Chapter 6

ALUMINUM DOPED AND INTRIZIC ZINC OXIDE (ZnO) WINDOW LAYER: GROWTH AND OPTIMIZATION
6. ALUMINUM DOPED AND INTRINSIC ZINC OXIDE (ZnO) WINDOW LAYER: GROWTH AND OPTIMIZATION

The optimization process of the RF magnetron sputtered Al-doped ZnO (AZO) thin films was carried out by studying its structural, optical, electrical, and morphological properties at different RF power and different working pressures for its use as a front-contact for the copper indium diselenide (CIGS) based thin film solar cell. The structural study suggests that the preferred orientation of grains is along the (002) plane having a hexagonal structure of the grains. The optical and electrical properties suggest that the films show an average transmission of 85 % and a resistivity of the order of $10^{-4}$ Ωcm. The morphology analysis suggests the formation of packed grains having a homogeneous surface. Also intrinsic ZnO (i-ZnO) thin films were grown by RF magnetron sputtering. The growth, structural, optical, and electrical properties of i-ZnO is studied.

6.1 NEED OF ZnO WINDOW LAYER

Thin films, which can be used as window layers in many optoelectronic devices, need to be transparent to the visible range of the light spectrum and be conductive enough. To date, the industry standard for transparent conducting oxide (TCO) is tin-doped indium-oxide (ITO). This material has a low resistivity of $\sim 10^{-4}$ Ωcm and a transmission greater than 80 %. However, in the field of solar cells, Al-doped ZnO (AZO) thin films have caught the attention for its use as a window layer because of its low cost and wide availability of its constituent raw materials compared to ITO. In the AZO thin films, the textured surface structure formation is easy compared to that in ITO [105], which increases the light trapping capability of the front surface of the solar cell and hence reduces the reflection losses. For the deposition of the AZO, the most commonly used technique is by radio frequency (RF) magnetron sputtering due to its high reproducibility [106, 107]. Besides, it permits the deposition to be carried out at low substrate temperatures, leading to smooth films with a good surface uniformity. Nowadays, there is an increasing interest in reducing the substrate temperature for many applications in order to minimize the inter-diffusion processes on prior deposited materials. Additionally, the use of flexible substrates such as plastic polymers replacing the conventional glass substrates becomes of great interest in the photovoltaic field as they contribute to cost reduction in the production processes [108].
In this study, we present the results regarding the optimization of AZO thin films deposited on soda lime glass substrate. The optimization process was performed by varying the RF power and working pressure and studying their influence on the structural, optical, morphological, and electrical properties, in order to achieve the highest transparency and lowest resistivity films. The outcome suggested its use as a window layer in the solar cell structure. To improve the performance of the CIGS based thin film solar cell a very thin layer of i-ZnO was placed between the CdS and AZO layer. The use of i-ZnO thin films in the CIS solar cells is to minimize the recombination of the photo-generated carriers at the CdS and AZO junction by means of reducing the lattice mismatch. Here we have used the optimized deposition parameter of AZO thin films for growing the thin i-ZnO thin films.

6.2 ALUMINUM DOPED ZINC OXIDE (Al-ZnO) THIN FILM PREPARATION

AZO thin films were optimized for the application of the Copper Indium Gallium diselenide (CIGS) thin film solar cells for the front-contact and with that i-ZnO thin films were optimized to reduce interface recombination of photo-generated carries using radio frequency (RF) magnetron sputtering system (HÜTTINGER Elektronik, 600 W, Germany). We have used a 50 mm diameter ceramic target of ZnO (doped with 2 % Al₂O₃) and i-ZnO. For the deposition of AZO thin films the vacuum chamber was first evacuated with a base pressure of \(1 \times 10^{-5}\) Torr using a vacuum coating unit (HINDHIGHVAC, model-15F6, Bangalore). By using the Ar gas flow (kept at 4 sccm constant), the pressure was controlled roughly and then by throttling the baffle valve a fine control on the chamber pressure was achieved. We have used mass flow controller (MFC) for the gas flow at constant rate made up from AALBORG, Germany. AZO thin films were grown on soda lime glass substrates. The glass substrates with a dimension of 50 × 50 mm² were cleaned ultrasonically in a vapour of acetone, ethanol, and deionized (DI) water, followed by drying in blowing nitrogen. At the time of the deposition, we rotate the substrate at a speed of 40 rpm for the uniform coating of AZO thin film. Before the deposition, pre-sputtering was applied for 5 minutes at 5 mTorr pressure to remove the surface contamination of the AZO target. The source to substrate distance was kept 70 mm for all AZO deposition. The thickness of all AZO films was kept constant viz. 450 nm, which was measured in-situ by using the quartz crystal thickness monitor. No any external heat treatment applies during the time of the deposition. Structural, optical, and electrical properties of RF magnetron sputtered AZO thin films were analyzed using an X-ray diffraction (XRD) (D8 ADVANCE, Bruker AXS, USA), a UV-VIS spectrophotometer (Thermo Fisher Scientific, USA), and a four-point probe method using Keithley 2420C source meter, respectively. The best optimized condition of AZO thin film is also applicable
for making i-ZnO thin film. We kept the RF power constant at 100 W and the working pressure is 1 mTorr. Prepared i-ZnO thin films were characterized by same way as AZO thin films listed above in this section.

### 6.3 EFFECT OF RF POWER

#### 6.3.1 Structural Characterization

The XRD spectrum of the AZO target is shown in Fig. 6.1. Through identifications of XRD, we found that all peaks presented in the spectra are from the ZnO crystal structure [109]. The XRD spectra of AZO thin films deposited at different RF power (80 W to 150 W) using AZO target is shown in Fig. 6.2. We have kept the working pressure constant at 10 mTorr.

![XRD spectra of the AZO target](image.png)

Fig. 6.1 The XRD spectra of the AZO target. The characteristic peaks well match with JCPDS data card 36.1451, confirm the wurtzite structure of ZnO.
Fig. 6.2 The XRD spectra of the AZO thin films deposited at different RF power shows a preferred orientation along the (002) plane.

The XRD spectra revealed a strong preferred orientation of the (002) peak indicating that the films were orientated with their axes perpendicular to the substrate plane and having a hexagonal structure [109]. Small diffraction intensity from (101) and (004) planes are also present in the XRD spectra. As the RF power varies the deposition rate also varies with it. It was increased from 0.16 nm/s to 0.28 nm/s by varying the RF power from 80 W to 150W. From the XRD data, the average crystallite size (D) can be evaluated by the Scherrer’s formula as follows [110],

\[
D = \frac{0.9 \lambda}{\beta \cos \theta}
\]  

(6.1)

where, D is the crystalline size, \( \lambda \) is the X-ray wavelength (0.154 nm), \( \theta \) is the Bragg angle, and \( \beta \) is the full-width at half-maximum (FWHM) of the AZO (002) diffraction peak. The crystallite size increases with increasing RF power. At 150 RF power, highest crystallite size of 10.18 nm was observed as shown in Table 6.1.
Table 6.1 The d-spacing, FWHM, and crystallite size of AZO thin films grown at different power keeping working pressure constant at 10 mTorr.

<table>
<thead>
<tr>
<th>RF power (W)</th>
<th>d-spacing (Å)</th>
<th>FWHM (degree)</th>
<th>Crystallite size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>2.56</td>
<td>0.95</td>
<td>8.50</td>
</tr>
<tr>
<td>100</td>
<td>2.55</td>
<td>0.85</td>
<td>9.66</td>
</tr>
<tr>
<td>150</td>
<td>2.56</td>
<td>0.79</td>
<td>10.18</td>
</tr>
</tbody>
</table>

In RF magnetron sputtering as the RF power increases the deposition rate increases because of the highly energetic ionized argon atoms bombarding on the target, which leads to an increase in the ejection rate of the sputtered atoms [111]. The XRD spectra of AZO thin films deposited at different RF power shows strong (002) diffraction peaks. Other peaks (004) with much less intensity were observed, indicating that the films are oriented with their c axis perpendicular to the substrate plane. The highest (002) peak value of AZO thin films was obtained at RF power of 100 W. The crystallite size of the AZO thin films was evaluated according to Scherrer's relation and found to be in range of 8.50 - 10.18 nm with the sputtering power ranging from 80 W to 150 W, and for highest value, 10.18 nm, was obtained at the power of 100 W. No Al₂O₃ related phase was found, which implied that Al atoms substitute Zn in the hexagonal lattice and Al ions may occupy the interstitial sites of ZnO or probably Al segregates to the non-crystalline region in grain boundaries and forms Al–O bond [112]. After 100 W, i.e. at 150 W in our case, we observed that the intensity of (002) peak decreases, due to deformation in the grains in the direction of (002) plane.

6.3.2 Optical Characterization

The influence of the RF power on the optical properties viz. transmission, energy band gap, $E_g$, and optical absorption, $\alpha$, of the AZO films was analyzed. Figure 6.3 shows the transmission spectra of the AZO thin films deposited at different RF power i.e., from 80 W to 150 W. The average transmittance is ~80 % observed between 450 and 800 nm range (visible range). From the optical transmission data, the value of $\alpha$, which provides the information of the band structure, is calculated from the lamberts law [113] and by using the transmission values the plot of $(\alpha h \nu)^2$ versus $h \nu$ is shown in Fig. 6.4 (a). The $E_g$ can be obtained by extrapolating the straight-line portion of plots to the photon energy axis. The value of $E_g$ for the as-deposited AZO films was in the range of 3.31 eV to 3.38 eV (Table 6.2). Figure 6.4 (b) shows the variation in $\alpha$ as a function of wavelength.
Fig. 6.3 The transmission spectra of the AZO thin films deposited at different RF power indicating an average transmission of 80 % over a visible region.

The transmission spectra of AZO thin film, Fig. 6.3, shows that at lower power, 80 W, there was a loss of transmission, which can be attributed to the limited solubility of the Al in the film. This is because of the reduction in the deposition rate at lower power. On increase the RF power, 150 W, due to the scattering of the light from the surface of the film, a loss of transmission observed. From the transmission spectra the calculated band gap values of our AZO thin films deposited at different power are higher than the value ($E_g = 3.25 \text{ eV}$) of pure ZnO. It is generally believed that the Burstein-Moss effect [114, 115] plays a key role in this phenomenon: ZnO is a natural n-type material and the Fermi level would move into the conduction band when it is doped with Al. Since the states below Fermi level in the conduction band are filled, the absorption edge should shift to higher energies. With the sputtering power, increasing from 80 W to 150 W, as Fig. 6.3 shows, absorption edge shifts negligibly to shorter wavelength observed, which indicates an increase of carrier concentration, known as the Burstein–Moss shift [116].
Fig. 6.4 Plot of \((\alpha h\nu)^2\) versus \(h\nu\) (a), and the variation in the absorption coefficient, \(\alpha\), (b) for AZO thin films deposited at different RF power.
The variation in the energy band gap and in the absorption coefficient is shown in Fig. 6.4 (a) and (b) respectively. It was observed from Fig. 6.4 (b) that, there was a negligible absorption of the photons in the visible region, which could be the important factor for its use as a window layer in solar cell.

6.3.3 Morphological Characterization

The surface morphology of the AZO thin film was observed using AFM. The morphology of the as deposited films indicates dense AZO grains, which is shown in Fig. 6.5. The surface morphology of the films i.e. the grain growth, depends upon the deposition flux, which increases, as the RF power increases. Due to that, the surface of the films becomes denser. The grain growth of the AZO thin films grown at different power is clearly observed from in Fig. 6.5. The surface roughness, as shown Table 6.2, increases from 17.73 nm to 36.77 nm as the RF power increases from 80 W to 150 W. The deformation of the grains observed at 150 W RF power is due to the higher deposition rate. The uniformity of the grains of AZO is found at 100 W RF power [116].

Fig. 6.5 The AFM images of the AZO thin films deposited at different RF power.
6.3.4 Electrical Characterization

For the use of AZO thin films as a window layer in the CIGS thin film solar cell, it has to behave as a metallic conductor. The sheet resistance ($R_{sh}$) and resistivity ($\rho$) of AZO thin films grown at different RF power were measured using the four-point probe method at room temperature. In addition, using the hot-probe method, we observed that all the AZO thin films showed n-type behavior.

Table 6.2 The variation in the values of energy band gap, sheet resistance resistivity and the surface roughness of AZO thin films, grown at 10 mTorr working pressure, as a function of RF power.

<table>
<thead>
<tr>
<th>RF Power (W)</th>
<th>Energy band gap, $E_g$ (eV)</th>
<th>Sheet resistance, $R_{sh}$ ((\Omega/\square))</th>
<th>Resistivity, $\rho$ ((\Omega\text{cm}))</th>
<th>Surface roughness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80</td>
<td>3.35</td>
<td>50</td>
<td>1.5\times10^{-3}</td>
<td>17.73</td>
</tr>
<tr>
<td>100</td>
<td>3.34</td>
<td>23</td>
<td>6.9\times10^{-4}</td>
<td>26.14</td>
</tr>
<tr>
<td>150</td>
<td>3.32</td>
<td>16</td>
<td>4.8\times10^{-4}</td>
<td>36.77</td>
</tr>
</tbody>
</table>

Traditionally, in the conduction mechanism of n-type ZnO, the intrinsic defects most commonly reported in the literature all the leading background donors in ZnO, namely the oxygen vacancy ($V_o$) and interstitial Zn ($Zn_i$) [117, 118]. For Al-doped ZnO films in our experiments, n-type conductivity will be enhanced by Al doping due to the contribution of extra free carriers via Al$^{3+}$ ions substituting Zn$^{2+}$ ions. The resistivity from four-point probe method was measured to be $1.5 \times 10^{-3}$, $6.9 \times 10^{-4}$, and $4.8 \times 10^{-4}$ \(\Omega\text{cm}\), when RF power was 50, 100 and 150 W, respectively, tabulated in Table 6.2. It indicates that the resistivity decreases with increasing RF power. This, dependence of the resistivity on RF power, leads to an improvement in the nucleation, crystallinity, and the ionized donors, hence a better conductivity, of the films.

6.4 Effect of Working Pressure

6.4.1 Structural Characterization

To study the effect of the working pressure, on the different properties of the AZO thin films, we have deposited the AZO thin film in the working pressure range of 2 to 20 mTorr at 100 W. By varying the working pressure, the deposition rate varies significantly. This is the key factor, which affect the properties of the thin films. In our case the deposition rate is higher (0.32 nm/s) for lower (2 mTorr) pressure and lower (0.15 nm/s) for higher pressure (20
mTorr). The XRD spectra of AZO thin film deposited at different working pressure (2 to 20 mTorr) at 100 W RF power is shown in Fig. 6.6.

![XRD spectra](image)

**Fig. 6.6** The XRD spectra of the AZO thin films deposited at different working pressures.

All AZO thin films show a preferred orientation along (002) direction. The intensity of (002) peak is observed highest at 10 mTorr working pressure and the highest crystallite size viz. 9.66 nm are tabulated in Table 6.3.

**Table 6.3** The d-spacing, FWHM, and crystallite size of the AZO thin films grown at different working pressure by keeping RF power constant at 100 W.

<table>
<thead>
<tr>
<th>Working pressure (mTorr)</th>
<th>d-spacing (Å)</th>
<th>FWHM (degree)</th>
<th>Crystallite size (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2.56</td>
<td>0.99</td>
<td>8.16</td>
</tr>
<tr>
<td>5</td>
<td>2.55</td>
<td>0.96</td>
<td>8.47</td>
</tr>
<tr>
<td>10</td>
<td>2.55</td>
<td>0.85</td>
<td>9.66</td>
</tr>
<tr>
<td>20</td>
<td>2.557</td>
<td>1.000</td>
<td>8.14</td>
</tr>
</tbody>
</table>
The XRD spectra of AZO thin films grown at different working pressures, Fig. 6.6, indicates that on increasing the working pressure from 2 mTorr to 10 mTorr the intensity of the (002) peak increases and by further increment in the working pressure i.e. at 20 mTorr the intensity decreases. In addition, other orientations, (101) and (004) are present in the XRD spectra. The improvement in the intensity of (002) peak up to 10 mTorr working pressure shows improvement in the crystallinity of the film, after that the intensity decreases. The crystallite size calculated from the Scherrer's formula is 8.16 nm for 20 mTorr working pressure and it is increased as the pressure increases and reaches at the maximum value of 9.66 nm. The variation in the crystallite size, FWHM, d-value and its corresponding 2θ value is tabulated in Table 6.3. The improvement in the crystalline quality of the films and the crystallite size show the enhancement in the possibility of Al doping in ZnO.

6.4.2 Optical Characterization

The optical transmission spectrum of AZO thin films grown at different working pressures is shown in Fig. 6.7. Using the transmission data, a plot of (ahv)^2 vs. hv and the variation in α as a function of wavelength are shown in Fig. 6.8 (a) and (b), respectively.

![Graph showing transmission spectra of AZO thin films deposited at different working pressures.](image)

Fig. 6.7 The transmission spectra of the AZO thin films deposited at different working pressures.

The influence of the working pressure is clearly seen in the transmission spectrum of AZO thin films. The transmission is ~85 % and the variation in the E_g is observed from 3.31
to 3.38 eV. The variation in the $E_g$ as a function of working pressure is shown in Table 6.4. Looking at Fig. 6.7, the transmission spectra of AZO thin films deposited at different pressure, the drop of the transmittance towards the higher wavelengths indicates that the films were not fully oxidized but it contained metallic (Al) inclusions. It directly impacts on the energy band gap of the films. As the pressure increases from 2 mTorr to 20 mTorr the energy band gap decreases from 3.38 eV to 3.31 eV, which is shown in Fig. 6.8 (a). This behaviour can be explained by examining the dependence of the Al inclusion as a function of working pressure. The variation in the absorption coefficient is shown in Fig. 6.8 (b).

Table 6.4 The variation in the values of energy band gap, sheet resistance resistivity and the surface roughness of AZO thin films, grown at 100 W RF power, as a function of working pressure.

<table>
<thead>
<tr>
<th>Working pressure (mTorr)</th>
<th>Energy band gap, $E_g$, (eV)</th>
<th>Sheet resistance, $R_{sh}$, ($\Omega/\square$)</th>
<th>Resistivity, $\rho$, ($\Omega\cdot$cm)</th>
<th>Surface roughness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3.38</td>
<td>50</td>
<td>$1.5 \times 10^{-3}$</td>
<td>19.21</td>
</tr>
<tr>
<td>5</td>
<td>3.36</td>
<td>37</td>
<td>$1.1 \times 10^{-3}$</td>
<td>23.29</td>
</tr>
<tr>
<td>10</td>
<td>3.34</td>
<td>23</td>
<td>$6.9 \times 10^{-4}$</td>
<td>26.14</td>
</tr>
<tr>
<td>20</td>
<td>3.31</td>
<td>29</td>
<td>$8.7 \times 10^{-3}$</td>
<td>22.70</td>
</tr>
</tbody>
</table>

Photon energy $h\nu$ (eV)

<table>
<thead>
<tr>
<th>3.0</th>
<th>3.1</th>
<th>3.2</th>
<th>3.3</th>
<th>3.4</th>
<th>3.5</th>
<th>3.6</th>
<th>3.7</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>1.0e+11</td>
<td>1.2e+12</td>
<td>2.0e+11</td>
<td>4.0e+11</td>
<td>6.0e+11</td>
<td>8.0e+11</td>
<td>1.0e+12</td>
</tr>
</tbody>
</table>

(a)
6.4.3 Morphological Characterization

Figure 6.9 shows the AFM image of the AZO thin films grown at different working pressures at 100 W RF power. As shown from the AFM images, the morphology is influenced by the working pressure significantly. The grain growth depends upon deposition flux, which was higher at lower working pressure due to the less scattering probability of the sputtered and gas atoms. Therefore, as the bombardment of energetic particles increases, that leads to a non-uniform growth of the grains are observed from the AFM images of 2 mTorr pressure. Reduction in the gas pressure results in the decrease of energetic particle bombardment, which was responsible for the uniform grain formation. The increased surface roughness from 19.21 nm to 26.14 nm by increasing the working pressure 2 mTorr to 10 mTorr is likely an indicator of increased grain size, consistent with the X-ray diffraction data. The variation in surface roughness is tabulated in Table 6.4.

6.4.4 Electrical Characterization

The variation in the sheet resistance ($R_{sh}$) and the resistivity ($\rho$), from Table 6.4, suggests that its future use as a front top metallic contact in the CIGS thin film solar cell. As the pressure...
increases from 2 mTorr to 10 mTorr the $R_{sh}$ decreases from 50 to 23 $\Omega/\square$. At 10 mTorr the resistivity was $6.9 \times 10^{-4}$ $\Omega$cm. The decrease in the sheet resistance can be explained by the increment in the surface roughness of the film. As the roughness increases due to the increment in the average grain size and so, the grain boundary reduces, which decreases the sheet resistance.

Fig. 6.9 The AFM images of the AZO thin films deposited at different working pressures.

6.5 INTRINSIC ZINC OXIDE (i-ZnO) THIN FILM PREPARATION

i-ZnO Target Preparation: High-quality sputtering targets are important in obtaining superior thin film properties. Transparent conducting oxide thin film targets can be divided into two types - metal targets and powder oxide-sintering targets. If metal targets are adopted, then oxygen gas must be first introduced into the chamber to form a thin-film oxide through chemical reactions. However, this method does not easily yield stable quality deposited film. Therefore, a powder oxide-sintering target is preferred [119]. Three conventional methods
viz. using a hot press, a hot isostatic press and normal sintering, exist for making powder oxide sintering targets.

ZnO powder (99.99 %) obtained from Sigma-Aldrich (U.S.A.) is used to prepare i-ZnO target. ZnO powder is dry-pressed or palletized by applying a force of 5 ton for three minutes in 51 mm diameter stainless steel die using droplets of acetone as binding material. The resultant disc shaped pellet (target) has 50 mm (± 1 mm) diameter. The target is first sintered at 400 °C temperature in an electric furnace at atmospheric pressure. The heating rate of furnace is kept at 4 °C per minute. The target is maintained at elevated temperature for six hour after which the temperature of the furnace is allowed to cool down to the laboratory temperature at the same rate. The shrinkage of the target is developed. Therefore, the target is crushed to powder using pestle and mortar. The sintered powdered material is then used to prepare the pellet (target) again. The target is sintered at 1150 °C for twenty-four hours. The sintered target is then ready for the deposition. The crystalline structure of i-ZnO target is investigated by X-ray diffraction (XRD) analysis in 2θ range from 20° to 100°. Figure 6.10 shows the XRD pattern of i-ZnO target. All major peaks for Zinc Oxide are identified in the XRD and agree well with the JCPDS data card no. 36-1451.

![XRD spectrum of i-ZnO target](image-url)
**i-ZnO Thin Film Preparation:** The front contact of CIGS based thin film solar cell consists of a highly conductive AZO layer on top of a highly resistive layer of i-ZnO. The very thin high resistive layer of i-ZnO prevents a shunt path between the molybdenum back contact and the aluminum doped zinc oxide front contact. For CIS based solar cell device application thickness of i-ZnO layer and its’ resistivity are important parameters. The correlation of the cell performance of CIS based solar cells with the thickness of highly resistive i-ZnO layer had been studied in detail by S. Ishizuka et al. [120]. Their study reveals that the efficiency of CIGS based thin film solar cell depends on i-ZnO thickness, and the highest efficiency is achieved when the thickness of i-ZnO layer is about 70 nm. In the case where i-ZnO layers are thinner than 40 nm, a slight degradation in cell performance was observed and cell efficiency reproducibility worsened. On the contrary, when i-ZnO layers were thicker than 70 nm, cell efficiency again degraded. In this study, we have deposited i-ZnO thin film of 70 nm thickness on glass substrates. We set the target substrate distance 50 mm, sputtering power is 100 W, deposition pressure is 1 mTorr. The deposition is carried out under the argon environment and no pre-heat treatment given to the substrate before deposition. The resistivity of i-ZnO thin film is $4.7 \times 10^5 \, \Omega \, \text{cm}$. The value of resistivity is close to the reported value for CIGS solar cell application by researchers [121]. The structural, morphological, and optical properties of i-ZnO thin film are investigated.

**6.5.1 Structural Characterization**

The crystalline structure and orientation of the i-ZnO thin film is investigated by X-ray diffraction (XRD) analysis, in 20 range 20º- 80º at a scan rate 0.05º s⁻¹ with Cu Kα ($\lambda = 0.154 \, \text{nm}$) radiation source. Figure 6.11 shows the XRD pattern of i-ZnO thin film deposited on glass substrate. Major peak is observed at diffraction angle 20 = 34.421º. This diffraction angle corresponds to (002) plane of reflections. JCPDS data card (file 36-1451) reveals that the film has strong c-axis orientation and hexagonal structure.

**6.5.2 Optical Characterization**

Figure 6.12 depicts transmission spectrum of i-ZnO layer. In order to obtain highly resistive i-ZnO layer deposition is carried out at higher deposition pressure. It is seen that i-ZnO layer exhibited very high transmission (above 85 %) in the visible range. The optical band gap of the film is calculated using plot of $(\alpha h\nu)^2$ vs. $h\nu$ (shown in Fig. 6.13). The value of energy band gap for i-ZnO thin film can be estimated by extrapolating the linear portion of the absorption edge with energy axis to find the intercept. Energy band gap of i-ZnO thin film
using the linear fit is 3.25 eV. It is in good agreement with the reported value by researchers using different deposition techniques [122, 123, 124].

![Graph showing X-ray diffraction pattern of i-ZnO thin film](image1)

**Fig. 6.11** X-ray diffraction pattern of i-ZnO thin film shows the preferred orientation of (002) plane.

![Graph showing transmission spectrum](image2)

**Fig. 6.12** Transmission spectrum of i-ZnO thin film showing the >95 % of transmission in visible range.
6.5.3 Morphological Characterization

The morphological characteristic of i-ZnO thin film is studied using atomic force microscope. Figure 6.14 shows two and three-dimensional AFM images of i-ZnO thin film. AFM image of the film reveals a structure with dense grains. The irregular shape of the grains suggests that the kinetic energy of molecules reaching the substrate is not sufficient for the coalescence of the grains. The surface roughness of the film approximated from AFM analysis is 4 nm.

Fig. 6.13 Energy band gap of i-ZnO thin film. Sharp transition observed at 3.25 eV of photon energy.

Fig. 6.14 AFM image of i-ZnO thin film showing the rough morphology with identical shaped grains.
AZO thin films have been obtained by RF-magnetron sputtering by varying the RF power and the working pressure. The structural, optical, electrical, and morphological properties of AZO thin films were analyzed. The obtained films were polycrystalline and had a preferred orientation with the c-axis perpendicular to the substrates. The lowest resistivity of $6.9 \times 10^{-4}$ $\Omega$cm is obtained at 100 W RF power and 10 mTorr working pressure. Transmission measurement shows that all films are highly transparent (~85%) in the visible region. Highly packed uniform grain structure was observed at 100 W at 10 mTorr working pressure. This work demonstrates the future use of Al doped zinc oxide (AZO) thin films as a window layer as well as a front-contact for the CIGS solar cell. Intrinsic ZnO (i-ZnO) layer also shows the preferred orientation as the AZO film shows. High resistive and above 85 % transmission in the visible region makes it most preferable to improve the performance of the CIGS thin film solar cell.