Chapter 7

FABRICATION OF CIGS THIN FILM SOLAR CELL DEVICE AND ITS CHARACTERIZATION
7. **FABRICATION OF CIGS THIN FILM SOLAR CELL DEVICE AND ITS CHARACTERIZATION**

The solar cell structure based on copper indium gallium diselenide (CIGS) as the absorber layer, cadmium sulfide (CdS) as a buffer layer un-doped (i) and Aluminium (Al) doped zinc oxide (ZnO) as a window layer was simulated using the one dimensional simulation program called analysis of microelectronic and photonic structures (AMPS-1D). The effect absorber thickness is been consider to check the performance of CIGS solar cell, demonstrated in the form of current-voltage (I-V) characteristics and quantum efficiency (QE). Fabrication part includes the deposition of each layer one by one on to the glass substrate. The structure of CIGS solar cell is already defined in the chapter 1. In this chapter, the influence of the thicknesses of i-ZnO and CdS layer has been observed. Also the influence of flash and evaporated CdS and the thermally evaporated CdS has been checked. The performance of fabricated CIGS thin film solar cell has been checked by the current-voltage (I-V) measurements and by the spectral response measurements.

7.1 **SIMUALTON OF CIGS SOLAR CELL**

The copper indium gallium diselenide, CuIn_{1-x}Ga_xSe_2 (CIGS), based solar cells have largest efficiencies on the laboratory scale [47] and as well as on the level of large-area modules [125]. In addition to high efficiencies, CIGS thin-film modules exhibit excellent outdoor stability [126] and radiation hardness [127, 128]. Therefore, this combination of high efficiency coupled with stability and radiation hardness makes CIGS a promising material for the low cost, high efficiency solar cells. Recently, Bloss et al. [129] have predicted a conversion efficiency (\(\eta\)) of 33.9% for CGS/CIS tandem solar cells at global air mass (AM) 1.5 illuminations. Song et al. have modeled a CGS/CIGS tandem solar cell and they have shown that \(\eta\) was 25% achievable when a high efficiency CGS top cell was used with an optimized CIGS bottom cell [130].

In this present work, a one dimensional simulation program called a analysis of microelectronic and photonic structures (AMPS-1D) [131] is used to simulate the CuIn_{1-x}Ga_xSe_2 : x=0.3 solar cell structure. AMPS-1D developed at Pennsylvania State University and Electric Power Research Institute by S. Fonash et al. The software is designed
to simulate various photonic semiconductor structures, such as solar cells and photodiodes, and has the ability to introduce illumination with a defined photon spectrum and the electric biasing. The output data is generated through the numerical solution of the Poisson’s equation for the charge distributions in semiconductor structures, and two continuity equations for the electron and hole currents flowing through the structures. Figure 7.1 shows the schematic of solar cell design studied in this work. The aim of the simulation of CIGS solar cell structure was to check the device performance by varying the thickness of the CIGS absorber layer. The device performance is mainly based on the material parameters, optical parameters, and electrical parameters of each layers used in the structure. In this simulation the required parameters of CIGS thin film having a thickness of 300 nm were taken from the elsewhere [132]. For the rest of the layers the standard parameters [133] were used.

The thickness of the CIGS, in general, was kept ~2000 - 2500 nm [134, 135] in the commercial available solar cell device. In concern with that in this work, we simulate the solar cell structure by increasing the thickness of CIGS from 300 to 3000 nm. It was found from the simulated results that the $\eta$, and quantum efficiency (QE) were considerable influenced by the absorber layer thickness. As the thickness of the absorber layer increases

![Fig. 7.1 CIGS solar cell device structure used for the simulation.](image-url)
from 300 to 3000 nm, the value of $\eta$ increases from 8.25 % to 10 % and the response of QE improves near to the band edge of CIGS.

### 7.1.1 MODEL DESCRIPTION

The AMPS software can operate in two distinct modes: the density of state (DOS) mode or the lifetime mode. A description of both modes can be found in the AMPS manual [131]; a comparative discussion is found in A.L. Fahrenbruch’s work on CdTe solar cells [136]. In essence, the lifetime mode accepts inputs in the form of carrier lifetimes, which are assumed constant, independent of light and voltage bias, and does not address the underlying recombination processes. The DOS mode allows the definition of multiple defect states, using densities, energy distributions, and capture cross-sections. Based on this information, the recombination current and defect occupancy is calculated using the Shockley-Read-Hall formalism.

To model the charge transport processes in the present structure shown in Fig. 7.1, the drift-diffusion approach is used as a function of device length, x. The three main equations are: the Poisson’s equation, continuity equation for free holes, and continuity equation for free electrons. Generally, the Poisson’s equation is [1],

$$\frac{d}{dx} \left( -\varepsilon(x) \frac{d\psi}{dx} \right) = q \left[ n(x) - p(x) + N_D^+(x) - N_A^-(x) + p_t(x) - n_t(x) \right] \quad (7.1)$$

where, $\Psi$ is the electrostatic potential, $n$, $p$ are the concentrations of free electrons and holes, $n_t$, $p_t$ are the concentrations of trapped electrons and holes, $N_D^+$, $N_A^-$ are the concentrations of ionized donors and acceptors, $\varepsilon$ is the dielectric permittivity of semiconductor, and $q$ is the electron charge.

The transport characteristics of an electronic device may be derived by the continuity equation for the holes and electrons. The continuity equations in steady state conditions are,

$$\frac{1}{q} \frac{dJ_n}{dx} = \frac{1}{R_n} = G(x) - R(x), \quad (7.2)$$

$$\frac{1}{q} \frac{dJ_p}{dx} = \frac{1}{R_p} = G(x) - R_p(x) \quad (7.3)$$

where, $J_n$, $J_p$ are electron and hole current density, $R_n$, $R_p$ are electrons and holes recombination velocities for direct band-to-band and indirect transitions, and $G$ is the optical generation rate which is expressed as a function of $x$ is,
\[
G(x) = -\frac{d}{dx} \sum_i \Phi^\text{FOR}_i(\lambda_i) + \frac{d}{dx} \sum_i \Phi^\text{REV}_i(\lambda_i)
\]

where, \(\Phi^\text{FOR}_i\) and \(\Phi^\text{REV}_i\) are, respectively, the photon flux of the incident light and the light reflected from the back surface at a wavelength, \(\lambda\) of \(i\) at some point \(x\), depending on the light absorption coefficient, and the light reflectance in the forward and reverse direction. In our simulation, the reflection indices for the forward and reverse directions are 0 and 0.6, respectively. The governing equations 7.1, 7.2, and 7.3 must hold at every position in a device, and the solution to these equations involves determining the state variables \(\Psi(x)\), the n-type quasi-Fermi level \(E_{F_n}\), and the p-type quasi-Fermi level \(E_{F_p}\) or, equivalently, \(\Psi(x)\), \(n(x)\), and \(p(x)\), which completely defines the system at every point \(x\). Because the governing equations for \(\Psi(x)\), \(E_{F_n}\), and \(E_{F_p}\) are non-linear and coupled, they cannot be solved analytically. There must be boundary conditions imposed on the set of equations. The Newton-Raphson technique is used in AMPS-1D. To be specific, the solutions to equations 7.1, 7.2, and 7.3 must satisfy the following boundary conditions:

\[
\begin{align*}
\Psi(0) &= \Psi_0 - V; \\
\Psi(L) &= 0; \\
J_{p'}(0) &= -qS_{po}[p'_n(0) - p(0)]; \\
J_{p'}(L) &= qS_{pl}[p(L) - p'_o(L)]; \\
J_{n'}(0) &= qS_{no}[n(0) - n'_o(0)]; \\
J_{n'}(L) &= -qS_{nl}[n(L) - n'_l(L)].
\end{align*}
\]  

(7.5)

\(S_{po}, \ S_{pl}, \ S_{no}, \ \text{and} \ S_{nl}\) appearing in those conditions are effective interface recombination speeds for holes and electrons at \(x = 0\), and \(x = L\).

AMPS-1D solves three coupled differential equations each subject to boundary conditions (Equation 7.5) and then calculates the electrostatic potential and the quasi-Fermi level for holes and electrons at all point in the solar cell. Once these values are known as a function of depth, it is straightforward to calculate the carrier concentrations, electric fields and currents, and device parameters like the open-circuit voltage \((V_{oc})\), short-circuit current density \((J_{sc})\), fill-factor \((FF)\), and the efficiency \((\eta)\). These parameters define the performance of a solar cell. The grid spacing was selected to be denser in the thinner top layers of the device, where more rapid changes are to be expected in the band structure. The grid point does not exceed the maximum limit of 400. Selected biases were entered as necessary; by default AMPS calculates QE and band structure for thermodynamic equilibrium, maximum power point, and under open-circuit conditions.
7.1.2 Simulation Parameters

In this study, a one-dimensional numerical analysis tool, AMPS-1D, is used to create various solar cell models and obtain its results. In AMPS-1D, four different layers are required for the modeling. More layers can be added as long as the grid points do not exceed the limitation, viz. 400-grid points. The four layers that are used in this modeling is the n-type Al doped ZnO, i-ZnO, CdS and CIGS. Table 7.1 show the description for the parameters used in the simulation and the base parameter that are used throughout the presented simulation [133].

Table 7.1 Parameters used for the CIGS thin film solar cell simulation.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>n$^+$-ZnO</th>
<th>n-[i-ZnO]</th>
<th>CdS</th>
<th>CIGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thickness (nm)</td>
<td>500</td>
<td>80</td>
<td>60</td>
<td>300*- 3000</td>
</tr>
<tr>
<td>Dielectric constant, $\varepsilon$</td>
<td>9</td>
<td>9</td>
<td>10</td>
<td>13.6</td>
</tr>
<tr>
<td>Electron mobility, $\mu_n$ (cm$^2$/Vs)</td>
<td>50</td>
<td>50</td>
<td>6</td>
<td>300</td>
</tr>
<tr>
<td>Hole mobility, $\mu_p$ (cm$^2$/Vs)</td>
<td>5</td>
<td>5</td>
<td>3</td>
<td>36*</td>
</tr>
<tr>
<td>Carrier density, n or p (cm$^{-3}$)</td>
<td>n:1.70E+19</td>
<td>n:5E+16</td>
<td>n:6E+16</td>
<td>p:2.0E+17*</td>
</tr>
<tr>
<td>Optical band gap, $E_g$ (eV)</td>
<td>3.3</td>
<td>3.3</td>
<td>2.4</td>
<td>1.20*</td>
</tr>
<tr>
<td>Effective density, $N_c$ (cm$^{-3}$)</td>
<td>1.00E+19</td>
<td>1.00E+19</td>
<td>1.00E+19</td>
<td>3.00E+18</td>
</tr>
<tr>
<td>Effective density, $N_v$ (cm$^{-3}$)</td>
<td>1.00E+19</td>
<td>1.00E+19</td>
<td>1.60E+19</td>
<td>1.50E+19</td>
</tr>
<tr>
<td>Electron affinity, $\chi$ (eV)</td>
<td>3.9</td>
<td>3.9</td>
<td>3.75</td>
<td>4.15</td>
</tr>
</tbody>
</table>

* Parameters of CIGS thin films grown by flash evaporation method on soda lime glass substrate [132].

The front and back contacts are solely defined by their work function and the reflectivity of the contact-semiconductor interface: work function for front contact is 0 eV i.e. at the Fermi level, $E_F$, and the reflectivity is 0.3. Similarly 0.9 eV work function i.e. above $E_F$ and reflectivity is 0.8. The AM 1.5G photon flux was used for the illumination (Fig. 7.2). The number of incident photons/(cm$^2$/s) was entered for wavelengths between 250 nm to 2500 nm, with a step size of 2 nm. The front panel of AMPS-1D simulation for CIGS solar cell structure is shown in Fig. 7.3.
Fig. 7.2 AM1.5G photon flux used as the illumination condition in the simulation.

Fig. 7.3 AMPS simulation front panel contains the device and layer grid parameters, and general layer parameters.
7.1.3 Results and Discussions of Simulation

CIGS solar cells have a complex multilayer structure. Cell analysis is also complexed by a complicated window structure, consisting of a thin buffer layer (CdS or an alternative) and a double TCO layer (e.g. nominally undoped ZnO followed by Al doped ZnO).

It is clear that numerical modeling is necessary to evaluate quantitatively the effect of a set of assumed input parameters. Figure 7.4 (a) shows the J-V characteristic, using AMPS-1D, of the CIGS solar cell structure having a different thickness of CIGS absorber layer. As the thickness of the layer increases from 300 nm to 3000 nm, the conversion efficiency increases from 8.25 % to 10 %. Figure 7.4 (b) shows the variation in the $V_{oc}$ and $I_{sc}$ including $\eta$ as a function of absorber thickness. It indicates that below 1500 nm thickness of absorber the cell shows the sharp decrease in the $V_{oc}$, $J_{sc}$ and therefore decrease in the $\eta$. The cell having a 300 nm thickness of CIGS shows the values of $V_{oc}$ and $J_{sc}$ is 0.452 volt and 25.4 mA/cm² respectively.

The spectral response shown in Fig. 7.5 indicates the absorber having a lower, 300 nm, thickness loose a part of $J_{sc}$ near to the band edge (~ 1000 nm) of the CIGS. As the thickness of the absorber layer increases, the recombination probability of the photon-generated carriers with back-contact is decreases. Recombination is mainly depending on the junction depth. As the thickness of the layer increases, the junction depth decrease relative to the thickness of the layer. Therefore, the photo-generated carriers are collected efficiently at higher thickness of the absorber layer. QE spectra shown in Fig. 7.5 suggest that at higher thickness of the CIGS absorber layer the maximum photon generated carriers are being collected and gives maximum ~70 % photon conversion efficiency.
Fig. 7.4 (a) J-V spectra for different CIGS thicknesses and, (b) Variation in the $V_{oc}$, $J_{sc}$, and efficiency as a function of CIGS thickness.
7.2 FABRICATION OF CIGS THIN FILM SOLAR CELL DEVICE

The fabrication part of CIGS solar cell includes the layer by layer growth of each individual layer on a glass substrate. Figure 7.6 shows the structure of the CIGS thin film solar cell fabricated in our laboratory. A frame-shaped shadow mask for each layer having a different area of exposing is used to avoid short-circuiting between the different layers from the edge. During the deposition of the different layers of the CIGS solar cell device, the structure is taken out from the vacuum chamber to change the source material and the shifting mask. The final active area of the device is 0.16 cm².

![Fig. 7.6 A schematic diagram of the CIGS solar cell structure with a frame-shaped shadow mask.](image-url)
Each layer in the solar cell structure plays an important role in the fabrication of p-n junction. In the CIGS thin film solar cell the p-n junction is formed between the CIGS and the CdS. ZnO bi-layer act as the conducting top window layer. The Molybdenum thin film acts as a back contact. Silver metal is used for the top contact as in finger type geometry. After each layer of deposition we had checked the behavior of the solar cell device for the confirming the goodness of the junction. In the summary we fabricated the CIGS thin film solar cell by varying the thickness of of CdS and i-ZnO layer. In addition we also use the thermal and flash evaporation method for growing the CdS layer. The performance of the CIGS solar cell was checked by the J-V measurements and the spectral response measurements.

7.2.1 Effect of Thermally Evaporated CdS Film Thickness on the performance of CIGS solar cell

In the CIGS thin film solar cell, the junction between CIGS and CdS plays the crucial role in the carrier generation and the recombination mechanism. In the fabrication process of CIGS solar cell, we have tried to optimize CIGS/CdS junction parameters by varying the thicknesses of CdS layer from 50 to 150 nm. Minimum series resistance and approach of ideality factor near to unity is the prime requirement for better pn junction. Figure 7.7 shows the dark J-V curve of CIGS/CdS junction with varying the thicknesses from 50 nm to 150 nm of CdS layer.

![Fig. 7.7 The dark J-V characteristics of CIGS/CdS hetero-junction having different thicknesses of CdS layer.](image-url)
The dark J-V curve of CIGS/CdS junction clearly indicates that as the thickness of CdS increases the slope of the curve is decreases, and then series resistance decreases. The lowest series resistance of 4.1 Ω and ideality factor of about 1.32 is observed for the 50 nm thickness of CdS layer. Table 7.2 shows the measured values of series resistance, ideal factor and the reverse saturation current density of CIGS/CdS junction for different thicknesses of CdS layer. It was observed that by reducing the CdS layer thickness from 150 nm to 50 nm, the series resistance reduces from 14.2 to 4.1 Ω and reverse saturation current density varies from $9.6 \times 10^{-10}$ to $3.6 \times 10^{-11}$ mA/cm$^2$. Lower reverse saturation current density, observed for thin CdS layer, may be responsible for the tunneling or shorting of the photo-generated carriers to the back contact. The value of ideality factor varies from 1.78 to 1.32 as the thickness of CdS reduces (Table 7.2). Still there is need to improve these values listed in Table 7.2. S. Nishiwaki et al. have observed near by values for stacked CGS based solar cells. According to their results of poor junction characteristics of CGS/ITO was observed [137].

Table 7.2 The series resistance, reverse saturation current density, and ideality factor of CIGS/CdS hetero-junction having a different thicknesses of CdS layer.

<table>
<thead>
<tr>
<th>CdS thickness (nm)</th>
<th>Series resistance (Ω)</th>
<th>Reverse saturation current density (mA/cm$^2$)</th>
<th>Ideality factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>4.1</td>
<td>$3.6 \times 10^{-11}$</td>
<td>1.32</td>
</tr>
<tr>
<td>60</td>
<td>6.4</td>
<td>$7.5 \times 10^{-11}$</td>
<td>1.41</td>
</tr>
<tr>
<td>70</td>
<td>8.2</td>
<td>$8.6 \times 10^{-11}$</td>
<td>1.55</td>
</tr>
<tr>
<td>100</td>
<td>9.2</td>
<td>$4.2 \times 10^{-10}$</td>
<td>1.63</td>
</tr>
<tr>
<td>150</td>
<td>14.2</td>
<td>$9.6 \times 10^{-10}$</td>
<td>1.78</td>
</tr>
</tbody>
</table>

Effect of Heat soaks on CIGS/CdS hetero-junction

Cd diffusion into CIGS surface and bulk layer occurs easily through Cu-deficient surface layer of CIGS. The Cd-doping is known to induce a type conversion of p-CIGS surface layer of about 5 to 10 nm thickness yielding n-CIGS/p-CIGS homo-junction [138], which may benefit photovoltaic performance due to the reduced interface recombination. Formation of this type of homo-junction need to be improve by means of thermal annealing [139]. Instead of annealing up to certain temperature, soaking pulse having a temperature of 200 °C was given to the CIGS/CdS junction and the effect of it was observed for different time intervals. The thickness of CdS was kept 70 nm, though it shows the higher value of series resistance, but it shows better surface coverage of film compared to the 50 nm thick CdS, which has a
lower series resistance. The dark J-V characteristics of CIGS/CdS junction, heat soaked for different time viz. 20 s, 40 s and 60 s is shown in Fig. 7.8.

![Graph of J-V characteristics](image)

**Fig. 7.8** The dark J-V characteristics of CIGS/CdS heterojunction heat soaked for different time.

As seen from the Fig. 7.8, the heat soak for less time interval, 20 s, shows significant improvement in the sharpness of the J-V. The threshold voltage for 20 s heat soak is 0.39 V and 0.44 V without heat soak as shown in Fig. 7.7. The series resistance is 3.4 Ω for 20 s heat soak CIGS/CdS junction, while it is 8.2 Ω without heat soak (Table 7.2).

<table>
<thead>
<tr>
<th>Heat soak time (s)</th>
<th>Series resistance (Ω)</th>
<th>Reverse saturation current density (mA/cm²)</th>
<th>Ideality factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>3.4</td>
<td>2.4 × 10⁻¹¹</td>
<td>1.19</td>
</tr>
<tr>
<td>40</td>
<td>7.2</td>
<td>6.3 × 10⁻¹¹</td>
<td>1.32</td>
</tr>
<tr>
<td>60</td>
<td>9.3</td>
<td>2.6 × 10⁻¹⁰</td>
<td>1.52</td>
</tr>
</tbody>
</table>

Table 7.3 The series resistance, reverse saturation current density, and ideality factor of CIGS/CdS hetero-junction having a different heat soak time.

This reduction in the series resistance and threshold values shows the clear indication of the improvement of CIGS/CdS by applying the heat soak for 20 s. By increasing the soak time the series resistance value increases. It reached to 9.3 Ω for 60 s heat soak pulse. The values
of series resistance, reverse saturation current density, and ideality factor for different heat soak pulse is shown in Table 7.3.

The light J-V measurements in the light (100 mW/cm²) are carried out after the ZnO bi-layer (intrinsic and Al-doped ZnO) deposition, on CdS layer. The layer of i-ZnO of about 70 nm is deposited on CdS and then the 450 nm thick AZO. After the ZnO bi-layer deposition the Al grid is deposited by thermal evaporation at room temperature. Couple of solar cells with Al grid did not show any photovoltaic effect. By microscopic observation of prepared CIGS solar cells, we observed blackish colored Al grid strips that may be due to the shadow effect of mask or Al diffusion into the AZO layer. Another couple of CIGS cell with similar kind of photovoltaic effect confirms the shorting of the junction due to the Al deposition. To overcome thus, we deposited the Silver (Ag) grid on AZO layer by thermal evaporation method at room temperature. Thin film of Ag, in the form of grid, shows nice appearance of reflecting silvery surface. The CIGS solar cells having an Ag grid shows Voc of about 0.35 mV and Jsc about 1 μA/cm². The light J-V characteristic is shown in Fig. 7.9.
Many research groups have observed and discussed about the shorting of the p-n junction due excess Cd atoms on the surface of CIGS [140]. A part of CdS adjacent at the CdS/CIGS interface and made a porous structure. In fact, it is a very thin layer rather than void. This porous structure may exist due to the evaporation loss of CdS at high temperature (>1400 °C) and locality of the material loss as well. Therefore, the pore evolution should be directly correlated with Cd and/or S diffusion out of CdS. The pore structure, i.e., excess Cd atoms may be reducing by controlling the surface composition of CdS layer. The flash evaporation was used instead of thermal evaporation technique of the deposition of CdS layer for improving the Cd and S composition.

7.2.2 Effect of Flash Evaporated CdS Film Thickness on the performance of CIGS solar cell

Flash evaporation technique is widely used by researchers to deposit binary/ternary semiconductor compound material owing to its simplicity and ease of operation. In this method, pulverized compound material is transported to an evaporation boat hot enough to provide a quick evaporation of the material, without splitting it into individual elements. The CdS layer is deposited by flash evaporation technique at the substrate temperature of 100 °C. We have varied the thickness of CdS from 120 nm to 180 nm. Below 120 nm the film’s
appearance not seems to be uniform. So, we have started the growth of CdS layer from 120 nm on CIGS layer. After the deposition of CdS layer we try to observe the dark and light J-V analysis. Figure 7.10 shows the dark J-V characteristics of CIGS/CdS junction having different thicknesses of CdS layer.

![Graph showing dark J-V characteristics](image)

**Fig. 7.10** The dark J-V characteristics of CIGS/CdS structure having a different thickness of flash evaporated CdS layer.

The dark J-V indicates that the threshold voltage is higher (~0.68 V) for the thicker CdS layer (180 nm). On the other hand the as thickness of CdS is decreases the threshold voltage is reduce and the reverse saturation current density increases. Higher values of reverse saturation current not been considered for the preparing the solar cell device. Physical the origin of this current can be due to extrinsic features related to the thin-film fabrication processes, such as the leakage path at the edge of the device, the presence of crystal defects or impurities, and pin holes [141]. All these factors are spatially non-uniform in nature, and thereby provide parasitic conduction paths. The values of the series resistance, reverse saturation current density and the ideality factor of the CIGS/CdS junction by varying the thickness of CdS is listed in the Table 7.3.

A light J-V measurement, Fig. 7.11, indicates that the 140 nm thickness has more $V_{oc}$ and $I_{sc}$ compared with other thicknesses of CdS. In the next part we have deposited i-ZnO layer (140 nm) on the CdS layer using the RF magnetron sputtering.
Fig. 7.11 The light J-V characteristics of CIGS/CdS structure having a different thickness of flash evaporated CdS layer.

Table 7.3 The series resistance, reverse saturation current density, and ideality factor of CIGS/CdS hetero-interface having different thicknesses of Flash evaporated CdS layer.

<table>
<thead>
<tr>
<th>CdS thickness (nm)</th>
<th>Series resistance (Ω)</th>
<th>Reverse saturation current density (mA/cm²)</th>
<th>Ideality factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>120</td>
<td>2.3</td>
<td>$1.8 \times 10^{11}$</td>
<td>1.13</td>
</tr>
<tr>
<td>140</td>
<td>2.2</td>
<td>$8.5 \times 10^{11}$</td>
<td>1.12</td>
</tr>
<tr>
<td>160</td>
<td>3.2</td>
<td>$9.6 \times 10^{11}$</td>
<td>1.19</td>
</tr>
<tr>
<td>180</td>
<td>5.3</td>
<td>$1.2 \times 10^{10}$</td>
<td>1.63</td>
</tr>
</tbody>
</table>

In the case of CIGS/CdS/i-ZnO structure also we measured the Dark and Light J-V. The dark J-V of the CIGS/CdS structure shows a noticeable Schottky behavior for the 140 nm thickness of CdS thin film. Figure 7.12 shows the dark J-V characteristics of CIGS/CdS/i-ZnO structure having different thicknesses of flash evaporated CdS layer. As the thickness of CdS decreases from 180 nm to 120 nm, the series resistance decreases from 400 Ω to 45 Ω and the diode ideality factor decreases from 3.8 to 1.6.
After the deposition of i-ZnO layer, we deposited AZO layer using the RF magnetron sputtering. Figure 7.13 shows the dark and light J-V of a complete CIGS solar cell having different thicknesses of CdS layer. The dark J-V plot shows the linear relationship between the voltage and the current density. This indicates the shorting of the junction which may be due to the deposition of high energy AZO sputtering particles for a longer time. Light J-V curve show a maximum value of $V_{oc}$ equal to 0.5 mV and $I_{sc}$ of 30 μA, which again confirms the major detrimental effect of AZO deposition.

The highly energetic particles can induce internal stresses and local defects [142, 143]. Moreover, the strong impact of oxygen may form aluminum oxide or excess oxygen inside AZO films. To reduce the internal stress we tried to reduce the thickness of i-ZnO layer and observed the performance of the solar cell device. The thickness of i-ZnO layer varied from 70 nm to 20 nm.
Fig. 7.13 (a) Dark and (b) Light J-V characteristics of CIGS complete solar cell having different thicknesses of flash evaporated CdS layer.
7.2.3 Effect of i-ZnO Film Thickness on the performance of CIGS solar cell

The dark J-V plots of CIGS/CdS/i-ZnO structure is shown in Fig. 7.14. It clearly shows a higher forward current after the threshold voltage (0.4 V) for 20 nm thin i-ZnO layer, compared to the film thickness of 35, 70 and 140 nm. This may be due to more optimal doping concentration and thus better conductivity across the junction. It also results the lowering the diode ideality factor. As seen from Fig. 14, the series resistance decreases from 96 Ω to 12.5 Ω as the thickness of i-ZnO reduces from 70 nm to 20 nm. The diode ideality factor also decreases from 1.5 to 1.23. On the other hand the reverse leakage current density increases as the thickness of i-ZnO decreases.

After observing the diode behavior, in the dark environment, up to i-ZnO layer, we have deposited AZO layer on to the i-ZnO layer and measured the dark and light J-V. Figure 7.15 (a) and (b) shows the dark and light J-V behavior of CIGS solar cell having a different thickness of i-ZnO layer, respectively. The dark J-V clearly shows that as the thickness of i-ZnO is reduced the diode behavior of CIGS solar cell improves. The value for the forward resistance of CIGS solar cell having a lowest thickness, i.e. 20 nm, of i-ZnO is 450 Ω and the reverse resistance is 491 Ω. In the case CIGS solar cells having a 35 nm and the 70 nm of i-ZnO the forward and reverse resistance is nearly same. That indicates the p-n junction has not been formed properly.
For all three thicknesses of i-ZnO layer, the photovoltaic effect of CIGS solar cell has been observed. The maximum $V_{oc}$ is of about 138 mV and the maximum $J_{sc}$ is of about 1.3 mA/cm$^2$ has been observed for the CIGS solar cell having a thickness of 20 nm thickness of i-ZnO. As the thickness of i-ZnO increases the values of $V_{oc}$ decreases, as shown in Fig. 7.15 (b). The possible reason for getting lower values of $V_{oc}$ and $J_{sc}$ is the higher reverse leakage current density, which indication the formation of the pore structure at the interface after the deposition of AZO layer.

The photo-current generation tells us the number of electron-hole pairs generation and distribution throughout the thickness of the device. The photo-generated current collection tells us the probability that these charge carriers will be collected by the external circuit, and therefore contribute to $J_{sc}$. This is generally expressed as a fraction and referred to as the collection efficiency. Depending on the depth within the device, different mechanisms are primarily responsible for photo current collection. Within the space-charge region (SCR) the built-in electric field sweeps electrons to the front of the device and holes towards the back, therefore collection is generally high. Outside of the SCR, carrier transport is limited by diffusion, and therefore collection is lower.
Fig. 7.15 The J-V characteristics, (a) in dark and, (b) in light of CIGS solar cell having different thicknesses of i-ZnO layer.

The influence of i-ZnO layer on the spectral response of CIGS solar cell has also been checked. The plot of spectral response for CIGS solar cell having different thickness of i-ZnO is shown in Fig. 7.16. The drop in spectral response below 520 nm wavelength is caused by the photon absorption in the CdS window layer (band gap $E_g = 2.4$ eV). The drop at higher wavelengths (~1100 nm) corresponds to the CIGS band gap of $E_g = 1.10$ eV. The CIGS solar cell having thin i-ZnO layer, i.e. 20 nm, shows maximum spectral response. As the thickness of i-ZnO increases from 20 nm the spectral response decreases. The experimental curve shows some optical interference in the range between 500 nm and 900 nm. AMPS simulation does not include interference effects and therefore the response will always give a smooth line.
Fig. 7.16 Spectral response of CIGS solar cell having different thicknesses of i-ZnO layer.

After observing the photovoltaic effect of CIGS solar cell having a 20 nm i-ZnO layer, we again made CIGS solar cells having different thicknesses of CdS, i.e. 120 nm to 180 nm, by keeping constant the thickness of i-ZnO layer i.e. 20 nm. The dark J-V plots of CIGS/CdS/i-ZnO structure having different thicknesses of CdS is shown in Fig. 7.17. It shows that as the thickness of CdS layer decreases the reverse saturation current increases and the forward threshold voltage decreases.

The minimum reverse saturation current density and the minimum threshold value is observed for 140 nm of CdS film thickness. The higher forward current after the threshold voltage (0.42 V) is due to a more optimal conductivity across the junction. It also improve the diode ideality factor. The dark J-V of CIGS/CdS/i-ZnO structure having different thicknesses of CdS layer, as seen from the Fig. 7.17, shows that as the thickness of CdS layer decreases from 180 nm to 120 nm the diode behavior improves, so the series resistance is reduces from 33 Ω to 11 Ω.
The deposition of AZO has been carried out on the i-ZnO layer. The dark and the light J-V characteristics of complete CIGS solar cell having different thicknesses of CdS is shown in Fig. 7.18 (a) and (b), respectively. The dark J-V of CIGS solar cells show that there is no diode like behavior of the junction which has the higher thickness of CdS films, viz. 160 and 180 nm. On the other hand, CIGS solar cell device having CdS thickness of 140 nm shows the diode behavior including the maximum reverse leakage current density. This diode behavior is responsible for getting the photovoltaic effect with the maximum Voc of about 138 mV and the maximum Jsc of 1.3 mA/cm². There is no photovoltaic effect observed for 120 nm CdS, which may be because of the non uniform CdS layer, providing the shunt path for the photo-generated carriers.

At higher thickness of CdS (180 nm), the forward voltage threshold has not observed from the dark J-V plot. Also there has been a minor photovoltaic effect is observed for 180 nm thickness of CdS. It is possible that the thicker high resistive CdS does not allows passing the photo-generated carriers. Similarly, the maximum spectral response has been observed for CIGS solar cells having 140 and 160 nm thickness of CdS layer as shown in Fig. 7.19. Finally, the fabricated CIGS solar cell is shown in the Fig. 7.20.
Fig. 7.18 Dark (a), and light (b), J-V characteristics of CIGS solar cell device having different thicknesses of CdS layer.
Fig. 7.19 Spectral response of CIGS solar cell having different thicknesses of CdS layer.

Fig. 7.20 The photograph of a complete CIGS solar cell with the measurement probe: Gold wire, a top contact on Ag grid and copper strip, a pressure contact on Molybdenum thin film. The inset photograph shows closer look of a single CIGS solar cell.
7.3 CONCLUSIONS

AMPS-1D is used to simulate the CIGS solar cell device. The simulated results suggested that the conversion efficiency increased until the thickness reached at around 2 μm. Further increase in the thickness of the films does not show any improvement in the efficiency. The maximum energy conversion efficiency of about 10% has been observed. These observation leads to the conclusion that for the optimum performance of the solar cell device the thickness of the absorber layer plays an important role. By fixing up the absorber layer thickness, i.e. 1 μm, we fabricated the CIGS solar cell. The variation with the thicknesses of i-ZnO and CdS is observed. At 140 nm thickness of CdS and 20 nm thickness of i-ZnO, we observed maximum $V_{oc}$ and $J_{sc}$ of CIGS thin film solar cell is about 138 mV and about 1.3 mA/cm$^2$. The influence of the thickness of i-ZnO and the CdS thin film has also been observed on the spectral response of CIGS thin film solar cell.