Higher Power Conversion Efficiency on Silicon based Heterojunction Device with FeZnO Dilute Magnetic Semiconductors

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Abstract. Improving the power conversion efficiency of the silicon based solar cell is possible by introducing new materials in the existing device structure to form silicon based heterojunction solar cells. The present research work investigates the modelling of heterojunction solar cell made of FeZnO dilute magnetic semiconductor (DMS) sandwiched between the P and N type silicon. Realized results show that the heterojunction device has more than two folds improved efficiency when compared to the solar cell made of single crystalline silicon. Key words: Heterojunction, Power Conversion Efficiency, Fill factor and Dilute Magnetic Semiconductors.

1. Introduction

Heterojunction solar cells have become very popular due to recent research works carried out resulting in better current conversion efficiency [1]. There has been an increase in productivity and current conversion efficiency of the solar cells due to the research works carried out with new categories such as heterojunction solar cells. Current conversion efficiency of the solar cells plays a very important role in defining the efficiency of the solar cell. To improve the light to electricity conversion, new materials and the exploration of new device architecture are much in need [2]. Recent research explores to enhance the productivity with which solar cells convert photon into electricity. Current photovoltaic technology has resulted in improved efficiency of around 40% with multi-junction cells with each layer tuned to absorb different frequencies of light [3].

Solar cells made of P and N layers of silicon have utilized surface texturing to increase the rate of absorption by each cell. These advancements results in increase in efficiency by only few percent. Recent research based on new materials like heterojunction solar cells has marked the way to achieve higher efficiencies [4]. To make the current conversion efficiency of the solar cell better, the phonons entering and incident on the surface of the material have to be absorbed better. Silicon has a lustrous surface and hence is covered with non-reflective layers to result in increased phonon absorption. A typical module efficiency of monocrystalline silicon is about 15-20%, polycrystalline is about 13-16% and amorphous is about 6-8%. To further improve the efficiency of the solar cells, alternate materials such as ZnO are considered due to its good electronic and optoelectric property.
Among the oxides of block d-metal, zinc oxide (ZnO) is considered to be a standout amongst the other semiconductor materials for innovative applications. A few of the applications based on ZnO are light emitting diodes, gas sensors, drug delivery, field effect transistors, window layer for thin film PV cells, transparent electrode, surface acoustic wave device, piezoelectric substance, photodiodes and optoelectronic device because of its wide band gap (3.37 eV), high transmission coefficient in the visible and near infrared range and high excitation binding energy (60 meV) at 25 °C [5-7]. ZnO exhibits improved properties when doped with transition metals.

Fe-Doped ZnO is a promising candidate because of its ability to enhance the light-harvesting characteristic of the cell and increases the charge collection efficiency and by blocking holes thereby reducing the recombination rate [7-12]. The combined optical and electrical improvements increase the maximum power produced and efficiency of the Heterojunction PV cell [13-18]. On sandwiching Fe-Doped ZnO in between an n-Si and p-Si, it has been observed that there is an immense improvement in enhancement of light absorption. This is confirmed by analyzing its short circuit current (Jsc) and open circuit voltage (Voc). Table 1 shows the efficiencies of various silicon based solar cells.

Table 1: Efficiencies of silicon based solar cells [1]

| Affiliation                        | Voc (mV) | Jsc (mA cm⁻²) | FF (%) | A (cm²) | Status | Year |
|-----------------------------------|----------|----------------|--------|---------|--------|------|
| Sanyo, Japan                      | 745      | 39.4           | 80.9   | 100, Cz | IC     | 2011 |
| Kaneka, Japan                     | 729      | 38.5           | 79.1   | 220, Cz | –      | 2011 |
| RRS, Switzerland                  | 735      | 38.5           | 77.5   | 4, Cz   | –      | 2011 |
| EPFL, Switzerland                 | 726      | 37.8           | 79.7   | 4, FZ   | –      | 2011 |
| HHI, Korea                        | 721      | 36.6           | 79.9   | _220    | –      | 2011 |
| CEA-INES, France                  | 732      | 36.9           | 78.3   | 105, FZ | –      | 2011 |
| CIC, Japan                        | 685      | 36.9           | 79.2   | 243, Cz | –      | 2011 |
| HZB, Germany                      | 639      | 39.3           | 78.9   | 1, FZ   | IC     | 2006 |
| NTUST, Taiwan                     | 690      | 39.1           | 72.7   | 1, FZ   | PR     | 2011 |
| Univ. Hagen, Germany              | 675      | 37             | 77.3   | FZ      | IC     | 2009 |
| FhG-ISE, Germany                  | 705      | 35.0           | _75    | 4, FZ   | –      | 2010 |
| LG, Korea                         | 694      | 35.7           | 74.2   | 0.55, Cz| IC     | 2008 |
| NREL, USA                         | 694      | 39.1           | 78.9   | 1, FZ   | –      | 2009 |
| Titech, Japan                     | 671      | 35.2           | 76     | <1, Cz  | PR     | 2008 |
| AIST, Japan                       | 656      | 35.6           | 75     | 0.2     | PR     | 2009 |
| Sungkyunkwan Univ., Korea         | 631      | 36.3           | 76.1   | Cz      | PR     | 2011 |
| LPICM, France                     | 701      | 30.8           | 79.6   | 4       | –      | 2011 |
| Utrecht Univ., the Netherlands    | 681      | 33.5           | 73.1   | 1 FZ    | –      | 2011 |
| CNR-IMM, Italy                    | 573      | 36.6           | 77     | 1, Cz   | –      | 2005 |
| Delft Univ, the Netherlands       | 646      | 32.9           | 74.3   | FZ      | PR     | 2011 |
| Univ. Toronto, Canada             | 679      | 31.7           | 72.4   | 4.2, FZ | –      | 2011 |
| Kyung Hee Univ, Korea             | 575      | 34.4           | 71     | Cz      | PR     | 2011 |
| ECN, the Netherlands              | 635      | 29.1           | 72     | 21, FZ  | –      | 2010 |
| KIER, Korea                       | <600     |                |        | Cz      | –      | 2009 |
| ENEA, Italy                       | 526      | 31.9           | 74     | mc      | –      | 2010 |
| UPC, Spain                        | 525      | 28.6           | 72.8   | FZ      | PR     | 2006 |
The present work is planned to work on the

- Simulation of the FeZnO based heterojunction photovoltaic device for improved efficiency.
- Modelling heterojunction photovoltaic device for improved power conversion efficiency
- To study the behaviour of the proposed device structure and existing p and n type silicon solar cells structures
- To understand the carrier concentration of the proposed device
- To study the open circuit voltage and short circuit current of the proposed device

2. Experimental

Figure 1 illustrates the device structure for the existing and heterojunction solar cell. Calculations were performed for the electrostatic potential and charge using Poisson’s and drift diffusion equations. These calculations were used to calculate the current density and efficiency of the device. Gummel’s and Newton’s method are used for solving the systems equations by iterations.

Device structure is modelled by defining the geometry on the x, y and z axis for length, width and height. Finally the contacts and the input parameters was defined in the device design. The designed model has generated various outputs such as hole current density, hole diffusion length, electron current density, electron diffusion length, optical generation rate, power and current density. Device geometry was defined for the regions of the device such as P type Silicon, N type Silicon, Fe ZnO optical spacer layer, SiO₂ glass layer and the electrical contacts of the device.

![Figure 1](image_url)

**Figure 1** Solar Cell structure a) Single crystalline Solar Cell b) Heterojunction Solar Cell

3. Results and Discussion

3.1. Electron Current Density (Jn):

The Figure 2(b) shows the increase in electron current density of heterojunction solar cell by a large factor compared to Figure 2(a) Open circuit voltage increases dramatically for increase in the current density. The current density relates the open circuit voltage and short circuit current .The charge accumulated during this process drives the solar cell. Drift current density due to electrons mobility is called electron current density. Electron moves from low potential emitter region to high potential base region. Electron Current density is high in heterojunction compared to conventional solar cell. Electrons move in the opposite direction of the electric field.
3.2. Hole Current Density ($J_p$):

Figure 3(b) depicts the increase in hole current density of heterojunction solar cell by a huge factor compared to figure 3(a). Open circuit voltage increases dramatically for increase in the current density. Drift current density due to holes is called hole current density. Holes move along with the direction of electric field. Holes move from high potential base region to low potential emitter region. Hole current density is high in heterojunction compared to conventional solar cell device. Both electron and hole current density help determine the recombination rate, thereby influencing the open circuit voltage.

3.3. Hole Diffusion Length ($L_p$):

Figure 4(b) depicts that the hole diffusion length of Fe doped ZnO is comparatively less than that of simple solar cell as shown in figure 4(a). Diffusion length plays an important role in determining the short circuit current of the solar cell. It is the average distance over which the minority carrier moves to recombine from its point of regeneration. Increasing the doping concentration in semiconductor compounds results in higher recombination rates and as a result of which they have shorter diffusion lengths.
Figure 4 Hole diffusion length of (a) Single crystalline Solar cell and (b) Heterojunction Solar cell

3.4. Electron Diffusion Length (Ln):

Figure 5(b) depicts the hole diffusion length of Fe doped ZnO, which is comparatively less than that of single crystalline solar cell as shown in figure 5(a). It is the average distance that the majority carrier travels to recombine from its point of regeneration. Both $L_p$ and $L_n$ play a very important role in deciding the short circuit current of solar cell. $L_p$ and $L_n$ is directly proportional to the short circuit current produced.

![Figure 5](image)

Figure 5 Electron diffusion length of (a) Single crystalline Solar cell and (b) Heterojunction Solar cell

3.5. Short-Circuit Current

The short circuit current is due to the generation and collection of light induced carriers. In an ideal solar cell with negligible resistance, the short circuit current is identical to the light induced current. The important material parameters that determine short circuit current are the diffusion length and surface passivation.

The mathematical statement for the short circuit current is shown in equation 1.

$$J_{sc} = qG(L_n + L_p) \quad \text{------------------------ (1)}$$
Where $G$ is the rate of generation, and $L_n$ and $L_p$ are the electron diffusion length and hole diffusion lengths respectively. The above mathematical statement demonstrates that the short-circuit current depends strongly on the generation rate and the diffusion length \[8-10\]. Short circuit current of the heterojunction solar cell is more of 51.2 mA/cm$^2$ when compared to the single crystalline solar cell of 29.1 mA/cm$^2$. It is evident from the results that the generation and collection of carriers in heterojunction solar cell is more when compared to the single crystalline solar cell made of silicon.

3.6. Open-Circuit Voltage

It is the maximum voltage available from the cell, and this happens at zero current. The open circuit voltage decides the forward bias voltage required to generate light induced carrier. Mathematical equation for $V_{oc}$, by setting the net current to zero is shown in equation 2.

$$V_{oc} = \frac{n k T}{q} \ln \left( \frac{L_n}{L_p} + 1 \right) \tag{2}$$

$V_{oc}$ depends on the saturation current of the solar cell and the light-induced current. While $I_{sc}$ typically has a little variation, the key impact is the saturation current, since this may fluctuate to an extent. The saturation current, $I_0$ depends on recombination in the PV cell. Open-circuit voltage is then a measure of the amount of recombination in the cell \[8-10\]. The open circuit voltage of the heterojunction solar cell is 620 mV when compared to the single crystalline solar cell of 562.22 mV.

3.7. Fill Factor

The short-circuit current and the open-circuit voltage are the maximum current and voltage generated from the cell. The "fill factor" is abbreviated as "FF" and is a parameter which includes both $V_{oc}$ and $I_{sc}$ to decide maximum power of the cell. The FF is characterized as ratio of maximum power to the product of the $I_{sc}$ and $V_{oc}$ \[11\]. The FF is most commonly determined from measurement of the IV curve and is defined as the maximum power by $I_{sc}$*$V_{oc}$. Equation for FF is shown in the equation 3.

$$FF = \frac{V_{mp}I_{mp}}{V_{oc}I_{sc}} \tag{3}$$

Fill factor of the single crystalline and heterojunction solar cell device is shown in the table 1. Fill factor of the heterojunction solar cell device is high when compared to the single crystalline solar cell. Since the open circuit voltage and short circuit current are higher in heterojunction solar cell when compared to the single crystalline solar cell, the fill factor of the heterojunction solar cell is 0.91 % and single crystalline solar cell is 0.81 %.

3.8. Efficiency

Efficiency is the ratio of output electrical energy from the solar cell to input phonon energy absorbed. Generally the efficiency is calculated in Air Mass (AM) 1.5 condition and at room temperature \[12, 13\]. The effectiveness of a solar cell is computed as the ratio of incident light intensity which is converted to electricity. Maximum power and efficiency is given by the equation 4 and 5.

$$P_{max} = V_{oc}I_{sc}F \tag{4}$$

$$\eta = \frac{V_{oc}I_{sc}FF}{P_{in}} \tag{5}$$

$$\eta = \frac{V_{oc}I_{sc}FF}{P_{in}} \tag{5}$$
Figure 6 and figure 7 shows the current density of the single crystalline and heterojunction solar cell. Maximum power delivered and efficiency of the device is based on the parameters such as open circuit voltage, short circuit current and fill factor. Based on the above factors the performance of the device is defined. Open circuit voltage gives the forward biased condition of the device with reference to the light generated current. Similarly, short circuit current is due to the generation and recombination of the carriers due to the intensity of light falling on the device surface. Efficiency of the heterojunction solar cell is almost more than two folds of 29.1465% when compared to the single crystalline solar cell of 13.4005%. The improved efficiency of the heterojunction solar cell is due to the higher open circuit voltage, short circuit current and fill factor. Improved efficiency of the heterojunction solar cell makes the device a better solar cell made of silicon based heterojunction.
Open circuit voltage $V_{oc}$ is very high in Fe-doped ZnO heterojunction PV cell compared to simple PV cell, because of its ability to enhance the light-harvesting characteristic of the cell and increases the charge collection efficiency and by blocking holes thereby reducing the recombination rate. The combined optical and electrical improvements increases the maximum power produced and efficiency of the Heterojunction PV cell. The combined electron current density $J_n$ and hole current density $J_p$ produced by the Fe-Doped ZnO PV is much higher than that of Simple PV. Short circuit current $J_{sc}$ of heterojunction is low compared to that of simple PV because of the two factors namely, electron diffusion length $L_n$ and hole diffusion length $L_p$. Electron and hole diffusion length of heterojunction PV cell is small compared to that of simple PV, consequently decreasing the short circuit current. Results on the present work on heterojunction photovoltaic device have matched well with the density functional theory (DFT) work carried out by Ravindiran in 2014 [14]. The below shown Table 2 are the comparison of Heterojunction Solar Cell.

| Sl.No | Device parameters       | PN Solar cell | Heterojunction Solar cell |
|-------|-------------------------|---------------|----------------------------|
| 1     | Open Circuit Voltage ($V_{oc}$) | 562.222 mV    | 620 mV                     |
| 2     | Short Circuit Current Density ($J_{sc}$) | 29.1 mA/cm² | 51.2 mA/cm²               |
| 3     | Maximum Power ($P_{max}$) | 13.4005 mW/cm² | 29.1465 mW/cm²           |
| 4     | Fill Factor (FF)         | 0.819069%     | 0.918172%                 |
| 5     | Efficiency ($\eta$)      | 13.4005%      | 29.1465%                  |

4. Conclusion

Results on the heterojunction solar cell has revealed that the power conversion efficiency is better when the single silicon is replaced with the FeZnO compound. Heterojunction solar cell has improved open circuit voltage, short circuit current and fill factor. Calculated efficiency of the heterojunction solar cell device is 29.1465%, which is higher than the existing single crystalline solar cell of 13.4005%. Device fabrication of the heterojunction solar cell will demonstrate a new trend in device’s made of silicon based heterojunction solar cells. Further improvement in the performance can be made possible with the geometry optimisation of the device for better efficiency.

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