CHAPTER 5

Preparation and characterisation of indium tin oxide thin films by rf magnetron sputtering

Indium tin oxide thin films were deposited onto glass substrates by rf magnetron sputtering at room temperature. Effect of annealing on the structural, electrical and optical properties was investigated. By vacuum annealing highly conducting and transparent films were obtained. The dependence of film properties on the substrate to target distance was also studied. Films deposited with a target to substrate spacing of 4cm showed the lowest resistivity of $3.07 \times 10^{-3} \ \Omega \ \text{cm}$ and maximum band gap of 3.89eV on annealing at a temperature of 250°C under high vacuum for 1 hour.
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5.1 Introduction

Nowadays, transparent conducting metal oxides (TCO) are used almost exclusively as the top contacts in CIS based solar cells. Narrow lined metal grids (Ni-Al) are usually deposited on top of the TCO in order to reduce the series resistance. The requirements for the electrical top contact of a CIS device are; sufficient transparency in order to let enough light to the underlying parts of the device, i.e. its band gap must be high enough, and sufficient conductivity to be able to transport the photogenerated current to the circuit without too much resistance losses. It also serves as the antireflection coating for the active region. Tin doped indium oxide (ITO) is one of the widely used transparent conducting front contacts for solar cells.

5.2 ITO – An overview of present status

Interest in transparent conductors can be traced back to 1907 when reports on transparent and conductive cadmium oxide (CdO) films first appeared [1]. Since then there has been a growing technological interest in materials with these unique properties as evidenced by not only their increased numbers but also the large variety of techniques that have been developed for their deposition. It is now known that non-stoichiometric and doped films of oxides of tin, indium, cadmium, zinc and their various alloys exhibit high transmittance and nearly metallic conductivity is achievable in them [2]. However, tin doped indium oxide (ITO) is the most popular among these thin films, which have found a host of electronic, opto-electronic and mechanical applications. Hence, some of the physical and technological aspects behind ITO films deposition and characterisation will be discussed in this chapter.

Although partial transparency with acceptable conductivity can be obtained for very thin metallic films, high transparency and simultaneously high conductivity cannot be attained in intrinsic stoichiometric materials. The only way this can be achieved is by creating electron degeneracy in a wide band gap ($E_g > 3$eV for transparent to visible radiation) material by
introducing non-stoichiometry and/or appropriate dopants. These conditions can be conveniently met for ITO as well as a number of other materials previously mentioned.

Uses of ITO have traditionally ranged from transparent heating elements of aircraft and car windows, antistatic coatings over electronic instrument display panels, heat reflecting mirrors, antirefection coatings and even in high temperature gas sensors. Early electro-optic devices using ITO include CCD arrays, liquid crystal displays and transparent electrodes for various display devices. More recently, ITO has been used as a transparent contact in advanced optoelectronic devices such as solar cells, light emitting and photo diodes, phototransistors etc. Thus it is becoming an integral part of modern electronic technology wherever there is a potential for improving optical sensitivity of light detecting devices or quantum efficiency of light emitting devices.

Indium tin oxide is a highly degenerate n-type semiconductor with a reported low electrical resistivity of $8.45 \times 10^{-5} \ \Omega \text{cm}$ [3]. ITO is a wide band gap (3.3–4.3 eV) material, which shows high transmittance in the visible and near IR regions of the spectrum. Their high conductivity results from the non-stoichiometry produced by oxygen deficiency and the introduction of tin as dopant [4]. Because of these characteristics, ITO films are widely used in opto-electronic applications, such as transparent electrodes in liquid crystal displays, ferro-electric photo conductor storage devices and photovoltaic devices. ITO films have good efficiency for hole injection into organic materials, and hence they are widely utilised as the transparent conducting anode contact for organic light emitting diodes [5].

ITO films can be prepared by a wide variety of techniques such as plasma enhanced metallorganic chemical vapour deposition (PEMOCVD) [6], ion assisted deposition [7], sputtering [8], Pulsed Laser Deposition (PLD) [3], dip coating [9] etc. Sputtering is one of the effective methods to obtain good quality ITO thin films. It is superior in both its controllability and the uniformity of the films deposited on a large area substrate [10]. Reports also
show that good quality polycrystalline ITO films can be grown at room temperature by adopting PLD technique coupled with laser irradiation of substrate [11]. Production of low resistivity films at room temperature is of importance in high performance Flat Panel Displays (FPDs), which use heat sensitive substrates such as polymers.

The optical and electrical properties of the films depend strongly on the preparation technique. Theoretical understanding of ITO has been limited especially on the electronic band structure level, even though some results have been known about electronic structure, defect chemistry and carrier generation mechanisms [12]. The deposition of ITO in a manufacturing environment is typically by means of dc-magnetron sputtering [13]. The choice of target – ceramic or metal – depends on the film quality sought and the process control available. The variables adjusted during process optimization include oxygen partial pressure, total gas pressure, residual water-vapour partial pressure, substrate temperature and target temperature (due to unintentional heating), sputter power, and target composition and configuration. The goals are the minimization of micro structural features and impurities that lead to reduced electron mobility, the maximization of substitutional Sn, and the creation of optimal oxygen sub stoichiometry. The oxygen non-stoichiometry is critical to the minimization of resistivity, since each doubly charged oxygen vacancy contributes two free electrons [13].

Indium Tin Oxide is essentially formed by substitutional doping of In$_2$O$_3$ with tin, which replaces the In$^{3+}$ atoms from the cubic bixbyite structure of indium oxide [14]. Sn thus forms an interstitial bond with oxygen and exists either as SnO or SnO$_2$ – accordingly it has a valency of +2 or +4 respectively. This valency state has a direct bearing on the ultimate conductivity of ITO. The lower valence state results in a net reduction in carrier concentration, since a hole is created which acts as a trap and reduces conductivity. On the other hand, predominance of the SnO$_2$ state means Sn$^{4+}$ acts as an n-type donor releasing electrons to the conduction band. However, in ITO, both substitutional tin and oxygen vacancies contribute to the high conductivity and the material can be represented as In$_{2-x}$Sn$_x$O$_{3-2x}$. 

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Indium tin oxide prepared by various techniques is found to be polycrystalline always. ITO has a structure of bulk undoped In$_2$O$_3$. The lattice constant value of ITO is found to be larger than those of the bulk undoped In$_2$O$_3$. The amount of increase in lattice constant is found to depend on the deposition parameters. Lattice constant value strongly depends on oxygen partial pressure during sputtering process. ITO films in general are found to exhibit a strong (111) or (100) preferred orientations depending on deposition conditions [12].

Odaka et al. [15] used first principles band structure calculations to show that tin atom replacing an indium atom – irrespective of its site – leads to the formation of three impurity bands with s-like symmetry. One of these bands overlaps the conduction band of In$_2$O$_3$, and the Fermi level of ITO is located in this band, thus essentially accounting for the free electron like properties. Furthermore, it was found that the Sn substitution did not significantly destroy the shape of the density of states around the bottom of the conduction band. A quantitative theoretical model explaining the optical properties of ITO has been reported by Granqvist et al. [16]. In the ultraviolet region of the ITO, the absorption is strong due to excitations across the fundamental band gap $E_g$. Substitutional doping of Sn on In sites in the In$_2$O$_3$ lattice shifts $E_g$ towards shorter wavelengths. This phenomenon is due to the Burstein-Moss effect, i.e. a blocking of the lowest states in the conduction band, which is partly balanced by many body effects [17,18].

Indium oxide films are generally doped with tin because Sn$^{4+}$ substitutes for In$^{3+}$ cation creating donor level in the energy band gap. Tin doping of indium oxide films decreases the electrical resistivity of the films. All tin doped indium oxide films have n-type conductivity. For optoelectronic applications, the transparent conductor must be carefully processed to maximize optical transparency in the visible regime, while achieving minimum electrical resistivity. The window of transparency in ITO extends from the band gap on the UV end to the plasma-absorption frequency at the IR end [13]. When the oxide is degeneratively doped, increasing carrier...
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density leads to a widening of the band gap due to the Burstein-Moss effect. The IR end of the transparency window is defined by the plasma-absorption frequency, which depends on the carrier density and the effective mass of the carrier.

The values of electrical parameters strongly depend on the dopant concentration, deposition and post-deposition process conditions. The decrease in mobility with increase of dopant level is due to enhancement of scattering mechanisms such as ionized impurity scattering. The substrate temperature is found to significantly affect the electrical properties [13]. The resistivity initially decreases as the substrate temperature increases. This type of dependence of resistivity on substrate temperature may be due to the fact that crystallinity of the films improves with increase in substrate temperature, thereby increasing conductivity. At higher substrate temperatures the resistivity increases again. This increase in resistivity may be due to the oxidation of tin doped indium oxide films. Oxidizing or reducing conditions will modify the oxygen-vacancy concentration and hence the carrier density. Increasing the substrate temperature creates more oxygen vacancies and hence higher conductivity [13].

ITO has good substrate compatibility. ITO thin films can be deposited at room temperature, and in general, its adhesion to most substrates is excellent. The deposition of ITO onto silicon for use in solar cell applications can lead to the formation of an interfacial layer of SiO₂ as indium oxide is reduced by silicon [19].

Low substrate temperatures and low oxygen partial pressures during low-power sputter deposition will result in amorphous or partially amorphous material [20]. Remarkably, amorphous indium oxide crystallizes rapidly at temperatures as low as 150°C with a change in electronic band structure [21]. Low substrate temperatures and high deposition rates severely limit the quality of the as-deposited ITO films by reducing the activation efficiency of the tin dopant and by producing more highly defect microstructures.
Inactivated tin decreases the electron mobility through impurity scattering and does not increase the carrier density [13].

ITO films deposited by evaporation and sputtering at room temperature are reported to be generally amorphous or composed of very small grains, therefore showing low transparency and high resistivity. In the case of sputter-deposited films, better quality can be achieved by substrate heating or by introducing oxygen during sputtering. But the presence of too much oxygen will increase the resistivity [22]. When In$_2$O$_3$–SnO$_2$ targets are used for sputtering better stoichiometric films have been obtained [23,24]. Generally post deposition annealing is not essential when ITO films are grown from oxide targets. Oxygen is usually added to the sputtering gas in order to improve the structural, electrical and optical properties. But such an improvement is possible only when the oxygen partial pressure is low and within a narrow pressure range, typically $(2–4) \times 10^{-5}$ Torr. Films deposited at low temperature are amorphous in nature, whereas films deposited at higher temperature $(250^\circ C – 400^\circ C)$ are polycrystalline [12]. It has been reported that the laser irradiation of the ITO films improves the structural, electrical and optical properties [25]. The laser treatment annihilates dislocations and promotes grain growth. Post deposition annealing in vacuum atmosphere is an effective method to decrease the resistivity of sputtered ITO films. Higuchi et al. have reported ITO films with resistivity $1.3 \times 10^{-4}$ $\Omega\text{cm}$ after the annealing at 300$^\circ$C in vacuum with an improved crystallinity and transmittance [12]. The results of the post deposition annealing in air and vacuum showed that, in both cases the transmittance and crystallinity of the films improved and the surface topography didn’t show any appreciable change. The resistivity of the ITO films is found to increase with air annealing above 300$^\circ$C, whereas the vacuum annealing showed decrease in resistivity. The resistivity is found to depend on the carrier concentration in the films. Carvalho et al. [13] studied the effect of rf power on the properties of ITO films deposited on transparent polymer substrates. Optical properties were sensitive to rf power below 45W and the surface morphology remained independent of rf power. The introduction of hydrogen into the sputtering gas during rf magnetron sputtering showed that
the surface morphology of the films improved and the films showed a reduced resistivity of $4.66 \times 10^{-4}$ Ωcm with a transmittance of more than 80%. The films prepared by this technique didn’t require any substrate heating or post deposition annealing [15]. Substrate temperature during the ITO deposition enhances crystallinity of the films. ITO films prepared by rf reactive magnetron sputtering onto glass substrates at different substrate temperatures showed a (222) peak showing a preferred orientation in the (111) direction. As the temperature increased, (400) peak intensity increases and results in a preferred orientation of (100) direction for the films prepared at 500°C [17]. The resistivity of the ITO films deposited by PLD method is reported to decrease from $3.8 \times 10^{-4}$ to $1.9 \times 10^{-4}$ Ωcm as the substrate temperature increased from 250°C to 300°C. This might be due to the increase in the crystalline size with respect to the increase in the substrate temperature, thus reducing the grain boundary scattering and increasing the conductivity. This decrease in resistivity can also be due to the increase in carrier mobility [18].

In this chapter, the studies on the indium tin oxide thin films deposited by rf magnetron sputtering are presented. The films were deposited at room temperature and the influence of target to substrate spacing and the post deposition annealing on the structural, electrical and optical properties of these films are investigated.

### 5.3. Experimental details

ITO films were deposited on to glass substrates by rf magnetron sputtering at room temperature using an ITO target (5 cm diameter) containing 95 wt% of In$_2$O$_3$ and 5 wt% of SnO$_2$. The target used for sputtering was prepared from In$_2$O$_3$ (99.999 % pure) and SnO$_2$ (99.999 % pure) powders. The powders were mixed in a mechanical shaker for 1 hour, pressed into a 5 cm diameter pellet at 15000lb and then sintered at 1300°C for 6hours in air. The sputtering time was adjusted in such a way that all the films studied have the same thickness irrespective of the substrate to target distance. The base pressure in the chamber was $5 \times 10^{-6}$ mbar. Sputtering was carried out in
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argon atmosphere at a pressure of 0.01 mbar with rf power of 20 watts. Deposition rate was found to decrease almost linearly from $35 \AA^0/\text{minute}$ to $12 \AA^0/\text{minute}$ as target to substrate distance was increased from 4 to 8 cm (Fig. 5.1). The films prepared at room temperature were then annealed at various temperatures ranging from 100°C to 300°C in high vacuum ($2 \times 10^{-5}$ mbar) for 1 hour.

![Fig.5.1](image)

**Fig.5.1** Growth rate of the ITO thin films for various target to substrate spacing.

RF power = 20

The thickness of the films was determined by Tolansky’s interference technique (see section 2.3.1). In the present study all the measurements were performed on the films having the thickness of 2500 $\AA^0$. Electrical measurements were carried out using a Hall measurement system (Model MMR technology H-50), which employs four-probe in Vanderpauw configuration (see section 2.3.6). Transmission spectra of the samples were recorded using a UV-VIS-NIR spectrophotometer (Hitachi U 3410). The crystallinity of the films were analysed using an X-ray diffractometer using the Cu-Kα radiation (1.5418 $\AA^0$).
5.4 Results and discussion

5.4.1 Influence of Target to substrate distance

The X-ray diffraction pattern of the ITO films deposited on glass substrates at various target to substrate spacings (T-S spacing = 4cm, 6cm, 8cm) is shown in figure 5.2. The substrates were not preheated intentionally. However, the substrate temperatures increased up to 55°C during deposition when the T-S spacing was 4cm, 45°C when the T-S spacing was 6cm and to 40°C when the T-S spacing was 8cm. From the XRD pattern it is evident that the as deposited films are polycrystalline even though the crystallization temperature of ITO is 150°C [26]. All of them showed a peak at \(2\theta = 30^\circ\), which correspond to (222) plane of In$_2$O$_3$ [27]. This is because of the greater kinetic energy of the sputtered particles reaching the substrate surface.

![XRD pattern of the ITO target and the as-deposited ITO thin films for various target to substrate spacing.](image)

Fig.5.2 XRD pattern of the ITO target and the as-deposited ITO thin films for various target to substrate spacing.
Generally, sputtered particles have kinetic energies of several electron volts. This kinetic energy enhances the surface migration of sputtered particles arriving at the substrate surface and the crystallinity of the films is greatly affected by them. Thus it is possible to deposit polycrystalline films even at room temperature by sputtering [28]. The crystallinity of ITO films showed a dependence on T-S spacing. With increase in T-S spacing, the kinetic energy of the sputtered particles reaching the substrate surface decreases. This retards the surface migration of sputtered particles and hence reduces the crystallinity of the films.

The grain size of the films as calculated from Scherrer’s formula [29] is in agreement with the above result. The variation of grain size and the (222) peak intensity with T-S spacing is shown in figure 5.3. The decrease in grain size with increase in T-S spacing confirms the degradation in crystallinity with T-S spacing.

![Graph showing variation of (222) peak intensity and grain size with target to substrate spacing](image)

**Fig.5.3** Variation of (222) peak intensity and the grain size with the target to substrate spacing for the as-deposited ITO films.
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The crystallinity, transparency, electrical resistivity and mobility of the films prepared at T-S spacing of 6cm and 8cm showed similar variations on annealing as that of the variation in these properties for films deposited at a T-S spacing of 4cm. However, better film properties viz. lower resistivity, higher crystallinity and better transparency were observed for the films deposited at T-S spacing of 4cm in comparison with the other two T-S spacing.

![Fig.5.4 Optical transmission spectra of the as-deposited ITO thin films for various target to substrate spacing. The inset shows the variation in band gap with the T-S spacing.](image)

The transmission spectra of the ITO films for various T-S spacings are shown in figure 5.4. All the films irrespective of T-S spacing were highly transparent. The average transmission in the visible region of the electromagnetic spectrum was >85%. The band gap of the ITO films was calculated from the transmission spectra. By assuming a parabolic band
structure for the material, the absorption coefficient and band gap can be related by the expression \( (\alpha h\nu) = \beta (h\nu - E_g)^1/2 \), since ITO is a direct band gap material [30]. The band gap \( E_g \) of the films was found out as described in section 2.3.5. It has been found that the band gap increases with increase in target to substrate spacing (Inset of figure 5.4).

The electrical characteristics of the films also showed dependence on target to substrate spacing. Figure 5.5 gives the variation of resistivity (\( \rho \)) and mobility (\( \mu \)) with T-S spacing. The decrease in mobility and the increase in resistivity with T-S spacing are related to the degradation in crystallinity of the films with T-S spacing. At greater T-S spacing, the smaller grains increase the grain boundary scattering of carriers and hence reduce the mobility of the films, which result in higher resistivity.

![Fig.5.5 Variation in mobility and resistivity of the as deposited ITO thin films with the target to substrate spacing.](image)
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The X-ray diffraction pattern of the films for the various targets to substrate spacings shows that the (440) peak becomes prominent for the target to substrate spacing of 4cm (Fig. 5.2). From the measurement of resistivity and transmission, it can be seen that a target to substrate spacing of 4cm gives better crystalline and highly conducting films. The as prepared films have lower band gap when target to substrate spacing is 4cm. The band gap is found to increase with the increase in target to substrate spacing.

5.4.2 Effect of post deposition annealing

The X-ray diffraction patterns of the ITO films (target to substrate spacing = 4 and 6 cm) annealed at various temperatures in vacuum are shown in figures 5.6 and 5.7. All the films showed a peak at $2\theta = 30^\circ$ corresponding to (222) plane, and the peak at $2\theta = 51^\circ$ corresponds to (440) plane of In$_2$O$_3$.

![XRD pattern of the ITO thin films (T-S spacing= 4cm) deposited at room temperature and annealed at various temperatures.](image)

Fig.5.6 XRD pattern of the ITO thin films (T-S spacing= 4cm) deposited at room temperature and annealed at various temperatures.
Fig. 5.7 XRD pattern of the ITO thin films (T-S spacing = 6 cm) deposited at room temperature and annealed at various temperatures.

Fig. 5.8 Variation of intensity ratio \([I(222)/I(440)]\) of the ITO films deposited at target substrate spacings 4 cm and 6 cm with annealing temperature. It was observed that, as the annealing temperature increases, the intensity of (222) peak increases and the intensity of (440) peak decreases; which is in...
agreement with the literature [31]. The ratio of the intensities of the (222) peak to that of (440) peak increases with the annealing temperature and is maximum at 250°C (Fig. 5.8). The films annealed at 250°C shows a preferred orientation along (222) plane.

Table 5.1 The grain sizes and the lattice constants of the ITO thin films

<table>
<thead>
<tr>
<th>Annealing temperature (°C)</th>
<th>Grain size (nm) T-S = 4 cm</th>
<th>Grain size (nm) T-S = 6 cm</th>
<th>Lattice constant (Å) T-S = 4 cm</th>
<th>Lattice constant (Å) T-S = 6 cm</th>
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<tr>
<td>as-deposited</td>
<td>19.4</td>
<td>13.9</td>
<td>10.14</td>
<td>10.21</td>
</tr>
<tr>
<td>100</td>
<td>15.8</td>
<td>15.9</td>
<td>10.13</td>
<td>10.23</td>
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<tr>
<td>150</td>
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<td>250</td>
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<td>15.7</td>
<td>9.89</td>
<td>10.16</td>
</tr>
<tr>
<td>300</td>
<td>14.4</td>
<td>14.4</td>
<td>10.13</td>
<td>10.19</td>
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</table>

The grain size of the films was calculated from the XRD pattern using the Scherrer’s formula and it was found that the grain sizes of the samples were in the range 14 to 20 nm. The lattice constants of the ITO films were also determined by analyzing the XRD patterns of the films. The calculated values of the average grain size and the lattice constants are given in Table 5.1. The lattice constant of the In₂O₃ thin films is reported as 10.117 Å [13]. Since the radius of Sn²⁺ ions (0.093nm) is greater than In³⁺ ions (0.079nm), the substitutional incorporation of Sn²⁺ ions into In³⁺ sites and the incorporation of Sn ions in the interstitial positions will result in a lattice expansion. All the films except the films annealed at 250°C (T-S spacing = 4 cm) showed lattice expansion compared to the undoped In₂O₃. The estimated lattice constant of the films annealed at 250°C was 9.89Å, which is same as that obtained for the ITO target used for the thin film deposition. The scanning electron micrographs of the as-deposited and the annealed ITO films (Fig. 5.9a and b) show that the crystallinity of the films improved due to the annealing with larger grains uniformly distributed over the surface.
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Fig. 5.9 SEM pictures of ITO thin films (T-S spacing = 6cm) (a) as-deposited (b) annealed at 150°C.

Fig. 5.10 Optical transmission spectra of the ITO thin films (T-S spacing = 4cm) deposited at room temperature and annealed at various temperatures. The inset shows the variation in band gap with the annealing temperature.
Fig. 5.11 Optical transmission spectra of the ITO thin films (T-S spacing = 6cm) deposited at room temperature and annealed at various temperatures. The inset shows the variation in band gap with the annealing temperature.

The rf magnetron sputtered ITO films are highly transparent in the visible region and are reflecting in the IR region of the electromagnetic spectrum. The reflecting edge shifts towards the lower wavelength region on annealing the film at high temperature. The shift in reflecting edge is due to increase in carrier concentration. The transmission spectra of the ITO films deposited with a target to substrate spacing of 4 and 6 cm are shown in figures 5.10 and 5.11.

The band gap of ITO films increase with annealing temperature showed a maximum at 250°C (3.89eV) and then decreased. The variation of band gap with annealing temperature is shown in the insets of figures 5.10 and 5.11. The increase in band gap can be explained on the basis of Burstein-Moss effect [33]. Burstein-Moss shift is proportional to carrier concentration. The
Preparation and characterisation of indium tin oxide ... variation of the carrier concentration and mobility of the ITO films (T-S spacing = 4cm) with the annealing temperature is shown in figure 5.12. The carrier concentration increases with annealing temperature and is maximum at 250°C. Increase in carrier concentration with increase in annealing temperature results in band gap widening showing a maximum at 250°C. The annealed films exhibited high transmission in the visible region with long tail in the IR region. It was seen that the reflecting edge shifted towards the lower wavelength region on annealing in vacuum (Figures 5.10 and 5.11). The shift in reflecting edge is due to increase in carrier concentration introduced by the oxygen deficiencies created during annealing.

![Fig. 5.12 Mobility (μ) and carrier concentration (n) of the ITO thin films annealed at various temperatures (T-S spacing = 4cm).](image)

The refractive index of the ITO film was determined from the transmission spectra of the film by the method of Manifacier et al. [34] as described in section 2.3.5. The refractive index of the films (Fig.5.13) remains almost a
constant in the visible range (≈1.8), which is in close agreement with the value reported in literature [35].

Fig. 5.13 Variation in refractive index of the as-deposited ITO films with the wavelength (T-S spacing = 4cm).

The resistivity of the ITO films was found to decrease with increase of annealing temperature. The lowest resistivity of 3.07 x 10⁻³ Ωcm was obtained for the film prepared with a target to substrate distance of 4cm and then annealed at 250°C. The resistivity showed similar behaviour on annealing, for the films prepared at various target to substrate spacings (Fig. 5.14). The mobility of the ITO films increased with the increase of annealing temperature (Fig. 5.12). In the case of ITO, oxygen deficiency is one of the reasons for high conductivity. Oxygen deficiencies induce free electrons as conduction carriers [36]. Vacuum annealing creates oxygen deficiency and this reduces the resistivity of the ITO films. The increase in carrier concentration, mobility and better crystallinity of the films are also
responsible for the decrease in resistivity. The films annealed at 250°C showed a preferred orientation in the (222) plane and possess minimum resistivity.

![Graph showing variation in resistivity of ITO thin films with annealing temperature.]

**Fig. 5.14** Variation in resistivity of the ITO thin films with the annealing temperature (T-S spacing = 4 and 6cm).

### 5.5 Conclusion

Tin doped indium oxide films were prepared at room temperature by rf magnetron sputtering. The effect of vacuum annealing and the target to substrate spacing, on the structural, electrical and optical properties were investigated. The films deposited at a target to substrate spacing of 4cm showed better crystallinity, transparency and low resistivity. The variation in optical and electrical properties of the ITO films with the annealing showed
similar behaviour irrespective of the target to substrate spacing. The films show a preferential orientation in the (222) plane. The X-ray diffraction pattern of the ITO films annealed at 250°C shows the maximum peak intensity for the (222) plane. The resistivity of the film decreases with the annealing temperature and resistivity is minimum at 250°C. The carrier concentration and band gap of the films were maximum for an annealing temperature of 250°C.
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[27] JCPDS card No. 06-0416