The pn junction is very narrow because of high doping. Connections are made from bottom P-layer(anode) and top N-layer (cathode) using metal contacts. An antireflection coating is provided on the top layer to prevent loss of light by reflection.

Working

Solar cell is a p-n junction diode under zero bias.

At zero bias, free electrons flow from n-region to p-region. These free electrons will recombine with holes in the p-region and become bound electrons. When solar radiation are incident at pn junction, more electron-hole pairs are formed producing an electric current in the external circuit. Thus solar energy is converted into electrical energy. Total output voltage can be increased by connecting a number of solar cells in series. A solar panel is an array of a number of solar cells connected together.

2.7.1 V-I characteristics of Solar Cell

Consider a solar cell connected with an ammeter, voltmeter and a load resistance as shown in figure (2.23) and it is exposed to sunlight.

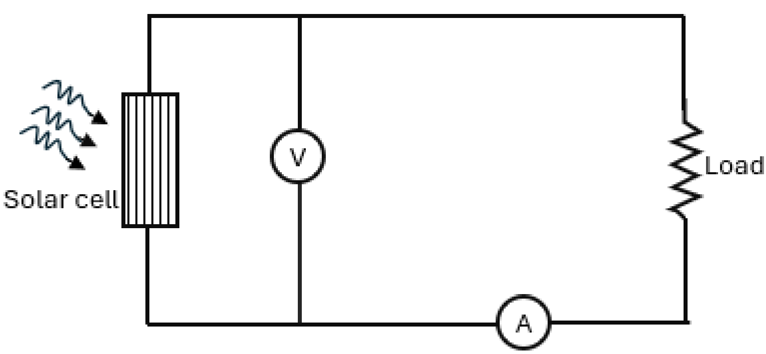

Figure 2.23: V-I characteristics of solar cell

If there is no load connected with the solar cell, an open circuit voltage V_{oc} is produced without a current. *The open-circuit voltage,V_{oc}*, is the maximum voltage available from a solar cell,and this occurs at zero current.

The open circuit voltage corresponds to the amount of forward bias on the solar cell junction due to illumination.

If the terminal of the solar panels are shorted together, the short circuit current I_{sc} flows without an output voltage. (*Short circuit current* is the current through the solar cell when the voltage across the solar cell is zero. The short-circuit current is due to the generation and collection of light-generated carriers.The short-circuit current is the largest current which may be drawn from the solar cell. The short circuit current depends on various factors like area of the solar cell, the power of incident light source etc. In both the cases, no power is delivered by the solar cell.

When a load is connected, a voltage is developed, a current flows in the circuit and there is an output power. Let V_m and I_m be the voltage and current corresponding to the maximum power. Maximum power is the condition under which solar cell generates its maximum power P_m. The power of the solar cell equals to the product of the diode voltage and current.

$$P_m = V_m I_m$$

V-I characteristics of solar cell is given in the figure 2.24.

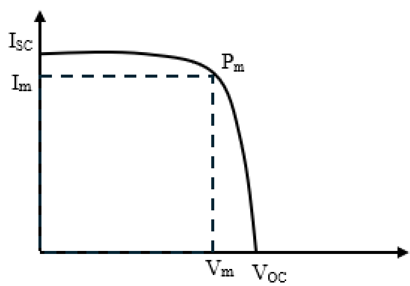

Figure 2.24: V-I characteristics of solar cell

2.7.2 Efficiency of Solar Cell

Efficiency is defined as the ratio of energy output from the solar cell to input energy from the sun.

The efficiency is the most commonly used parameter to compare the performance of one solar cell to another. Efficiency of a cell also depends on the solar spectrum, intensity of sunlight and the temperature of the solar cell.

$$\text{Efficiency, } \eta = \frac{\text{Electrical power delivered}}{\text{Solar power incident}}$$

$$\eta = \frac{V_m I_m}{P_{in}}$$

$$\text{Also,} \quad \eta = \frac{P_{max}}{\text{light intensity} \times \text{area of the solar cell}}$$

Fill factor (FF) is the ratio of the maximum power from the actual solar cell to the maximum power from a ideal solar cell.

$$FF = \frac{\text{Maximum power from real cell}}{\text{Maximum power from ideal cell}} = \frac{V_m I_m}{V_{oc} I_{sc}}$$

Then efficiency can be written as

$$\eta = \frac{V_{oc} I_{sc} \times FF}{P_{in}}$$

2.7.3 Stringing of Solar Cells to Solar Panel

Stringing of solar cells to form a solar panel refers to the process of connecting individual photovoltaic (PV) cells in a specific configuration to create a solar module or panel. This process is crucial because individual solar cells generate relatively low voltage and current, and by stringing them together, we can increase the overall power output of the solar panel.

To achieve higher voltage and current outputs, solar cells are connected in series and parallel configurations, depending on the desired output power. Stringing can help optimize the overall efficiency of the solar panel by reducing losses due to resistive elements.

Series Connection: Solar cells are connected end-to-end, where the positive terminal of one cell is connected to the negative terminal of the next cell. This increases the voltage while the current remains the same.

Parallel Connection: Solar cells are connected such that their positive terminals are connected together, and their negative terminals are connected together. This increases the current while the voltage remains the same.

Advantages

Solar cells offer lots of benefits, making them a popular choice for renewable energy solutions. Here are some key advantages.

- **Renewable energy source:** Solar energy is abundant and freely available, ensuring a long-term, sustainable energy source.
- **Clean energy:**Solar energy produces no harmful emissions, reducing greenhouse gas contributions which causes climate change.
- **Low maintenance:** Solar panels require minimal maintenance, such as occasional cleaning, making them a hassle-free energy solution.
- **Versatility:** Solar cells can be installed on various surfaces, including rooftops, ground mounts, and even portable systems for camping or off-grid applications.

Applications

Solar cells, or photovoltaic cells, convert sunlight into electricity and have a wide range of applications across different fields.

- **Telecommunication stations:** Solar cells power remote communication towers, weather stations, and satellites where conventional power sources are impractical.
- **Solar-powered vehicles:** Solar cells are integrated into cars, boats, and even airplanes to supplement power or, in some cases, serve as the primary energy source.
- **Satellites:** Solar panels power satellites, space stations, and spacecraft, providing a continuous energy supply in space where traditional fuels are impractical.
- **Solar water pumps:** In areas where grid electricity is unavailable, solar cells power water pumps for irrigation and livestock.
- **Solar farms:** Large-scale solar power plants use vast arrays of solar cells to produce electricity that is fed into the grid, helping to power cities and industries.
- **Rural electrification:** Solar cells are used to provide electricity to remote villages in developing countries.

2.8 Light Emitting Diode (LED)

LED is a heavily doped pn junction diode of suitable materials that emits light when it is forward biased. The symbol of LED is given in Figure 2.25.

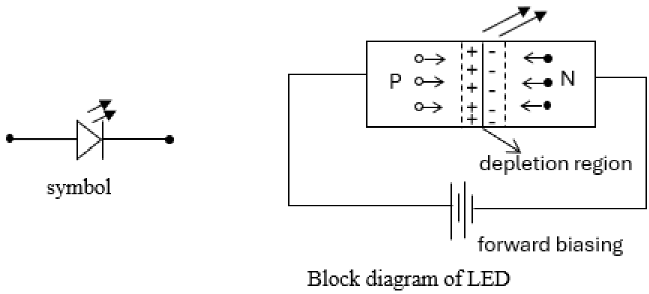

Figure 2.25: Symbol and block diagram of LED

During forward bias, free electrons from conduction band of n region combines with the holes from valence band of p region crossing the barrier at p-n junction. During recombination, electromagnetic radiation is emitted with energy equal to band gap energy of semiconducting material. Some semiconducting materials like GaAs, GaP, GaAsP etc have band gap energy ΔE_g in the range of about 1.5 – 3.0 eV, which provides radiation in the visible/ infrared region.

$$\Delta E_g = h\nu = \frac{hc}{\lambda}$$

where ν is frequency, c is the velocity of light and λ is the wavelength.

$$\nu = \frac{\Delta E_g}{h}$$

The band gap energy determines the colour or wavelength of the emitted light. The intensity of the light emitted due to recombination process is directly proportional to the rate of (electron-hole) recombinations at the junction.

Now-a-days, Organic Light Emitting Diodes (OLEDs) and Polymer Light Emitting Diodes (PLEDs) are also available. LEDs are increasingly using quantum dots to enhance color accuracy and energy efficiency. Quantum dot LEDs (QLEDs) embeds nanoscale semiconductor particles into

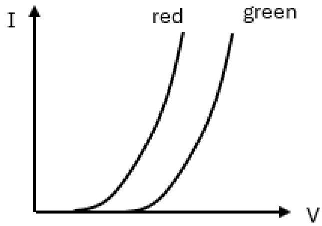

Figure 2.26: VI characteristics of LED

LEDs, enabling them to produce a wider and more vibrant color spectrum, particularly useful for high-quality displays. It also help reduce energy consumption.

Applications

Light emitting diodes are widely used in small indicators, warning lights and in alphanumeric display devices like calculators etc.

It is used in optical communication.

It is used for fancy light and decoration.

LEDs with invisible radiation are used in remote control devices, burglar alarm systems etc.

Advantages of LED

Light Emitting Diodes (LED) have several advantages over traditional lighting technologies like incandescent and fluorescent lights. Here are some key benefits:

- **Energy efficiency:** LEDs consume significantly less energy compared to traditional light sources. They convert more energy into light rather than heat, which reduces power consumption.

- **Long lifespan:** LEDs have a much longer operational life, often lasting up to 50,000 hours or more.

- **Directional lighting:** LEDs emit light in a specific direction, which reduces the need for reflectors and diffusers and ensures more efficient use of light.

- **Low heat emission:** Unlike incandescent bulbs that release 90% of their energy as heat, LEDs emit very little heat. This makes them safer to handle and reduces the need for additional cooling.
- **Durability:** LEDs are highly durable and can withstand rough conditions such as vibrations and impacts better than other lighting technologies, making them suitable for outdoor and industrial use.

2.9 Solved Numerical Problems

Example 2.9.1 The applied input a.c. power to a half-wave rectifier is 100 watts. The d.c. output power obtained is 40 watts. What is the rectification efficiency ?

Solution

Rectifier efficiency,

$$\eta = \frac{\text{dc outpower}}{\text{ac outpower}} = \frac{40}{100} = 0.4 = 40\%$$

Example 2.9.2 An input voltage $v_i = 10 \sin \omega t$ is applied to a half wave rectifier with a diode having forward resistance 15 Ω and load resistance 600 Ω. Determine

1. Maximum value of current, dc current and rms value of current.
2. ac power input and dc power output.
3. Efficiency of rectification.

Solution

Given input voltage, $v_i = 10 \sin \omega t$

Comparing with standard form, $v_i = V_m \sin \omega t$, $V_m = 10$ V

Forward resistance of diode, $r_f = 15\ \Omega$ and load resistance, $R_L = 600\ \Omega$

1. Maximum value of current, $I_m = \dfrac{V_m}{r_f + R_L}$

$$= \frac{10 \text{ V}}{15\ \Omega + 600\ \Omega}$$
$$= 16.3 \text{ mA}$$

$$\text{dc current, } I_{dc} = \frac{I_m}{\pi} = \frac{16.3 \text{ mA}}{\pi} = 5.2 \text{ mA}$$
$$\text{rms current, } I_{rms} = \frac{I_m}{2} = \frac{16.3 \text{ mA}}{2} = 8.15 \text{ mA}$$

2. ac power, $P_{ac} = I_{rms}^2(r_f + R_L)$
$$= (8.15 \times 10^{-3})^2(15 + 600) = 0.041 \text{ watts}$$

dc power output, $= (I_{dc}^2)R_L$
$$= (5.2 \times 10^{-3})^2 \times 600 = 0.016 \text{ watts}$$

3. Rectification efficiency, $= \dfrac{P_{dc}}{P_{ac}} \times 100$
$$= \frac{0.016}{0.041} \times 100 = 39\%$$

Example 2.9.3 The input voltage applied to the primary of a 4:1 step down transformer of a full wave center-tap rectifier is 230 V, 50 Hz. If the load resistance is 600 Ω and forward resistance is 20 Ω. Determine the following parameters of the full wave rectifier.

1. dc power output
2. Rectification efficiency
3. PIV

Solution

rms value of primary voltage, $V_1 = 230$ V

rms value of secondary voltage, $V_2 = V_1 \times \dfrac{N_2}{N_1} = 230 \times \dfrac{1}{4} = 57.5$ V rms value of voltage between centre tap and each side of secondary

$$V = \frac{V_2}{2} = \frac{57.5}{2} = 28.75 \text{ V}$$

Then maximum value of voltage $V_m = \sqrt{2} \times 28.75 = 40.7$ V

Maximum value of current, $I_m = \dfrac{V_m}{r_f + R_L} = \dfrac{40.7}{20 + 600} = 65.64$ mA

dc current, $I_{dc} = \dfrac{2I_m}{\pi} = \dfrac{2 \times 65.64 \text{ mA}}{\pi} = 41.79$ mA

rms current, $I_{rms} = \dfrac{I_m}{\sqrt{2}} = \dfrac{65.64}{\sqrt{2}} = 46.41$ mA

Ac input power, $P_{ac} = I_{rms}^2(r_f + R_L)$

$$= (46.41 \times 10^{-3})^2(20 + 600) = 1.335 \text{ W}$$

1. dc output power $= I_{dc}^2 R_L = (41.79 \times 10^{-3})^2 600 = 1.047$ W

2. Rectification efficiency $= \dfrac{P_{dc}}{P_{ac}} \times 100 = \dfrac{1.047}{1.335} \times 100 = 78.4\%$

3. PIV of full wave rectifier $= 2V_m = 2 \times 40.7 = 81.4$ V

Example 2.9.4 A solar cell with an area of $100cm^2$ has an open-circuit voltage of 0.6 V and a short-circuit current of 3 A. If the solar irradiance is $1000W/m^2$, calculate the efficiency of the solar cell if its fill factor is 0.75.

Solution

Given area of the solar cell is $100cm^2 = 0.01m^2$

Solar power input is $1000W/m^2 \times 0.01m^2$ = 10 W

$$\text{Efficiency, } \eta = \frac{\text{Electrical power delivered}}{\text{Solar power incident}}$$

$$\eta = \frac{V_{oc} I_{sc} FF}{P_{in}}$$

$$= \frac{0.6 \times 3 \times 0.75}{10} = 0.135$$

Therefore, the efficiency of the solar cell is 13.5

Example 2.9.5 A light emitting diode is made of GaAsP having a band gap of 1.9eV. Determine the wavelength and colour of radiation emitted.

Solution

$$\lambda = \frac{hc}{E_g} = \frac{6.626 \times 10^{-34} \times 3 \times 10^{8}}{1.9 \times 1.6 \times 10^{-19}} = 652.6nm$$

2.10 Exercises

1. A single solar cell of dimension (10cm x 10cm) produces a voltage of 0.5V and current 2.5 A. The intensity of light absorbs by cell is 800 W/m^2. What is the efficiency of cell?
Hint: $\eta = 15.6\%$

2. Given that a solar cell has V_{OC} = 4.2V, $I_{SC} = 45mA$, and FF=60%, what is the efficiency? If the solar irradiance is $1000W/m^2$ and the area of the cell is $50cm^2$.
Hint: $\eta = 2.27\%$

3. At room temperature, the voltage across an LED was measured to be 1.67 V. What is the band gap of this semiconductor, and what wavelength of light is emitted?
Hint: E_g = 1.67eV and λ = 744nm in red part of the visible spectrum

4. A semiconductor diode laser has a peak emission wavelength of 1.55 μm. Find its band gap in eV.
Hint: $E_g = 0.8eV$

Chapter 3

Superconductivity

The phenomenon of sudden disappearance of electrical resistance in a material, when it is cooled below a certain temperature is known as superconductivity. This was discovered by Dutch physicist Heike Kammerlingh Onnes in 1911. During his investigations on the conductivity of metals at low temperature, he found that the resistance of a mercury sample dropped to a small value just at the boiling temperature of liquid helium.
T_c for Mercury is 4.2K and that for Aluminium is 1.175K

The variation of the electrical resistance with temperature for mercury is as shown in Figure 3.1. It is found that electrical resistance of pure mercury suddenly drops to zero when it is cooled below 4.2K.

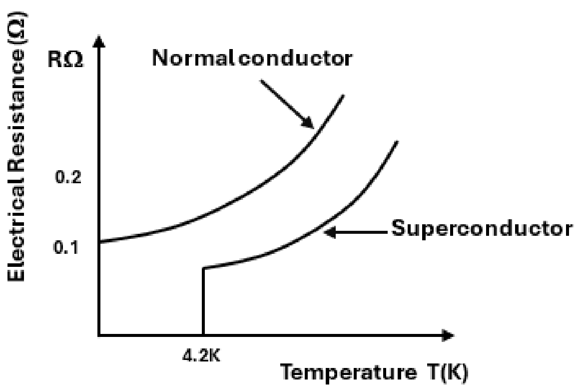

Figure 3.1: Resistance- Temperature graph for superconductors and non superconductors.