How a Diode Tames the Sun

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Abstract

With growing interest in renewable energy, a large work force would be required to engineer, install and maintain devices for energy harvesting. The current trend points to the non-polluting use of solar energy. Recognising this, it becomes necessary to have a large audience understand the basic working of solar cells. This article focuses on the conceptual understanding of a p-n semiconductor junction and how by material engineering the junction can be used to harvest solar energy. The manuscript provides an insight into the simple semiconductor physics and its implementation at the device level.

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1 Introduction

To meet the growing demands of energy and with limited reserve of fossil fuels, there is a great need for low cost, enviornmental friendly renewable energy resources. Among other natural energy resources like wind, hydrothermal, biomass etc solar energy stands out to be most promising candidate with the Sun being the never-ending source of light energy with wavelength range spanning the electromagnetic spectrum from UV to Infrared [1, 2]. When a material is incident with light having energy greater than or equal to the band-gap of the material, the electrons absorb this energy and is excited from the valance band to the conduction band, becoming free for conduction process. This phenomenon of producing voltage or electric current is known as photovoltaic effect and the device working on this principle is known as the solar cell. It was first discovered by a french scientist, Edmund Becquerel in 1839 who also give this phenomenon its name [3]. However, the world got its first practical solar cell much later in 1954 when Chapin et al at Bell laboratories, UK developed a simple p-n junction Silicon-solar cell with 6 % conversion efficiency of solar energy into elecrticity [4]. Till date Si-solar cells with efficiency ≈ 25 % dominate the photovoltaic industry. However, due to high processing cost and expensive Si-technology, focus has been shift towards a large number of other organic and inorganic materials eg. P3HT, CdS, SnS, CIGS etc. as solar cell absorbing layer [5, 6, 7, 8, 9, 10], leading to a rise of thin film solar cell technology. Thin film solar cells although have cut down the manufacturing cost by great margins but they still have to go a long way as far as conversion efficiency is concerned.

In this manuscript, we will discuss how a simple p-n junction solar cell works and what important parameters one has to consider while designing a thin film solar cell. But before going into the details of photovoltaics, lets begin with an over-view os a simple p-n junction.

2 p-n junction

A p-n junction is formed when a p-type semiconductor (having holes as majority carriers) is grown over a n-type semiconductor (electrons as majority carriers) or vice-versa, using one of the fabrication methods such as thermal evaporation, lithography, wet chemical methods etc.. Because of the difference in electron's and hole's concentration in the two layers, a concentration gradient is set leading to diffusion of charge carriers. Electrons move from n-type region (where they are the majority charge carriers) to p-type region (where they are in minority) and similarly holes move from p-type to n-type region. Since this type of carrier movement results in an increase in number of minority carriers on both p and n-side of the junction, this process is called minority-carrier injection and the resulting current is known as diffusion current.

These diffused minority charge-carriers recombine with the majority carriers present in the layers and eventually deplete all the free charge carriers in the vicinity of junction (on both sides) leaving behind immobile charge ions, donors ions ($\mathrm{N_d}$, positive) on n-side and acceptor ions ($\mathrm{N_a}$, negative) on p-side of junction. This region, depleted of mobile charge-carriers is known as depletion region/space charge region and extends upto $\mathrm{x_p}$ and $\mathrm{x_n}$ in the two layers as shown in fig 1. The loss of charge neutrality in depletion region give rise to an electric field with direction from n-side (positive donor ions) to p-side (negative acceptor ions).

This electric field prevents the further diffusion of charge carriers and itself exerts a force on the carriers causing a drift of electrons from p-side to n-side and that of holes from n-side to p-side i.e. in the direction opposite to the diffusion current. Therefore, the electric field builds upto a point where equilibrium is reached and both diffusion and drift currents balance each other i.e.

$$I_{diffusion} = I_{drift} = I_o \tag{1}$$

At equilibrium, the electrochemical potential[1] represented by fermi-levels, on either side of the junction are equal. This allignment of fermi levels results in bending of bands in the depletion region and hence to an electric potential known as built-in voltage 'V_o' or 'V_{bi}'.[2] Since the electric field is maximum at the junction while zero in the neitral region, it implies that there exists a potential gradient in the depletion region. The distribution of space-charge and the potential in this region is given by Poisson's equation [11] For depletion region $0 < x < x_n$

$$\frac{d^2V}{dx^2} = \frac{-q}{\epsilon_s}(N_d) \tag{2}$$

And for depletion region $-x_p < x < 0$

$$\frac{d^2V}{dx^2} = \frac{q}{\epsilon_s}(N_a) \tag{3}$$

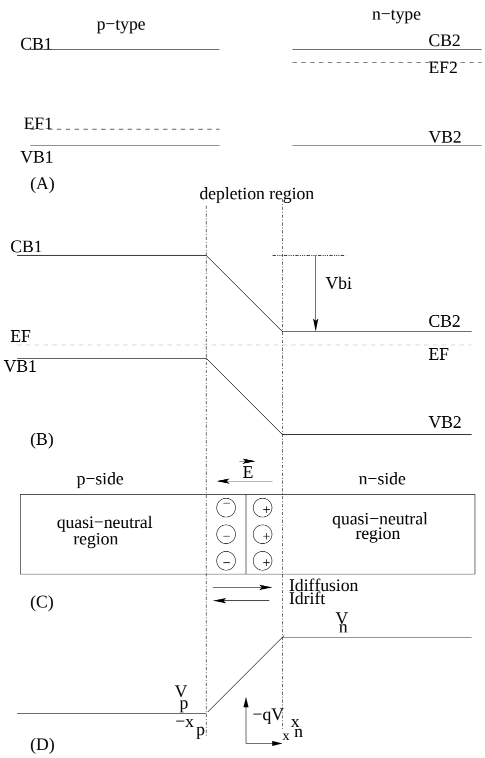

Figure 1: Figure showing (A) energy-band diagrams of isolated p-type and n-type semiconductor (B) energy-band diagrams of a p-n junction (C) different regions of a diode with direction of currents flowing through it (D) distribution of electrostatic potential across the diode.

Where, 'ϵ_s' is the dielectric constant of the semiconductor material and $x = 0$ at the junction and increases as we move away from the junction into the depletion region. The potential is 'V_p' and 'V_n' at '$-x_p$' and 'x_n' respectively. V_{bi} is given as

$$V_o = V_n - V_p \tag{4}$$

i.e. the potential difference between the constant potentials in the neutral regions.

Therefore, any p-n junction device (as shown in the fig 1) consists of three regions:

(i) Depletion or the space-charge region

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[1] It describes the average energy of carriers, generally given in terms of electron energy.

[2] In order for the charge carriers to diffuse further, they have to overcome the potential barriers 'V_{bi}' which is also known as knee voltage i.e. V_{bi} is the minimum voltage that must be applied across the junction in order for the current to start flowing through the diode. It is necessary for maintaining equilibrium at the junction and is not an external potential and therefore can't be measured using a voltmeter.

(ii) Quasi-neutral region on both sides of depletion region, where charge carrier concentration equals the carrier concentration of neutral p or n-region.

(iii) Contact electrodes to collect the charge-carriers generated in the p-n junction device and connect it to external circuit.

3 p-n junction under applied bias

Forward bias and Reversed bias

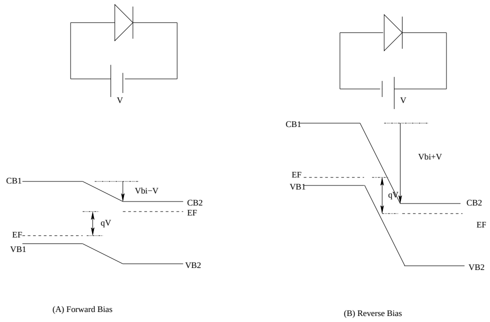
When an external bias (V) is connected across the junction such that the p-side is connected to positive terminal of the battery and n-side to negative terminal, the junction is said to be forward bias. Forward bias lowers the junction potential to $(\mathrm{V_{bi}} - \mathrm{V})$ and thereby increases the probability of carrier diffusion across the junction, by a factor of $\mathrm{e}^{\frac{\mathrm{qV}}{\mathrm{KT}}}$ (known as Boltzman factor). Therefore, diffusion current under FB is given as its equilibrium value multiplied by the Boltzman factor. Under reverse bias condition, p-side is connected to lower potential than n-side, the barrier height at the junction is increased to $(\mathrm{V_{bi}} + \mathrm{V})$ thereby decreasing the diffusion current.

In both the cases, drift current $(\mathrm{I_o})$ being independent of the voltage remains the same. It mainly depends on the number of charge carriers crossing the junction, which depends on the elctron-hole pairs being produced in the depletion region. Therefore, it is also known as the generation current or reverse saturation current as it is the only current flowing through the diode when it is reversed biased.

Therefore under an applied bias, total current flowing through the junction is given as

$$I = I_o(e^{\frac{qV}{KT}} - 1) \tag{5}$$

Where, $\mathrm{V} = +\mathrm{V}$ for forward bias and $\mathrm{V} = -\mathrm{V}$ for reverse bias. The above equation is known as Schokley equation. It is the fundamental equation for micro-electronic devices.



(A) Forward Bias

(B) Reverse Bias

Figure 2: Figure depicting energy-band diagram of a diode under (A) Forward bias (B) Reverse bias

In both the biasing, the drop (V) in the built-in voltage causes an equivalent shift (qV) in fermi level positions from its equilibrium position in absence of biasing on both sides of junction with respect to each other as shown in fig 2.

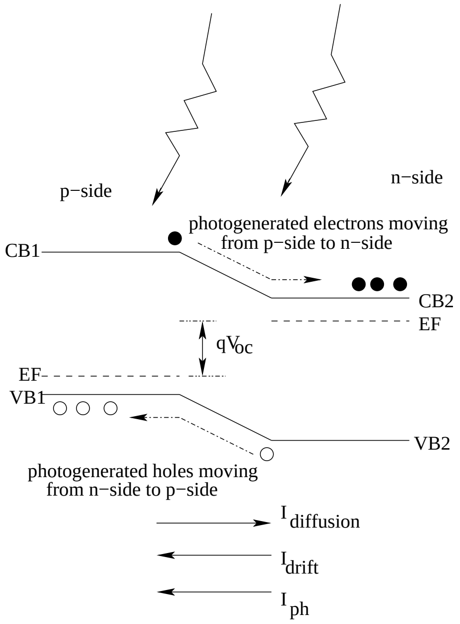


Figure 3: Figure showing energy-band diagram of a p-n junction under illumination.

4 p-n junction under illumination

When a p-n junction is exposed to light having energy greater than the band-gap of the semiconductor in use, electron-hole pairs are produced both at the junction (i.e. in depletion region) as well as in the quasi-neutral region. However, due to presence of large concentration of majority (mobile) carriers in neutral region, rapid recombinations take place. Thus, the total number of photogenerated charge carriers are effectively those generated in depletion region only. In the space-charge region on p-side of the junction, holes (from generated electron-hole pairs) get recaptured by the acceptor ions present there and the elctrons are swept towards the n-side. Similarly the electrons generated on the n-side depletion region, get recaptured by the donor ions there and holes cross the junction to reach p-side. This decreases the number of donor and acceptor ions in the space-charge region and hence decreases the total potential across the junction to ($V_{bi} - V_l$), just like in FB case.

$$I = I_o(e^{\frac{qV_l}{KT}} - 1) - I_{ph} \qquad (6)$$

'V_l' in above equation is the drop in the built-in volatage across the junction on exposure to light, the maximum value it can take is called open-circuit voltage or V_{oc} beyond which the diffusion current will start dominating. The maximum drop in the built-in potential under illumination or the value of V_{oc} is decided by the difference in the position of Fermi-levels of the two materials before junction formation [12] i.e. $E_{fn} - E_{fp}$ (see fig 3), This is the limiting value of open-circuit voltage as fermi-levels can not be shifted beyond these positions in absence of ant external voltage bias. I_{ph} being a negative current i.e. in opposite direction to the convential forward-bias current (I_{diff}), it will shift down the I-V curve to IVth quadrant, as shown in fig 4. V_{oc} can also be seen as the maximum voltage that can be generated across the solar cell terminals i.e. when it is not connected to external load (open-circuit condition). In this case, the charge carriers crossing the junction will reach the respective electrodes and get accumulated there resulting in a potential drop (positive on p-side and negative on n-side). Hence, it is called the open-circuit

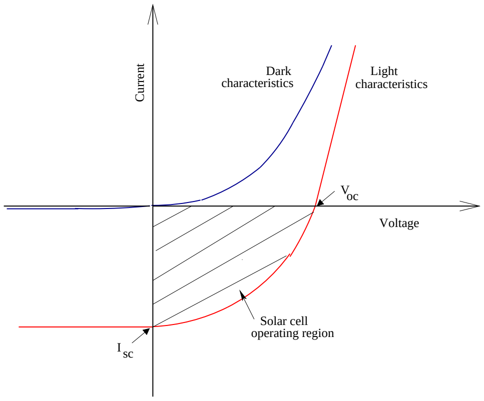


Figure 4: I-V characteristics of a solar cell.

voltage (V_{oc}). It can be derived from eqn (5) as

$$V_{oc} = \frac{KT}{q} ln \left(\frac{I_{ph}}{I_o} + 1 \right) \tag{7}$$

Similarly, the maximum light-current that can be produced on illumination is called short-circuit current or I_{sc}. As the name suggests, it is the maximum current which will flow through the external circuit when p- and n-sides of the junction are short-circuited[3]. Since this current depends on the area of solar cell, J-V curve is generally reported instead of I-V curve, where J is known as the current density and is given as (J = I/area). Such a device which converts solar energy into electrical energy is known as phtovoltaic device or more simply a solar cell.

A p-n junction works as a solar cell in the forth quadrant, where power is negative ($P = V \times (-I)$) i.e. instead of dissipating power, the device is generating the power. But, does that mean all the p-n junctions will work as solar cells under illumination? The answer is 'NO'. For better understanding, we have to look into the details of solar cell physics from a material enggineering point of view. The ability of a p-n diode to work as a solar cell depends on a large number of factors such as

(i) Material's ability to generate carriers upon excitation.

(ii) Length of p- and n-layers and other parameters influencing the charge-carrier transport.

(iii) Selection of electrodes for collection of generated charge carriers.

Before discussing the above points into details, please note that uptil now, we have considered both p and n-layers to be absorbers as in case of crystalline-Silicon solar cells (c-Si). We will now shift our discussion from c-Si type solar cells to thin film solar cells for simplicity. These solar cells have only one absorber layer (p-type or n-type) and the other is just a complimentory layer (transparent to sunlight) forming the junction with the absorber layer.[4] Lets discuss the itemized aspects of device physics one by one.

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[3] In this case, the potential barrier remains unchanged as the total work done is zero i.e. qV = 0

[4] In this article, we are basically dealing with inorganic solar cells which rely on the junction property for charge carrier generation and separation. There are a large number of other solar cells also like oraganic solar cells, dye-sensitized solar cells etc. having different working principle than the inorganic ones. However, the basic material engineering and selection criteria remains the same.

5 Material selection for juction formation

For a p-n junction to operate as solar cell, the two layers forming the junction must fulfil the following criteria.

5.0.1 Optimum band-gap

When a material is exposed to sun, it will absorb light having energy (E) greater than or equal to its band-gap (E_g) while being transparent to other wavelengths. Energy equal to the band-gap is used by the charge carriers to move from valance band to conduction band and rest of the energy ($E-E_g$) is lost/dissipated as heat. Therefore, for applications in solar cells, the material should have an optimum band-gap to absorb maximum portion of solar spectrum with minimum heat dissipation. As we all know that the amount of sunlight reaching the earth's surface depends on the latitude and longitude of the place, for testing purposes the solar spectrum is standardized as AM 1.5,[5] major portion of the spectrum comprises of VIS-IR region. Theoretically, the band-gap for maximum solar cell output is estimated to be ≈ 1.5 eV for AM 1.5 spectrum [11].

5.1 Minimum lattice-mismatch between layers

The layers forming the junctons should have minimum lattice mismatch in their crystal structure so as to avoid the formation of any defect at the interface. These defects hinder the movement of charge-carriers and might result in trapping or recombination and hence degrade the solar cell performance.

5.2 Band discontinuity between lattice-matched p and n-layers

Under the section 'p-n junctions', we have already discussed the band-bending considering both the p- and n-layers are of the same material eg.(p-Si/n-Si) and therefore have their conducton band and valance band at same level in energy-diagram and the only difference is in the position of fermi-levels due to different doping type in the two layers. Such p-n junctions are called homo-junctions (as shown in fig 1). However, when a juncton is formed using p- and n-layers of different materials eg.(p-SnS/n-ZnO), having different band-gap and electron effinities,[6] a discontinuity is generated in their band-structure as Fermi levels line up at equilibrium [13]. The discontinuity in conduction band of the two layers is known as the conduction band offset (E_c) and is given as the difference in the electron effinities of the two layers. Sim-

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[5] 'AM' stands for air mass and is given as the secant of angle that the sun makes with the zenith, for AM 1.5 spectrum, this angle is 45°.

[6] electron effinity of a semiconductor is defined as the energy difference between it's conduction band edge and the vacuum level

ilarly, the discontinuity in valance band is known as valance band offset ($\mathrm{E_v}$) (see fig 5). These junctions are called heterojunctions. If the absorber layer is of p-type, then the $\mathrm{E_c}$ (with respect to n-type junction layer) plays a major role [14] while for a solar cell having n-type absorber layer, $\mathrm{E_v}$ (with respect to p-type junction layer) decides the junction quality [15]. If ($\mathrm{E_c}$) or ($\mathrm{E_v}$) is large (greater than 0.3 V), it will effect the band-bending and would lead to the formation of spike or cliff structures at the junction as shown in fig 5. The shape of the energy bands can be easily found out by solving Poisson's equation with boundary conditions of continuous electric flux density at the junction (i.e. $\epsilon_\mathrm{p}\mathrm{E_p} = \epsilon_\mathrm{n}\mathrm{E_n}$), where '$\epsilon_\mathrm{p}$' and '$\epsilon_\mathrm{n}$' are the dielectric constants of the p- and n-layers. Formation of spike or cliff at the junction degrade the junction quality by trapping the carriers instead of promoting the charge-separation.

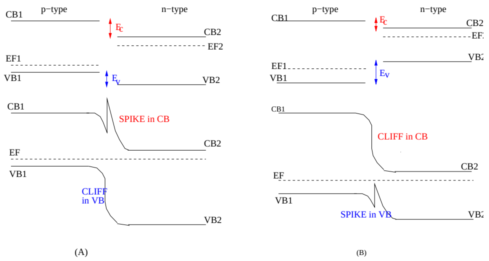

Figure 5: Figure showing the spike and cliff formation in a heterojunction.

6 Length of different regions of p-n junction

After separation at the junction, the generated charge carriers have to travel different regions (depletion region and quasi-neutral regions) to reach the external circuit. The length of each region effects the carrier transport and in turn effects the overall solar cell efficiency. Some of the factors effecting the thickness of these leyers are

6.1 Absorption coefficient

The absorption of light by a material does not only depend on the band-gap and energy of incident photon but also depends on the ability of a material to absorb and is given by the absorption coefficient (α).

Absorption coefficient (unit cm^{-1}) determines the length traversed by the light (of a perticular wavelength, λ) in a material before getting absorbed. It can be easily derived from Beer Lambert's law [16]

$$I_z = I_o e^{-\alpha z} \tag{8}$$

where, '$\mathrm{I_z'}$ is the light intensity after travelling distance 'z' in the material. '$\mathrm{I_o'}$ is the incident light intensity. Penetration depth is given as ($\frac{1}{\alpha}$ cm).

Absorption coefficient of the material should be large enough to absorb maximum sunlight incident on it so that the minimum amount of material is required (it will minimize the material's cost). Therefore, the length of absorber layer should be optimized according to its absorption coefficient such that considerable amount of light reach the junction before getting completely absorbed by the material since effective number of charge carriers are generated in depletion region (near the junction) only as discussed in sections above.

6.2 Diffusion length of carriers

Another major factor deciding the lengths of quasi-neutral and space-charge regions in solar cell is the diffusion-length of the charge carriers. Diffusion length by principle, is the distance travelled by a charge carrier between subsequent collisions or before getting recombine. It is propotional to the product of mobility μ and life-time τ of charge-carriers i.e. $\sqrt{\mu\tau}$ [11].

The electron-hole pair produced inside space-charge region should cross the junction before getting recombine i.e. electrons have to reach n-side and holes p-side without recombination. Since these carriers are minority carriers in the region where they are produced, the depletion layer width should be less than the diffusion length of the minority carriers produced on that side of the junction. This implies that the optimum depletion layer width on p-side of the junction would be decided by the diffusion length of the electrons in p-type material and similarly the optimum width of depletion region on n-side would depend on the diffusion length of holes in n-type material.

Upon crossing the junction, holes and electrons have to travel p-region and n-region respectively (where they are majority carriers) to reach the electrodes. However, during their journey across the quasi-neutral region, these charge carriers can encounter a large number of collisions and recombinations[7] [11] with mobile carriers already present there implying that even in these regions, they have a finite lifetime associated with them. Thus, conductivity of the material becomes another decisive factor as it will effect the mobility of the respective charge-carrier and hence the majority carrier's diffusion length. To sum up, the optimum length of the depletion region is decided by the minority carrier's diffusion length while that of quasi-neutral regions by majority carrier's diffusion length, making conductivity (or doping)[8] a major decisive factor.

7 Contact electrodes

To collect the photo-generated carriers and to feed them to external circuit, metal contacts are made on both sides of semiconductor layers. Contact on the side from where light enters into the cell is known as front contact and the contact on the opposite side is known as the back contact.

Depending on the work function of the metal and the semiconductor, two types of junctions/contacts are formed between them

(i) Ohmic contact

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[7] There are mailny four different types of recombinations in a semiconductor namely band to band recombination, R-G cenetrs recombination, excitonic recombination and Augur recombination.

[8] conductivity (σ) of a material is related to carrier concentration (N) by relation $\sigma = \mathrm{q}\mathrm{N}\mu$

(ii) Rectifying contact

Ohmic contacts follow the linear V = IR relation and are best for collection of charge carriers. While in case of rectifying contacts, a junction is formed at the metal-semiconductor interface (i.e. ohm's law does not apply anymore) leading to loss of carriers in overcoming the junction barrier. For a p-type absorber layer, metal work function should be more as compared to the p-type semiconductor material used to obtain an ohmic contact while it should be less for making an ohmic contact with n-type semiconductor as shown in fig 6. Conventionlly, metals like Al, In, Cu, Ag and Au are used for making contacts. Front contact is generally made in form of very thin metal strips to allow maximum light to enter the cell while thin metal sheets are grown as back contacts to prevent light from escaping the cell. Now-a-days special type of wide-band semiconductors having low sheet resistance ($< 10\ \Omega/\Box$) and high transmittance are gaining populaity. These semiconductors are known as Transparent conducting oxides or TCO's. Some of the widely used TCO's are ZnO, Al:ZnO, FTO, ITO etc. While for back contacts, metals remain the best choice for their good reflectivity.

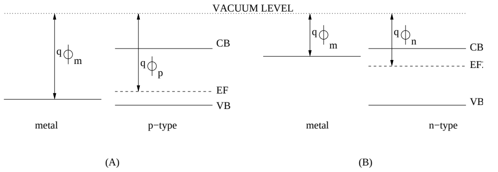

Figure 6: A representative of energy-band allignment suitable for ohmic-junction formation between (A) metal and p-type semiconductor (B) metal and n-type semiconductor.

8 Ideal solar cell

Concluding from above discussion, an ideal solar cell should only have depletion region with no (or zero length) neutral region and electrodes placed at the junction boundary at $\mathrm{x_n}$ and $\mathrm{x_p}$ as shown in fig 7. If diffusion length of holes and electrons in n- and p-region be $\mathrm{L_p}$ and $\mathrm{L_n}$ respectively. Then

$$x_n \le L_p$$
$$x_p \le L_n$$

or

$$(x_n + x_p) \le (L_p + L_n) \tag{9}$$

Now, if penetration length is $\left(\frac{1}{\alpha}\right)$, then following condition has to be satisfied for all the depletion region to be illuminated

$$\left(\frac{1}{\alpha}\right) \ge (L_p + L_n) \ge (x_n + x_p) \tag{10}$$

However, to have a zero neutral region is not possible but ts length can be minimized by careful material engineering.

9 Characteristics of a solar cell

Once a p-n junction is made, it is tested to check whether it will function as a solar cell

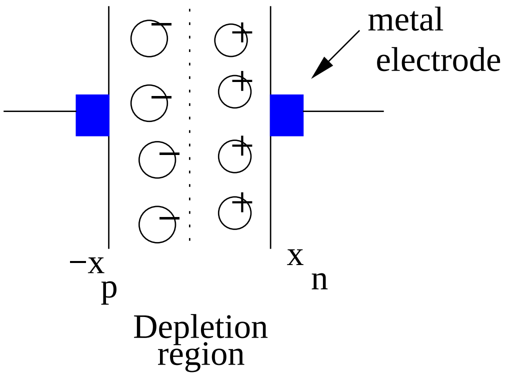

Figure 7: An ideal solar cell.

on exposure of light or not? for this purpose, I-V or (J-V) characteristics of the junction are recorded for a moving bias of (-V to +V) under AM 1.5 spectra.

Negative bias (-V to 0) is applied to ensure the quality of the junction i.e. it should not break down under the reverse bias conditions. Also under reverse bias conditions, charge carriers are “sucked out” of the device resulting in a current, flowing opposite to the direction of conventional diode current (I_{diff} during forward bias). Therefore, reverse bias ensures that the current flowing through the cell is purely due to generation of charge carriers in the device.

A p-n junction will continue to function as a solar cell (i.e. I-V in IVth quadrant) until the applied bias reaches V_{oc}, beyond which the diode gets forward bias or in other words the barrier at junction get so reduced that the forward current starts dominating.

To check the quality of the fabricated solar cells, following quantities are defined

Fill Factor (FF)

To draw maximum power from a device, the area of the rectangle enclosed[9] by the J-V curve should be maximised or in other words the squareness of the I-V curve should be increased. The point at which the rectangle touches the I-V curve (fig 8)is known as the maximum power-point and the corresponding output voltage and current are labelled as V_m and I_m. The parameters used to define/quantize the squareness of a solar-cell I-V curve is called Fill factor (FF) and is given as

$$FF = \frac{areaoflargestrectangle}{totalareaunderI - Vcurve} = \frac{V_m I_m}{V_{oc} I_{sc}} \quad (11)$$

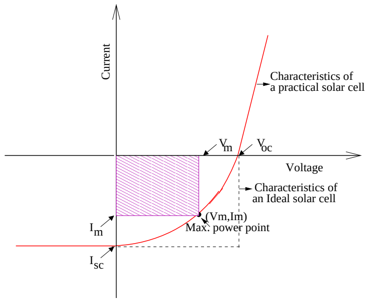

Figure 8: I-V characteristics of a practical and an ideal solar cell.

Power Efficiency (η)

The power efficiency of a solar cell is simply the ratio of maximum power that can be

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[9] The power generated/dissipated by any device is the area of rectangle completely enclosed by the I-V curve.

extracted from it to the total optical power incident.

$$\eta(\%) = \frac{V_m I_m}{P_{in}} = \frac{FF \times V_{oc} I_{sc}}{P_{in}} \times 100(\%) \quad (12)$$

A p-n junction with good Fill factor will ensure a higher efficiency and hence would be a good solar cell.

Power efficiency (η) as discussed above is basically concerned with the total output power from a solar cell which along with material's ability to convert photons to electron-hole pairs include a lot of other factors such as design of solar cells such as shape and size of different solar cell layers, biasing of solar cell etc.

To characterize the intrinsic nature of solar cells (i.e. number of electrons produced per incident photon) and to separate it from rest of the factors, another term has been defined by the researchers known as the Quantum efficiency. Two types of efficiencies have been defined

Internal Quantum efficiency (IQE)

It tells about the junction quality, separating it from the material's ability of absorbing the photon. It is defined as the ratio of number of electrons collected to the totatl number of photons absorbed.

External Quantum efficiency (EQE)

It takes into account the solar cell design along with the property of the material. It is given as the ratio of the number of electrons collected to the total number of photons incident.

10 Modeling of a solar cell

To model an ideal solar cell, a current source is used connected in parallel with a diode [11] as shown in fig 9. The current source is used as the photogenerated current remains constant for a given illumination level irrespective of the load connected across the solar cell while the diode element indicates the directional property of the current (i.e. from p to n-side). This is the main difference between a solar cell and a battery (apart from battery's limited lifetime) that the battery provides a constant emf across its terminals while varying the current depending on the circuital elements. In solar cells, the current depends on the number of photogenerated charge carriers while the voltage is determined mainly by the

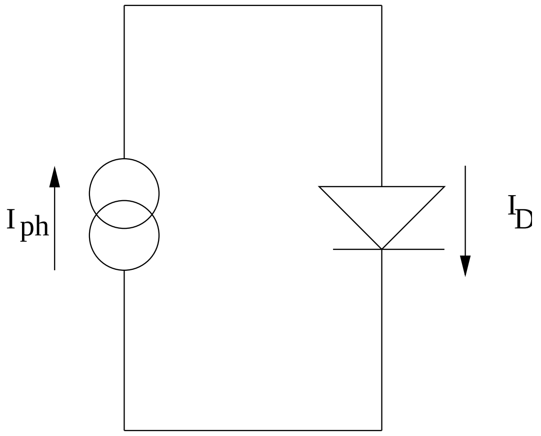

Figure 9: Equivalent model of an ideal solar cell.

load connected[10]. However, during their journey from junction to electrodes, these charge carriers have to travel various regions having different resistances and can face recombination at grain boundaries, bulk and at interfaces between layers etc. All thses losses are modelled as series and shunt resistances connected across the solar cell and indicate a decrease in its efficiency by dissipating power [11]. Series resistance represents the difficulty of hole and electron motion due to bulk resistances of semiconductors and metals used and the contact resistances between the two. Shunt resistance arises from current leakage through the device (around the edges and between the contacts), it also includes the effect of foreign impurities and crystal defects induced while fabrication. The resultant equivalent circuital model of solar cell is shown in fig 10. This is a standard one-diode model. Two or more diodes are also used in some cases to account for increased recombinations due to grain boundaries etc. However, in this article we will limit our discussion to one-diode model only. In the figure ‘$\mathrm{I}'_{\mathrm{ph}}$ is the photo-current, ‘V'_{D} and ‘I'_{D} are the diode voltage and current given, ‘V' and ‘I' are total voltage and current through the circuit.

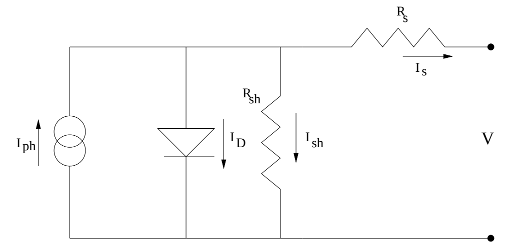

Figure 10: One-diode equivalent model of a solar cell.

Applying KCL gives,

$$I_{ph} - I_D - I_{sh} - I = 0 \tag{13}$$

Using eqn (5)

$$I = I_{ph} - I_o(e^{\frac{qV_D}{KT}} - 1) - I_{sh} \tag{14}$$

Also $\mathrm{V_D = V + IR_s}$ and

$$I_{sh} = \frac{V + IR_s}{R_sh} \tag{15}$$

substituting in eqn (14) gives

$$I = I_{ph} - I_o(e^{\frac{q(V+IR_s)}{KT}} - 1) - \frac{V + IR_s}{R_sh} \tag{16}$$

As seen in previous sections, the photogenerated charge carriers undergo recombination in the depletion region as well as the neutral regions. To include this effect, the eqn 5 is modified as

$$I = I_o(e^{\frac{qV}{nKT}} - 1) \tag{17}$$

Where, ‘n’ is the ideality factor, it determines the departure of a p-n junction characteristcs from the ideal diode characteristics. Generally, n varies from 1 to 2 for a practical solar cell with n = 1 for an ihere deal junction solar cell. However, there have been reports of p-n junction, with n = 2/3 (due to Auger recombination taking place) and n > 2 (due to recombinations at the grain boundaries and tunneling effects). Therefore, eqn 18 becomes

$$I = I_{ph} - I_o(e^{\frac{q(V+IR_s)}{nKT}} - 1) - \frac{V + IR_s}{R_sh} \tag{18}$$

This is the characteristic equation of a practical solar cell.

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[10] Assuming that all the generated carriers are collected at the electrodes.

10.1 Effect of R$_s$ and R$_{sh}$ on I-V characteristics of a solar cell

R$_s$ being a series connection between the etrnal circuit and the cell, controls the value of maximum current flowing through the device (under the assumption $R_{sh} \gg R_s$). For a very small value of R$_s$, I $\approx$ I$_{sc}$. While controlling I$_{sc}$, it does not affect the open-circuit voltage of the cell as at this point, the photo-generated current and hence the current through R$_s$ is zero. As seen from the equivalent circuit in fig 10, R$_{sh}$ provides an alternate path for current and thus affects the voltage across the solar cell terminals. This voltage will be equal to V$_{oc}$ for R$_{sh}$ $\approx \infty$. Generally, $R_{sh} \gg R_s$ therefore, it does not affect the total current (I) as already discussed. The values of R$_{sh}$ and R$_s$ can be estimated using the I-V curve as

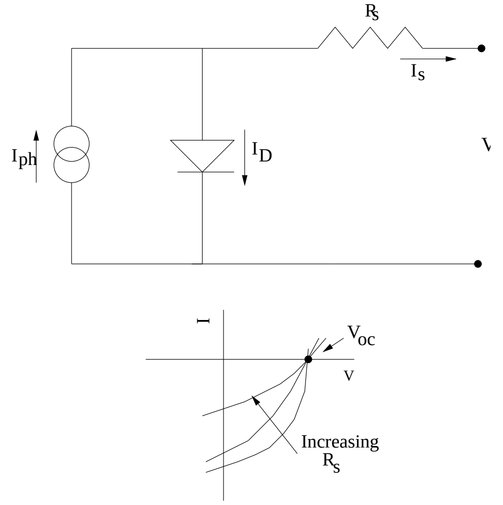

Figure 11: Effect of R$_s$ on solar cell characteristics.

$$R_s = \left(\frac{dV}{dI}\right)_{V=V_{oc}} \quad (19)$$

$$R_{sh} = \left(\frac{dV}{dI}\right)_{V=I_{sc}} \quad (20)$$

Values of both the resistances greatly affects the sharpness of I-V curve. R$_s$ alters the short-circuit current, which will decrease as the value of R$_s$ increases, keeping open-circuit voltage constant fig 11. On the other hand, as the value of shunt resistance decreases, the voltage across the diode will decrease and hence the V$_{oc}$ will decrease as shown in fig 12. The I-V curve will take the shape of a straight line intersecting the two axis at V$_{oc}$ and I$_{sc}$ if the values of the two resistances diverge greatly from their ideal values.

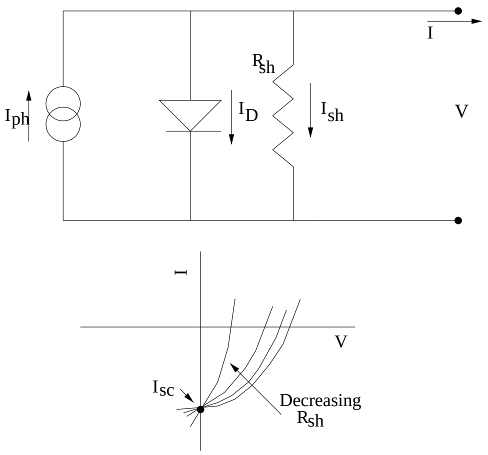

Figure 12: Effect of R$_{sh}$ on solar cell characteristics.

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