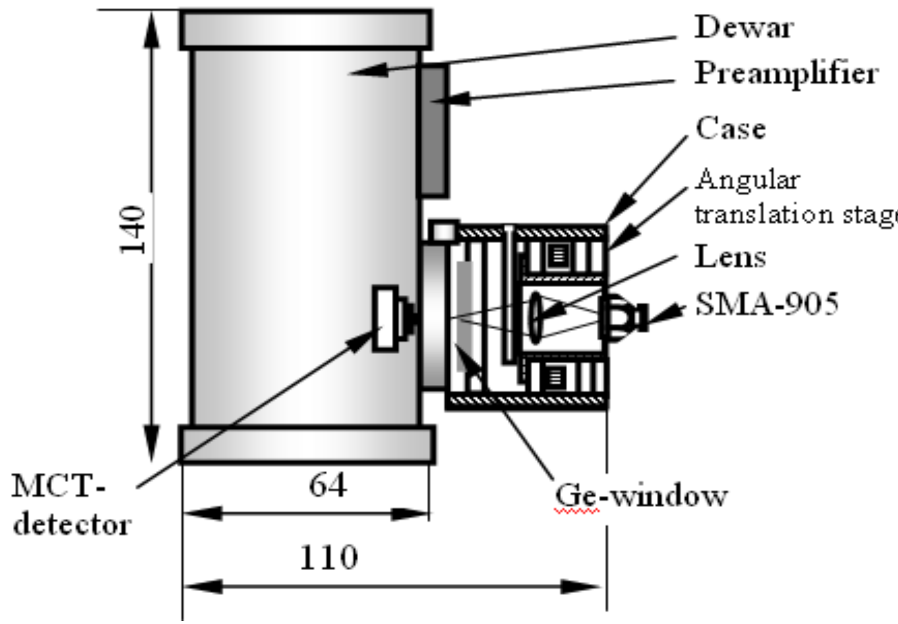
Example: HCT photoconductor detector

- Detection occurs when an infrared photon of sufficient energy kicks an electron from the valence band to the conduction band. Such electrons are then collected by an external circuit, and transferred to an electric signal.

- It finds wide applications in military field, remote sensing, and infrared astronomy.

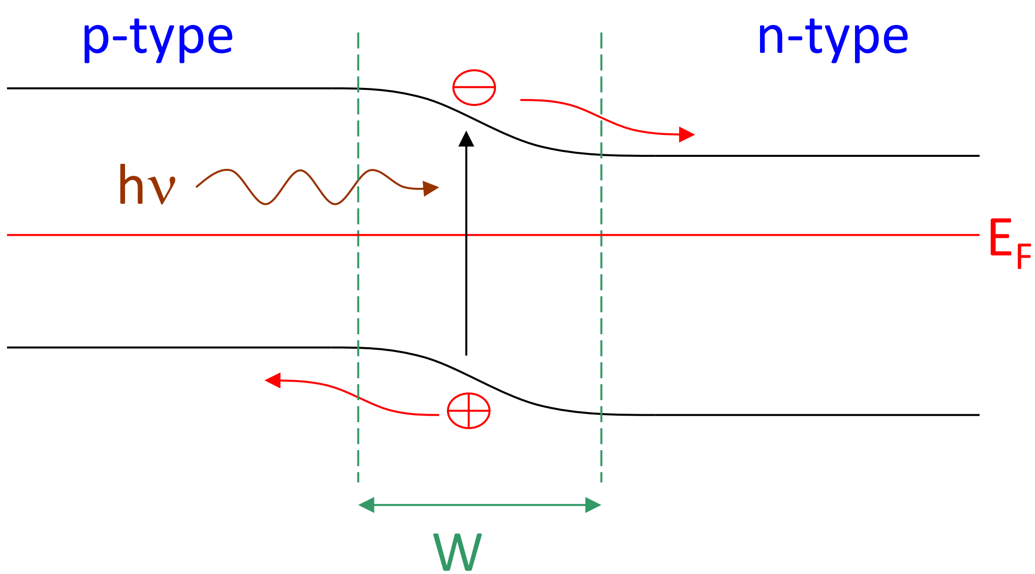
- For example, for military applications, it is used for night vision camera, and a variety of heating-seeking missiles also equipped with HCT detectors. HCT detectors are also found in majority research telescopes.

Example: HCT photoconductor detector



3.3. Junction Detectors

When a p-n junction is formed in a semiconductor material, a region depleted of mobile charge carriers is formed with a high internal electric field across it; known as the depletion region.



If an e^-–h^+ pair is generated by photon absorption within the depletion region, then the internal field will cause the e^- and h^+ to separate.

A. if the pn junction is left on open circuit, an externally measurable potential will appear between the p and n regions.

This called the photovoltaic mode of operation, which is the basis of solar cell.

B. if the pn junction is operated under a reversed biased voltage.

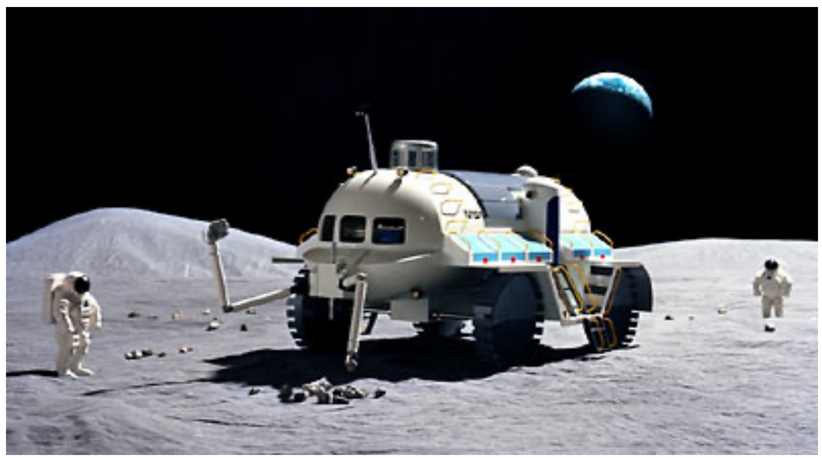
This called the photoconductive mode of operation, which is the basis of photodiode.

3.3.1 Solar Cells

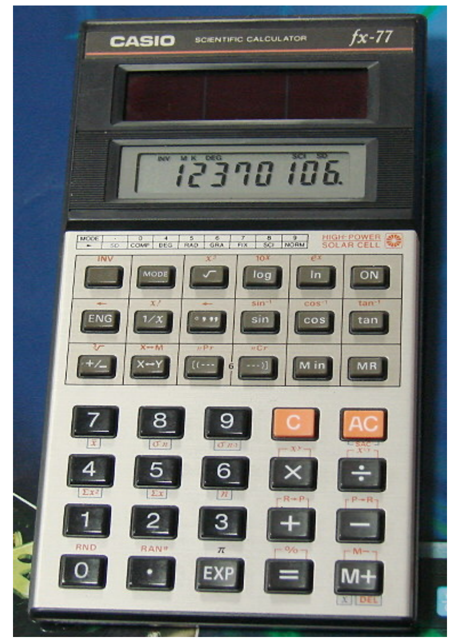
The solar cell converts photon power into electrical power, and deliver this power to load.

These devices have long been used for the power supply of satellites and space vehicles, as well as calculators.

Solar panels on the international space station absorb light from both sides.



Solar panels on the space vehicle.



Solar powered calculators

Wide applications of Solar Cells

Solar powered light house at Montague Island, a National Parks and Wildlife sanctuary on the East coast of Australia.

Home solar-powered system

solar-powered boat

Renewable energy for almost everything !

Solar-powered airplane

Solely solar-powered car by Toyota.

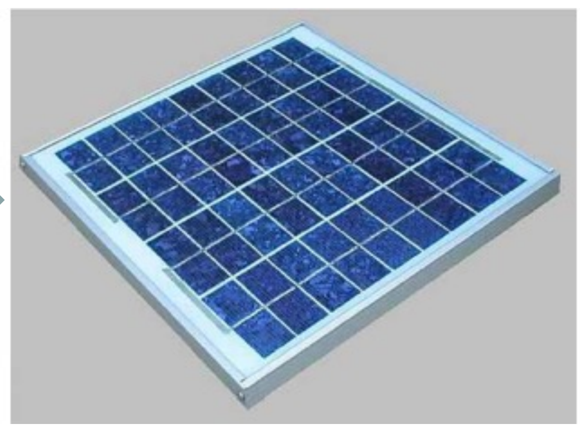
More about Solar Cells…

Silicon solar cells are widely adopted.

The cell is the basic building block, ~ 100 cm^2 in size, it generates a DC photovoltage of 0.5 – 1 volt.

The cell are connected in series into modules, and systems to generate voltage of 12V or more.

A **solar cell made from** a monocrystalline silicon wafer



A crystalline-silicon solar cell **module**

Solar cell **array**

How does it work?

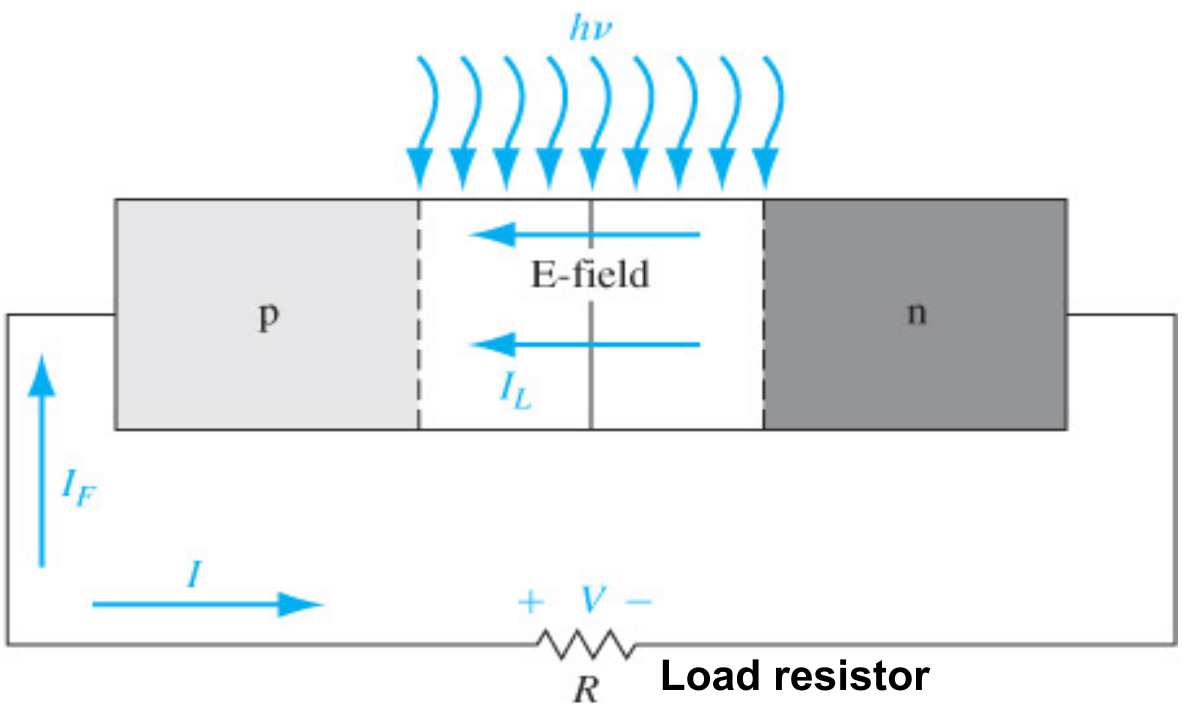


Fig.3.1 A pn junction solar cell with resistive load

We will consider the simple pn junction solar cell, shown in Fig.3.1 with uniform generation of excess carriers.

- A solar cell is a pn junction device with no voltage directly applied across the junction, see Fig.3.1. This is the basis for solar cells.

- Even with zero bias applied, an electric field exists in the space charge region, shown in Fig.3.1.

- Light illumination can create e-h pairs in the space charge region, which produces the photocurrent I_L in the reverse-biased direction.

- The photocurrent I_L produces a voltage drop (V) across the resistive load. This voltage drop is in the forward-bias direction. Positive potential on the p-type side, and negative potential on the n-type side.

- This forward-bias voltage then produces a forward-biased current ***I_F*** as shown in Fig.3.1.

- Then, in the forward-bias direction, and from Eqn. (2.6) in the laser part, the net pn junction current ***I***, is:

$$I + I_L = I_F$$

$$\Rightarrow \quad I = I_F - I_L$$

$$= \boxed{I_S\left[\exp\left(\frac{qV}{kT}\right) - 1\right] - I_L}$$

For the first-order approximation, the photocurrent ***I_L*** can be treated as a constant.

Then, it is equivalent to say, with light illumination, the IV curve (black curve, without light) is shifted down by $-I_L$.

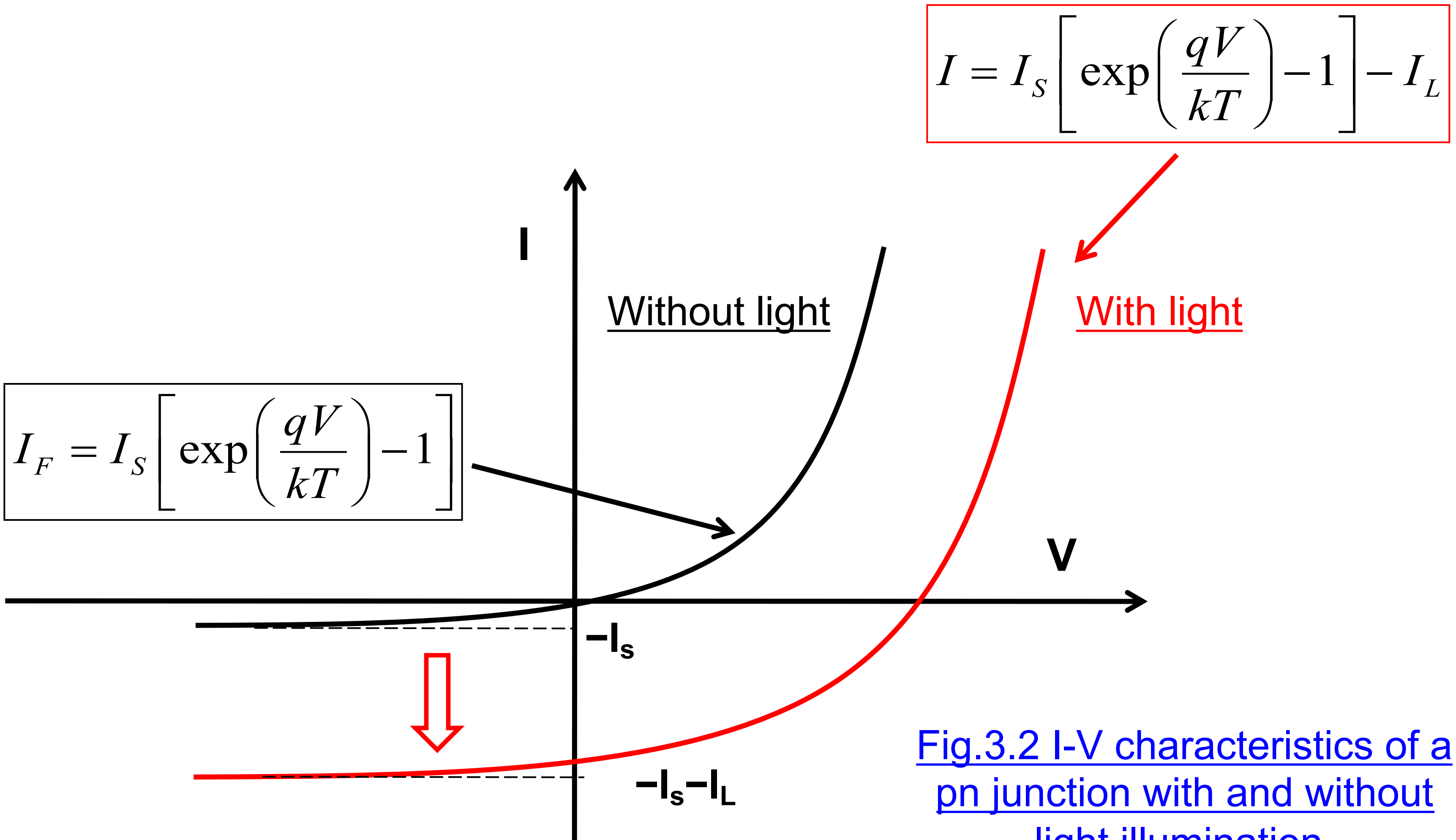


Fig.3.2 I-V characteristics of a pn junction with and without light illumination.

- As the diode becomes forward biased, the magnitude of the electric field in the space charge region decreases. But it does not go to zero or change direction.

- The photocurrent is always in the reverse-biased direction, the voltage across the diode is always in the forward-biased direction (positive value), and the net solar cell current is always a negative value.

- This region is the solar cell operational region (photovoltaic region).

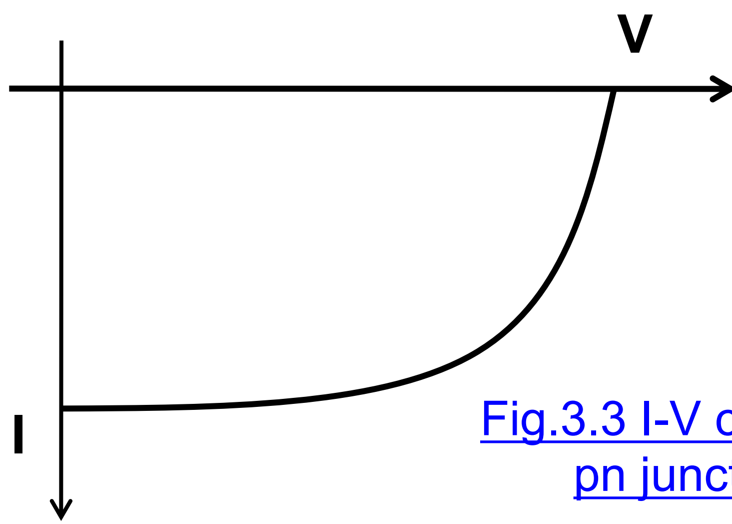


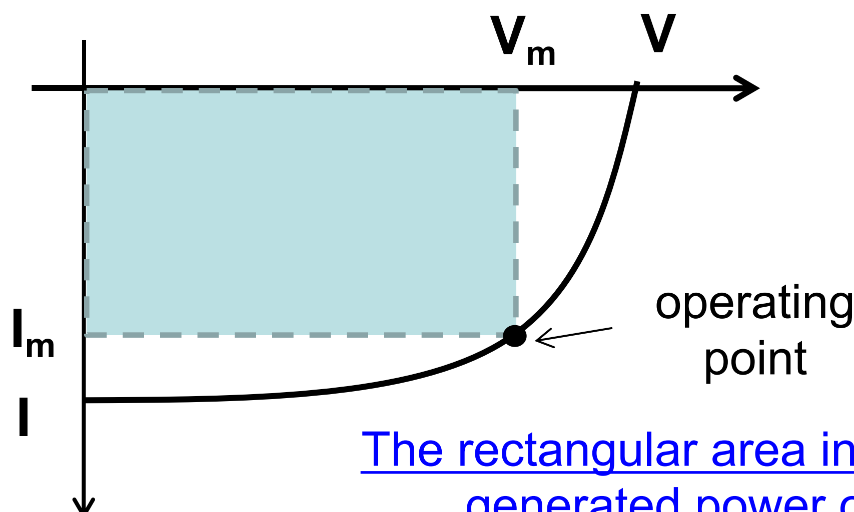
Fig.3.3 I-V characteristics of a pn junction solar cell.

Discussions:

- When the diode is illuminated with solar energy, the aim is to maximize the resulting power output from the diode.

- The output power $P = I \times V$, thus the main aim is to increase the rectangular area as indicated in the figure below.

- The photocurrent is due to the flow of excess carriers generated by the absorption of photons.



The rectangular area indicates the generated power output.

3.3.2 Photodiode

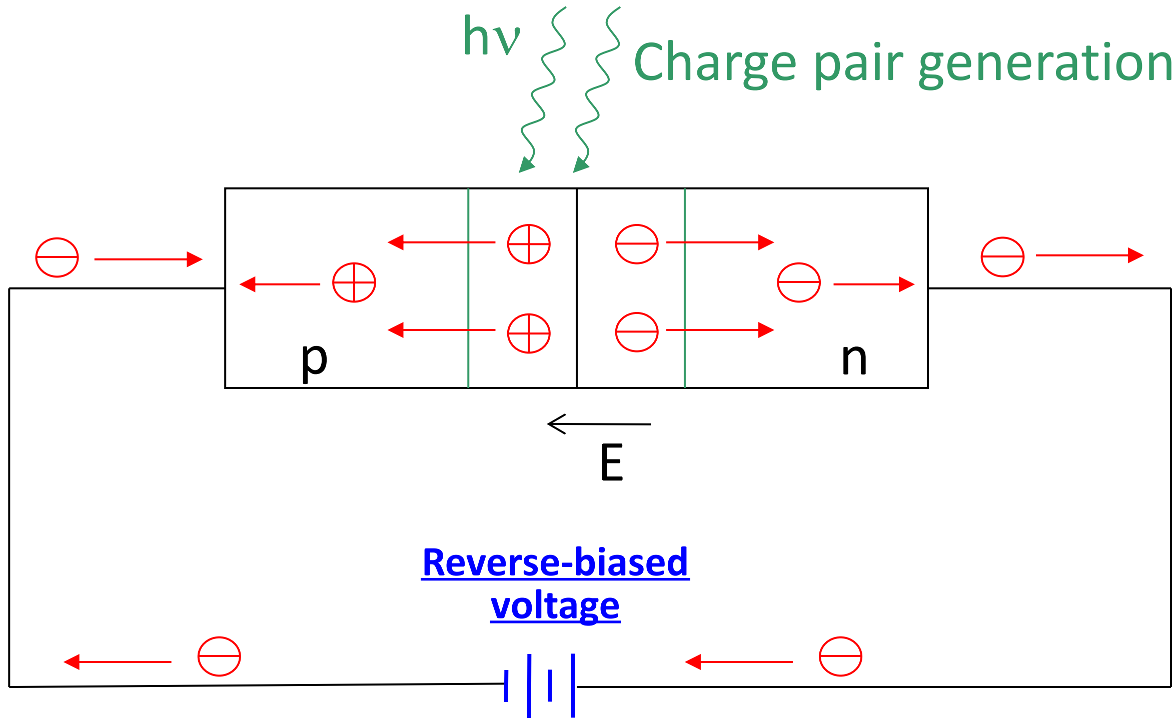


Figure 3.2 Simple p-n junction photodiode

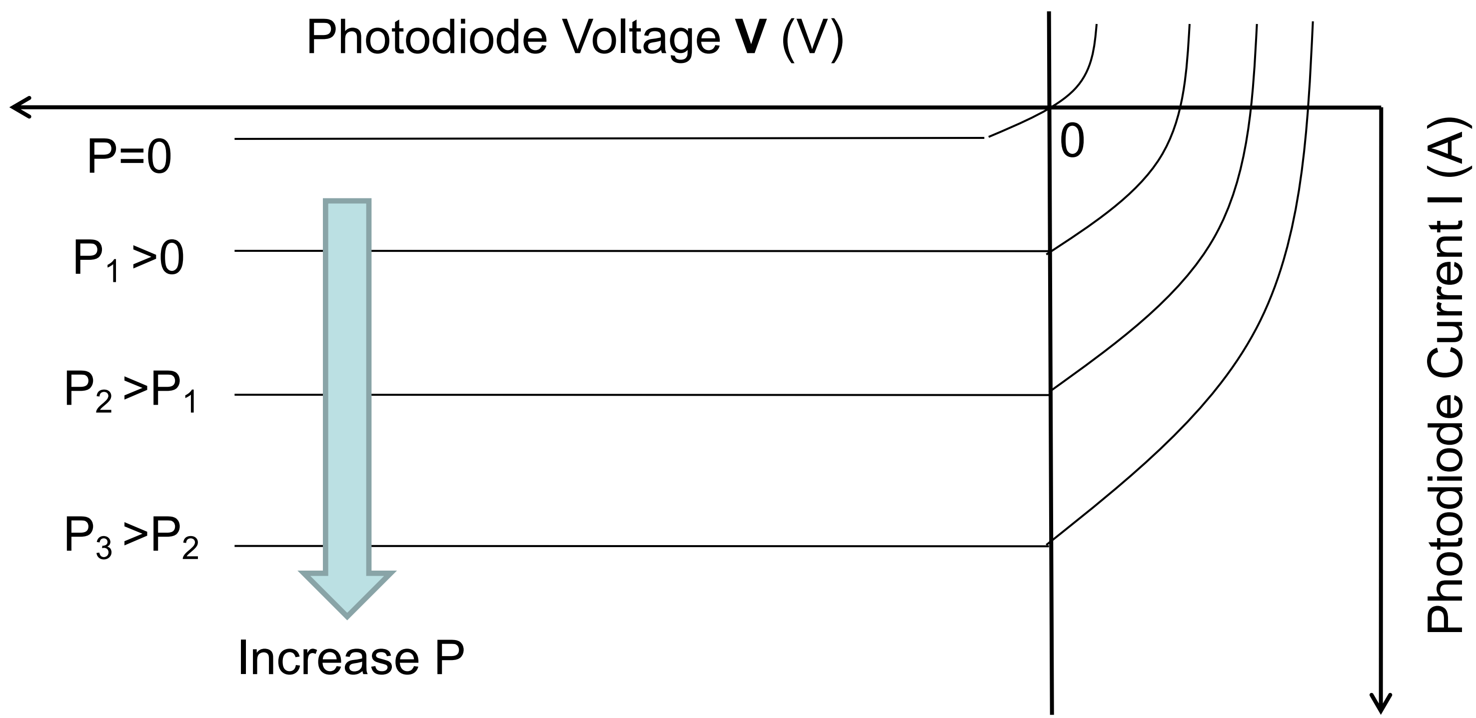
A photodiode is a pn junction diode operated in a reverse-biased voltage condition. This is called the photoconductive mode operation.

Compared to Fig. 3.1, the load resistor in a solar cell is replaced by a reverse-biased voltage source in a photodiode.

- In the photoconductive region, the photodiode voltage is always reverse-biased (negative value). The photocurrent is always in the reverse-bias direction (also negative values).

- With the increase of the input optical power, the photocurrent increases. We will show later that the photocurrent is linear proportional to the optical power.

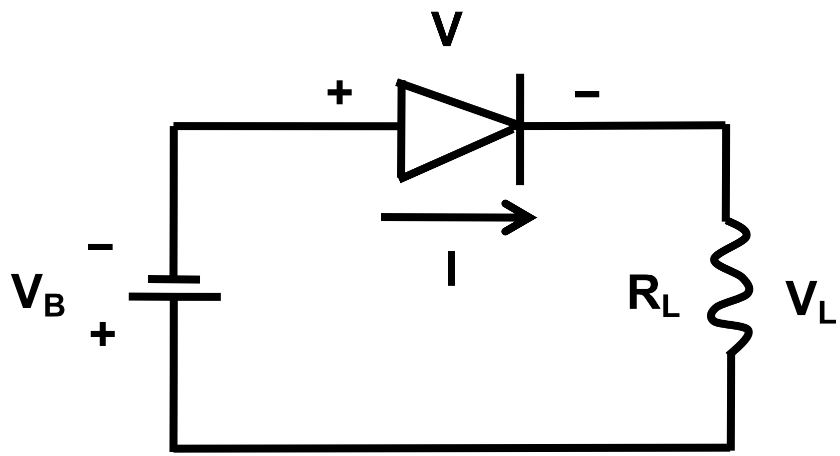
Then, the I-V characteristics v.s. optical power can be expressed in the following figure.



Photoconductive Region

Photovoltaic Region

3.3.3 Current-Voltage characteristics of photodiode



Equivalent circuit of a photodiode

V and *I* are the voltage and current across the photodiode, in the forward-bias direction. V_B is the applied external voltage, and R_L is the load resistance.

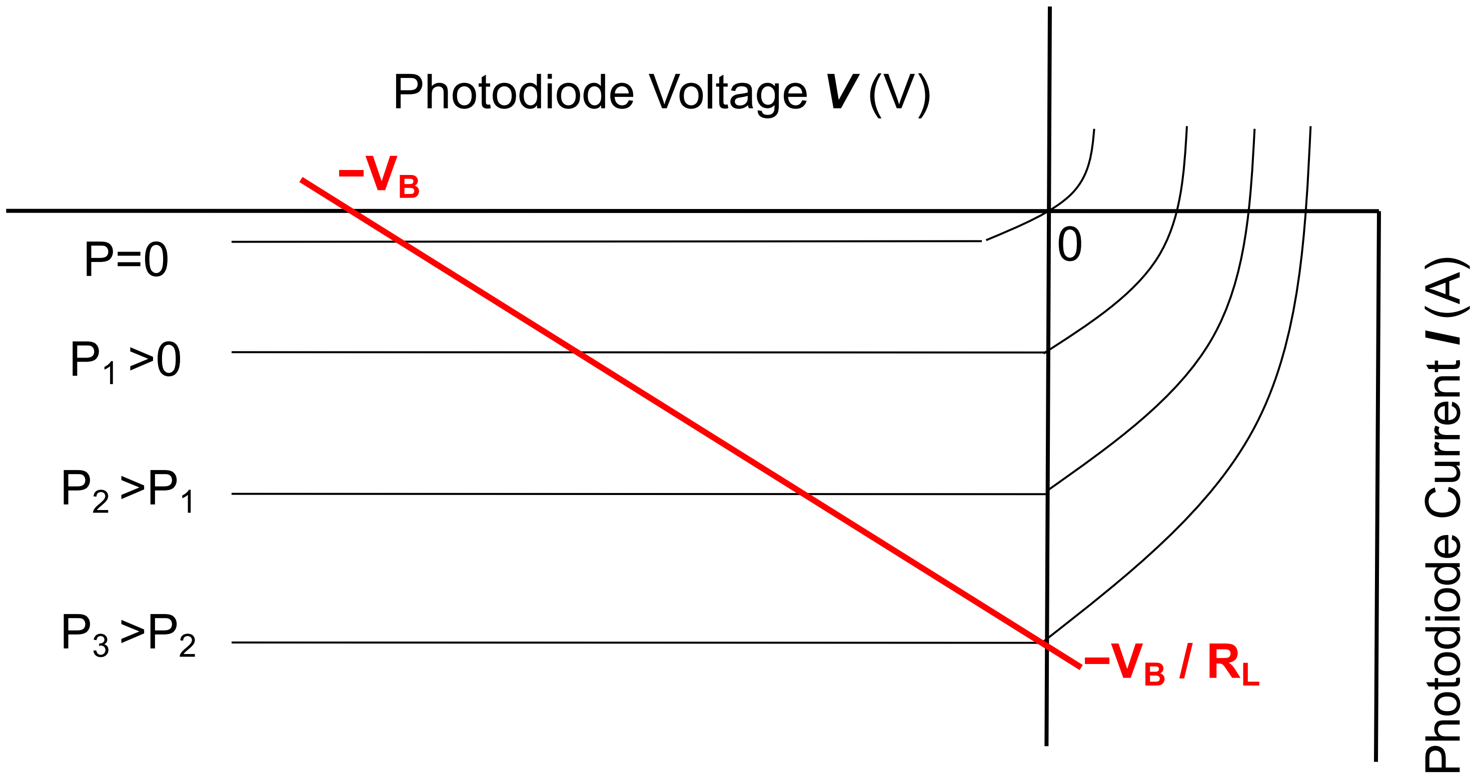
Thus, in the reverse bias condition, *V* and *I* are negative values.

Then, from this circuit, we have the I-V relations

$$\boxed{V_B + I \times R_L + V = 0} \quad \text{or} \quad \boxed{I = -\frac{V}{R_L} - \frac{V_B}{R_L}} \qquad (3.1)$$

The red line in the figure below is called the load line, showing the relation between *I* and *V* visually. It can be obtained using the two extreme conditions:

$$I = 0 \quad V = -V_B$$
$$V = 0 \quad I = -V_B/R_L$$



Which means, given any optical input power, one can determine the photodiode voltage and current based on the load line.

Example:

Given a photodiode whose external applied voltage V_B = 20V, the load resistance R_L = 1MΩ . If the measured photocurrent is −10 μA, what is the measured photodiode voltage?

V_B=20V; R_L=1MΩ; I = −10 μA

From Eqn (3.1),

$$V_B + I \times R_L + V = 0$$

Thus,

$$20V - 10 \times 10^{-6} A \times 10^{-6} \Omega + V = 0$$

$$V = -10 \quad volts$$

Summary

- Photodetectors are semiconductor devices that convert optical signals into electrical signals.

- In photoconductors, the change in conductivity of the semiconductor is due to the generation of e-h pairs by the incident photons.

- For solar cell, it is operated when zero external bias is applied. This is in the photovoltaic mode.

- Photodiodes are diodes that are reversed voltage biased. It is operated in the photoconductive mode.

3.4 General Detector Parameters

a) Responsivity

A general parameter commonly used to evaluate the performance of a detector is Responsivity.

Responsivity (R) is the ratio of the detector output current to its input optical power. Unit is typically in A/W or 1/V.

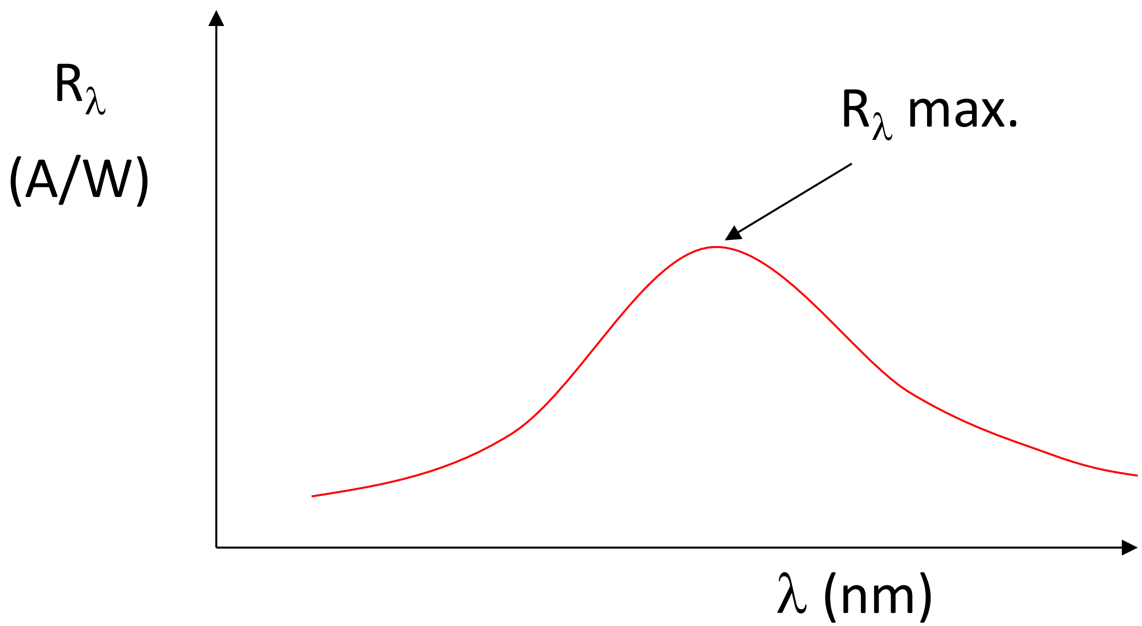
$$\boxed{I = RP = \left(\eta \frac{e}{E_g}\right) P = \left(\eta \frac{e\lambda}{hc}\right) P} \qquad (3.2)$$

$$\boxed{\eta = N_e / N_p} \qquad (3.3)$$

η is the external quantum efficiency of the detector, where N_e and N_p are the number of the generated electrons and the input photons, respectively.

- Typical values of *R* range from 0.5 A/W to 1.0 A/W.

- R varies with wavelength (λ), and should be designated R_λ. A typical R_λ *vs.* λ curve looks like:



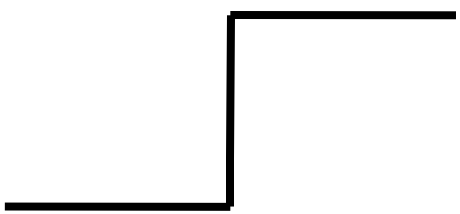
- Responsivity R is also a function of light modulation frequency.

b) Response Time

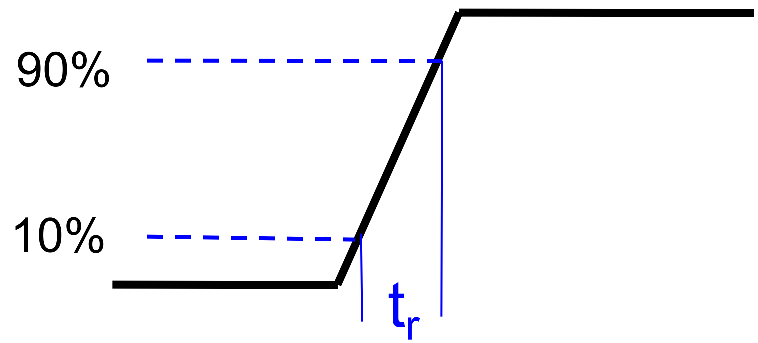
In general, most detectors respond to a step change in input with an exponential rise or fall determined by a response time or time constant (t_r).

It is defined by the time period for photocurrent intensity rising from 10% to 90%.

A detector can only give an accurate representation of an input signal pulse if its response time is short compared with the pulse width.



Input power waveform



Output current waveform from detector

c) Detector Noise

Presence of detector noise also limit the ability of the detector to detect small signals. There are several general sources of noise in a photodetector.

- **Shot noise**
  - The actual number of photon arrivals at a particular time at the photodetector is unknown, hence, the number of photogenerated electrons at any particular instance is a random variable.
  - Deviation of the actual number of electrons from the average number is known as shot noise.

- **Thermal noise**

  – Electron motion due to temperature (that is, external thermal energy) occurs in a random way. Thus, the number of electrons flowing through a given circuit at any instance is a random variable.

  – The deviations of an instantaneous number of electrons from their average value because of temperature change is called thermal noise.

- **1/f noise**

  – A photodiode generates noise in complete darkness other than dark-current noise. This noise is inversely proportional to frequency.

  – This is called 1/f noise current.

Other detector parameters are:

- Bandwidth
- Temperature range
- Dynamic range
- Modulation frequency

Example:

Given a photodiode whose external applied voltage V_B = 20V, the load resistance R_L = 1MΩ . The responsivity of this photodetector is 0.5 A/W, if the input optical power is 20 μW, what is the measured photodiode voltage?

V_B=20V; R_L=1MΩ; P = 20 μW; and R = 0.5 A/W

From Eqn (3.2) $$|I| = RP = 0.5A/W \times 20\mu W = 10\mu A$$

From Eqn (3.1) $$V_B + I \times R_L + V = 0$$

Thus, $$20V - 10 \times 10^{-6} A \times 10^{-6} \Omega + V = 0$$

$$V = -10 \quad volts$$

Summary

- The absorption and emission of light (photons) in semiconductors lead to the study of a general class of devices, called optoelectronics.

- The photon absorption process has been discussed.

- Photodetectors are semiconductor devices that convert optical signals into electrical signals.

- In photoconductors, the change in conductivity of the semiconductor is due to the generation of e-h pairs by the incident photons.

- Photodiodes are diodes that are reversed voltage biased.

Thank you for listening!

You made it!