

SOLAR CELLS

2.1 Introduction

The direct conversion of solar energy into electrical energy by means of the photovoltaic effect, that is, the conversion of light into electricity. The photovoltaic effect is defined as the generation of an electromotive force as a result of the absorption of ionizing radiation. Energy conversion devices which are used to convert sunlight to electricity by the use of the photovoltaic effect are called solar cells.

Photovoltaic cells are made of semiconductors that generate electricity when they absorb light. As photons are received, free electrical charges are generated that can be collected on contacts applied to the surfaces of the semiconductors. These cells have theoretical efficiencies of the order of 25 percent. The best known application of photovoltaic cells for electrical power generation has been in space craft. Solar cells have also been used to operate irrigation pumps, navigational signals, highway emergency call systems, rail road crossing warnings etc, in location where access to utility power lines is difficult.

2.2 Solar Cell Principles

When photons from the sun are absorbed in a semiconductor, they create free electrons with higher energies than the electrons which provide the bonding in the base crystal. Once these electrons are created, there must be an electric field to induce these higher energy electrons to flow out of the semi-conductor to do useful work.



To obtain a useful power output from photon interaction in a semiconductor three processes are required.

1. The photons have to be absorbed in the active part of the material and result in electrons being excited to a higher energy potential.
2. The electron-hole charge carrier created by the absorption must be physically separated and moved to the edge of the cell.
3. The charge carriers must be removed from the cell and delivered to a useful load before they lose their extra potential.

When photons are absorbed by a p-n junction diode, the free electrons of the n-side will tend to flow to the p-side and the holes of the p-side will tend to flow to the n-region to compensate for their respective deficiencies. This diffusion will create an electric field E_F from the n-region to the p-region. This field will increase until it reaches equilibrium for V_e , the sum of the diffusion potentials for holes and electrons. This is the basis of photovoltaic conversion, that is, the conversion of solar energy into electrical energy. The combination of n-type and p-type semiconductors thus constitutes a photovoltaic cell (PV) or solar cell. All such cells generate direct current which can be converted into alternating current if desired.

The figure 2.2.1 shows a p-n junction semiconductor. The junction of the p-type and n-type materials provides an inherent electric field which separates the charge created by the absorption of sunlight. This p-n junction is usually obtained by putting a p-type base material into a diffusion furnace containing a gaseous n-type dopant. Such as phosphorous and allowing the n-dopant to diffuse in to the surface about 0.2 m. The collection of charges from the front of the cell is aided by a fine grid of narrow metallic fingers. The surface coverage of the conducting collectors is

typically 5% in order to allow as much light as possible to reach active junction area.

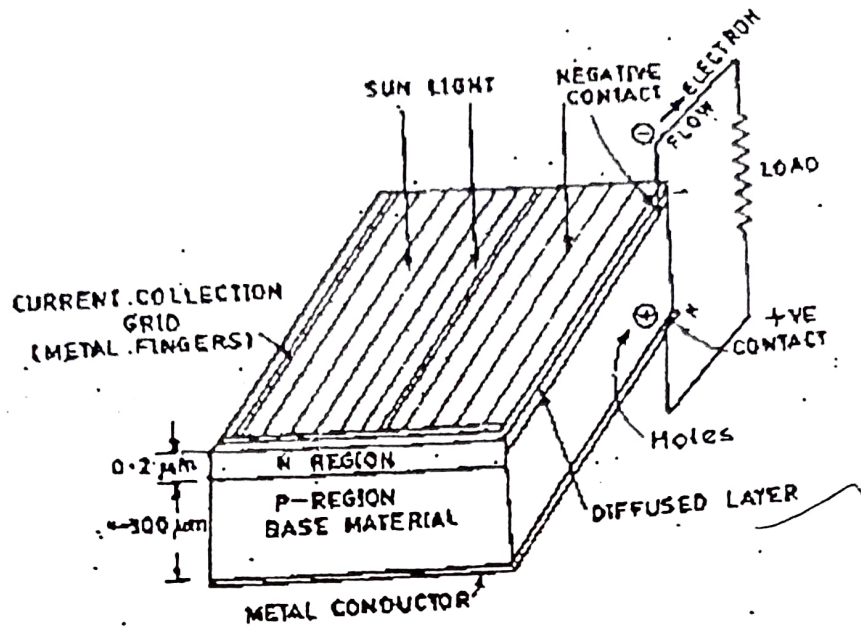


Fig. 2.2.1. p-n junction semiconductor

The figure 2.2.2 demonstrates how this p-n junction provides an electrified that sweeps the electrons in one direction and the positive holes in the other.

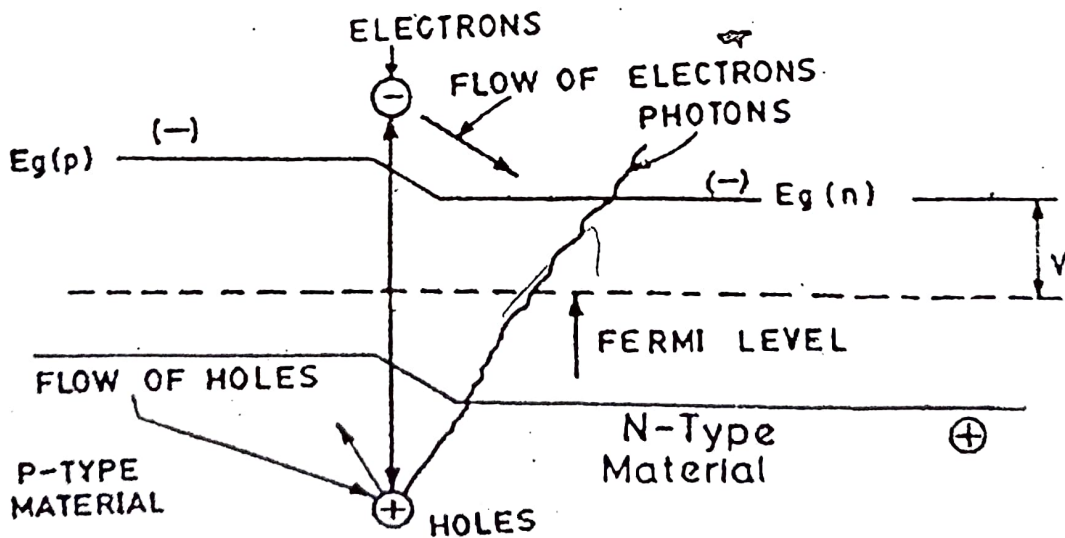


Fig. 2.2.2. p-n junction electric fields

If the junction is in thermodynamic equilibrium, then the fermi energy, must be uniform throughout. Since the Fermi level is near the top of the gap of an n-doped material and near the bottom of

the p-doped side, an electric field must exist at the junction providing the charge separation function of the cell.

Each of the individual solar cells will produce power at about 0.5V with the current directly proportional to the cell's area. The individual cells are connected in series-parallel combination to meet the voltage, power and reliability requirements of the particular application.

2.3. Solar Cell Electrical Characteristics Conversion Efficiency and Power Output

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A solar cell usually uses a p-n junction. Its physical configuration is shown in figure 2.2.1. Current and voltage relationship is given by

$$j_i = j_0 [\text{Exp}(Ve/kT) - 1] \Rightarrow J = J_L - J_0 \quad \text{--- (1)}$$

Where

- j_0 - the saturation current also called the dark current and is obtained when a large negative voltage is applied across the diode
- V - the voltage across junction
- e - the electronic charge
- k - the Boltzmann's constant
- T - the absolute temperature

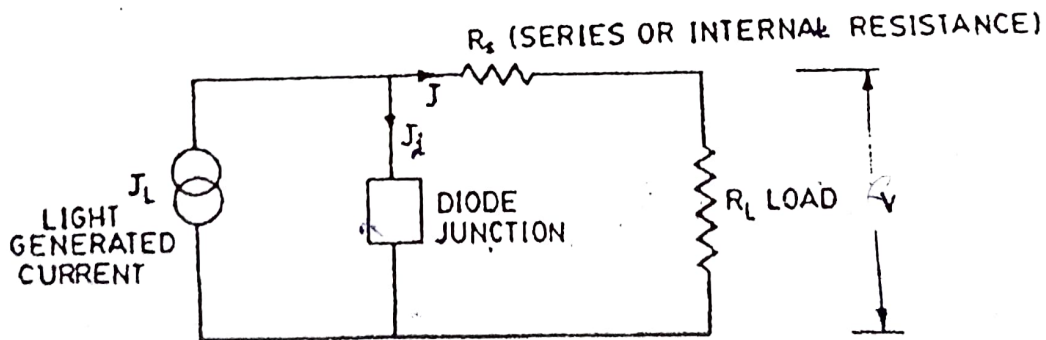


Fig. 2.3.1. The equivalent circuit of a solar cell

When light impinges on the junction, electron hole pairs are created at a constant rate providing an electrical current flow across the junction. The net current is thus the difference between the normal diode current and light generated current J_L . The equivalent circuit for the cell is shown in the above figure.

The internal resistance R_s is mostly due to the high sheet resistance of the diffused layer which is in series with the junction. The net current J is given by

$$\begin{aligned} J &= J_L - J_1 \\ &= J_L - J_0 [\text{Exp}(Ve/kT) - 1] \end{aligned} \quad \text{--- (2)}$$

The internal voltage drop in a cell can usually be minimized, and for ideal cell $R_s = 0$. With these the corresponding J-V plot is given in the figure 2.3.2.

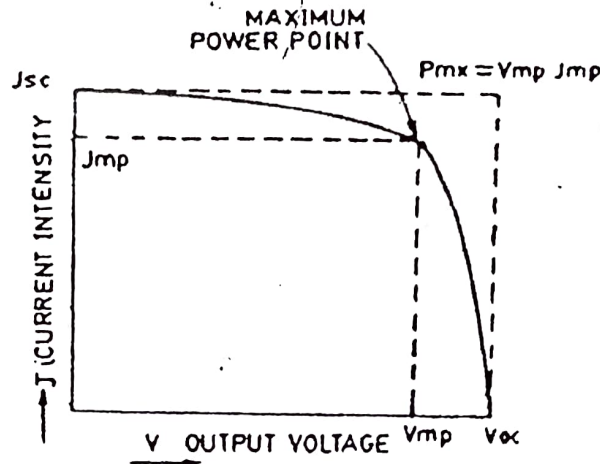


Fig. 2.3.2. Current Voltage Curve

Open circuit voltage V_{oc} for the ideal cell is given by

$$V_{oc} = (kT/e) \ln[J_L/J_0 + 1] \quad \text{--- (3)}$$

Since $J_L \gg J_0$, the 1 in the equation can be neglected. Then open circuit voltage

$$V_{oc} = (kT/e) \ln J_L/J_0 \quad \text{--- (4)}$$

In practice, the open-circuit-voltage of the cell decreases with increasing temperature.

The maximum power that can be derived from the device is given by

$$P_{max} = V_{mp} \times J_{mp} \quad \text{--- (5)}$$

Where V_{mp} and J_{mp} are the voltage and current at maximum power point.

$$\text{Efficiency, } \eta = \frac{(V_{mp} \times J_{mp})}{P_{sun}} \quad \text{---(6)}$$

Where P_{sun} is the total power density of sunlight

$$\eta = \left[\frac{J_L E_g}{e P_{sun}} \right] \left[\frac{J_{mp} V_{mp}}{J_L V_{oc}} \right] \left[\frac{e V_{oc}}{E_g} \right]$$

Fill Factor
Voltage factor

$$\text{Fill Factor, } FF = \frac{J_{mp} V_{mp}}{J_L V_{oc}} \quad \text{---(7)}$$

Solar cell designers, strive to increase the fill factor values, to minimize internal losses. Maximum Power can be defined in terms of V_{oc} and J_L and is given by

$$P_{max} = J_L \times V_{oc} \times FF \quad \text{---(8)}$$

A typical value of the fill factor for a good silicon cell is about 0.8. The voltage factor $(e \times V_{oc})/E_g$ is determined by the basic properties of the materials in the cell and is typically about 0.5 for a silicon cell.

Limits to cell efficiency

Photovoltaic cells are limited in efficiency by many losses. Some of these are avoidable but others are intrinsic to the system and may be described as follows :

1. The electric current leaves the top surface by a web of metal contacts arranged to reduce the series resistance losses in the surface. These contacts have a finite area and block the incident solar radiation.
2. Without special parameters, the reflectance from semiconductor is high (about 40% of the incident solar radiation). However, this may be reduced to 3% or less by the use of the film surface.
3. Photons of quantum energy $h\nu < E_g$ cannot contribute to photovoltaic current generation. For silicon, the inactive wavelength include 23% of insolation.
4. The excess energy of active photons $(h\nu - E_g)$ appears as heat. This loss is about 33% of the insolation.

5. Quantum efficiency: The fraction of incident absorbed active photons producing electron-hole pairs is usually very high. The design of the cell should be such that at least 95% absorption takes place.
6. Collection efficiency is defined as the proportion of radiation generated electron-hole pairs that produce current in the external circuit. For 10% overall efficiency cells, the collection efficiency factor is usually about 0.7. Increasing these too about 0.9 would produce 20% overall efficiency cells.
7. Each absorbed photons produced electron-hole pair with an electric potential difference of E_g/e . However, only a part (V_{oc}) of this potential is available for EMF of an external circuit. The voltage factor F_v is equal to $(eV_{oc})/E_g$. The missing EMF occurs because in open circuit the Fermi level across the junction equates at the dopant n and p levels and not at the displaced conduction to valence band levels. Increased dopand concentration increases F_v . The loss due to voltage factor is about 20% of the insolation.
8. The solar cell I-V characteristic is strongly influenced by the p-n diode characteristics. Thus as the solar cell output raised towards V_{oc} , the diode becomes increasingly forward bias, so increasing the internal recombination current I_r across the junction. This necessary behaviour is treated as a fundamental loss in the system. The loss due to curve factor is about 4% of the insolation.
9. In practice the cell characteristic equation is represented as,

$$I = I_0 \exp \left\{ \left(\frac{eV}{AkT} \right) - 1 \right\} - I_L$$

The factor A results from increased recombination in the junction and tends to change V_{oc} and I_0 . Thus, in general, optimum output would occur if $A=1$. Within the cell recombination is lessened if :

1. Diffusion paths are long (>50 to $100 \mu\text{m}$ in Si). This requires long minority carrier life times.
2. Junction is near the top surface (within 0.15 m).
3. Material has few defects other than the dopant.

2.4. Solar Cell Parameters

1. Maximum Power Point (P_{max})

A solar cell may operate over a wide range of voltages (V) and current (I). By increasing the resistive load (voltage) in the cell from zero (including a short circuit) to infinitely high values (including an open circuit) one can determine the maximum power point (the maximum output electrical power), $V_{max} \times I_{max} = P_{max}$, in Watt.

2. Energy Conversion Efficiency (η)

A solar cell energy conversion efficiency (η) is the percentage of power converted (from absorbed light to electrical energy) and collected, when a solar cell connected to an electrical circuit. This term is calculated using the ratio of P_m divided by the input light irradiance under standard test conditions (E , in W/m^2) and the surface area of the solar cell (A_c in m^2). At solar noon on a clear March or September equinox day, the solar radiation at the equator is about $1000 \text{ W}/\text{m}^2$. Hence the standard solar radiation (known as the air mass 1.5 spectrum) has power density $1000 \text{ W}/\text{m}^2$. Thus, as 12% efficiency solar cell having 1 m^2 of surface area in full sunlight at solar noon at the equator during either the March or September equinox will produce approximately 120W of peak power.

$$\eta = \frac{P_m}{E \times A_c}$$

3. Fill Factor

Another defining term in the overall behaviour 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}).

That is $\left(FF = \frac{P_m}{(V_{oc} \times I_{sc})} = \frac{(\eta \times A_c \times E)}{(V_{oc} \times I_{sc})} \right)$

4. Quantum Efficiency

Quantum efficiency refers to the percentage of absorbed photon that produces electron-hole pairs (or charge carriers). This is a term intrinsic to the light absorbing material and not the cell as a whole (which becomes more relevant for thin-film solar cells). (This term should not be confused with energy conversion efficiency, as it does not convey information about the power collected from the solar cell.)

5. Comparison of Energy Conversion Efficiencies

For example, single crystal silicon solar cells cannot currently convert more than 24% of the solar energy into electricity, because the radiation in the infrared region of the electromagnetic spectrum does not have enough energy to separate the positive and negative charges in the material. However PV cells made of multi-junction Gallium Arsenide and other similar alloys have achieved efficiencies as high as 30%.

2.5 Single Crystal Solar Cell

Single crystalline solar cells made from high purity material show excellent efficiencies and long term stability.

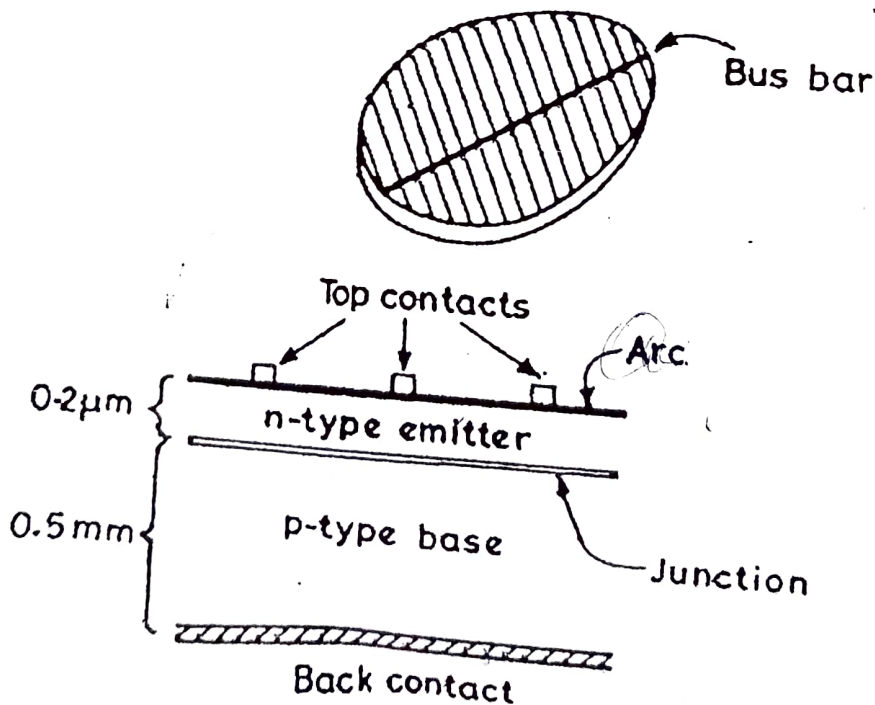


Fig. 2.5.1. The structure of single crystal solar cell

Figure 2.5.1 shows the diagram of a silicon cell. The electric current generated in the semiconductor is extracted by contact to the front and rear of the cell. The cell is covered with thin layer of dielectric material, the antireflecting coating or ARC. The total series resistance of the cell can be expressed as

$$R_s = R_{cp} + R_{bp} + R_{cn} + R_{bn} \quad \dots(1)$$

Where, R_{cp} is the metal contact p-type semiconductor resistance, R_{bp} the bulk p-type resistance, R_{cn} the contact to n-type semiconductor resistance and R_{bn} the bulk n-type resistance.

The idealized junction current is given by,

$$I = I_0 \{ \exp [e(V - IR_s) / (kT)] - 1 \}$$

In addition, a shunt path may exist for current flow across the junction due to surface effect or poor junction region. The alternate path for current constitutes a shunt resistance R_p across the junction.

Then,
$$I = I_0 \{ \exp [e(V - IR_s) / (AKT)] - 1 \} - (V - IR_s) / R_p \quad \dots(2)$$

Where A is an empirical non-ideality factor.

Open circuit voltage V_{oc} for the ideal cell is given by

$$V_{oc} = (KT/e) \ln [J_L / J_0 + 1] \quad \dots(3)$$

Since $J_L \gg J_0$, the 1 in the equation can be neglected. Then open circuit voltage

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In practice, [the open circuit voltage of the cell decreases with increasing temperature.

The maximum power that can be derived from the device is given by

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Where V_{mp} and J_{mp} are the voltage and current at maximum power point.

$$\text{Efficiency, } \eta = (V_{mp} \times J_{mp}) / P_{sun}$$

Where P_{sun} is the sunlight.

$$\eta = \left[\frac{J_L E_g}{e P_{sun}} \right] \left[\frac{J_{mp} V_{mp}}{J_L V_{oc}} \right] \left[\frac{e V_{oc}}{E_g} \right] \quad \dots(6)$$

Fill factor
Voltage factor

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2.6. Poly crystalline silicon solar cells

The silicon solar cells made from poly crystalline silicon are of low cost and of low efficiency 15% to 10%. Considerable loss of photogenerated carriers concur at grain boundaries known as short circuiting.

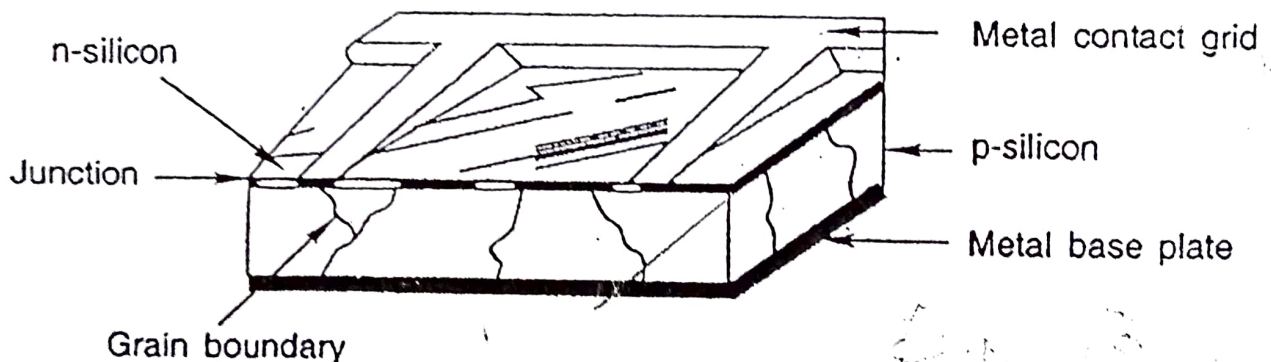


Fig. 2.6.1. Cross section of poly crystalline silicon solar cell

There are three groups of solar cell structures which are prepared using polycrystalline silicon. These cells are either p-n junction cells or metal-insulator-semiconductor cells or conducting oxide-insulator-semiconductor cells. In a p-n junction solar cell, the poly crystalline silicon film can be deposited by any one of the techniques like dipping, chemical vapour deposition or vacuum evaporation on various substrate like graphite, glass, ceramic, sapphire, metallurgical grade silicon metal.

The idea of a metal-semiconductor junction is quite attractive since it simplifies the manufacturing process and is of low cost. These cells show a similar short circuit. Current I_{sc} and low open circuit voltage V_{oc} compared to p-n junction cells resulting in low cell efficiency. Considerably higher dark current is produced in these cells. By inserting a very thin insulating layer in between the metal and semiconductor, this problem can be solved and such cells are termed as metal-insulator-semiconductor (MIS) solar cells.

By making the insulating layer very thin, the V_{oc} can be increased and can become almost equal to that of the p-n junction cell. Sometimes, the oxide layer already present on the semiconductor material was used as an insulating material but this uncontrolled layer of oxide has given overall poor performance and therefore in more recent cells a controlled freshly prepared thin oxide layer is used which has given good performance.

In the conducting oxide-insulator-semiconductor cells a window semiconductor is used over an active semiconductor substrate. This thin film oxide window which has high transmittance for solar radiation and high electrical conductivity also acts as positive anti-reflection coating. Several window materials such as SnO_2 , InO_2 and ITO have been tried with different deposition techniques such as spray deposition, chemical vapour deposition and electron beam deposition. SnO_2 /sliced semi crystalline silicon substrate cell has given an efficiency of 10.1%.

2.6.1. The CdS/CdTe Solar Cell

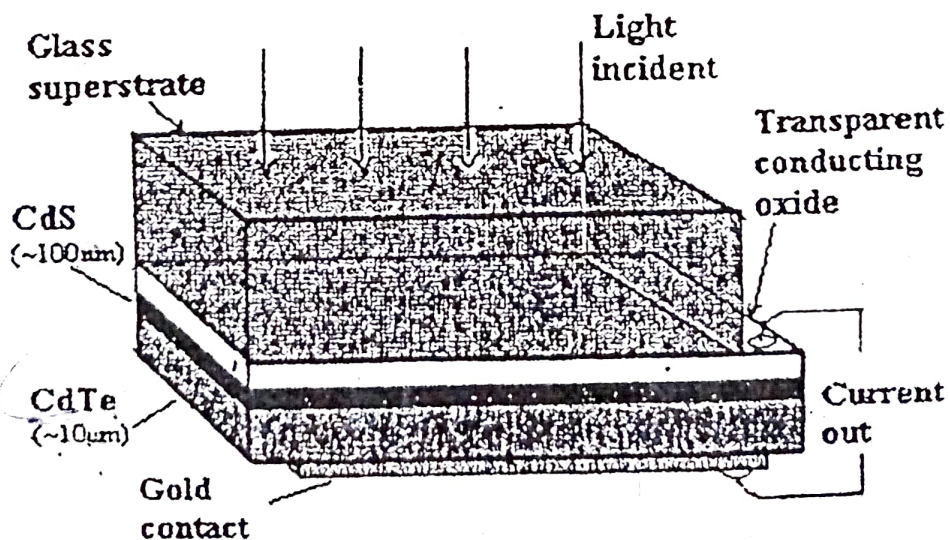
Currently, the semiconductor most widely used in solar cells is single-crystal silicon. Because of the cost involved in producing the bulk material, cells produced by this method are prohibitively expensive for all but the smallest scale or most specialized applications. Higher efficiencies have been produced by using single-crystal III-V semiconductors and more elaborate constructions but this advantage has always been more than offset by the resultant increase in cost. The thin-film cadmium telluride/cadmium sulphide solar cell has for several years been considered to be

a promising alternative to the more widely used silicon devices. It has several features, which make it especially attractive:

1. The cell is produced from polycrystalline materials and glass, which is potentially much cheaper construction than bulk silicon.
2. The chemical and physical properties of the semiconductors are such that the polysilicon thin film can be deposited using a variety of different techniques
3. CdTe has a bandgap, which is very close to the theoretically calculated optimum value for solar cells under unconcentrated sunlight.
4. CdTe has a high absorption coefficient of that approximately 99% of the incident light is absorbed by a layer thickness of only 1 μm , cutting down the quantity of semiconductor required.

2.6.2 Cell Construction

The CdTe/CdS solar cell is based around the heterojunction formed between n-type CdS and p-type CdTe. The basic composition of the cell can be seen in figure 2.6.2. The functions of the different layers are as follows :



1. Glass

The solar cell is produced on a substrate of ordinary window glass because it is transparent, strong and cheap. Typically around 2-4 mm thick, this protects the active layers from the environment and provides the entire device's mechanical strength. The outer face of the pane often has an anti-reflective coating to enhance its optical properties.

2. Transparent conducting oxide

Usually of tin oxide or indium tin oxide (ITO), this acts as the front contact to the device. It is needed to reduce the series resistance of the device, which would otherwise arise from the thinness of CdS layer.

3. Cadmium Sulphide

The polycrystalline CdS layer is n-type doped and therefore provides one half of the p-n junction. Being a wide band gap material ($E_g \sim 2.4\text{eV}$ at 300K) it is transparent down to wavelengths of around 515nm, and so is referred to as the window layer. Below that wavelength, some of the light will still pass through to the CdTe, due the thinness of the CdS layer ($\sim 100\text{nm}$).

4. Cadmium Telluride

The CdTe layer is, like the CdS, polycrystalline, but is p-type doped. Its energy gap (1.5eV) is ideally suited to the solar spectrum, and it has a high absorption coefficient for energies above this value. It acts as an efficient absorber and is used as the p side of the junction. Because it is less highly doped than the CdS, the depletion region is mostly within the CdTe layer. This is therefore the active region of the solar cell, where most of both the carrier generation and collection occur. The thickness of this layer is typically around $10\mu\text{m}$.

5. Back contact

Usually of gold or aluminium, the back contact provides a low resistance electrical connection to the CdTe. P-type CdTe is a notoriously difficult material on which to produce an ohmic contact,

and so the junction will inevitably display some Schottky diode characteristics. Due to its high conductivity, the metal layer needs only be a few tens of nanometers in thickness.

Deposition techniques

The polycrystalline layers of CdS and CdTe can be deposited by a number of different methods, including, amongst others, those outlined below:

Physical Vapour Deposition (PVD) involves the vaporization in a vacuum of a source of either the compound (CdS or CdTe) or the separate elements (Cd+S or Cd+Te). The resulting vapours recombine on the surface of the substrate to deposit the required polycrystalline.

Close-Space Sublimation (CSS): which has been used to produce the highest efficiency cells so far, is based on the reversible dissociation of the materials at high temperatures.
Eg: $2\text{CdTe}(s) = \text{Cd}(g) + \text{Te}(g)$

The source is of a large area and is positioned close to the substrate. The substrate is maintained at a high temperature such that the elemental vapours will not become deposited on the substrate but the compound form will, due to its lower equilibrium vapour pressure.

Chemical Vapour Deposition (CVD): can also be used to deposit both semiconductors. It involves chemical reactions between vapours to produce the required species, which then condense on the substrate to form the compound.

Chemical Bath Deposition: is sometimes used for depositing CdS films, and involves producing the required ions in a solution by chemical means, which combine and precipitate out onto the substrate if the required equilibrium conditions are met.