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# Analytically Performance Study of Newly Modeled HIT Solar Cell with Different Materials

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***Abstract:*** **Improvement of Solar cell Efficiency along with cost effectiveness is an important critical issue in the present renewable energy scenario. Amorphous Silicon is the mostly used material as an emitter layer for HIT solar cells. The existing ITO/a-Si(n)/a-Si(i)/c-Si(p)//a-Si(p)/ITO structure has achieved a solar cell efficiency of more than 23%. But in this work, it is shown that due to higher carrier mobility, band gap and the lower refractive index, ZnO and ZnTe is better than a-Si as an emitter layer material. This work is concentrated on the modeling of a new structure by replacing the emitter layer of a-Si with ZnO and ZnTe, to achieve higher efficiency. In this work the two proposed structures are ITO/ZnO(n)/a-Si(i)/c-Si(p)/a-Si(p)/ITO and ITO/ZnTe(p)/a-Si(i)/c-Si(n)/a-Si(n)/ITO based on the basis of analytical study of mobility, band-gap and refractive index of materials. These two structures are modeled in AFORS-HET simulating environment and a comparison is done for these 3 structures. From this work, it is observed that ITO/ZnTe(p)/a-Si(i)/c-Si(n)/a-Si(n)/ITO structure shows the highest solar cell efficiency among these 3 structures. The analytical modeling of the model HIT solar structure ITO/ZnTe(p)/a-Si(i)/c-Si(n)/a-Si(n)/ITO significantly achieved the optimum efficiency.**

***Key Words:*** **Hetero jJunction Intrinsic Thin film(HIT), Zink Oxide (ZnO), Zink Telluride(ZnTe), AFORS-HET(Automat FOR Simulation of Hetero-structures), a-Si (Amorphous Silicon)**

## I. INTRODUCTION

Now a days we get approximately 80% of our energy from non-renewable energy sources. Solar energy has become one of the most focused sources of obtaining 'green' energy in last few decades.

Silicon based heterojunction with intrinsic thin layer (HIT) solar cells combine the advantages of c-Si solar cells such as high efficiency and high stability with those of a-Si solar cells such as low temperature and relatively less costly process. In the year 1994, the first HIT solar cell was developed by 'SANYO' Ltd [1]. In November 2014, the Panasonic Corporation (Sanyo) announced a record efficiency of 25.6% at research level using HIT solar cell [2].

In this paper it is discussed why Zinc Telluride(ZnTe) is better than amorphous silicon(a-Si) and Zink Oxide (ZnO) as an emitter layer for HIT solar cell and a new structure of HIT solar cell is proposed to improve the efficiency of the solar cell, the cell is developed in AFORS-HET[3] simulation software environment. Also, an analytical analysis of Capacitance - voltage relation and the response time of the proposed structures are emphasized in this paper.

AFORS-HET (Automat FOR Simulation of Hetero-structures) software has been developed by a group from the Hahn-Meitner Institute of Berlin and is used for Simulating the hetero-junction solar cells [3] [4].

## II. MATERIAL STUDY

Zinc telluride is II-VI chemical compound semiconductor which is usually a p-type semiconductor. Zinc telluride can be easily doped, and for this reasons it is one of the more common semiconducting materials used in optoelectronics. Owing to its wide band gap of 2.23–2.28 eV at room temperature, high absorption coefficient close to$10^5 cm^{-1}$ and low electron affinity 3.73eV, Zinc telluride (ZnTe) is one of the most promising II–VI semiconductor candidates for the development of low-cost and high-efficiency thin film solar cells[4][5]. Most of the wide band gap II-VI materials are favorable to n-type doping but resist to p-type doping. But in the case of ZnTe, p-type doping is much easier compared to n-type doping[4].This is why a p-doped ZnTe layer of acceptor concentration of 1x10^20$cm^{-3}$ is used as emitter layer in the proposed structure. Effective Conduction band and valance band densities of ZnTe are 1.176x10^18 $cm^{-3}$ and 1.166x10^19 $cm^{-3}$ respectively. The electron and hole mobility of ZnTe is 340$cm^2$/Vs and 100 $cm^2$/Vs respectively [5]. Refractive index and extinction co-efficient of ZnTe is 3.56 and 0.2 respectively.

Another material, ZnO is a wide band gap semiconductor material of the II-VI semiconductor group. The doping of the semiconductor due to oxygen vacancies or zinc interstitials is n-type. This semiconductor material has several favorable properties, including good transparency, high electron mobility and wide band gap. Those properties are valuable for solar cell. ZnO is a direct band gap semiconductor with $E_g$ = 3.4 eV. ZnO normally forms in the hexagonal crystal structure with a = 3.25 Å and c = 5.12 Å [6]. The electron and hole mobility of ZnO is 200 $cm^2$/Vs and 5-50 $cm^2$/Vs respectively. The dielectric constant of ZnO is 8.6.

Amorphous silicon (a-Si) is the non-crystalline form of silicon. The density of amorphous Si is 2.285 g/cm$^3$ at 300 K. The band gap of a-Si semiconductor is Eg = 1.72 eV. The electron and hole mobility of a-Si is 20cm2/Vs and 5 cm2/Vs respectively. The dielectric constant of a-Si is 11.9. The basic properties of ZnO, ZnTe, a-Si is given below in the table 1

Table1: Properties of ZnO, ZnTe and a-Si:

| Properties | ZnO | ZnTe | a-Si |
|---|---|---|---|
| Density | 5.606 g/cm3 | 6.34 g/cm$^3$ | 2.3290 g/cm$^3$ |
| Melting point | 1975°C | 1,295 °C | 1,441 $^0$C |
| Dielectric constant | 8.56 | 10.3 | 11.9 |
| Refractive index | 2.008 | 3.56 | 3.9 |
| Band gap | 3.4eV | 2.26 eV | 1.72 eV |
| Electron mobility | 200 cm2/(V•s) | 340 cm$^2$/(V·s) | 20 cm2/(V•s) |
| Hole Mobility | 5-50 cm2/(V.s) | 100 cm$^2$/(V.s) | 5 cm2/(V•s) |
| Electron Affinity | 4.29 eV | 3.53 eV | 3.9 eV |

## III. STRUCTURES OF SOLAR CELLS AND THEIR COMPARATIVE STUDY

The HIT solar cell structure with a-Si and c-Si heterojunction is very common. The Structure is ITO/a-Si(n)/a-Si(i)/c-Si(p)//a-Si(p)/ITO[2][9](Model 1) shown in Fig.1(a), (b) & (c). In the existing structures a-Si has been used as emitter layer, but in this paper we proposedanother two structures (Model 2 and Model 3) ZnO and ZnTe respectively has been used as the emitter layer.

The surface recombination velocities of electrons and holes are both set as 10$^7$ cm/s. The defect density in c-Si layer is chosen as defect at 0.56eV with a concentration of 1x10$^{10}$$cm^{-3}$ [9]. For amorphous layers, the density of states has been assumed to be both acceptor like states (in the upper half of the gap) and donor like states (in the lower half of the gap). Both of these acceptor and donor like states consist of exponential band tail and Gaussian mid-gap states. The solar AM1.5 radiation is adopted as the illuminating source. Those structures of HIT solar cells are developed in AFORS-HET simulation software environment.

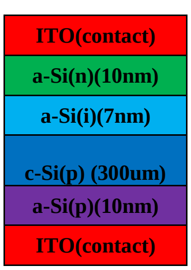


Fig.1(a)

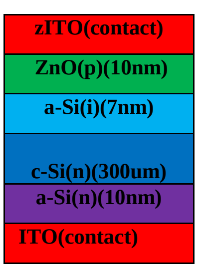


Fig.1(b).

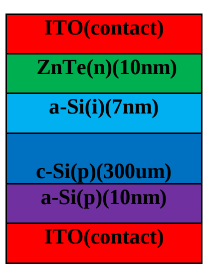


Fig.1(c)

Fig1(a): Schematic structure of model- 1 Fig1(b):Schematic structure of model- 2 and Fig1(c):Schematic structure of model-3

## IV. RESULTS AND DISCUSSION

### *A. Comparison between the three models :*

Those structures of HIT solar cells are developed in AFORS-HET simulation software environment. For model 1, the open circuit voltage (Voc), short circuit current (Isc), fill factor (FF) and efficiency (Eff) has been achieved 730.1mV, 38.91mA/cm$^2$, 81.11% and 23.04% respectively for a-Si/c-Si heterojunction structure. For model 2, the open circuit voltage (Voc), short circuit current (Isc), fill factor (FF) and efficiency (Eff) has been achieved 734.6mV, 42.39mA/cm$^2$, 82% and 25.54% respectively for our proposed structure. For model 3, the open circuit voltage (Voc), short circuit current (Isc), fill factor (FF) and efficiency (Eff) has been achieved 729.3mV, 44.69mA/cm$^2$, 85.03% and 27.71% respectively for another proposed structure. The performance comparison of the proposed structure with the existing structures is shown in Fig.2 and table 2.

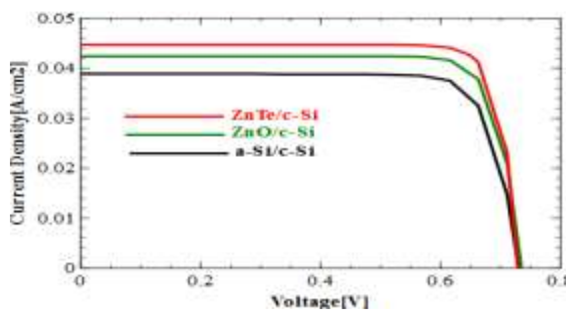


Fig.2. Comparison between the three models of HIT solar cell structures' I-V curve

Table.2. Performance comparison of the proposed structure with the existing structure of HIT solar cell

| Structure | Voc (mV) | Jsc (mA/cm$^2$) | F.F (%) | Eff (%) |
|---|---|---|---|---|
| ITO/ZnTe(p)/a-Si(i)/c-Si(n)/a-Si(n)/ITO | 729.3 | 44.69 | 85.03 | 27.7 |
| ITO/ZnO(n)/a-Si(i)/c-Si(p)/a-Si(p)/ITO | 734.6 | 42.39 | 82 | 25.54 |
| ITO/a-Si(n)/a-Si(i)/c-Si(p)/a-Si(p)/ITO [2] | 730.1 | 38.91 | 81.11 | 23.04 |

Table3: Parameter values of different layers [6] [9] [10] [11] [12]

| Properties | ZnTe(p) | ZnO(n) | a-Si (n) | a-Si(i) | c-Si (p) |
|---|---|---|---|---|---|
| Dielectric constant | 7.3 | 8.56 | 11.9 | 11.9 | 11.9 |
| Electron affinity | 3.53 | 4.3 | 3.9 | 3.9 | 4.05 |
| Band gap | 2.3 | 3.4 | 1.74 | 1.72 | 1.12 |
| Effective conduction band density | 1.17E18 | 1E20 | 1E20 | 1E20 | 2.8E19 |

| | | | | | |
|---|---|---|---|---|---|
| **Effective valance band density** | 1.16E19 | 1E20 | 1E20 | 1E20 | 1.04E19 |
| **Electron mobility** | 340 | 200 | 20 | 20 | 1040 |
| **Hole mobility** | 100 | 5-50 | 5 | 5 | 412 |
| **Doping concentration of acceptors** | 1E20 | 0 | 0 | 0 | 1E16 |
| **Doping concentration of donors** | 0 | 1E20 | 1E20 | 0 | 0 |

After comparing the output parameters of the three structures (model 1, model 2, model 3), it is observed that the Model-3 structure ITO/ZnTe(p)/a-Si(i)/c-Si(n)/a-Si(n)/ITO exhibits highest solar cell efficiency. Though due to comparatively higher band gap of ZnO, ITO/ZnO(n)/a-Si(i)/c-Si(p)/a-Si(p)/ITO(model 2) structure shows highest open circuit voltage , other performance parameters such as short circuit current, fill factor, efficiency are better for model-3 (ITO/ZnTe(p)/a-Si(i)/c-Si(n)/a-Si(n)/ITO) primarily due to higher carrier mobility . it is observed that though the band gap of ZnTe is smaller than ZnO, it causes better efficiency when employed as emitter layer for HIT solar cell.

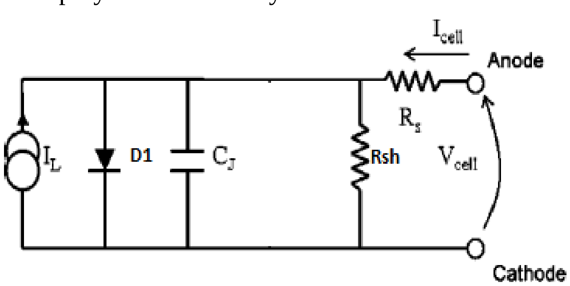


Fig 3: Equivalent model of the solar cell

From this comparison, it can be concluded that band gap is not only a parameter to determine the performance of the HIT solar cell. The performance of HIT solar cell depends on various material parameters such as mobility, band gap, refractivity, dielectric constant etc.

In the next part of this work, ITO/ZnTe(p)/a-Si(i)/c-Si(n)/a-Si(n)/ITO structure is modeled analytically.

*B. Equivalent resistance and capacitance model for model 3 structure:*

A photovoltaic cell may be represented by the equivalent circuit model shown in Figure.3. This model consists of current due to optical generation (IL), a diode that generates a current [$I_s$(exp(qV/kT))], a series resistance ($R_s$), shunt resistance ($R_{sh}$), junction and depletion capacitance ($C_j$) [13].

The series resistance is due to the resistance of the contacts, ohmic losses in the front surface of the cell, impurity concentrations, and junction depth. The series resistance is an important parameter because it reduces both the short-circuit current and the maximum power output of the cell. Ideally, the series resistance ($R_s$) should be zero ohm. The shunt resistance represents the loss due to surface leakage along the edge of the cell or due to crystal defects. Ideally, the shunt resistance should be infinite ($R_{sh} = \infty$).

In a simple solar cell, in the dark, the response to an applied voltage can be modeled as a diode with a given capacitance. This capacitance is due to the charge accumulated in the space charge region of the PN junction, and this charge depends on the applied voltage, so there are a relation between the capacity and the voltage.

*1. Series and Shunt resistance calculation:*

There are two causes for the series resistance are: firstly, the movement of current through the emitter and base of the solar cell; secondly, the contact resistance. The main impact of series resistance is to reduce the fill factor, although the high values may also reduce the short-circuit current. The equation for a solar cell in presence of a series resistance is:

$$I = I_L - I_0 \exp\left(\frac{q(V+IR_s)}{nkT}\right) \ldots\ldots\ldots\ldots. \text{(i)}$$

Where, $I$ is the cell output current, $I_L$ is the light generated current, $V$ is the voltage across the cell terminals, $T$ is the temperature, q and k are constants, $n$ is the ideality factor, and $R_S$ is the cell series resistance.

The power losses are caused by the presence of a shunt resistance ($R_{SH}$). Low shunt resistance causes power losses in solar cells by providing an alternate current path for the light-generated current. The amount of current flowing through the solar cell junction and reduces the voltage from the solar cell. The effect of a shunt resistance is particularly severe at low light levels, since there will be less light-generated current. The loss of this current to the shunt therefore has a larger impact. In addition, at lower voltages where the effective resistance of the solar cell is high, the impact of a resistance in parallel is large. The equation for a solar cell in presence of a shunt resistance is:

$$I = I_L - I_0 \exp\left(\frac{qV}{nkT}\right) - \left(\frac{V}{R_{sh}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots. \text{(ii)}$$

*2. Capacitance-voltage measurements:*

For the C−V measurement analysis, it is necessary first to express the width of the SCR as a function of voltage. For the SCR on the side of the ZnTe we can write [14] as following equation

$$W_{ZnTe-p} = \sqrt{\frac{2.\epsilon_0 \epsilon_{ZnTe}}{q.N_A}\left(V_D^{ZnTe} - V^{ZnTe}\right)} \qquad \ldots..\text{(iii)}$$

And for the crystalline silicon

$W_{c-Si-n}=\sqrt{\frac{2.\epsilon_0\epsilon_{c-si-n}}{q.N_D}(V_D^{c-si-n}-V^{c-si-n})}$ …..(iv)

Where $V_D^{ZnTe}$ and $V_D^{c-si-n}$ are diffusion voltages in ZnTe and crystalline silicon, while $V^{ZnTe}$ and $V^{c-si-n}$ are drops of potential at the SCR on the side of the ZnTe and crystalline silicon, respectively.

The capacitance on the side of the ZnTe, $C_{ZnTe}$, is expressed as [14] bellow:

$C_{ZnTe}=\frac{\epsilon_{ZnTe}\,\epsilon_0}{W_{ZnTe}}$ ……………….(v)

Amorphous silicon can be considered as dielectric, so the capacitance on the side of the amorphous silicon may be expressed as [13] the following

$C_{a-si-i}=\frac{\epsilon_{a-si-i}\epsilon_0}{d_{a-si-i}}$ ………….……………..(vi)

Where $d_{a-Si:H}$ is the thickness of the intrinsic amorphous silicon.

The capacitance for layer c-si-n can be expressed as [14]

$C_{c-si-n}=\frac{\epsilon_{c-si-n}\epsilon_0}{W_{c-si-n}}$……………………………..(vii)

The total measured capacitance of the structure is ex-pressed by [14]

$\frac{1}{C}=\frac{1}{c_{ZnTe}}+\frac{1}{c_{a-si-i}}+\frac{1}{c_{c-si-n}}$……………..….. (viii)

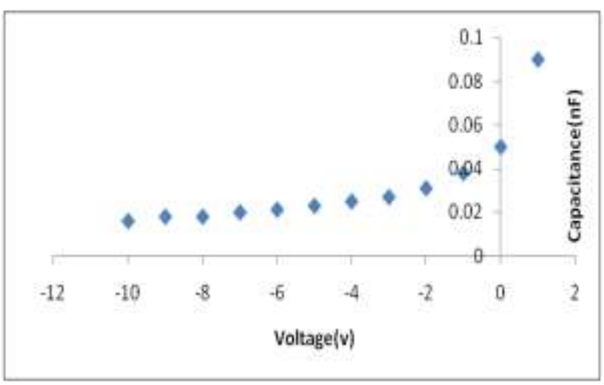


Fig4: Capacitance - Voltage curve

### 3. *Time Response:*

In the study of the influence of irradiance (*G*), the RC time constant $\tau_c$. The time constant $\tau_c$ can be expressed as [15]

$\tau_c=\frac{C}{g_s+g_{sh}+g_d}$……………………………. (ix)

Where, $g_s = 1/Rs$, $g_{sh} = 1/R_{sh}$, and $g_d$ is differential conductance of the diode D1.

We know that,

$I_d=I_0(e^{\frac{qV}{kT}}-1)$

$\frac{dI}{dV}=I_0e^{\frac{qV}{kT}}$

So, $g_d=I_0e^{\frac{qV}{kT}}$, The following equation (xiii) can be derived using simplified equations for C and $g_d$ is

$\tau_c=\frac{\tau_d}{2}\frac{I_d}{(I_d+(g_s+g_{sh})V_T}$…………………..…. (x)

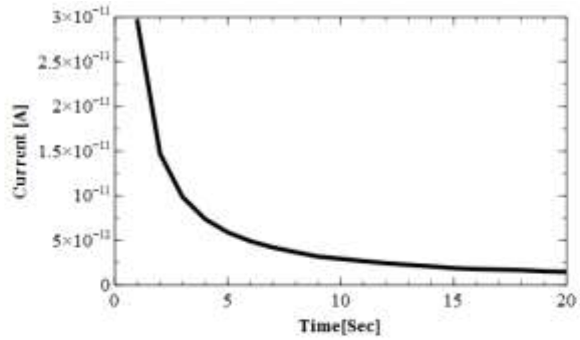


Fig5: Response time of the Solar cell

### 4. *Effect of temperature on the I-Vcharacteristics:*

Current-Voltage characteristics of solar cell sample at $20^0$, $30^0$, $40^0$, $50^0$c temperatures have been shown in figure below. As can be seen, V-I characteristics of solar cell vary under different temperature. Increases in temperature reduce the band gap of a solar cell, whereby effecting the solar cell electrical parameters.

All the semiconductor devices, solar cells are sensitive to temperature. Increases in temperature reduce the band gap of the semiconductor, thereby effecting most of the semiconductor material parameters. The decrease in the band gap of a semiconductor with increasing temperature can be viewed as increasing the energy of the electrons in the material. Lower energy is therefore needed to break the bond. In the bond model of a semiconductor band gap, reduction in the bond energy also reduces the band gap. Therefore increasing the temperature reduces the band gap.

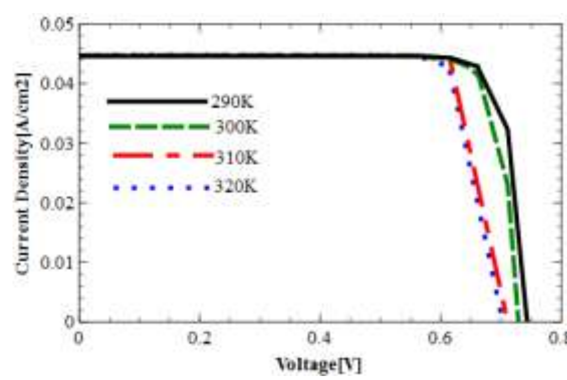


Fig6. I-V characteristics of solar cell under different temperature

All the semiconductor devices, solar cells are sensitive to temperature. Increases in temperature reduce the band gap of the semiconductor, thereby effecting most of the semiconductor material parameters. The decrease in the band gap of a semiconductor with increasing temperature can be viewed as increasing the energy of the electrons in the material. Lower energy is therefore needed to break the bond. In the bond model of a semiconductor band gap, reduction in the bond energy also reduces the band gap. Therefore increasing the temperature reduces the band gap. In a solar cell, the parameter most affected by an increase in temperature is the open-circuit voltage (Voc). The open circuit voltage is given by-

$$V_{oc} = \frac{nkT}{q} \ln\left(\frac{I_L}{I_0}\right)$$

Where k is the Boltzmann constant, T is the temperature, q is Electric charge, $I_L$ is light generated current, and $I_0$ is the reverse saturation current

According to the above equation, the open-circuit voltage decreases with temperature due to the temperature dependence of the reverse saturation current ($I_0$)

$$I_0 = qA\frac{Dn_i^2}{LN_D}$$

Where D is the diffusivity of the minority carrier given; A is the area of the cell; L is the diffusion length of the minority carrier; $N_D$ is the doping; q is the electronic charge;

In the above equation, intrinsic carrier concentration ($n_i$) has most significant on $I_0$ due to the lower band gaps giving a higher intrinsic carrier concentration so higher temperatures results the higher $n_i$ .

Table 3 shows the output parameters of solar cell simple under different temperature.

The fill factor (FF) parameter for solar cells can be expressed as

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

Where $V_{oc}$ and $I_{sc}$ are the open circuit voltage and short circuit current, The efficiency (η) for a solar cell is given by

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

Where, $P_{in}$ is the incident light power

Table 3: OUTPUT PARAMETERS OF SOLAR CELL SIMPLE UNDER DIFFERENT TEMPERATURE

| **Temp/$^0$C** | **Voc [mv]** | **Isc [mA/cm2]** | **FF [%]** | **η [%]** |
|---|---|---|---|---|
| **20** | **742.7** | **44.62** | **85.59** | **28.37** |
| **30** | **729.4** | **44.69** | **84.98** | **27.7** |
| **40** | **716.1** | **44.75** | **83.75** | **26.84** |
| **50** | **702** | **44.81** | **83.87** | **26.38** |

## V. CONCLUSION

In this work, it is observed that the performance of the HIT solar cell, in terms of efficiency, is improved significantly. The efficiency of the proposed HIT solar cell Structure model-3 is achieved 27.7% through the simulation software, by using p-doped Zinc Telluride (ZnTe) instead of a-Si as the emitter layer of the cell. The analytical analysis of Capacitance - voltage relation and the response time of the proposed structure is reported in this paper.

Introduction of ZnTe in the emitter layer of the HIT solar cell is a novel idea for improvement of HIT solar cell efficiency. In this work, the structure is developed and the performance characteristic is done with AFORS-HET simulation tool. In future the physical fabrication and performance characteristics of the fabricated cell will validate the novelty of this work.

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