Impacts of Temperature on the Performance of CdTe Based Thin-Film Solar Cell

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Abstract: In this investigation, the effect of temperature on the performance of CdTe based thin film solar cells has been studied. The parameters such as open circuit voltage ($V_{oc}$), short circuit current density ($J_{sc}$), fill factor ($FF$) and efficiency ($\eta$) determines the performance of solar cell. And an important diode parameter, reverse saturation current density, $J_0$ controls the impacts of temperature on the performance parameters. The reverse saturation current density of the CdTe photovoltaic cell, $J_0 = CT^3\exp\left(-\frac{qE_g}{kT}\right)$ was determined as optimum for $C = 17.90 \text{ mAc m}^{-2}\text{k}^{-3}$ yields $CT^3 = 4.74 \times 10^9\text{m.Acm}^{-2}\text{.}$ In this case, 298 K is considered to be more suitable temperature to achieve optimized $V_{oc}$, $J_{sc}$, $FF$, and $\eta$ calculated for AM1.5G illumination spectra. The maximum attained values of performance parameters are compared with the experimental and theoretical results in the literature of CdTe solar cells. Moreover, the rate of change in performance parameters due to temperature are also measured and compared with the results available in the earlier published works.

Keywords: CdTe solar cell, efficiency, reverse saturation current, temperature effect.

1. INTRODUCTION

Solar cell is one of the most important optoelectronic devices that is used to convert the solar energy to electrical energy [1]. As the cell performances are mostly affected by the temperature ($T$), the temperature effect on solar cell disclosed to draw attention among the photovoltaic researchers. Recently, the CdTe based solar cell has attained the highest efficiency of 22.1% [2]. However, the temperature usually ranges from 288 K to 323 K in terrestrial applications [3], whereas the temperature grading in concentrator and space systems is typically higher than in terrestrial system [3]. Several previous works showed that the cell performance deteriorates with enhancing temperature [3]-[6]. The effect of temperature on solar cell performance parameters is controlled by two important diode parameters, ideality factor ($n$) and reverse saturation current density ($J_0$) [6]. Also the shunt resistance, $R_{sh}$ and the series resistance, $R_s$ along with those diode parameters contribute to control the effect of temperature on $V_{oc}$, $J_{sc}$, $FF$, and $\eta$ [6].
It has been proved that the open circuit voltage, $V_{oc}$ decreases and the short circuit current density, $I_{sc}$ increases a bit when $T$ increases [3-7]. Due to this degradation in $V_{oc}$, the FF and the efficiency, $\eta$ decreases with the increasing temperature. The efficiency is slightly affected with the change in $R_s$ and $R_{sh}$ [8], when increasing the $J_0$ in an exponential manner with the increase in $T$ degrades $V_{oc}$ rapidly. That is why $J_0$ is considered as a vital material dependent parameter that affects the performance of a photovoltaic cell. And the band gap of the optoelectronic materials used in solar cell design affect this reverse saturation current density, $J_0$.

The direct band gap semiconductor materials, for example, CdTe and CdS have become more effective panoramas for using in thin-film technology [9]. The CdTe based solar cells generally form hetero junction with CdS buffer or another window layer materials [9]. In CdTe solar cell, germanium (Ge) is typically used as a substrate [9]. Besides thickness, doping concentration, band gap, mobility, effective density of states etc., the effect of temperature is an important factor to improve the performance of a solar cell.

In this study, we investigate the temperature effect on the performance parameters of CdTe based solar cells in the temperature range from 273 to 523 K. This study will be helpful to prefigure and utilize the further analysis of the performance of single junction and tandem solar cells with respect to temperature.

2. THEORETICAL BASIS

The equivalent electric circuit of an ideal photovoltaic cell has been shown in Figure 1. The current density vs. voltage characteristics also familiar as ‘J-V characteristics’ of a solar cell that forms a p-n junction under steady state illumination condition can simply be presented using a particular exponential model as,

$$J = -J_{ph} + J_0(e^{qV/kT} - 1)$$

where, $J_{ph}$ is the photo-generated current density, $V$ represents the terminal voltage, $n$ is the ideality factor and $k$ is the Boltzmann constant. As the efficiency of a solar cell is slightly affected with the change in $R_s$ and $R_{sh}$ with temperature [3-7], these two terms are disregarded in this study. And the ideality factor of the diode is considered to be 1 in this work.

![Figure 1. Equivalent circuit diagram of an ideal photovoltaic solar cell](image-url)
2.1. Basic Formulation

The mathematical equations described in this section are taken from the literature [3, 11-13]. The simulation results are analyzed by a one-dimensional online photovoltaic simulator, ADEPT 2.1 [10]. However, when the photons have an energy higher than the energy band gap \( E_g \) of the semiconductor materials, then those photons are absorbed and make electron-hole pairs [1]. Moreover, the cut-off wavelength of any photons is useful for carrier generation. And this band gap dependent cut-off wavelength and temperature dependent band gap are defined by Equation (2) and (3) [11, 12].

\[
\lambda_g = \frac{1240}{E_g(eV)} \text{ (nm)}
\]  
\[
E_g(T) = E_g(0) - \frac{\alpha r^2}{(T+\beta)}
\]

Here, \( E_g(T) \) represents the band gap energy at some temperatures \( T \), \( E_g(0) \) is the band gap of the semiconductor at \( T \approx 0 \) \( K \), \( \alpha \) and \( \beta \) are two constants. The band gap parameters of the semiconductor materials, ZnO, CdS, CdTe, and Ge are listed in Table 1.

\[
\begin{align*}
\text{ZnO [14]} & : 3.516 \quad 2.00 \quad 325 \\
\text{CdS [12]} & : 2.583 \quad 4.02 \quad 147 \\
\text{CdTe [12]} & : 1.608 \quad 3.10 \quad 108 \\
\text{Ge [11]} & : 0.741 \quad 4.56 \quad 210
\end{align*}
\]

The short circuit current density, \( J_{sc} \) is defined by Equation (4) which shows that the \( J_{sc} \) depends on the solar spectral irradiance and on the initial photon flux, \( N_{ph} \).

\[
J_{sc} = q \int_{h_v=E_g}^{E_{max}} \frac{dN_{ph}}{dh_v} dh_v
\]  
\[
\text{To calculate the } FF \text{ of the solar cell more accurately, Green [13] has given an expression as shown by Equation (6),}
\]

\[
FF = \frac{v_{oc}-\ln(v_{oc}+0.72)}{v_{oc}+1}
\]

Where, \( v_{oc} = (V_{oc}/V_{th}) \), also known as ‘normalized \( V_{oc} \)’ and \( V_{th} = kT/q \).

Additionally, the efficiency measurement of a solar cell can be done using Equation (7),
\[ \eta = \frac{V_{oc}J_{sc}FF}{P_{in}} \quad (7) \]

Where, \( P_{in} \) is the solar irradiance on earth under AM1.5G illumination spectra.

Finally, the temperature dependent performance parameters, such as \( dJ_{sc}/dT \), \( dV_{oc}/dT \), \( dFF/dT \), and \( d\eta/dT \) are estimated by fitting the available data.

### 2.2 Device Simulation

The global AM1.5 (1000 Wm\(^{-2}\), AM1.5G) is the solar spectrum for incident light on the earth. It includes direct as well as diffuse rays of light from the sun and used as a standard in the photovoltaic (PV) industries [15]. The performance measurements of the cells depend mainly on the distribution of the solar spectra that are used to compare their performance. However, as mentioned earlier, ADEPT 2.1 has been used in this work to simulate the numerical data correspond to the different semiconductor materials constituting CdTe based thin-film solar cell. Table 2 shows the most essential values of the device parameters of CdTe solar cell needed to conduct the simulation [3, 9, 16-19].

| Properties                      | CdTe  | CdS   | ZnO   |
|---------------------------------|-------|-------|-------|
| Thickness, \( \tau \) [nm]      | 1600  | 50    | 200   |
| Band gap, \( E_g \) [eV]        | 1.50  | 2.42  | 3.40  |
| Electron affinity, \( \chi_e \) [eV] | 3.90  | 4.40  | 4.55  |
| Donor concentration, \( N_d \) [cm\(^{-3}\)] | -     | 1×10\(^{17}\) | 3×10\(^{17}\) |
| Acceptor concentration, \( N_a \) [cm\(^{-3}\)] | 5×10\(^{16}\) | - | - |
| Hole mobility, \( \mu_p \) [cm\(^2\)V\(^{-1}\)s\(^{-1}\)] | 40    | 25    | 30    |
| Electron mobility, \( \mu_e \) [cm\(^2\)V\(^{-1}\)s\(^{-1}\)] | 320   | 100   | 70    |

### 3. Result and Discussions

The performance, essentially, the efficiency of a solar cell has been calculated as a function of temperature and band gap under the AM1.5G illumination condition. It is also to be noted that an optimum value of \( C \) as mentioned in the abstract section has been used by Nell [20]. This value has been used to compute the performance parameters of the photovoltaic cells. The performance variation in the cell due to varying temperature from 273 to 523 K has been plotted in Figure 2. The changes in performance parameters, \( dJ_{sc}/dT \), \( dV_{oc}/dT \), \( dFF/dT \), and \( d\eta/dT \) have been figured out in Figure 2(a), Figure 2(b), Figure 2(c), and Figure 2(d) respectively.
Figure 2. (a) Short circuit current versus temperature, $dJ_{sc}/dT$; (b) Open circuit voltage versus temperature, $dV_{oc}/dT$; (c) Fill factor versus temperature, $dFF/dT$; (d) Efficiency versus temperature, $d\eta/dT$.

The J-V characteristic curve for optimized CdTe solar cell is shown in Figure 3. It is obvious that when temperature increases, the efficiency decreases.

Figure 3. J-V characteristic curve of optimized CdTe solar cell
Table 3 shows the comparison between the performance of calculated result in this work with the experimental work [2].

| Description         | $V_{oc}$ (mV) | $J_{sc}$ (mA/cm$^2$) | FF (%) | $\eta$ (%) |
|---------------------|---------------|-----------------------|--------|------------|
| Reference work [2]  | 887.20        | 31.69                 | 78.50  | 22.10      |
| Proposed study      | 980.91        | 36.57                 | 81.03  | 29.07      |

4. CONCLUSIONS

The temperature dependent performance parameters $V_{oc}$, $J_{sc}$, FF, and $\eta$ of CdTe based solar cell has been analyzed with the temperature change ranges from 273 to 523 K. The impact of $J_0$ on these cell performance parameters has also been discussed. Under AM1.5G illumination spectra, it has been seen that with increasing temperature, $J_0$ increases, and thus, $V_{oc}$ decreases. And therefore, the fill factor and the efficiency of the cell also decrease. Concurrently, increasing temperature results in decreasing the band gap and hence $J_{sc}$ increases. The increased $J_{sc}$ contributes to make the efficiency better. Thus, this trend of $J_{sc}$ to increase $V_{oc}$ to decreasewith temperature increase in the cell yields a decrease in the energy conversion efficiency, $\eta$. At 298 K temperature, the cell performance appears to be more appropriate and allows the best agreement between the computed data and experimental values available in the literature for CdTe based solar cells. The estimated rate of change of parameters of the cell performance with temperature, such as $dJ_{sc}/dT$, $dV_{oc}/dT$, $dFF/dT$, and $d\eta/dT$ are well matched with the available experimental data. The performance analysis from the numerical simulation using ADEPT 2.1 substantiates that the theoretical efficiency of the CdTe based cell has been improved to 29.07% with a FF of 81.03%.

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