Analysis on Conversion Efficiency of Homojunction and Heterojunction Solar Cell Using Semiconductor Materials

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Abstract:- With the aim of analyzing the performance of solar cell, the most frequently used parameter is the conversion efficiency. In this paper, the conversion efficiencies for homojunction and heterojunction solar cells are determined. There are four types of solar cell semiconductor materials used in this system which are group IV elemental semiconductor material, group III-V binary compounds, group II-VI binary compounds and group III-V ternary compounds. For group IV elemental semiconductor material, silicon (Si) material is used. For group III-V binary compounds, gallium arsenide (GaAs) and indium phosphide (InP) are used. For group II-VI binary compounds, cadmium telluride (CdTe) and cadmium sulphide (CdS) are used. For group III-V ternary compounds, aluminium gallium arsenide ($Al_xGa_{1-x}As$), gallium indium arsenide ($Ga_{1-x}In_xAs$) and gallium indium phosphide ($Ga_{1-x}In_xP$) are used. Firstly, the conversion efficiencies are calculated by combining these materials as homojunction. Secondly, the conversion efficiencies are evaluated by combining these materials as heterojunction. Finally, the obtained conversion efficiencies are compared and determined whether it is more suitable in p-side or n-side for each material.

Keywords:- *Conversion Efficiency, Homojunction, Heterojunction.*

I. INTRODUCTION

A solar cell is an electronic device which directly converts the light of the brightest star into electrical energy. A current and a voltage that generated while shining light on the solar cell produce the electrical power. This process requires two stages. Firstly, the light absorbed by semiconductor materials create an electron at the high energy state, and finally, that electron moves from the solar cell into an external load [4].

The conversion efficiency is the important candidate in the comparison of solar cell performance and in mathematical development of semiconductor materials. Silicon is left the material of choice for solar cell because of its non-toxicity, abundance, stable and high cell efficiencies, and the advancement of production infrastructure. The short-circuit current I_{sc} of solar cell reaches peak value when the energy band gap is zero and becomes less when the energy band gap is increased. Depending on the photon current that is absorbed, this current will be changed. The open-circuit voltage V_{oc} is zero when the energy band gap is zero and increases when the energy band gap is increased. Therefore, the conversion efficiency η is zero in two conditions. These two conditions are at the energy band gap is zero and at the energy band gap is infinity. The peak conversion efficiency occurs between these two conditions [1].

Homojunction is a semiconductor interface that can be found between layers of similar semiconductor material. These materials have similar band gaps but typically have dissimilar doping [6]. Heterojunction is a semiconductor interface that can be found between two dissimilar semiconductor materials. In contract to homojunction, the materials have different band gaps. A device by combining the multiple heterojunction together is called a heterostructure [7].

AM1.5 is the typical spectrum for solar cell conversion, considering absorption and scattering in the atmosphere. AM is the short form for air mass and is assigned by $1/\cos\theta$. The Shockley-Queisser limit is the greatest amount for the conversion from sunlight to electricity of a single junction solar cell for a given illumination spectrum [2].

The rest of the paper is catalogued as follows. Section II describes the theoretical background of analysis. Section III mentions the implementation and analysis for conversion efficiency for solar cells based on the semiconductor materials. Section IV discusses on the results of the implementation simulated by MATLAB. After all, section V concludes the research work.

II. BACKGROUND THEORY

In order to maximize the solar cell conversion efficiency, the following processes are required:

- accelerating the amount of light accumulated by the cell that is altered into carriers;
- accelerating the accumulation of carriers generating light by the p-n junction;
- attenuating the dark current flow by forward biasing;
- choosing the current flowing from the solar cell not including resistive losses [5].

A. Solar Cell Efficiency

The allocation of sunlight converted to electric energy by means of photovoltaics by the solar cell is known as the solar cell efficiency. Thermodynamic efficiency, reflectance efficiency, charge carrier collection efficiency, conduction efficiency and charge carrier separation efficiency are some factors that relate a conversion efficiency value. Other parameters like quantum efficiency, open circuit voltage ratio, and fill factor are measured as a substitute because these parameters can measure directly with difficultly. There are six technical methods to get better conversion efficiency which are choosing optimum transparent conductor, supporting light scattering in the visible spectrum, radiative cooling, antireflective coatings and textures, rear-surface passivation and using thin-film materials [10].

B. Doping

Doping is the addition of impurities into a semiconductor material to the defined conversion of conductivity. Boron with 3 valence electrons and phosphorus with 5 valence electrons are two of the most effective materials that can be doped with silicon [8]. Other materials are antimony (5-valent), indium (3-valent), aluminium and arsenic [8].

The dopant is combined into the lattice structure of the semiconductor material; the number of electrons at outermost shell define the doping type. For p-type doping, elements with 3 valence electrons are used and elements with 5 valence electrons are used for n-doping. The conductivity of an advisedly impure silicon can be increased by 10^6 [8].

For n-doping, the outer electron of silicon atom is less than the 5-valent dopant. While the fifth electron is moved in random motion and serves as charge carrier, one silicon atom is compounded with other four outer electrons. The electrons which cause the intrinsic conductivity of silicon require much more energy than this free electron requires much less energy to be raised from the valence band into the conduction band [8]. An electron donor is the dopant which emits an electron. The dopants are positively charged by means of the loss of negatively charged carriers. When the conductivity of semimetal is based on the negatively free electrons, that semimetal is called n-type [8]. In this type of doping, the free electrons are called the majority charge carriers and the free mobile holes are called the minority charge carriers as a result of the higher number of free electrons [8].

For p-doping, other outer electron can be caught by the 3-valent dopants, consequently leaving a hole in the valence band of silicon atom. Therefore, the electrons in the valence band can move. The directions for the movement of electrons and holes are opposite. The negatively charged dopants are known as the acceptors with the addition of an electron. Again, only the positive charge can be moved when the dopant is definite in the crystal lattice [8]. These semiconductors are called p-type because of positive holes. In contract to n-doped semiconductors, the holes are the majority charge carriers and the electrons are the minority charge carriers [8].

P-n junctions are made by joining p-type and n-type semiconductor materials. Electrons diffuse from the n-type side to the p-type side since the concentration of electron in the n-type region is high and the concentration of hole in the p-type region is high [9]. Similarly, holes diffuse from the p-type side to the n-type side. This diffusion process would keep up until the concentration of electrons and holes on both sides are the same if the electrons and holes are not charged. However, they leave behind exposed charges on dopant atom sites, which are fixed in the crystal lattice and are unable to move when the electrons and holes move to the other side of the junction in a p-n junction. Positive ion cores are exposed on the n-type side. Negative ion cores are exposed on the p-type side. An electric field occurs between the negative ion cores in the p-type material and positive ion cores in the n-type material. This region is known as the depletion region because the free carriers are swept out quickly in the electric field, therefore the region is depleted of free carriers [9].

III. IMPLEMENTATION

The conversion efficiency is the relationship between solar cell output energy and sunlight input energy. With the purpose of analyzing the performance of solar cell, the conditions under which efficiency is checked must be carefully controlled. The terrestrial solar cells are measured when the temperature is 25ºC under AM1.5. The solar cell used in space are measured under AM0. The conversion efficiency of AM1.5 solar cell can be calculated according to the following procedure.

The band edge concentration parameters for conduction band and valence band are:

$$N_{C,V} = 2\left(\frac{2\pi m^*_{e,h} kT}{h^2}\right)^{3/2} \quad (1)$$

$$n = N_C e^{(E_F - E_C)/kT} \quad (2)$$

$$p = N_V e^{(E_V - E_F)/kT} \quad (3)$$

The energy difference in the conduction band is

$$\Delta E_C = q(\chi_2 - \chi_1) \quad (4)$$

The energy difference in the valence band is

$$\Delta E_V = \Delta E_g - \Delta E_C \quad (5)$$

The energy band difference is

$$\Delta E_g = E_{g1} - E_{g2} \quad (6)$$

The contact potential is

$$V_0 = \frac{E_{gp} + \Delta E_C - (F_p - E_{Vp}) - (E_{CN} - F_N)}{q} \quad (7)$$

The depletion width is

$$x_W = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{N_A + N_D}{N_A N_D}\right) V_0} \quad (8)$$

The intrinsic concentration is

$$n_i^2 = N_c N_v \exp\left[-\frac{E_g}{kT}\right] \tag{9}$$

The diffusion coefficient is

$$D_{p,n} = \frac{kT}{q}\mu_{p,n} \tag{10}$$

The minority carrier lifetime is

$$\tau_{p,n} = \frac{1}{B \times p,n} \tag{11}$$

The diffusion length of minority carrier is

$$L_{p,n} = \sqrt{D_{p,n} \times \tau_{p,n}} \tag{12}$$

The saturation current is

$$J_0 = \frac{I_0}{A} = \frac{qD_n n_i^2}{L_n N_A} \times \frac{qD_p n_i^2}{L_p N_D} \tag{13}$$

The absorption coefficient is

$$\alpha = 2 \times 10^4 \sqrt{hf - E_g} \tag{14}$$

The generation rate of electron-hole pair is

$$G = \alpha\left(\frac{P_{opt}}{hf \times q}\right) \tag{15}$$

The load current is

$$J_L = qG(L_n + x_w + L_P) \tag{16}$$

The open-circuit voltage is

$$V_{oc} = \frac{kT}{q}\ln\left[\frac{J_L}{J_o} + 1\right] \tag{17}$$

The fill factor is

$$FF = \frac{v_{oc} - \ln(v_{oc} + 0.72)}{v_{oc} + 1}, \tag{18}$$

$$v_{oc} = \frac{V_{oc}}{kT/q} \tag{19}$$

Finally, the conversion efficiency can be calculated

$$\eta = \frac{V_{oc} \times FF \times J_L}{P_{in}} \tag{20}$$

IV. RESULTS

The theoretically maximum light to electricity conversion efficiency related to band gap for single junction solar cells calculated for AM 1.5 is shown in Fig. 1. The efficiency curve is not smooth at all as a result of atmospheric absorption bands. The two apexes are occurred at 1.1 eV and 1.3 eV. At 1.1 eV, the conversion efficiency is 32.7% and 33.1% at 1.35 eV, it is 33.1%. The material with band gap energy in the range of 1.1 to 1.5 eV has the best performance because the efficiency in this range reach the peak value.

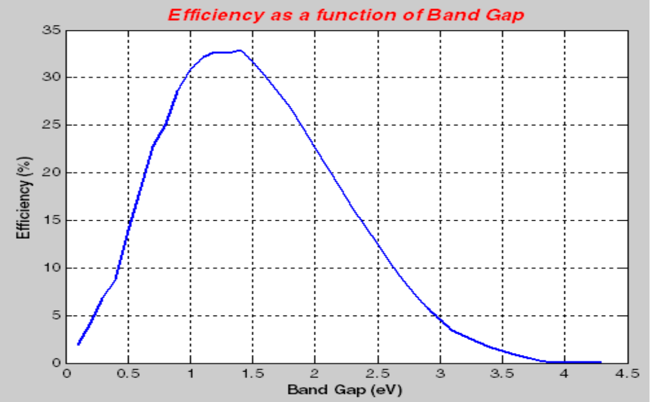

Fig. 1:- Conversion efficiency as a function of band gap energy.

Table 1 shows the conversion efficiency values for each material used in this system.

Material	Band Gap Energy, E_G (eV)	Conversion Efficiency, η (%)
Si	1.12	32.25
InP	1.344	32.69
GaInP	1.35	32.6
AlGaAs	1.42	32.11
GaAs	1.424	32.11
GaInAs	1.43	32.2
CdTe	1.49	31.64
CdS	2.42	14.42

Table 1:- Conversion Efficiency For Materials

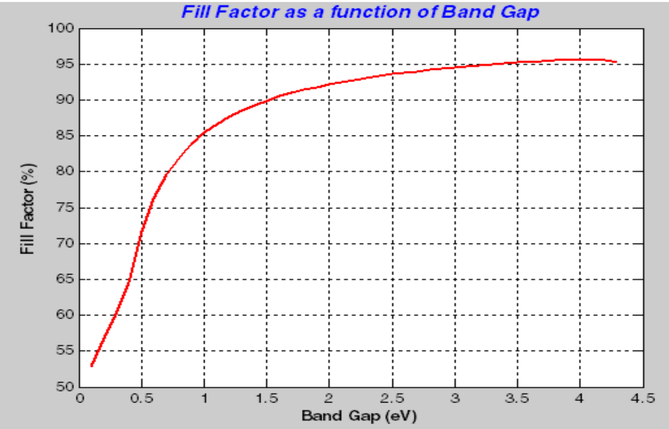

Fig. 2:- Fill factor as a function of band gap energy.

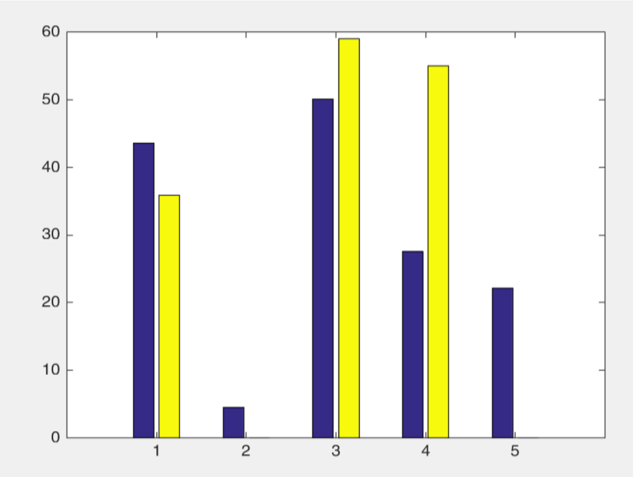

Fig. 3:- Comparison of conversion efficiency.

The fill factor is a key specification which determines the maximum power from a solar cell. It is the actual maximum power divided by the product of the open circuit voltage and short circuit current. The maximum values of current and voltage from a solar cell are the short circuit current and the open circuit voltage, respectively. However, the power from the solar cell becomes zero at open circuit voltage and short circuit current point. It is illustrated in Fig. 2. It is operated at its maximum conversion efficiency. The fill factor is raising to above 60% up to 85% generating a highest conversion efficiency at low band gap energies below 1 eV.

Fig. 3 shows the comparison of conversion efficiency for one homostructure and seven heterostructures. The first design is AlGaAs/GaAs heterojunction structure. The second design is Silicon homostructure. The third design is GaInP/GaAs heterojunction structure. The next one is GaInAs/InP heterojunction structure. The final design is CdS/CdTe heterojunction structure.

Table 2 shows the comparison of conversion efficiency for heterojunction structures to know clearly that which material is more suitable in either p-type or n-type.

No.	**N-type**	**P-type**	**Conversion Efficiency (%)**
1	AlGaAs	GaAs	43.56
	GaAs	AlGaAs	35.86
2	Si	Si	4.5
3	GaInP	GaAs	50.1
	GaAs	GaInP	58.99
4	GaInAs	InP	54.95
	InP	GaInAs	27.58
5	CdTe	CdS	22.11

Table 2:- Comparison of Conversion Efficiency

V. CONCLUSION

The efficiency plays in vital role when analyzing the performance of solar cell. The efficiency reaches the peak value when band gap energy of materials is between 1 to 1.5 eV. So, this system chooses to use the materials whose band gap is between this range. Semiconductor materials with energy band gap between 1 eV and 1.5 eV are acceptable for solar cell operation. For heterojunction solar cell, the materials are doped in p-side and n-side, alternatively. GaAs is more suitable as p-type side of junction because its conversion efficiency has 43.56% at p-side than n-side which has conversion efficiency 35.86%. GaInP is more suitable as p-type side of junction because its conversion efficiency has 58.99% at p-side than n-side which has conversion efficiency 50.1%. GaInAs is more suitable as n-type side of junction because its conversion efficiency has 54.95% at n-side than p-side which has conversion efficiency 27.58%. For the last design, the conversion efficiency is 22.11%.

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