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

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M2U2 Plan

1. p-n junction diode – forward and reverse conditions

2. Solar cell

M2U2 Plan

1. p-n junction diode – forward and reverse conditions
2. Solar cell

Optoelectronics

- Electronics is the study of controlling electrical signals.
- Any electrical signal is characterized by its current and voltage properties.
- Electronics is broadly classified into three areas –
  - **Microelectronics** – here we study switching electrical signals, which is useful to represent binary logic. This is necessary for computation. This is also called **digital electronics**. Since power is not a concern, signals have currents of the order of microamperes (hence the name microelectronics) and voltages of the order of few volts
  - **Power electronics** – here we study amplifying electrical signals to transfer energy. This is necessary for energy requirements of society as it is well known that electrical energy is efficient way of energy transfer. Signals have currents of the order of hundreds of amperes and voltages of the order of thousands of volts. This is also called **analog electronics**.
  - Opto-electronics [1] – here we harness the interaction between electron and photon. The advantages of light like its high velocity, free source of energy (Sun light), are combined with the advantages of electron like its easy manipulation to develop devices of specific requirements.

[1] Opto-electronics is a combination of optics and electronics

Opto-electronic devices

Definition

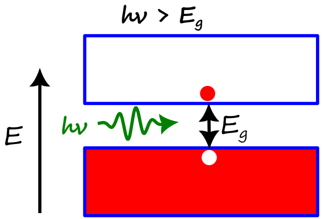
- A electrical device is a electrical component with a characteristic or signature $I - V$ behaviour.
- An opto-electronic device is an electrical device whose $I - V$ characteristic is determined by the interaction of light.

- The interaction of light with opto-electronic devices is of two-types –
  - optical absorption
  - Radiative recombination
- The opto-electronic devices based on optical absorption are
  - solar cell
  - photo-diode
- whereas the opto-electronic devices based on radiative recombination are
  - Light Emitting Diode (LED)
  - Laser Diode

Optical absorption

Definition

- Optical absorption is defined as the process of absorption of photon that leads to the generation of charge carriers.
- The generated electron-holes pairs are additional to the already present. Hence they are called **excess charge carriers**.



- In semiconductors, photon with energy greater than energy band gap E_g, it is absorbed and leads to generation of electron-hole pair.

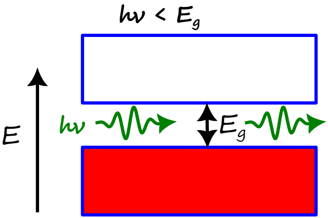
Key Insight

In optical absorption, the photon is the source of energy.

Optical transparency

Definition

Optical transparency is defined as the process of propagation of photon without the generation of charge carriers.



- If the photon energy is less than energy band gap, it is not absorbed and instead propagates through the semiconductor.

Problem

Why common glass is transparent to visible light. [*Hint:* $E_g^{\mathrm{SiO_2}} = 9\,\mathrm{eV}$.]

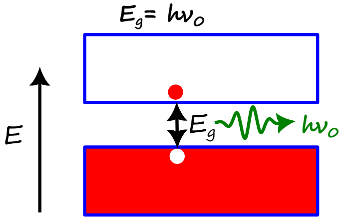
Key Insight

In optical transparency, the photon is not absorbed.

Radiative recombination

Definition

Radiative recombination is defined as the process of generation of photon upon combination of excess charge carriers.



- In semiconductors, electron-hole pair recombine to form the covalent band and release the energy equal to energy band gap as a photon.

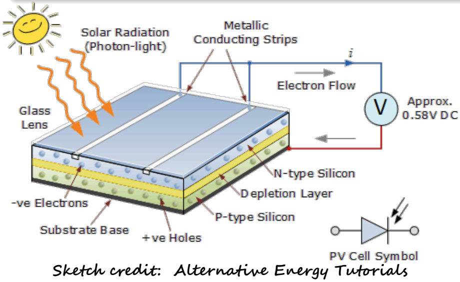
Key Insight

In radiative recombination, the charge carriers are the source of energy.

Solar cell – construction

Definition

- Solar cell, also technically called the **photovoltaic cell** is an opto-electronic device based on pn junction that can generate electrical power when illuminated.
- A collection of cells in series and parallel combination is called a solar panel



Sketch of solar panel. Sketch taken from Alternative Energy Tutorials

- The main aim of solar cell operation is to convert solar energy into electrical energy.
- Electrodes are deposited on both sides of junction. The top metal electrode is in the form of metal grid with fingers, which permits sunlight to pass through it.

Solar cell – working principle

Definition

The working principle of solar cell involves three processes–

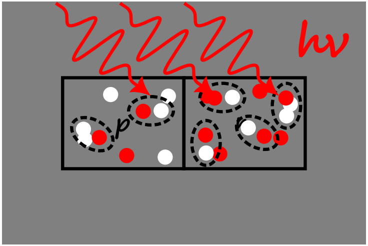
1. Generation of **excess** electron-hole pairs upon the illumination of light, and
2. Separation of electrons from holes **before** radiative recombination due to the built-in electric field.
3. Generation of voltage due to **accumulation** of excess separated charge carriers at the ends of the pn junction

- The solar cell pn junction is operated without bias i.e. zero bias.
- Upon illumination with photons of suitable energy, the photon are absorbed through the surface area. The covalent bonds of the lattice are broken releasing the free electrons and holes into the conduction band and valence band respectively.

Problem

A material has bandgap of 5 eV*. Can it be used as solar cell material?*

Working principle – 1. Excess electron-hole pairs

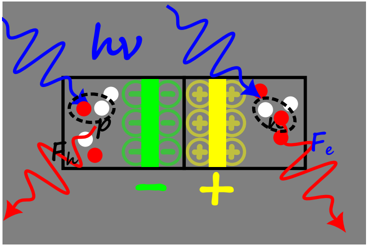


- Upon illumination with photons with energy greater than the band gap, optical absorption takes place.
- This results in the generation of excess electron-hole pairs throughout the device.

Key Insight

Optical absorption generates excess electron-hole pairs.

Working principle – 2a. Illumination away from depletion region

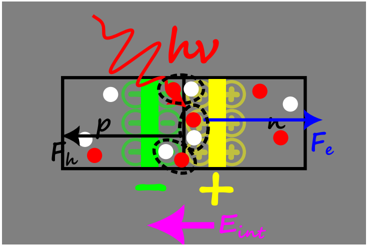


- In the neutral regions far away from the depletion region, the excess charge carriers again undergo radiative recombination and release photons.

Key Insight

Away from depletion region, generation of excess charge carriers is followed by radiative recombination.

Working principle – 2b. Illumination at depletion region



- At the depletion region also, the excess charge carriers are generated.
- However, before they undergo radiative recombination, the built-in electric field sweeps them out of the depletion.

Key Insight

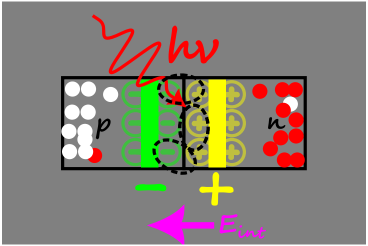
At the depletion region, separation of excess charge carriers prevents radiative recombination.

Working principle – 3. Photo-voltage

Definition

Photovoltage, also called photo e.m.f. [a] is the voltage appearing across the device due to the separation of excess charge carriers.

[a] e.m.f. stands for electro motive force



- The swept excess electrons and holes **accumulate** at the n region and p region edges respectively
- The accumulation of positive charge at the p-edge and negative charge at the n-edge leads to the generation of a voltage V_L.
- Since the source of voltage is illumination of photons, it is called **photovoltage**.

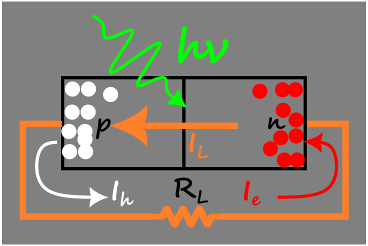
Key Insight

The photovoltage forward biases the pn junction.

Solar cell – Photocurrent

Definition

Photocurrent is the current flowing through the solar cell when it is connected across a load resistance.



- Solar cell can be used to drive currents through loads.
- Upon connection to a load resistance R_L, the accumulated holes at the p-edge flow anti-clockwise whereas the accumulated electrons at the n-edge flow clockwise.
- Clockwise flow of holes leads to clockwise hole current I_h whereas anti-clockwise flow of electrons leads to clockwise electron current I_e.
- The net current I_L is called photocurrent [2] and is given by $I_L = I_h + I_e$.

Key Insight

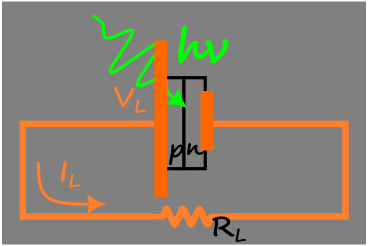
The photocurrent flows from n to p region.

[2] suffix L stands for light and **not load**.

Solar cell – Power source

Definition

Photocurrent is the current flowing through the solar cell when it is connected across a load resistance.

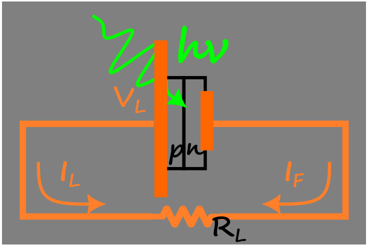


- The photo-voltage drop V_L is from p-n region.
- The photo-current I_L is from n-p region.
- Since the voltage drop is opposite the current direction across the solar cell, the power dissipated is negative.
- In other words, the **power generated is positive** and solar cell acts like a battery.

Key Insight

Solar cell under illumination acts as a power source.

Solar cell – Load biasing



- However, the photo-voltage also forward biases the p-n junction.
- This results in a forward bias current I_F in the anti-clockwise direction.
- The net current through the load resistance is

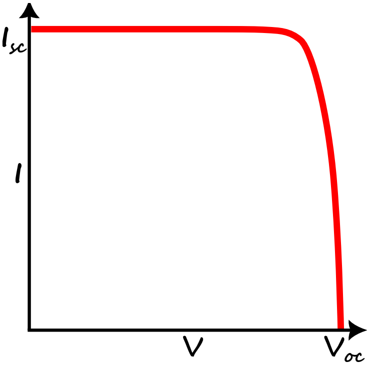
$$I_{net} = I_L - I_F$$

- Though the solar cell is operating under zero bias, upon connection to load, the load forward biases the pn junction.

Key Insight

Load forward biases the illuminated solar cell.

Solar cell – $I - V$ characteristics



- From Kirchoff voltage law, the photo-voltage is given by

$$V_L = I_L R_L$$

- From diode $I - V$ characteristics, the forward current I_F is given by

$$I_F = I_s \left[\exp\left(\frac{eV_L}{k_B T} \right) - 1 \right]$$

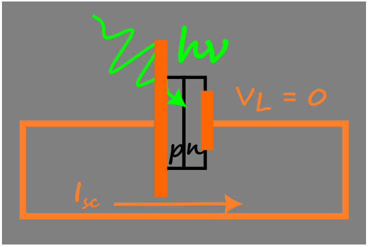
- Therefore the solar cell $I - V$ characteristics is given by

$$\begin{aligned} I_{\text{net}} &= I_L - I_F \\ &= I_L - I_s \left[\exp\left(\frac{eV_L}{k_B T} \right) - 1 \right] \end{aligned}$$

Solar cell – short circuit current

Definition

Short circuit current is defined the current through solar cell when it is short circuited or zero load resistance is connected.



- When the load resistance is zero, the solar cell generates maximum current. This condition is called short circuit condition.
- At short circuit condition, $R_L = 0$, so the voltage drop across load is zero

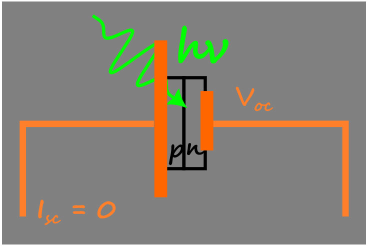
$$V_L = I_L R_L = 0$$

- The net current is the short circuit current I_{sc} and is given by

$$\begin{aligned} I_{sc} &= I_L - I_s\left(e^0 - 1\right) \\ &= I_L \end{aligned}$$

Definition

Open circuit voltage is defined the voltage across solar cell when it is open circuited or infinite load resistance is connected.



- When the load resistance is infinite, the solar cell generates maximum voltage. This condition is called open circuit condition.
- At open circuit condition, $R_L = \infty$, so the current is zero

$$I_L = \frac{V_L}{R} = 0$$

- The photovoltage is the open circuit voltage V_{oc} and is given by

$$I_L - I_s\left[\exp\left(\frac{eV_{oc}}{k_B T}\right) - 1\right] = 0 \Rightarrow I_L = I_s\left[\exp\left(\frac{eV_{oc}}{k_B T}\right) - 1\right]$$

$$\exp\left(\frac{eV_{oc}}{k_B T}\right) = \frac{I_L}{I_s} + 1 \Rightarrow V_{oc} = \left(\frac{k_B T}{e}\right)\ln\left(1 + \frac{I_L}{I_s}\right)$$

Solar cell – Power optimization

- A solar cell is a power generating device. However, at the limiting conditions, the power generated is zero.
- At short circuit condition, the power generated is

$$P_{sc} = V_{sc} I_{sc} = 0 \cdot I_{sc} = 0$$

- Similarly, at open circuit condition, the power generated is

$$P_{oc} = V_{oc} I_{oc} = V_{oc} \cdot 0 = 0$$

- The electrical power generated is a function of drop across load resistance $V = IR_L$ and is given by

$$P = V \cdot I = V \cdot \left[I_L - I_s \left\{ \exp\left(\frac{V_L}{V_t} \right) - 1 \right\} \right],$$

where

$$V_t = \frac{k_B T}{e}$$

is the thermal voltage associated with thermal energy.

Solar cell – Power optimization

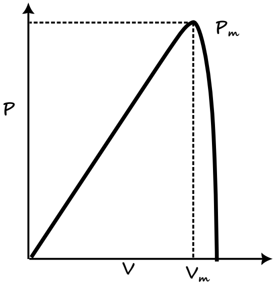
- To maximize P with respect to V, we need to find V_m, the voltage across the load when power is maximized. This is given by

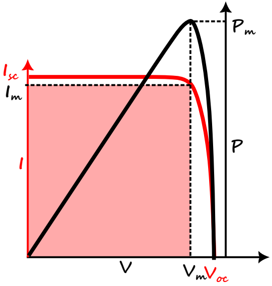
$$
\begin{aligned}
\left.\frac{\mathrm{d}P}{\mathrm{d}V}\right\|_{V_m} &= 0, \\
\Leftrightarrow I_L - I_s\left\{\exp\left(\frac{V}{V_t}\right) - 1\right\} - I_s\frac{V}{V_t}\exp\left(\frac{V}{V_t}\right)\Bigg\|_{V_m} &= 0, \\
\Leftrightarrow I_L + I_s - I_s\exp\left(\frac{V_m}{V_t}\right)\left(1 + \frac{V_m}{V_t}\right) &= 0, \\
\Leftrightarrow \left(1 + \frac{V_m}{V_t}\right)\exp\left(\frac{V_m}{V_t}\right) &= \frac{I_L + I_s}{I_s}.
\end{aligned}
$$

$$
\therefore \left(1 + \frac{V_m}{V_t}\right)\exp\left(\frac{V_m}{V_t}\right) = 1 + \frac{I_L}{I_s}
$$

- The value of V_m can be determined by trial and error.

Solar cell – $P - V$ characteristics



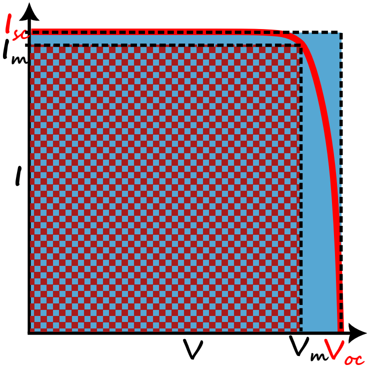


- The power generated in solar cell is completely consumed in the load resistance.
- If the photocurrent at V_m is I_m then the maximum power is

$$P_m = V_m I_m$$

- In $P - V$ curve, this is represented as as (V_m, P_m).
- The $I \& P - V$ curves show the mappings of $I - V$ and $P - V$ curves. In $P - V$ curve, maximum power is represented as as red rectangle.

Output electrical power – Fill factor



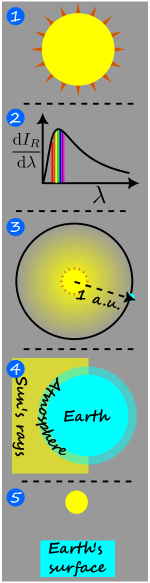
- From the $I - V$ characteristics of solar cell, it is evident that the maximum current generated cannot exceed the short circuit current I_{sc} and the maximum voltage generated cannot exceed the open circuit voltage V_{oc}.
- The theoretically possible maximum power that can be generated should be less than the product of I_{sc} and V_{oc}. In the $I - V$ curve, this is represented as blue rectangle.
- The ratio of experimentally possible maximum power to theoretically possible maximum power is called Fill Factor and is given by

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}}$$

Key Insight

Fill factor is a material property.

Input optical power – Solar irradiance



Definition

Solar irradiance is the solar power incident on the Earth's surface per unit area.

1. Sun as blackbody – Since sun is the major source of light energy, the input power is determined by the properties of sun.
2. Planck's blackbody radiation law – Sun is emitting photons of various wavelengths per unit time. Each photon with a given wavelength has an energy given by the Planck's law.
3. Sun -Earth separation – However, we are only receiving a fraction of the Sun's power.
4. Solar irradiance outside atmosphere – It is $1360\,\mathrm{W\,m^{-2}}$.
5. Solar irradiance at Earth's surface – It is nearly $1000\,\mathrm{W\,m^{-2}}$ at noon due to losses in atmosphere.

Practical considerations – Solar cell efficiency

Definition

Conversion efficiency is defined as ratio of output electrical power to input optical power.

- To harness solar energy, the following practical limitations need to be considered.
- All the power cannot be harnessed as the optical absorption by a solar cell has a cut off wavelength due to the energy band gap.
- The photons with energy greater than energy band gap also generate electron-hole pairs. However, the difference of photon energy and band gap is dissipated as heat.
- The sum total of all these considerations is that a fraction of incident optical power is converted into electrical power and is given by the conversion efficiency η as

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100$$

Solar cell – applications

Chandrayaan 2 misson at glance [Click for video]

Image credits: ISRO

Problem

From the data in above figure, estimate the conversion efficiency of material used in Pragyan rover.

Problems on solar cell

Problem

A silicon solar cell under standard test conditions has $I_{sc} = 35\,\mathrm{A\,cm^{-2}}$, $V_{oc} = 0.60\,\mathrm{V}$, *Fill Factor (FF) = 0.80. The incident power is* $100\,\mathrm{mW\,cm^{-2}}$. *Calculate the efficiency of the cell.*

Problem

A solar panel has an efficiency of $18\,\%$ *under standard irradiance of* $1000\,\mathrm{W\,m^{-2}}$. *What panel area is required to generate* $200\,\mathrm{W}$ *of electrical power?*

Problem

Each silicon solar cell has an open-circuit voltage of $0.60\,\mathrm{V}$ *under illumination. How many such cells are needed in series to obtain an open-circuit voltage of approximately* $18\,\mathrm{V}$*?*

Problems on solar cell (Fun problems)

Problem

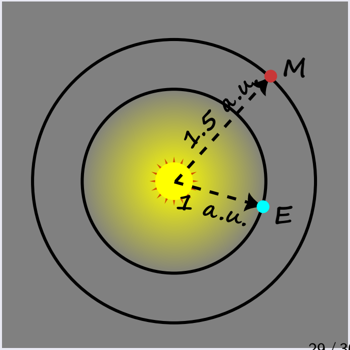
An alien ship crashlanded onto Earth's surface. From the debris, the solar panel used for power generation is found to have a band gap of 5 eV. *Estimate the temperature of the alien Sun. [Hint: Solve below problem.]*

Problem

Find the surface temperature of our Sun. For our sun, λ_{max} *of blackbody body radiation spectrum is* 510 nm *(green), i.e., the greatest part of its radiation lies within the visible region of the spectrum. [Hint: Wien's displacement law* ($\lambda_{max} T = 2.898 \times 10^{-3}$ m K.*]*

Problem

The power rating of solar panels of Pragyan rover is 50 W. *If ISRO is successful to transport it onto Mars, what will be its Martian power rating?*



Tough problems

Problem

The reverse saturation current density for a solar cell pn junction is $J_s = 3.6 \times 10^{-11}\,\mathrm{A\,cm^{-2}}$. *What is the photocurrent density required to produce open circuit voltage of* $0.60\,\mathrm{V}$*?*

Problem

For the same solar material used in above problem, the fill factor is 0.8. What is the maximum power per unit area generated if the photocurrent density is $150\,\mathrm{mA\,cm^{-2}}$*?*