CHAPTER 3

SOLAR CELLS MODULES & ARRAYS

3.1 Introduction

A solar cell, also called a *photovoltaic cell*, is used to convert solar energy into electrical energy. Solar cells are the basic elements of a solar module (also known as a solar panel). Silicon is by far the commonest of a variety of semiconductors from which solar cells are made. A typical modern solar cell is squared-shaped measuring 10 cm × 10 cm. It is covered by a clear anti-reflection coating (ARC) that reduces the amount of light lost to reflection at the cell surface.

3.2 Three generations of solar cells

Solar Cells are classified into three generations which indicates the order of which each became important. At present there is concurrent research into all three generations while the first generation technologies are most highly represented in commercial production, accounting for 89.6% of 2007 production.

3.2.1 First Generation

First generation cells consist of large-area, high quality and single junction devices. First Generation technologies involve high energy and labor inputs which prevent any significant progress in reducing production costs. Single junction silicon devices are approaching the theoretical limiting efficiency of 33% and achieve cost parity with fossil fuel energy generation after a payback period of 5–7 years.

3.2.2 Second Generation

Second generation materials have been developed to address energy requirements and production costs of solar cells. Alternative manufacturing techniques such as vapour deposition, electroplating, and use of Ultrasonic Nozzles are advantageous as they reduce high temperature processing significantly. It is commonly accepted that as manufacturing techniques involved production costs will be dominated by constituent material requirements, whether this be a silicon substrate, or glass cover.

3.2.3 Third Generation

Third generation technologies aim to enhance poor electrical performance of second generation (thin-film technologies) while maintaining very low production costs.

Current research is targeting conversion efficiencies of 30-60% while retaining low cost materials and manufacturing techniques. They can exceed the theoretical solar conversion efficiency limit for a single energy threshold material, that was calculated in 1961 by Shockley and Queisser as 31% under 1 sun illumination and 40.8% under the maximal artificial concentration of sunlight (46,200 suns, which makes the latter limit more difficult to approach than the former).

There are a few approaches to achieving these high efficiencies including the use of Multifunction photovoltaic cells, concentration of the incident spectrum, the use of thermal generation by UV light to enhance voltage or carrier collection, or the use of the infrared spectrum for night-time operation.

3.3 Different types of solar cell

There are three main types of solar cells, which are distinguished by the type of crystal used in them. They are *monocrystalline*, *polycrystalline*, and *amorphous*. To produce a monocrystalline silicon cell, absolutely pure semiconducting material is necessary. Monocrystalline rods are extracted from melted silicon and then sawed into thin plates. This production process guarantees a relatively high level of efficiency.

Material	**Efficiency in lab (%)**	**Efficiency of production cell (%)**
Monocrystalline Silicon	about 24	14-17
Polycrystalline Silicon	about 18	13-15
Amorphous Silicon	about 13	5-7

The production of polycrystalline cells is more cost-efficient. In this process, liquid silicon is poured into blocks that are subsequently sawed into plates. During solidification of the material, crystal structures of varying sizes are formed, at whose borders defects emerge. As a result of this crystal defect, the solar cell is less efficient.

If a silicon film is deposited on glass or another substrate material, the result is a so-called amorphous or thin-layer cell. The layer thickness amounts to less than 1µm – the thickness of a human hair for comparison is 50-100 µm. The production costs of this type are lower because of the lower material costs. However, the efficiency of amorphous cells is much lower than that of the other two cell types. As a result, they are used mainly in low power equipment, such as watches and pocket calculators, or as facade elements.

3.4 From cells to modules

In order to provide suitable voltages and outputs for different applications, solar cells are connected together to form larger units. Cells connected in series have a higher voltage, while those connected in parallel produce more current. The interconnected solar cells are usually embedded in transparent ethylene vinyl acetate, fitted with an aluminum or stainless steel frame, and covered with transparent glass on the front side to make a solar module.

Typical peak power ratings of such solar modules range from 10 W to 100 W. The characteristic data refer to the standard test conditions of 1000 W/m^2 solar radiation at a cell temperature of 25° C (77° F). The manufacturer's standard warranty of 10 or more years is quite long and shows the high quality standards and life expectancy of today's products.

3.5 Principle of solar cell

A solar cell or photovoltaic cell is a device that converts sunlight directly into electricity by the **photovoltaic effect**. Sometimes the term *solar cell* is reserved for devices intended specifically to capture energy from sunlight, while the term *photovoltaic cell* is used when the light source is unspecified. Assemblies of cells are used to make solar panels, solar modules, or photovoltaic arrays. *Photovoltaic* is the field of technology and research related to the application of solar cells in producing electricity for practical use. The energy generated this way is an example of *solar energy* (also called *solar power*).

Solar cells are essentially semiconductor junctions under illumination. Light generates electron-hole pairs on both sides of the junction, in the n-type emitter and in the p-type base. The generated electrons (from the base) and holes (from the emitter) then diffuse to the junction and are swept away by the electric field, thus producing electric current across the device. Note how the electric currents of the electrons and holes reinforce each other since these particles carry opposite charges. The p-n junction therefore separates the carriers with opposite charge, and transforms the generation current between the bands into an electric current across the p-n junction.

3.6 How solar cells work

Like all semiconductor devices, solar cells work with a semiconductor that has been doped to produce two different regions separated by a p-n junction. Across this junction, the two types of charge carrier – electrons and holes – are able to cross. In doing so, they deplete the region from which they came and transfer their charge to the new region. This migration of charge results in a potential gradient or electrical slope, down which charge carriers tend to slide as they approach the junction.

When sunlight strikes a solar cell, atoms are bombarded with particles of light called photons, and give up electrons. When an electron is kicked out of an atom, it leaves behind a hole, which has an equal and opposite (positive) charge. If either carrier wanders across the junction, the field and the nature of the semiconductor material discourage it from recrossing. A proportion of carriers that cross the junction can be harvested by completing a circuit from a grid on the cell's surface to a collector on the backplane. In the cell, the light "pumps" electrons out one side of the cell, through the circuit, and back to the other side, energizing any electrical device that is connected along the way.

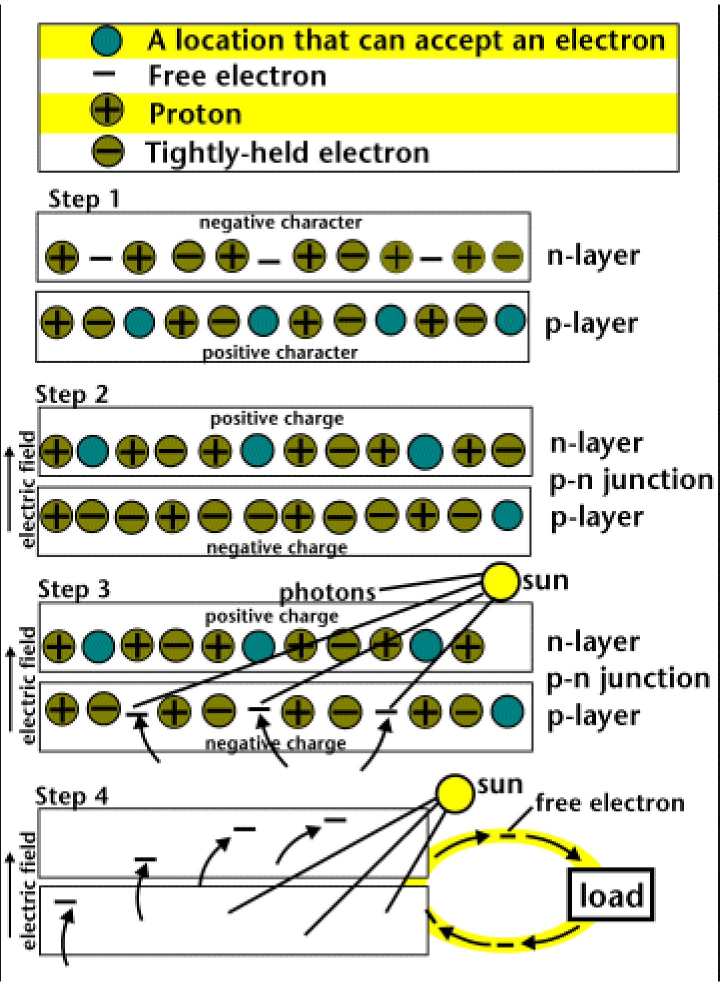
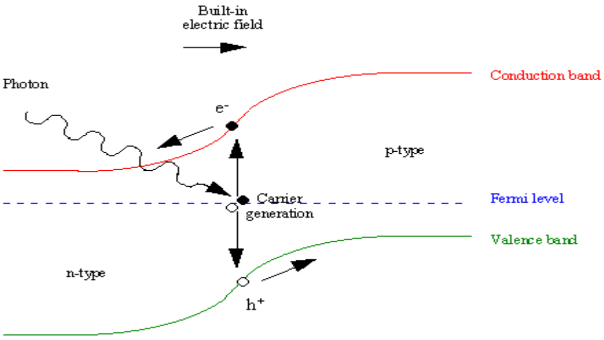
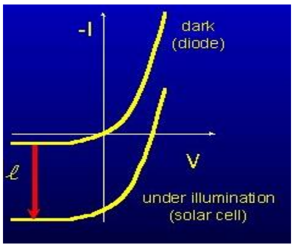


Fig: 3.1 How Solar Cell Works.

The current generated in the semiconductor is extracted by contacts at the top and bottom of the cell. The top contact structure, which must allow light to pass through, is made of thin, widely-spaced metal strips (usually called fingers) that supply current to a larger bus bar. The cell is covered with a thin layer of dielectric material – the anti-reflection coating – to minimize light reflection from the top surface.

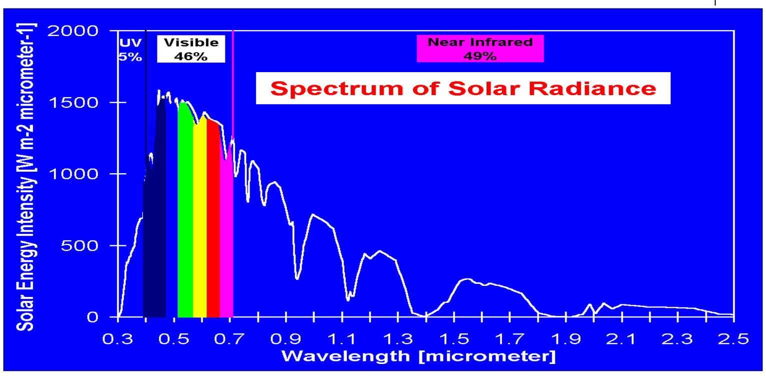
Solar cell – Working Principle





- Operating diode in fourth quadrant generates power

Solar Energy Spectrum



- Power reaching earth 1.37 KW/m^2

3.7 Characteristics of a solar cell

The usable voltage that a solar cell produces depends on what semiconductor material it's made from. In the case of silicon-based cells, the output is approximately 0.5 V. Although the current increases with increasing luminosity, the terminal voltage is only weakly dependent on the amount of light falling on the cell. A 100 cm^2 silicon cell generates a maximum current of about 2 A when radiated by 1000 W/m^2.

3.8 The p-n junction

The most commonly known solar cell is configured as a large-area p-n junction made from silicon. As a simplification, one can imagine bringing a layer of n-type silicon into direct contact with a layer of p-type silicon. In practice, p-n junctions of silicon solar cells are not made in this way, but rather, by diffusing an n-type dopant into one side of a p-type wafer (or vice versa).

If a piece of p-type silicon is placed in intimate contact with a piece of n-type silicon, then a diffusion of electrons occurs from the region of high electron concentration (the n-type side of the junction) into the region of low electron concentration (p-type side of the junction). When the electrons diffuse across the p-n junction, they recombine with holes on the p-type side. The diffusion of carriers does not happen indefinitely however, because of an electric field which is created by the imbalance of charge immediately on either side of the junction which this diffusion creates. The electric field established across the p-n junction creates a diode that promotes charge flow, known as drift current, that opposes and eventually balances out the diffusion of electron and holes. This region where electrons and holes have diffused across the junction is called the depletion region because it no longer contains any mobile charge carriers. It is also known as the "space charge region".

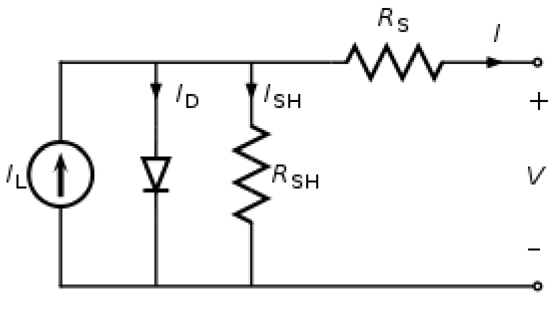


Fig:3.2 The equivalent circuit of a solar cell

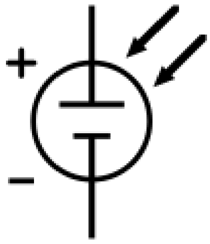


Fig:3.3 The schematic symbol of a solar cell

To understand the electronic behavior of a solar cell, it is useful to create a model which is electrically equivalent, and is based on discrete electrical components whose behavior is well known. An ideal solar cell may be modeled by a current source in parallel with a diode; in practice no solar cell is ideal, so a shunt resistance and a series resistance component are added to the model.

3.9 P-Types, N-Types, and The Electric Field

To induce the electric field within a PV cell, two separate semiconductors are sandwiched together. The "p" and "n" types of semiconductors correspond to "positive" and "negative" because of their abundance of holes or electrons (the extra electrons make an "n" type because an electron actually has a negative charge).

Although both materials are electrically neutral, n-type silicon has excess electrons and p-type silicon has excess holes. Sandwiching these together creates a p/n junction at their interface, thereby creating an electric field.

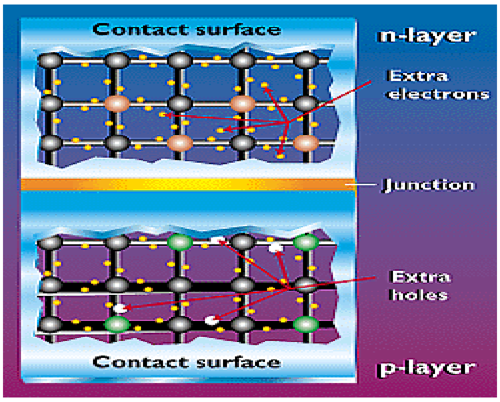


Fig:3.4: P-type,N-type & electric field

When the p-type and n-type semiconductors are sandwiched together, the excess electrons in the n-type material flow to the p-type, and the holes thereby vacated during this process flow to the n-type. Through this electron and hole flow, the two semiconductors act as a battery, creating an electric field at the surface where they meet (known as the "junction"). It's this field that causes the electrons to jump from the semiconductor out toward the surface and make them available for the electrical circuit. At this same time, the holes move in the opposite direction, toward the positive surface, where they await incoming electrons.

3.10 Making n and p Material

The most common way of making p-type or n-type silicon material is to add an element that has an extra electron or is lacking an electron. In silicon, we use a process called "doping."
We'll use silicon as an example because crystalline silicon was the semiconductor material used in the earliest successful PV devices, it's still the most widely used PV material, and, although other PV materials and designs exploit the PV effect in slightly different ways, knowing how the effect works in crystalline silicon gives us a basic understanding of how it works in all devices.

3.11 Absorption and Conduction

In a PV cell, photons are absorbed in the p layer. It's very important to "tune" this layer to the properties of the incoming photons to absorb as many as possible and thereby free as many electrons as possible. Another challenge is to keep the electrons from meeting up with holes and "recombining" with them before they can escape the cell. To do this, we design the material so that the electrons are freed as close to the junction as possible, so that the electric field can help send them through the "conduction" layer (the n layer) and out into the electric circuit. By maximizing all these characteristics, we improve the Conversion efficiency* of a solar cell.

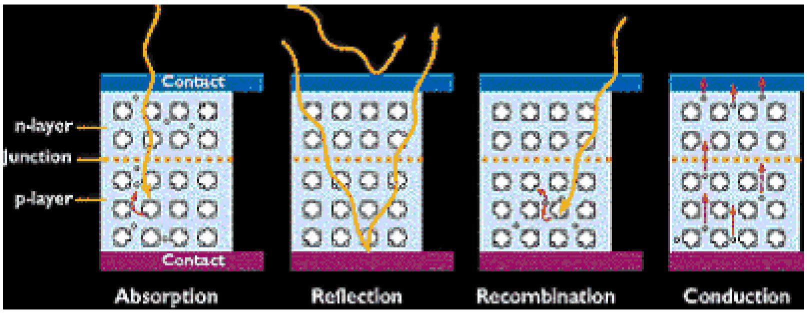


Fig:3.5 Absorption & Conduction

To make an efficient solar cell, we try to maximize absorption, minimize reflection and recombination, and thereby maximize conduction.

*The conversion efficiency of a PV cell is the proportion of sunlight energy that the cell converts to electrical energy. This is very important when discussing PV devices, because improving this efficiency is vital to making PV energy competitive with more traditional sources of energy (e.g., fossil fuels). Naturally, if one efficient solar panel can provide as much energy as two less-efficient panels, then the cost of that energy (not to mention the space required) will be reduced. For comparison, the earliest PV devices converted about 1%-2% of sunlight energy into electric energy. Today's PV devices convert 7%-17% of light energy into electric energy. Of course, the other side of the equation is the money it costs to manufacture the PV devices. This has been improved over the years as well. In fact, today's PV systems produce electricity at a fraction of the cost of early PV systems.

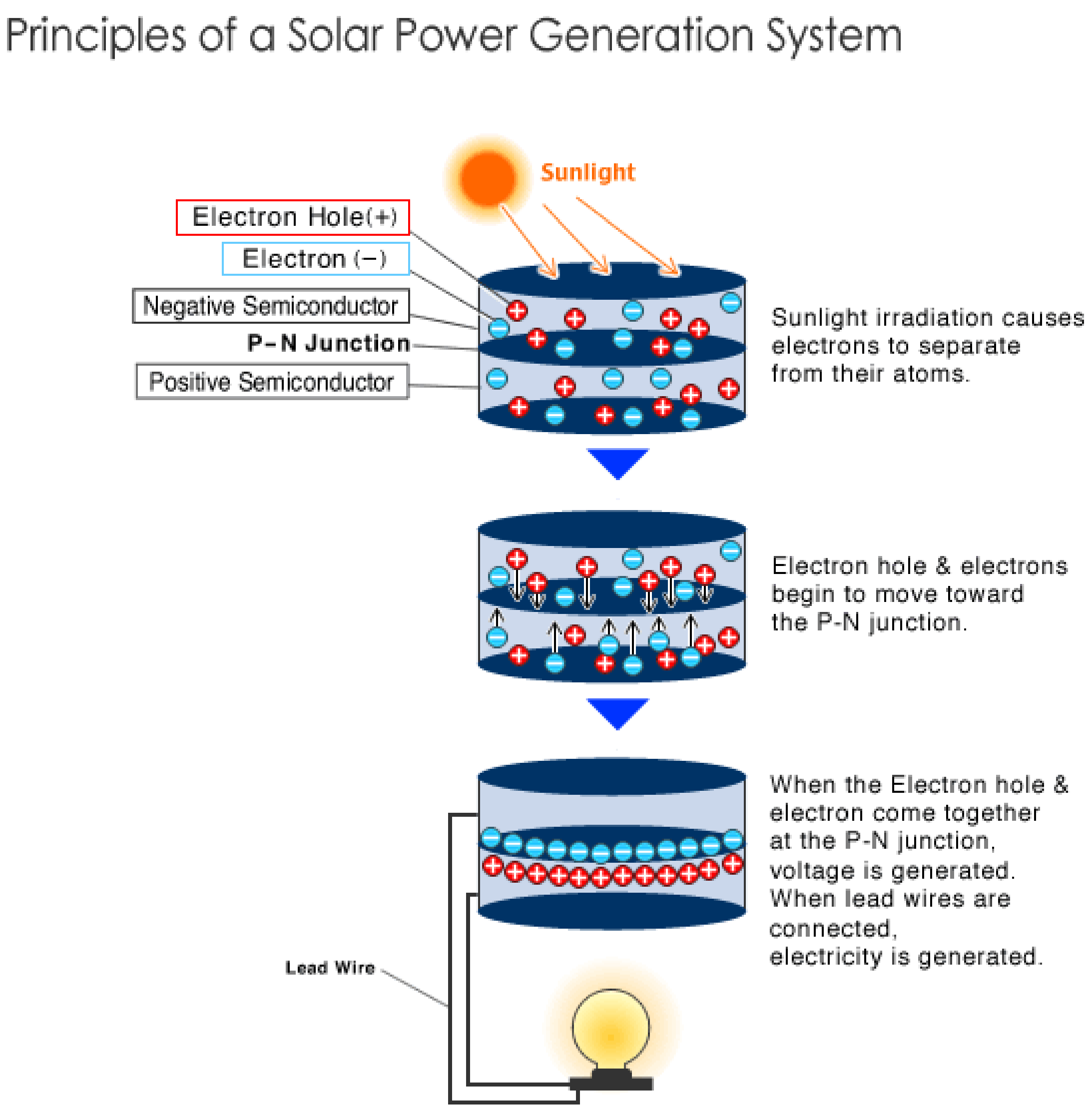


Fig: 3.6 Solar Power Generation System

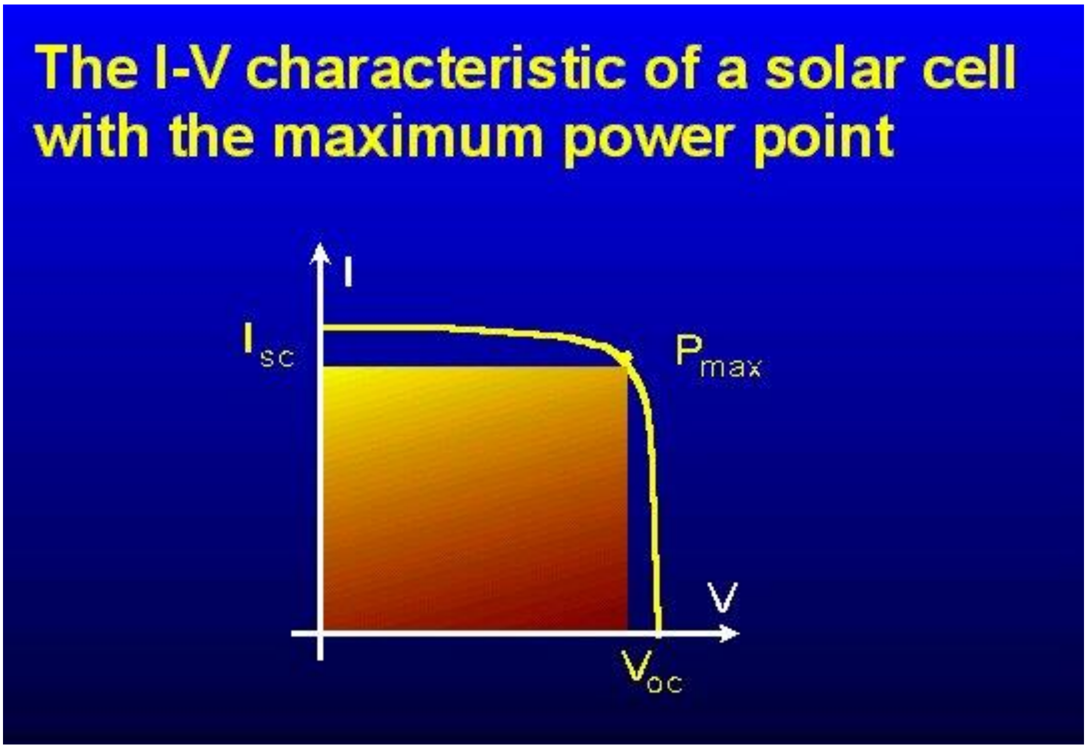


Fig:3.7 I-V Characteristics of Solar Cell

3.12 IDEAL CHARACTERISTICS OF A SOLAR CELL

The load current I_L for a solar cell is given by the following expression,

$$I_L=I_R-I_O[E^{qVL/KT}-1]..............(3.1)$$

equation 3.1 is the equation of an ideal solar cell. from the equation it can be shown that,

under condition of open circuit i.e. I_L=0, the open circuit voltage V_{OC} is given by,

$$V_{OC}=KT/q \ln[I_R/I_O+1]............(3.2)$$

B. Under short circuit condition (V_L=0), the short circuit current I_{SC} can be given by,

$$I_L=I_{SC}=I_R..........................(3.3)$$

an ideal load characteristics is given in Fig.3.4 and gives a relationship between V_L and I_L.

the power (P_L) obtained from the solar cell (ideal)

$$P_L=I_L^2R_L .... (3.4)$$

where R_L=load resistance
or,

$$P_L= [I_R-I_O(e^{qVL/KT}-1)^2.R_L$$

and the maximum power is obtained if R_L is properly adjusted such that

$$dP_L/dR_L=0$$

it is convenient to define maximum load power(P_{LMAX})

$$P_{LMAX}=V_{LMAX}XI_{LMAX}=V_{OC}XI_{sc}FF..........(3.5)$$

where,

V_{Lmp} is the voltage at maximum power
I_{Lmp} is the current at maximum power
FF is the fill factor.

the efficiency of a solar cell is defined as:

$$\eta= output/input=P_{LMAX}/P_{input}........(3.6)$$

P_{input}=1KW/m^2 X (area of the cell in m^2)

the maximum power obtained from a solar cell depends upon the open circuit voltage, short circuit current and fill factor.

3.12.1 Fill factor

Another defining term in the overall behavior of a solar cell is the *fill factor* (*FF*). This is the ratio of the *maximum power point* divided by the *open circuit voltage* (V_{oc}) and the *short circuit current* (I_{sc}):

$$FF = \frac{P_m}{V_{oc} \times I_{sc}} = \frac{\eta \times A_c \times E}{V_{oc} \times I_{sc}}.$$

The fill factor is directly affected by the values of the cells series and shunt resistance. Increasing the shunt resistance (Rsh) and decreasing the series resistance (Rs) will lead to higher fill factor, thus resulting in greater efficiency, and pushing the cells output power closer towards its theoretical maximum value.

3.12.2 SERIES AND SHUNT RESISTANCE

Series resistance

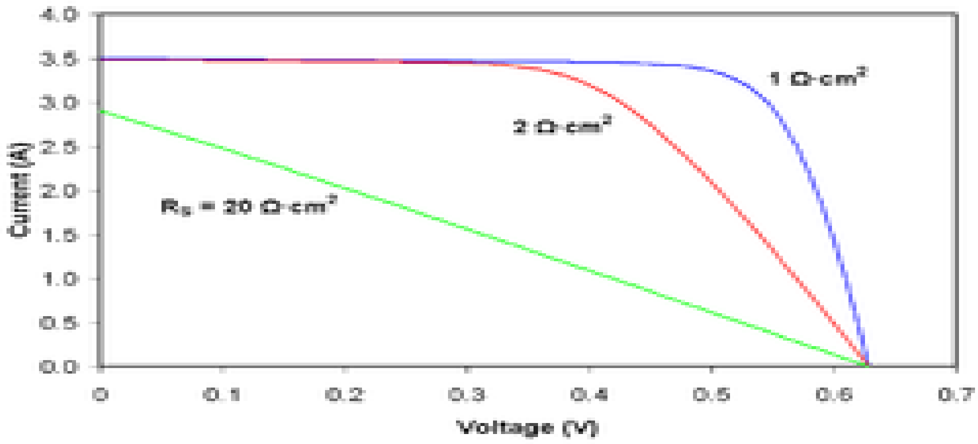


Fig: 3.8 Effect of series resistance on the current-voltage characteristics of a solar cell

As series resistance increases, the voltage drop between the junction voltage and the terminal voltage becomes greater for the same flow of current. The result is that the current-controlled portion of the I-V curve begins to sag toward the origin, producing a significant decrease in the terminal voltage *V* and a slight reduction in I_{SC}, the short-circuit current. Very high values of R_S will also produce a significant reduction in I_{SC}; in these regimes, series resistance dominates and the behavior of the solar cell resembles that of a resistor. These effects are shown for crystalline silicon solar cells in the I-V curves displayed in the above figure.

Shunt Resistance

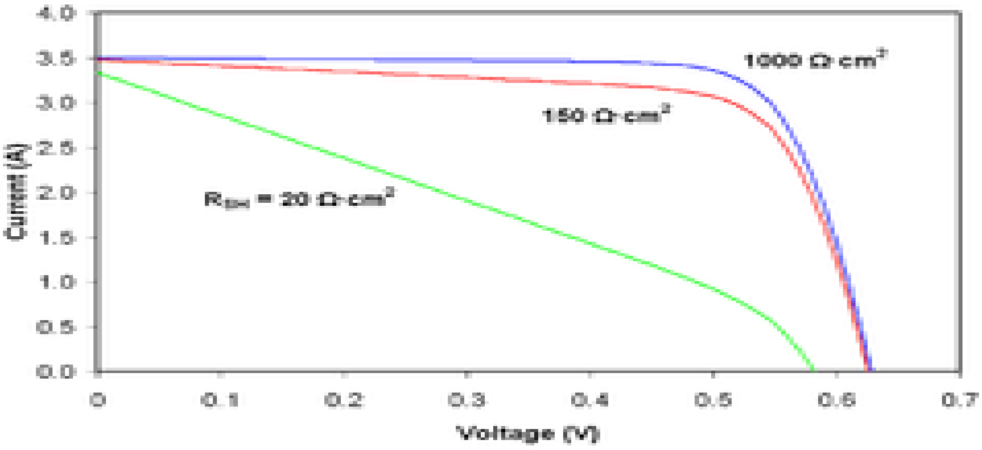


Fig:3.9 Effect of shunt resistance on the current-voltage characteristics of a solar cell

As shunt resistance decreases, the flow of current diverted through the shunt resistor increases for a given level of junction voltage. The result is that the voltage-controlled portion of the I-V curve begins to sag toward the origin, producing a significant decrease in the terminal current *I* and a slight reduction in V_{OC}. Very low values of R_{SH} will produce a significant reduction in V_{OC}. Much as in the case of a high series resistance, a badly shunted solar cell will take on operating characteristics similar to those of a resistor. These effects are shown for crystalline silicon solar cells in the I-V curves displayed in the above figure.

3.12.3 Reverse saturation current

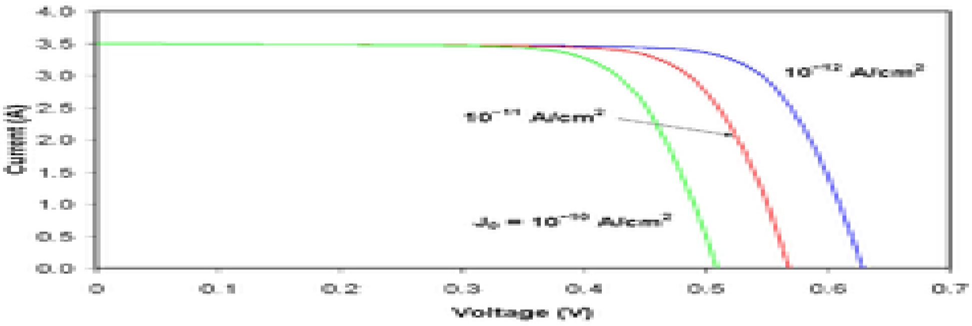


Fig:3.10 Effect of reverse saturation current on the current-voltage characteristics of a solar cell

If one assumes infinite shunt resistance, the characteristic equation can be solved for V_{OC}

$$V_{OC} = \frac{kT}{q} \ln \left(\frac{I_{SC}}{I_0} + 1 \right).$$

Thus, an increase in I_0 produces a reduction in V_{OC} proportional to the inverse of the logarithm of the increase. This explains mathematically the reason for the reduction in V_{OC} that accompanies increases in temperature described above. The effect of reverse saturation current on the I-V curve of a crystalline silicon solar cell are shown in the above figure . Physically, reverse saturation current is a measure of the "leakage" of carriers across the p-n junction in reverse bias. This leakage is a result of carrier recombination in the neutral regions on either side of the junction.