

Solar Cells Technology: An Engine for National Development

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Abstract: An overview of the available solar cells was discussed in this work. These include how solar cells work starting from the electronic properties of semiconductor, the overall structure of the cell and explanation on how it produces electricity. Discussion on the price fall of a solar cell material (silicon), the price fall of the cell and the price fall of the module. Various applications were mentioned together with power losses which occur during operation (recombination loss, losses dependent on the structure of the device, and loss as a result of the inability of the semiconductor to absorb the below band gap light). Measures on how to reduce the power losses was discussed. Also the most important effect that must be allowed for operation under standard conditions was discussed.

Keywords: solar cells, semiconductor, electrons and holes, energy band, irradiance

Nomenclature:

E_c =conduction band

E_h =hole energy

E_v =valence energy

E_e =electron energy

E_g =energy gap

G = irradiance, W/m^2

I_{sc} = short circuit current, A

I_e =light- generated current, A

I_m =current at maximum power, A

I_o =Dark saturation current, A

m =Non-ideality factor

I. Introduction

Solar cells represent the fundamental power conversion unit of a photovoltaic system. They are made from semiconductors and have much in common with other solid-state devices, such as diodes, transistors and integrated circuits. They are usually assembled into modules for practical operation[1]. The range of solar cells spans different materials and different structures in the quest to extract maximum power from the device while keeping the cost to a minimum. This device with efficiency exceeding 30 percent have been demonstrated in the laboratory while the efficiency of the commercial devices is usually less than half this value. Cheap cells are now often made from multi-crystalline material, rather than from the more expensive single crystal. Hence, crystalline silicon cell modules have a long lifetime(20 years or more) and their best production efficiency is approaching 18 percent. Cheaper but less efficient types of silicon cells, made in the form of amorphous thin films are used to power various consumer products which include solar- powered watches and calculators [1].

Also, compound semiconductor can also be used to manufacture thin-film cells(cadmium telluride(CdTe) or copper indium diselenide(CuInSe₂). These modules are now beginning to appear on the market and hold the promise of combining low cost with acceptable conversion efficiencies. However, particular class of high-efficiency solar cells from single crystal silicon or compound semiconductor(gallium arsenide(GaAs) or indium phosphide (InP)) are used in specialized applications such as power satellites or in system which operate under high- intensity concentrated sunlight[2].

Below is a sketch showing the price of the silicon material, solar cell and module cost:

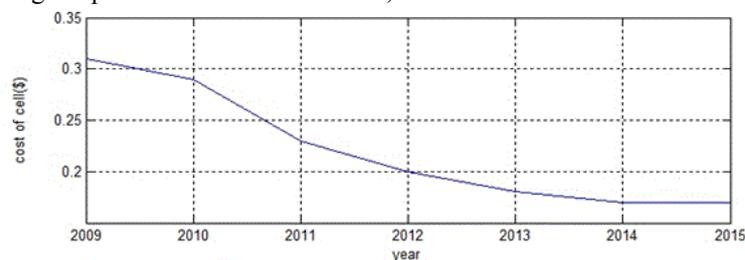


Fig. 1: Graph of cost of cell(\$) against year

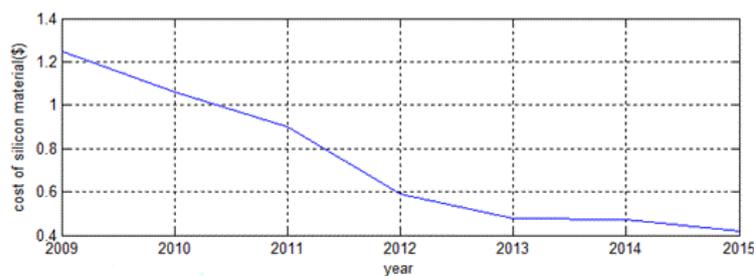


Fig. 2: Graph of cost of silicon material (\$) against year

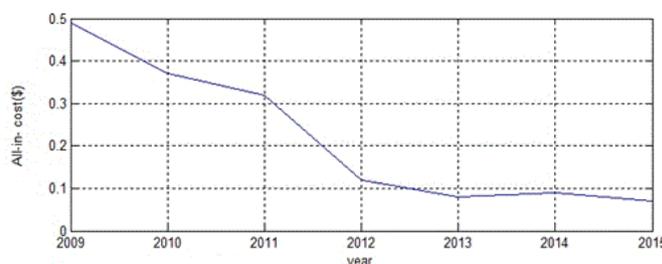


Fig. 3: Graph of All-in-cost (module) (\$) against year

II. Review Of Electronic Structure Of Semiconductor

The principles of semiconductor physics are best illustrated by the example of silicon, a group 4 elemental semiconductor. The silicon crystal forms the so-called diamond lattice where each atom has four nearest neighbors at the vertices of a tetrahedron. The four-fold tetrahedral coordination is the result of the bounding arrangement which uses the four outer (valence) electrons of each silicon atom. Each band contains two electrons. This crystal structure has a profound effect on the electronic and optical properties of the semiconductor.

According to the quantum theory, the energy of an electron in crystal must fall within well-defined bands. The energy of valence orbital which form bonds between the atoms represent just such a band of states; the valence band. The next higher band by the energy gap or band gap. The width of the band gap $E_c - E_v$ is a very important characteristic of the semiconductor and is usually denoted by E_g . Below gives the table of band gaps of the most important semiconductors for solar cell application [1,2].

Table 1: Energy gaps of principal semiconductor for photovoltaic applications [1]

Material	Energy gap(eV)	Type of gap	Remarks
Crystalline Si	1.12	Indirect	Gap values are at room temperature.
Amorphous	1.75	Direct	
CuInSi ₂	1.65	Direct	
CdTe	1.45	Direct	
GaAs	1.42	Direct	
InP	1.34	Direct	

A pure semiconductor (intrinsic) contains just the right number of electrons to fill the valence band and the conduction band is therefore empty. Electrons in the full valence band cannot move (a pure semiconductor is an insulator). Semiconductor can only conduct electricity if carriers are introduced into the conduction band or removed from the valence band. This can be done by alloying the semiconductor with impurity (doping)[1]. This makes it possible to exert a great deal of control over the electronic properties of a semiconductor. Some group 5 impurity atoms (phosphorus) are added to the silicon melt from which the crystal is grown. Four of five outer electrons are used to fill the valence band and the one extra electron from each impurity atom is therefore promoted to the conduction band, these impurity atoms are called donors. The electron in the conduction band are mobile and the crystal becomes a conductor, since the current is carried by negatively charged electrons, this type of semiconductor is called n-type. Similarly the same situation occurs when silicon is doped with group 3 impurity atoms (boron) which are called acceptors. Since four electrons per atom are needed to fill the valence band completely; this doping creates electron deficiency in this band. The missing electrons (holes) behave as

positively charged particles which are mobile and carry current[1,3,4]. A semiconductor where the electric current is carried mainly by holes is called p-type. The prevailing charge carries in a given semiconductor are called majority carries(in an n-type semiconductor -electrons, in a p-type semiconductor-holes). The opposite type of carrier whose concentration is generally much lower are called minority carriers.

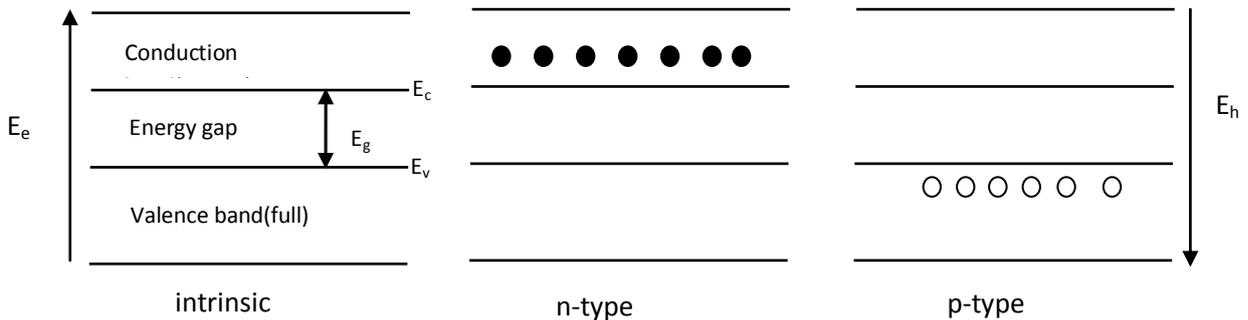


Fig.4: Band diagram and electron-hole distribution in semiconductor

2.1 How Solar Cells Work

The solar cell operation is based on the ability of semiconductor to convert sunlight directly into electricity by exploiting the photovoltaic effect. In the conversion process, the incident energy of light creates mobile charged particles in the semiconductor which are then separated by the device structure and produce electrical current. The operation of solar cells is based on the information of a junction. The simplest form is the n-p junction(an interface between the n-and p-type regions, resulting in a wider transition zone [1].

In general, the properties of metal contacts with a semiconductor depend on the actual materials in question. For each semiconductor, some metals form a Schottky barrier(a junction formed at an interface between a metal and a semiconductor) but some form an ohmic contact where the barrier is absent. These contacts are used to extract electrical current from the device. The most important feature of all junction is that they contain a strong electric field. These electric field in the junction pulls the electrons and holes in opposite directions. To illustrate how this field comes about, imagine a situation where the p-n junction is formed by joining together two pieces of semiconductor, one p-type and the other n-type(although this manner of junction formation is not normally employed in practice. It is a convenient means to demonstrate the relevant principles. In separation, there is electron surplus in the n-type material and hole surplus in the p-type. When the two piece are brought into contact, electrons from the n region near the interface diffuse into the p side leaving behind a layer which is positively charged by the donors. Similarly, holes diffuse in the opposite direction leaving behind a negatively charged layer stripped of holes. The resulting junction region then contains practically no mobile charge carries and the fixed charges of the doping atoms create a potential barrier acting against a further flow of electrons and holes in opposite directions.

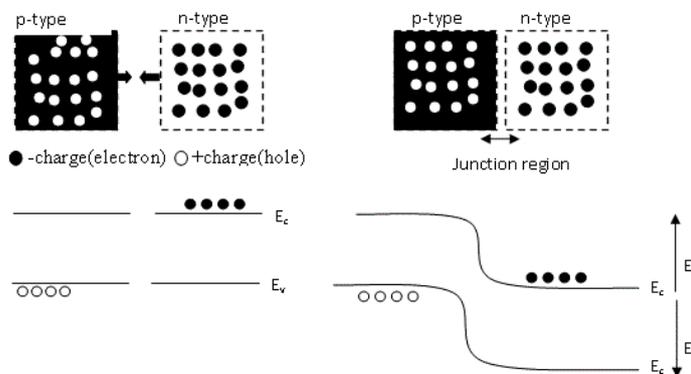


Fig.5 Diagram of p-n junction formation and the resulting band

2.2 Light Absorption By A Semiconductor

Photovoltaic energy conversion relies on the quantum nature of light whereby we perceive light as a flux of particles-photos which carry the energy.

$$E_{ph}(\lambda) = \frac{hc}{\lambda} \tag{1}$$

Where h is the planck constant, c is the speed of light, and λ is the wavelength of light (Note: on a clear day, about 4.4×10^{17} photos strike a square centimeter of the earth's surface every second). Only some of these photos- those with energy in excess of the band gap can be converted into electricity by the solar cell. When such a photo enters the semiconductor. It may be absorbed and promote an electron from the valence to the conduction band. Since a hole is left behind in the valence to the valence band, the absorption process generates electron-hole pairs. Each semiconductor is therefore restricted to converting only a part of the solar spectrum. Analyzing the equation above, the nature of the absorption process also indicates how a part of the incident photo energy is lost in the event. Indeed, it is seen that practically all the generated electron-hole pairs have energy in excess of the band gap. Immediately after their creation, the electron and hole decay to states near the edges of their respective bands. The excess is lost as heat and cannot be converted into useful power. This represent one of the fundamental loss mechanism in a solar cell [1,4,5].

More so we can roughly estimate the magnitude of electrical current produce. Interpreting the light-induced traffic across the band gap as electron current, called the generation current. A solar cell can indeed transform this fictitious current into real electric current across the device. Neglecting losses, each photo then contributes one electron charge to the generating current. The electric current is then equal to

$$I_e = qNA \tag{2}$$

Where N is the number of photo in the highlighted area of the spectrum and A is the surface area of the semiconductor that is exposed to light. The current density is given as

$$J_e = I_e A \tag{3}$$

The electric power is produced by separating the light-generated electron and holes to the terminals of the device. This separation can only proceed if the electrostatic energy of the charges after separation equal to the band gap. This sets an upper limit on the voltage in the form

$$V = \frac{E_g}{q} \tag{4}$$

Thus the maximum voltage in volts is thus numerically equal to the band gap of the semiconductor in electron volts. It therefore imply that wide-band gap semiconductor produce higher voltage. Many semiconductor are good light absorbers and absorb all the above-band gap light in a layer of few micrometers thick. They are called direct- band-gap semiconductor while others are indirect-gap semiconductor ;which include also crystalline silicon. Note that a quantum of lattice vibration must participate in the conversion of a photo into an electron-hole pair to conserve momentum which hinders the process and decrease the capability of the semiconductor to absorb light. Also several hundred micro-meters of silicon are necessary to absorb all the above-band gap light but few micro meters of a direct-gap material (GaAs) are sufficient for this purpose [1].

III. Power Losses In Solar Cells

FUNDAMENTAL LOSSES: Carrier generation in the semiconductor by light involves considerable dissipation of the generated carrier energy into heat. In addition, a considerable part of the solar spectrum is not utilized because of the inability of a semiconductor to absorb the below band gap light. This sum up to power losses in the solar cells. But with a simple device called tandem cell(a stack of several cells each operating according to the principles that we have described) can be used to reduce these loss. The top cell must be made of a high band gap semiconductor and converts the short- wavelength radiation. The transmitted light is then converted by the bottom cell. This arrangement increases considerably the achievable efficiency [1].

RECOMBINATION LOSSES: An opposite to carrier generation is recombination when an electron hole pair is annihilated. Recombination is most common at impurities or defects of the crystal structure, or at the surface of the semiconductor where energy levels may be introduced inside the energy gap. These levels act as stepping stones for the electrons to fall back into the valence band and recombine with holes. An important site of recombination are also the ohmic metals contacts to the semiconductor. Surface recombination and recombination at contacts which are considerable in the conventional silicon cell can be reduced by adapting the device structure. Here the external surface of the semiconductor are protected by a layer of passivating oxide to reduce surface recombination(the top layer of GaAIAs in GaAs cell has a similar purpose). The contacts are surrounded by heavily -doped regions acting as minority- carrier mirrors which impede the minority carriers

from reaching the contacts and recombining. Recombination reduces both the voltage and current output from the cell.

Other losses to the current produced by the cell arise from light reflection from the top surface, shading of the cell by the top contacts and incomplete absorption of light. The last feature is particularly significant for crystalline silicon cells. The top contact shading is of particular concern for cells which operate under concentrated high-intensity sunlight. It is then advantageous to eliminate the shading altogether, as in the Stanford point-contact cell, by moving both contacts to the back of the cell. The top surface reflection can be reduced further by the application of two or more layers. Also surface texturing when combine with a single-layer ARC, the reflectivity of the surface can be brought down to 1 percent [1,2,5].

The absorption of light in silicon cell can be improved by making the back contact optically reflecting. When combine with a textured top surface this geometry result in effective light trapping which provides a good countermeasure for the low absorption of silicon. The transmission of electric current produced by the solar cell involves ohmic losses. These can be grouped together and included as a resistance in the equivalent circuit. it is seen that the series resistance affects the cell operation mainly by reducing the fill factor.

The I-V characteristic of a practical solar cells is sometimes best approximated by a modified expression

$$I = I_e - I_o \left[\exp\left(\frac{qV + IR_s}{mkT}\right) - 1 \right] \quad (5)$$

Which also includes the series resistance R_s .

Here, m is an empirical non-ideality factor whose value is usually close to unity. The light-generated current is taken as a measured parameter which takes into account all the current losses in the cell. Below is a summary of the losses discussed assuming the solar cell absorb 100Mw.

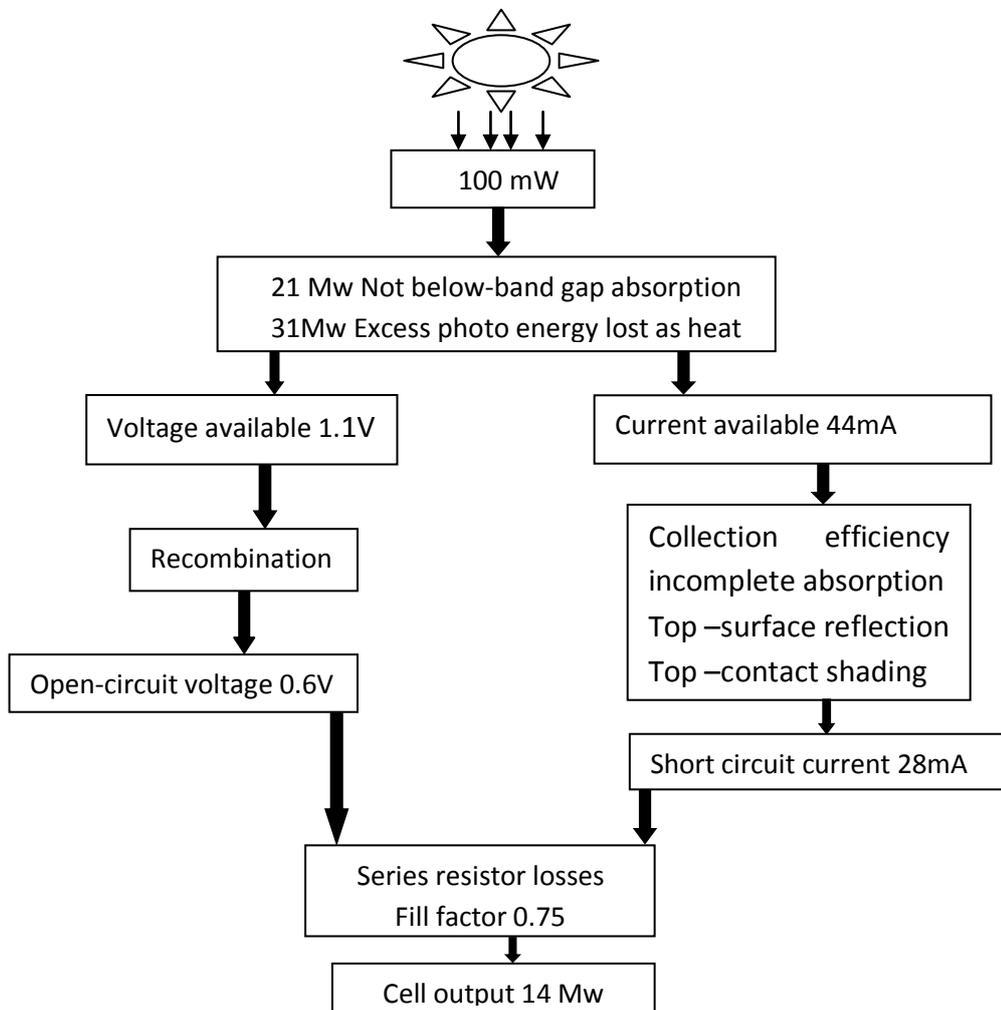


Fig.6: Power losses in silicon solar cells

The losses which we have discussed are summarized above. It is seen that the fundamental losses reduce the maximum theoretical efficiency of a silicon cell to about 48 percent. Additional voltage losses is approximately 36 percent, current losses is approximately 10 percent and losses associated with the fill factor is approximately 20 percent then explain the efficiency of about 23 percent for the best silicon cell today. Higher efficiencies have been obtained under concentrated sunlight, in de vice from other materials or in tandem structure.

3.1 TEMPERATURE AND IRRADIANCE EFFECTS ON SOLAR CELLS

In practical application ,solar cells do not operate under standard conditions. The two most important effects that must be allowed for are due to the variable temperature and irradiance[1].

Temperature: This has an important effect on the power output from the cell. The most significant is the temperature dependence of the voltage which decreases with increasing temperature (its temperature coefficient is negative). The voltage decrease of a silicon cell is typically 2.3mV per °C. The temperature variation of the current or the fill factor are less pronounced and are usually neglected in the PV system design.

Effects of irradiance: This is solar cell characteristics under different levels of illumination. The light generated current is proportional to the flux of photos with above- band gap energy. Increasing the irradiance increases, in the same proportion, the photo flux which in turn generates a proportional higher current. Hence the short circuit of a solar cell is directly proportional to the irradiance, it depends logarithmically on the irradiance and is usually neglected in practical applications.

IV. Conclusion

The solar cell is a semiconductor device that converts the quantum flux of photons into electric current. When light is absorbed, it first creates electron-hole pairs. These mobile charges are then separated by the electric fields at the junction. The electrical output from the cell is described by the I-V characteristic whose parameters can be linked to the material properties of the semiconductor. In this work, various solar cell structure were discussed in relation to the principal power losses in a solar cell. In addition to the fundamental losses associated with light absorption-(loss as a result of the inability of a semiconductor to absorb the below band gap light), other losses including recombination and losses dependent on the structure of the device have been analyzed in some detail. However, the price of silicon material, solar cell, module are decreasing with an average rate of about 0.19 \$ per year. Also it has been proven that solar cells as an alternate source of power generation is environmentally friendly.

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