Computer Simulation Study of Materials Parameters Influence on Solar Cell Performance

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ABSTRACT

Silicon solar cells are prevailing types in the commercial market due to their stability, robustness and reliability. In this article, we explored the important controllable design parameters affecting the performance of the silicon p-n junction solar cells by using the computer program Analysis of Microelectronic and Photonic Structures (AMPS-1D) for simulation. Through the simulation process we also determined the sensitivities of each parameter. Besides that, some hypothetical materials are also examined to explore the effect of band gap which cannot be easily modified by the processing or doping process. Furthermore, a case study about a new type of solar cell—p-n junction made by p-type crystalline silicon and n-type doped crystalline zinc oxide is performed. In this case, we have come out the optimum parameters to achieve the best performance of this type of cell and made a comparison with simple p-n junction silicon cells.

INTRODUCTION

Simulation using AMPS-1D

AMPS-1D is developed by the professor Fonash’s group in Pennsylvania State University. It is used to analyze and design the photovoltaic devices. Its basic principle is to solve the Poisson equation and the continuity equations subject to associated boundary conditions of the free electrons and holes using Newton-Raphson Method. It can generate the I-V characteristic curve of the device with or without illumination. At the same time, it is capable to solve the detailed band structure for the whole device, especially for the junction. It is applicable to mono and poly-crystalline and amorphous materials. The structure can be homo-junction and hetero-junction.

For one successful simulation, input parameters include: the thickness of p-type and n-type material, the doping density, bandgap, electron affinity, effective conduction and valence band density, the absorption coefficient for the sun light spectra [1], dopant and acceptor energy levels, temperature, mobilities of electrons and holes and capture cross sections of electrons and holes. If the material is not a single crystal, additional information about defect level and grain boundaries is needed.

I-V characteristics for p-n junction solar cell

Ideal p-n junction solar cell I-V relationship is characterized by

$$i = I_s \left[ \exp \left( \frac{\phi_p}{n k T} \right) - 1 \right] - I_L$$  \hfill (1)

where $I_s$ is given by
\[ I_L = I_S \exp \left( -\frac{E_g}{kT} \right) = eA N_e N_h \left( \frac{D_n L_n}{p_n \tau_n} + \frac{D_p L_p}{p_p \tau_p} \right) \exp \left( -\frac{E_g}{kT} \right) \]  

where \( I_L \) is the photocurrent, \( I_S \) is the saturation current, \( n \) is the ideality factor counting for recombination current. \( E_g \) is the banggap energy, \( D_n, D_p \) are the diffusion coefficient of electrons and holes. \( L_n, L_p \) are diffusion length of electrons and holes in p-region and n-region. \( N_e, N_h \) are the doping density of n-region and p-region. \( F_n \) and \( F_p \) are coefficients of electrons and holes determined by the surface recombination rate and the diffusion length of electrons and holes. [2]

**Short circuit current \( I_{sc} \):** When \( V=0 \), the current is the short circuit current \( I_{sc} \). From equation (1), we can get

\[ I_{sc} = I_L \]  

where \( I_L \) can be calculated by

\[ I_L = A \int_{v_m}^{\infty} \left( J_p + J_n + J_{dp} \right) dv \]  

where \( A \) is the cross section of the cell, \( J_p, J_n \) and \( J_{dp} \) are the photocurrent densities generated from the p, n and depletion regions, respectively. \( v_m \) is the minimum frequency causing photovoltaic reactions.

In general, \( I_L \) is strongly dependent on the illumination conditions, absorption and transport properties of each region.

**Open circuit voltage:** When \( I=0 \), \( V \) is the open circuit voltage, which is the maximum voltage available for given conditions. From equation (1) set \( I=0 \),

\[ V_{oc} = \frac{kT}{e} \ln \left( \frac{v_{oc}}{v_{oc} + 1} \right) \]  

**Fill factor:** Definition: \( FF = \frac{P_{max}}{V_{oc} I_{oc}} \) with \( P = IV - I^2 \frac{kT}{e} \ln \left( \frac{v_{oc} + 1}{v_{oc}} \right) \), take the derivative of \( P \) to find the maximum, for the ideal case (\( n=1 \)),

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

where \( v_{oc} = \frac{kT}{e} V_{oc} \). [3]

**Efficiency:** Definition: \( \eta = \frac{FF \times I_{sc}}{P_{in}} \), which is determined by the above three primary parameters.

**SIMULATION DETAILS**

Two types of solar cells are simulated: single crystalline p- n junction cell and single crystalline p-Si-n-ZnO.

Single crystalline silicon p-n junction cell.
Table 1. Major input parameters for crystalline silicon p-n junction solar cell.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative permittivity $\varepsilon_r$</td>
<td>11.9</td>
</tr>
<tr>
<td>Mobility $\mu$ (cm²V⁻¹s⁻¹)</td>
<td>$\mu_p$: 1350, $\mu_n$: 450</td>
</tr>
<tr>
<td>Doping density $Na/Nd$ (cm⁻³)</td>
<td>$Na$: $(10^{16} - 10^{19})$, $Nd$: $(10^{14} - 10^{16})$</td>
</tr>
<tr>
<td>Band gap $Eg$ (eV)</td>
<td>1.12</td>
</tr>
<tr>
<td>Affinity $\Phi$ (eV)</td>
<td>4.05</td>
</tr>
<tr>
<td>Effective conduction/valence band density $Nc/Nv$ (cm⁻³)</td>
<td>$Nc$: $2.80 \times 10^{19}$, $Nv$: $1.04 \times 10^{19}$</td>
</tr>
<tr>
<td>Thickness of p/n layer (nm)</td>
<td>Variable (2nm---20mm)</td>
</tr>
<tr>
<td>Temperature $T$(K)</td>
<td>Variable (100---300)</td>
</tr>
</tbody>
</table>

(Note: Absorption coefficient, spectra response and capture cross section input data are not shown.)

Table 1 gives variable parameters of Si solar cells being investigated, including, doping density, thickness, temperature and band gap.

Single crystalline p-type silicon and n-type ZnO junction cell

Table 2. Major input parameters for crystalline silicon p Si and n ZnO junction solar cell.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative permittivity $\varepsilon_r$</td>
<td>8.75</td>
</tr>
<tr>
<td>Mobility $\mu$ (cm²V⁻¹s⁻¹)</td>
<td>$\mu_p$: 200, $\mu_n$: 50</td>
</tr>
<tr>
<td>Doping density $Na/Nd$ (cm⁻³)</td>
<td>$Na$: $10^{17}$, $Nd$: $(10^{14} - 10^{16})$</td>
</tr>
<tr>
<td>Band gap $Eg$ (eV)</td>
<td>3.32</td>
</tr>
<tr>
<td>Affinity $\Phi$ (eV)</td>
<td>4.45</td>
</tr>
<tr>
<td>Effective conduction/valence band density $Nc/Nv$ (cm⁻³)</td>
<td>$Nc$: $2.94 \times 10^{19}$, $Nv$: $1.13 \times 10^{19}$</td>
</tr>
<tr>
<td>Thickness of p/n layer (nm)</td>
<td>Variable (2nm---20mm)</td>
</tr>
<tr>
<td>Temperature $T$(K)</td>
<td>Variable (240---320)</td>
</tr>
</tbody>
</table>

Similar as in the silicon cell case, parameters investigated for Si-ZnO cell includes doping density of n-type ZnO, the thickness of p-layer and n-layer and temperature as seen in Table 2.

RESULTS AND DISCUSSION

Crystalline silicon p-n junction cell.

a. Doping density

Table 3. The summarized results obtained by changing the doping density at p-type silicon. Fixed parameters include $T$=300K, p-layer thickness=n-layer thickness=1000nm and $Nd=1.0 \times 10^{17}$ cm⁻³.
Table 4. The summarized results obtained by changing the doping density at n-type silicon. Fixed parameters include T=300K, p-layer thickness=n-layer thickness=1000nm and Na=Nd=1.0×10^{17} cm^{-3}.

<table>
<thead>
<tr>
<th>Na(cm^{-3})</th>
<th>Jsc(mA/cm^2)</th>
<th>Voc(V)</th>
<th>FF</th>
<th>η(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0×10^{15}</td>
<td>8.433</td>
<td>0.424</td>
<td>0.738</td>
<td>2.642</td>
</tr>
<tr>
<td>1.0×10^{17}</td>
<td>7.346</td>
<td>0.478</td>
<td>0.781</td>
<td>2.74</td>
</tr>
<tr>
<td>1.0×10^{18}</td>
<td>7.158</td>
<td>0.506</td>
<td>0.795</td>
<td>2.882</td>
</tr>
<tr>
<td>1.0×10^{19}</td>
<td>7.113</td>
<td>0.512</td>
<td>0.798</td>
<td>2.903</td>
</tr>
<tr>
<td>1.0×10^{20}</td>
<td>6.948</td>
<td>0.511</td>
<td>0.799</td>
<td>2.838</td>
</tr>
<tr>
<td>1.0×10^{21}</td>
<td>6.948</td>
<td>0.511</td>
<td>0.807</td>
<td>2.868</td>
</tr>
</tbody>
</table>

Table 3 and 4 show that when either Na or Nd is increased from the range of 1.0×10^{15} cm^{-3} to 1.0×10^{21} cm^{-3}, short circuit current Jsc decreases while the open circuit voltage Voc increases. Fill factor increase along with the increasing Voc while efficiency η increases first to a maximum then decrease a bit.

The dependence relationship on doping density can be explained well by the ideal p-n junction I-V relationship. The increment of Na/Nd would decrease the life time and thus the diffusion length of minor carriers generated by increase density of recombination centers. In this way, the photocurrent density is reduced hence results a smaller short circuit current. For the open circuit voltage, from equation (2), increasing Na/Nd leads to a smaller saturation current Is. Voc increases as predicted by equation (5) though decreases. The increment of fill factor is because of the increase of the open circuit voltage derived from Equation (6). Finally, efficiency increases as the doping density increases as the balanced results of Jsc, Voc and FF. However, the increment is not significant when the doping density is high enough (~1.0×10^{19} cm^{-3}). The optimum doping concentration is found to be Na=Nd=1.0×10^{17} cm^{-3}.

b. Thickness
Table 5. Simulation results of effect of varying p-layer thickness. Fixed parameters: \( \text{Na} = \text{Nd} = 10^{17} \text{cm}^{-3} \), \( T = 300 \text{K} \), n-layer thickness=1199995.4nm.

<table>
<thead>
<tr>
<th>p thickness (nm)</th>
<th>Jsc (mA/cm²)</th>
<th>Voc (V)</th>
<th>FF</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>31.589</td>
<td>0.46</td>
<td>0.786</td>
<td>11.419</td>
</tr>
<tr>
<td>5</td>
<td>31.586</td>
<td>0.46</td>
<td>0.786</td>
<td>11.423</td>
</tr>
<tr>
<td>10</td>
<td>31.573</td>
<td>0.461</td>
<td>0.785</td>
<td>11.431</td>
</tr>
<tr>
<td>100</td>
<td>29.354</td>
<td>0.484</td>
<td>0.786</td>
<td>11.176</td>
</tr>
<tr>
<td>1000</td>
<td>28.834</td>
<td>0.529</td>
<td>0.806</td>
<td>8.031</td>
</tr>
<tr>
<td>10000</td>
<td>7.094</td>
<td>0.561</td>
<td>0.818</td>
<td>3.256</td>
</tr>
<tr>
<td>199995.4</td>
<td>1.042</td>
<td>0.571</td>
<td>0.82</td>
<td>0.487</td>
</tr>
<tr>
<td>1199995.4</td>
<td>0.142</td>
<td>0.529</td>
<td>0.811</td>
<td>0.061</td>
</tr>
</tbody>
</table>

Table 6. Simulation results of effect of varying n-layer thickness. Fixed parameters: \( \text{Na} = \text{Nd} = 10^{17} \text{cm}^{-3} \), \( T = 300 \text{K} \), p-layer=10nm.

<table>
<thead>
<tr>
<th>n-thickness (nm)</th>
<th>Jsc (mA/cm²)</th>
<th>Voc (V)</th>
<th>FF</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>2.43</td>
<td>0.386</td>
<td>0.763</td>
<td>0.715</td>
</tr>
<tr>
<td>100</td>
<td>6.1</td>
<td>0.413</td>
<td>0.766</td>
<td>1.93</td>
</tr>
<tr>
<td>1000</td>
<td>14.088</td>
<td>0.437</td>
<td>0.766</td>
<td>4.72</td>
</tr>
<tr>
<td>199995.4</td>
<td>25.563</td>
<td>0.455</td>
<td>0.784</td>
<td>9.126</td>
</tr>
<tr>
<td>199995.4</td>
<td>30.609</td>
<td>0.46</td>
<td>0.788</td>
<td>11.094</td>
</tr>
<tr>
<td>1199995.4</td>
<td>31.573</td>
<td>0.461</td>
<td>0.785</td>
<td>11.431</td>
</tr>
<tr>
<td>2999995.3</td>
<td>31.443</td>
<td>0.461</td>
<td>0.78</td>
<td>11.31</td>
</tr>
</tbody>
</table>

From Table 5 and Table 6, it shows that the geometric design of solar cell has an enormous effect on the solar cell performance. Table 5 indicates that when the p-layer thickness decreases, Jsc increases rapidly. However, the increment is insignificant when p-layer thickness is less than 10nm. Voc along with the FF drops with decreasing p-layer thickness. The overall efficiency increases dramatically mainly due to the large increment of Jsc. While in Table 6, p-layer is chosen to be the optimum value 10nm and show the effect of n-layer. Increasing n-layer thickness results in a substantial increment of Jsc. Voc and FF also increase. The efficiency increases dramatically until thickness reaches ~0.1 millimeter.

A large fraction of light is absorbed close to the front surface. By making the front p-layer very thin, a large fraction of the electron hole pairs generated by the incident light are created within a diffusion length to the p-n junction. The pairs would be readily collected. Hence, the thickness of p-layer should less or comparable to the diffusion length of electron in the p-region. On the other hand, if the p-layer is very thin, the junction is not as abrupt as in bulk case. The voltage across the junction is smaller which leads to a smaller open circuit voltage. For the n-layer, enough thickness is required to make sure it can absorb large fraction of the longer wavelength and also decrease the probability of surface recombination at the back end. In some cases, a heavily doped n+ layer is added at the back to form the “passivation” layer.
Overall, thin p-layer and thick n-layer are required to optimize the performance of the solar cell. In the numerical example, 10nm p-layer with 10mm n-layer works the best for given doping density. If we change the doping density to the optimum value (1.0 × 10^{17} cm^-2) obtained in last section, the efficiency can reach to 12% with Voc 0.6V at 300K.

c. Temperature

Table 7. Silicon cell I-V parameters at various temperatures. (Na=Nd=1.0 × 10^{17} cm^-2, p-layer thickness: 10nm, n-layer thickness 1199995.4 nm.)

<table>
<thead>
<tr>
<th>T(K)</th>
<th>Jsc(mA/cm^2)</th>
<th>Voc(V)</th>
<th>FF</th>
<th>η(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>31.49</td>
<td>0.823</td>
<td>0.932</td>
<td>24.156</td>
</tr>
<tr>
<td>200</td>
<td>31.539</td>
<td>0.643</td>
<td>0.871</td>
<td>17.645</td>
</tr>
<tr>
<td>300</td>
<td>31.573</td>
<td>0.461</td>
<td>0.785</td>
<td>11.431</td>
</tr>
</tbody>
</table>

The feature of Table 7 is that, Voc and FF decreased dramatically with increasing temperature while Jsc increases slightly. Efficiency decreases at similar manner as Voc.

When T increases, Is increases via an exponential term from Equation (2). The increase of Is lead to a decrease of Voc though equation (5). The decrement amount is approximately proportional to the temperature change. While the slight increment in Jsc is due to the thermal excitation creating more electron-hole pairs besides photo excitation. Other parameters also change with temperature such as bandgap, however, only the band gap of 1.12 eV is considered in this simulation.

d. Band gap

Table 8. The solar cell performance parameters with structure p-Si+n-X (X stands for an unknown material), the band gap of n-X can be tuned while other properties retained. Fixing parameters: T=300K. p-layer thickness=n-layer=1000nm, and the band gap of p-Si is 1.12 eV. Assumption: There exists a hypothetical material with other parameters same as Si expect Eg.

<table>
<thead>
<tr>
<th>Eg of n-X(eV)</th>
<th>Jsc(mA/cm^2)</th>
<th>Voc(V)</th>
<th>FF</th>
<th>η(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>4.726</td>
<td>0.073</td>
<td>0.405</td>
<td>0.14</td>
</tr>
<tr>
<td>0.8</td>
<td>7.346</td>
<td>0.193</td>
<td>0.63</td>
<td>0.896</td>
</tr>
<tr>
<td>1.12</td>
<td>7.346</td>
<td>0.478</td>
<td>0.781</td>
<td>2.74</td>
</tr>
<tr>
<td>1.5</td>
<td>7.232</td>
<td>0.485</td>
<td>0.782</td>
<td>2.744</td>
</tr>
<tr>
<td>2</td>
<td>5.044</td>
<td>0.476</td>
<td>0.78</td>
<td>1.87</td>
</tr>
<tr>
<td>2.5</td>
<td>4.954</td>
<td>0.474</td>
<td>0.78</td>
<td>1.836</td>
</tr>
<tr>
<td>3</td>
<td>4.685</td>
<td>0.474</td>
<td>0.779</td>
<td>1.73</td>
</tr>
<tr>
<td>3.5</td>
<td>4.685</td>
<td>0.474</td>
<td>0.779</td>
<td>1.73</td>
</tr>
</tbody>
</table>

Table 9. The solar cell performance parameters with structure n-Si+p-X, the band gap of p-X can be tuned while other properties retained. T=300K. p-layer thickness=n-
layer=1000nm, and the band gap of n-Si is 1.12 eV. Assumption: There exists a hypothetical material with other parameters same as Si except Eg. The increase of Eg is to 1.5 eV only, as the simulation program does not allow higher gap values 2.0 and 2.5 eV to run.

<table>
<thead>
<tr>
<th>Eg of p-X (eV)</th>
<th>Jsc (mA/cm²)</th>
<th>Voc (V)</th>
<th>FF</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.12</td>
<td>7.346</td>
<td>0.478</td>
<td>0.781</td>
<td>2.74</td>
</tr>
<tr>
<td>1.5</td>
<td>6.736</td>
<td>0.507</td>
<td>0.785</td>
<td>2.67</td>
</tr>
</tbody>
</table>

From Table 8 and Table 9, the general feature is that the open circuit voltage increases while the short circuit current decreases except for very small band gap (0.5eV). The increment of Voc can be explained by equation (2) and (5), larger Eg leads to smaller Is and thus results a larger Voc. While the decreasing of Jsc is due to that, smaller amount of photons have enough energy to generate electron-hole pairs. These two factors compete with each other to determine the changing of efficiency.

**Crystalline p-type Si and n-type ZnO cell**

**a. Thickness**

Table 10. Si-ZnO solar cell performance parameters with various n-layer thickness. Fixed parameters: Na=Nd=10^{15} cm^{-6}, T=300K, p-layer thickness=10nm. P-Si is the front layer facing the sun.

<table>
<thead>
<tr>
<th>ZnO thickness (nm)</th>
<th>Jsc (mA/cm²)</th>
<th>Voc (V)</th>
<th>FF</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>2.315</td>
<td>0.392</td>
<td>0.744</td>
<td>0.675</td>
</tr>
<tr>
<td>1000</td>
<td>5.33</td>
<td>0.414</td>
<td>0.747</td>
<td>1.648</td>
</tr>
<tr>
<td>10000</td>
<td>7.399</td>
<td>0.423</td>
<td>0.768</td>
<td>2.407</td>
</tr>
<tr>
<td>100000</td>
<td>7.903</td>
<td>0.425</td>
<td>0.774</td>
<td>2.602</td>
</tr>
<tr>
<td>1199995.4</td>
<td>7.942</td>
<td>0.426</td>
<td>0.769</td>
<td>2.599</td>
</tr>
<tr>
<td>2199995.4</td>
<td>7.915</td>
<td>0.425</td>
<td>0.764</td>
<td>2.572</td>
</tr>
</tbody>
</table>

Table 11. Si-ZnO solar cell performance parameters with various p-layer thickness. Fixed parameters: Na=Nd=10^{15} cm^{-6}, T=300K, ZnO-layer thickness=100000nm. P-Si is the front layer facing the sun.

<table>
<thead>
<tr>
<th>p-Si thickness (nm)</th>
<th>Jsc (mA/cm²)</th>
<th>Voc (V)</th>
<th>FF</th>
<th>η (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>8.084</td>
<td>0.43</td>
<td>0.765</td>
<td>2.663</td>
</tr>
<tr>
<td>30</td>
<td>8.189</td>
<td>0.435</td>
<td>0.754</td>
<td>2.692</td>
</tr>
<tr>
<td>50</td>
<td>8.179</td>
<td>0.441</td>
<td>0.748</td>
<td>2.698</td>
</tr>
<tr>
<td>100</td>
<td>7.763</td>
<td>0.452</td>
<td>0.749</td>
<td>2.628</td>
</tr>
<tr>
<td>500</td>
<td>5.807</td>
<td>0.481</td>
<td>0.777</td>
<td>2.17</td>
</tr>
</tbody>
</table>
Comparing Table 10 and 11 with Table 5 and 6, the trend of the change of $J_{sc}$, $Voc$, FF and efficiency is the same. The difference lies in the absolute values. From Tables 10 and 11, we get the optimum thickness is 50nm p-Si with 0.1mm n-ZnO. However, the efficiency of Si-ZnO cell is much poorer than purely silicon cell. There are basically two factors contribute to its low efficiency. Firstly, n-ZnO can only absorb a small fraction of light due to its large band gap. Secondly, the discontinuity of the band structure traps the electric carriers and hence increases the density of recombination centers on the interface.

b. Doping density of n-ZnO

Table 10. Effect of the doping density of n-Zn on the solar cell performance. Fixed parameters: $T=300K$, p-Si thickness 50nm, n-ZnO thickness 100000nm. P-Si is the front layer facing the sun.

<table>
<thead>
<tr>
<th>$Nd (cm^{-3})$</th>
<th>$J_{sc} (mA/cm^2)$</th>
<th>$Voc (V)$</th>
<th>FF</th>
<th>$\eta (%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.0 \times 10^{15}$</td>
<td>8.179</td>
<td>0.441</td>
<td>0.748</td>
<td>2.698</td>
</tr>
<tr>
<td>$1.0 \times 10^{16}$</td>
<td>8.953</td>
<td>0.438</td>
<td>0.723</td>
<td>2.839</td>
</tr>
<tr>
<td>$1.0 \times 10^{17}$</td>
<td>9.164</td>
<td>0.434</td>
<td>0.75</td>
<td>2.979</td>
</tr>
<tr>
<td>$1.0 \times 10^{18}$</td>
<td>9.183</td>
<td>0.43</td>
<td>0.767</td>
<td>3.025</td>
</tr>
<tr>
<td>$1.0 \times 10^{19}$</td>
<td>9.198</td>
<td>0.426</td>
<td>0.777</td>
<td>3.044</td>
</tr>
</tbody>
</table>

Table 10 shows that when the doping density of ZnO increases, $J_{sc}$ increases, $Voc$ decreases, FF factor increases and efficiency increases. However, all the magnitude of change is not very large. This behavior is quite different from the silicon homojunction cell. The optimum doping density for n-ZnO is $10^{18} cm^{-3}$.

c. Temperature

Table 11. The solar cell performance under different working temperatures. Fixed parameters: $Na=1.0 \times 10^{17} cm^{-3}$, $Nd=1.0 \times 10^{19} cm^{-3}$, p-Si thickness 50nm, n-ZnO thickness 100000nm. P-Si is the front layer facing the sun.

<table>
<thead>
<tr>
<th>T(K)</th>
<th>$J_{sc} (mA/cm^2)$</th>
<th>$Voc (V)$</th>
<th>FF</th>
<th>$\eta (%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>240</td>
<td>9.187</td>
<td>0.543</td>
<td>0.834</td>
<td>4.258</td>
</tr>
<tr>
<td>250</td>
<td>9.183</td>
<td>0.523</td>
<td>0.826</td>
<td>3.969</td>
</tr>
<tr>
<td>270</td>
<td>9.183</td>
<td>0.484</td>
<td>0.809</td>
<td>3.594</td>
</tr>
<tr>
<td>300</td>
<td>9.198</td>
<td>0.426</td>
<td>0.777</td>
<td>3.044</td>
</tr>
<tr>
<td>320</td>
<td>9.184</td>
<td>0.387</td>
<td>0.752</td>
<td>2.675</td>
</tr>
</tbody>
</table>

Comparing with Table 7, all the parameters in Table 11 shows the same trend with different magnitudes. The p-Si/n-ZnO is less sensitive to the temperature comparing with
simple silicon cell. There is an approximation equation \([6]\) to depict the sensitivity of temperature affected by other material parameters:

\[
\Delta V_{oc} \approx \frac{eV_{bi}}{kT} - \frac{E_g}{eT} \Delta T
\]

(7)

where \(E_g\) is the band gap at 0K, \(\gamma\) is a parameter that summarizes the temperature dependence of \(I_L/I_0\). ZnO has a larger \(E_g\) than that of silicon, the influence of temperature is then smaller from equation (7) comparing with the silicon cell.

CONCLUSIONS

Intrinsic material properties including band gap, electron affinity, doping profile, geometric construction and working temperature are import factors influencing the solar cell performance. The numerical simulation is an efficient approach to select the optimum value for the best performance.

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References


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