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Investigation of Electrical and Optical Transport Properties of N-type Indium Oxide Thin Film

M. A. Islam[1], M. Nuruzzaman[1], R. C. Roy[2], J. Hossain[2], K.A. Khan[2]
([1]Department of Physics, Rajshahi University of Engineering & Technology, Rajshahi-6204, Bangladesh)
([2]Department of Applied Physics & Electronic Engineering, University of Rajshahi, Rajshahi-6205, Bangladesh)

ABSTRACT : *Indium Oxide (In_2O_3) thin films were prepared on glass substrate by electron beam technique. The films were characterized by Scanning Electron Microscopy (SEM), electrical, optical and Hall measurement studies. SEM study revealed that the surfaces of the as-deposited films are distributed through the uniform small grains. The electrical resistivity decrease with the increase of temperature indicating that In_2O_3 thin films are semiconducting in nature. The reduction in the resistivity is associated with thermally activated conduction mechanism. The effect of the magnetic field on Hall coefficient (R_H), carrier concentration (n) and Hall mobility (μ_n) were also studied. From Hall study It is observed that the films exhibit n-type electrical conductivity with carrier concentration of about $10^{19}(cm^{-3})$. The optical properties such as transmittance (T), absorption coefficient (α), were determined. The absorption coefficient is found to be the order of 10^4 (cm^{-1}). The study of absorption coefficient of the In_2O_3 thin films shows a direct type of transition. The optical band gap for In_2O_3 thin film ranges 3.34 -3.69 eV.*

KEYWORDS - *Thin films, e-beam, as-deposited, Electrical conductivity, Hall coefficient, Optical band gap*

I. INTRODUCTION

Indium oxide (In_2O_3) is a prominent material for microelectronic applications [1]. Indium oxide belongs to transparent conducting oxide (TCO) are widely used in engineering and electronic industry. It has variety of applications including transparent conductive electrodes in flat-panel displays and solar cells, coating for architectural glasses [2], and optoelectronic devices [3] because of its good electrical conductivity, high optical transparency in the visible region, and high reflectivity in the IR region. Indium oxide is a wide-band-gap semiconductor with energy gap of E_g ~3.70 eV as found in literature. As a wide-band-gap semiconductor, Indium oxide exhibits an isolating behaviour in its stoichiometric form (In_2O_3) [4]. It is also used as antireflection coating in solar cells owing to its less optical reflectivity. In_2O_3 thin films have been deposited by several techniques in order to improve the structural, optical and electrical properties of the material such as dc magnetron sputtering [5], evaporation [6-8], thermal oxidation of indium films [9], atomic-layer epitaxial growth [10], pulsed laser deposition [11-12], sol-gel process [13], and chemical pyrolysis to metal organic chemical vapour deposition [14]. Although there have been several studies on the growth and characterization of In_2O_3 thin films, there is still a lack of understanding of the structural, electrical and optical properties. These properties of Indium oxide thin films are strongly affected on the preparation techniques and experiment conditions [4-5].

In this work, electron beam (e-beam) evaporation technique was used to deposit indium oxide thin films on to glass substrate. E-beam evaporation technique yields high quality epitaxial thin films with smooth surfaces. Here we report the surface morphological, electrical and optical properties of indium oxide (In_2O_3) thin films.

II. EXPERIMENTAL DETAILS

In_2O_3 thin films were deposited on to glass substrate by e-beam evaporation technique at a pressure of 3×10^{-3} Pa from In_2O_3 powder (99.999% pure) obtained from Aldrich Chemical Company, USA.

When the chamber pressure reduced to ~ 3×10^{-3} Pa, the deposition was then started with 30 mA current by turning on the low-tension control switch. All the films were deposited at room temperature. The deposition rate was about 5 nms^{-1}. The film thickness was measured by the Tolanasky interference method with an accuracy of ± 5nm [15]. The thickness of the In_2O_3 films ranges from 50 to 150 nm, respectively.

Electrical conductivity and Hall effect measurement investigated by the Van-der-Pauw technique [15]. The optical transmittance spectra of In_2O_3 films was recorded from 400 nm to 1100 nm wavelength using a SHIMADZUUV- double beam spectrophotometer.

III. RESULTS AND DISCUSSION

3.1 Morphological Study

Scanning Electron Microscope (SEM) has been used to study the surface morphology of In_2O_3 thin films. SEM micrographs of the as-deposited In_2O_3 thin film of different magnifications are shown in Fig. 1. It shows a uniform surface morphology with a more dense homogeneous distribution of grains. The average grain sizes observed from SEM images are approximately equal.

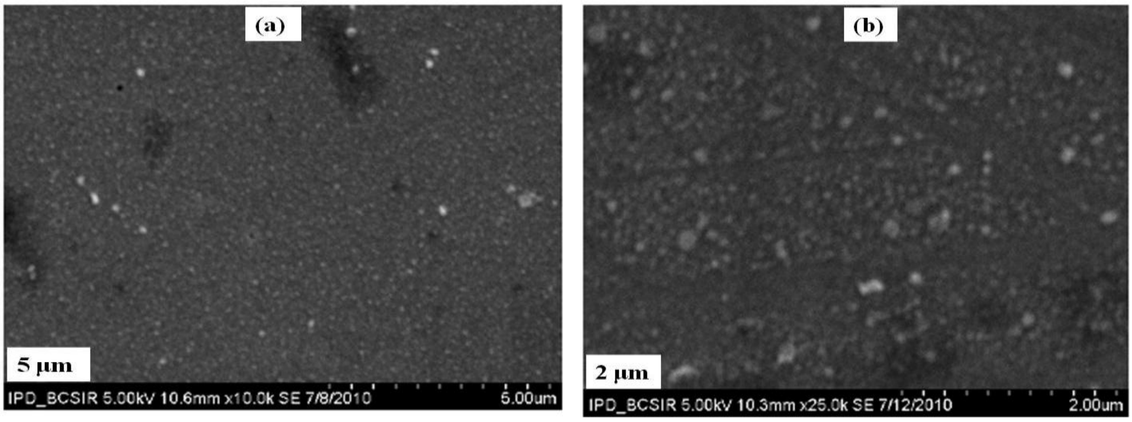

Fig. 1: SEM micrograph of the as-deposited In_2O_3 thin films of thickness 200 nm at two different magnifications.

3.2. Temperature Dependence of Electrical Resistivity and Activation Energy

Figure 2 shows the temperature dependence of electrical resistivity of In_2O_3 films of different thicknesses in the temperature range 300-475K.The resistivity decrease with increase in temperature confirms the semiconductor nature of the as-deposited In_2O_3 films. It is seen from Fig.2 that the resistivity of the films depends upon thickness, and the resistivity of the thicker films is found to be comparatively less than that for thinner films. At room temperature, resistivity reduced from 10^{-1} to 10^{-2} (Ω-cm) as the thickness varies from 50 to 150nm. This decrease in resistivity with thickness can be attributed on the basis of grain boundary scattering as explained by Wu and Chiou [16]. As the grain size increases with thickness (not shown in Figure), the size of grain boundaries become relatively reduced; which in turn reduces the grain boundary scattering, consequently reducing the resistivity. The gradual decrease in resistivity up to around 435 K for all films is associated with thermal activation process which leads to an increase in carrier concentration. At higher temperature regions, the behaviour of resistivity becomes almost independent of temperature.

The activation energy is calculated by the following relation:

$$\sigma = \sigma_0 \exp(-\Delta E/2K_BT) \qquad (1)$$

where ΔE is the activation energy, σ_0 is the conductivity at 0 K, K_B is the Boltzmann constant, and T is the absolute temperature. The logarithmic variation of electrical conductivity as a function of inverse temperature at several thicknesses is shown in Fig. 3.The activation energies calculated from linear least square fit of Arrhenius relation are tabulated in Table-1. From Table-1 it is observed that the activation energy of In_2O_3 films decreases with increasing film thickness which is associated with the reduction of scattering at grain boundaries as mentioned earlier. This behaviour of activation energy with thickness also implies semiconducting behaviour of the films [17]. It is also observed from the Table-1 that activation energy is found to increase with increasing temperature. It can be assumed that, at higher temperature, the carriers activated to the localized states moves towards the Fermi level.

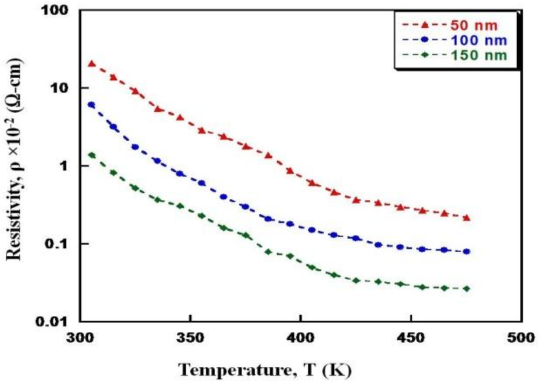

Fig. 2: Variation of resistivity of In_2O_3 thin films of different thicknesses with temperature.

3.3 Hall Effect Study

The Hall coefficient (R_H) was calculated by the following relation [15]:

$$R_H = \pm V_B t/IB \quad (m^3/coulomb) \qquad (2)$$

where V_B is the generated Hall voltage, t is the film thickness, and B is the applied magnetic field. It is well known that the negative value of R_H indicates the n-type semiconducting behaviour of the materials. The negative value of R_H, as seen in the Fig.4 (a), indicates that In_2O_3 samples are n-type conductivity with electrons as majority charge carriers which is well agreed with the reported value [18]. The following relation was used to calculate the value of carrier concentration:

$$R_H = \pm 1/ne \qquad (3)$$

where e is the electronic charge. Figure 4(b) shows the plot of the carrier concentration versus the applied magnetic field. The carrier concentration is found to be the order of 10^{19} cm^{-3} [19]. Figure 4(c) shows the variation of Hall mobility with magnetic field. It is seen that Hall mobility decreases with increasing magnetic field.

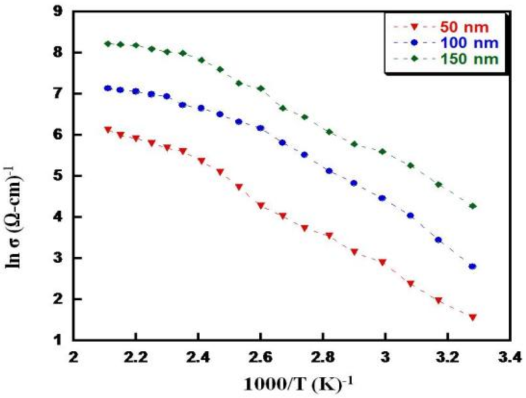

Fig. 3: Plot of In(σ) versus 1000/T of as-deposited In_2O_3 thin films of different thicknesses.

Table-1: The Activation Energies of In_2O_3 Thin Films of Different Thicknesses

Thickness (nm)	**Activation energies, ΔE in (eV)**	
	Temperature ranges	
	305-435K	435-475K
	ΔE (eV)	ΔE (eV)
50	0.52	0.85
100	0.11	0.78
150	0.09	0.66

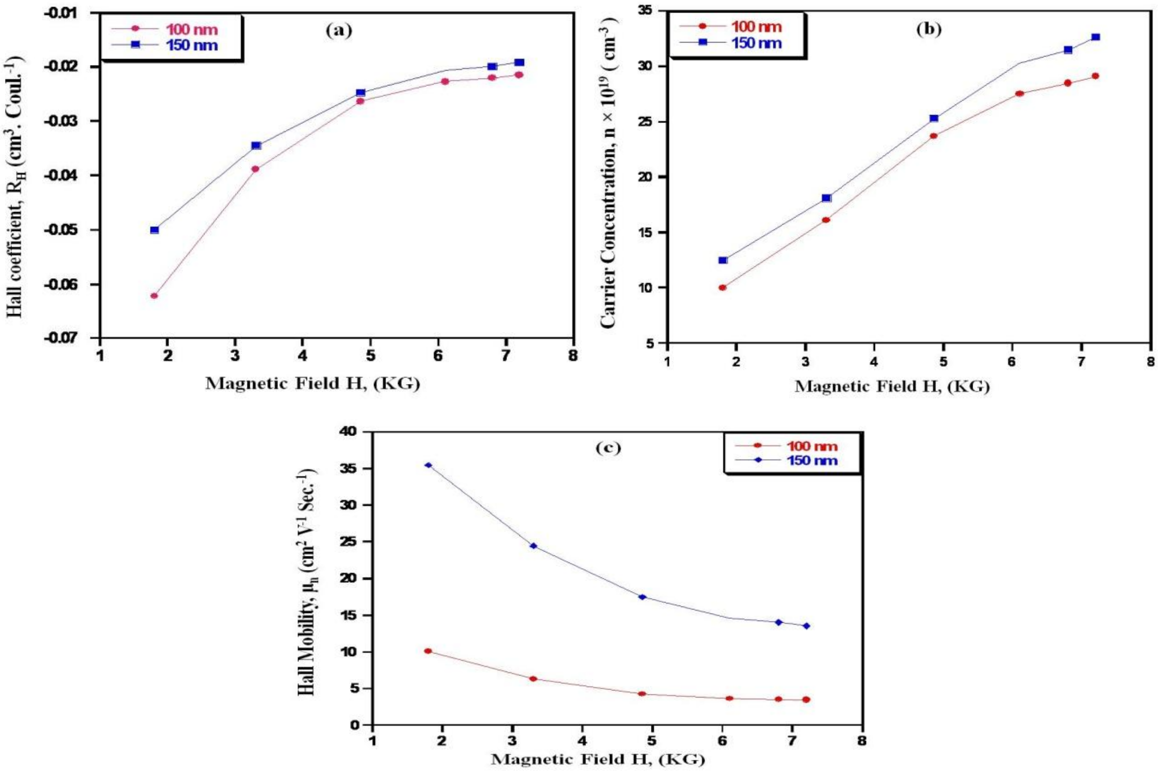

Fig. 4: Variation of (a) Hall coefficient (R_H), (b) carrier concentration (n), and (c) Hall mobility (μ_n) with magnetic field (H) of In_2O_3 thin films.

3.4 Optical Transmittance and Band Gap Studies

Optical transmittance *T* (%) were measured at wavelength (λ) range $400 \leq \lambda \leq 1100$ nm using a "UV-Visible SHIMADZU double beam spectrophotometer" at room temperature. The variation of transmittance *T* (%) with wavelength (λ) for the as-deposited films of different thicknesses is shown in Fig. 5. A high optical transparency of about 85% for films with thickness 50 - 100 nm was observed in the visible and near infrared region, and it decreases with decreasing wavelength towards UV region. The transmittance decreases appreciably when the thickness of the film increase to 150 nm.

The absorption coefficient α was calculated from the transmittance (*T*) measurement, using the following relation:

$$\alpha = \frac{1}{t} \ln\left(\frac{1}{T}\right) \qquad (4)$$

where t is film thickness in nm and *T* is the transmittance. Figure 6 shows the variation of absorption coefficient with photon energy of the as-deposited In_2O_3 thin films of two different thicknesses of 50nm and100nm, respectively. The absorption coefficient is found to be the order of 10^4 cm^{-1}.

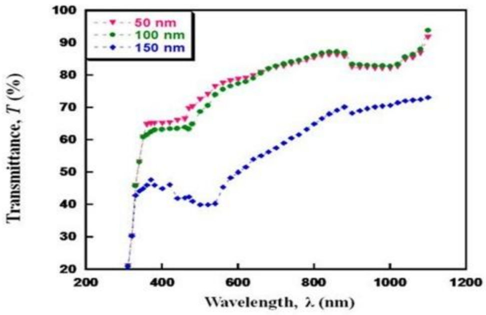

Fig. 5: Spectral variation of transmittance of as-deposited In_2O_3 thin film.

Since the reflectance of the film with thickness 150 nm is relatively high (not shown here), the absorption coefficient of that film is not shown in Fig.6. The absorption coefficient of In_2O_3 thin films was used to calculate the energy band gap. In order to determine the value of optical band gap, $(\alpha h\nu)^n$ versus photon energy (hν) curves have been plotted. The values of the tangents, evaluated by least mean square method, intercepting the energy axis give the values of optical band gap (E_g). From these curves it is observed that best fit is obtained for $(\alpha h\nu)^2$ vs. hν which indicates direct allowed transition. The plot of $(\alpha h\nu)^2$ vs. photon energy (hν) of the as-deposited In_2O_3thin films for the different thicknesses is shown in Fig.7. The direct optical band gap is varies between 3.34 and 3.69eV [20].It is also seen that band gap increases with increases of film thickness.

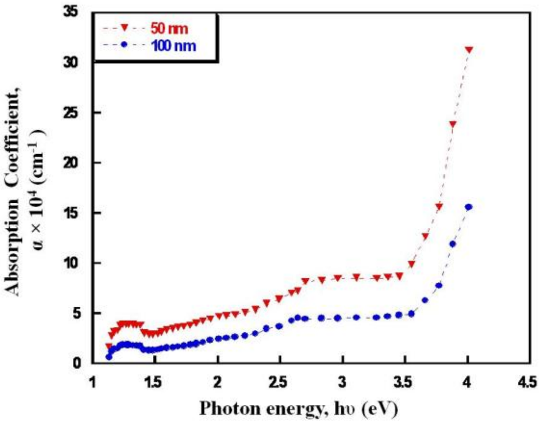

Fig. 6: Absorption coefficient (α) vs. photon energy (hν) of as-deposited In_2O_3 thin films.

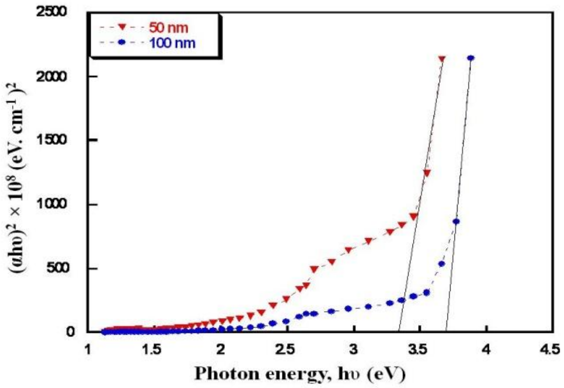

Fig. 7: Plots of $(\alpha h\nu)^2$ vs. hν of as-deposited In_2O_3 thin films of two different thicknesses.

IV. CONCLUSIONS

In_2O_3 thin films of different thicknesses have been successfully deposited on well cleaned glass substrates by e-beam evaporation technique. SEM micrograph shows a uniform surface morphology with a relatively small grain structure. The electrical conductivity variation with temperature indicating semiconducting nature of the as-deposited In_2O_3 films. In the studied temperature range, the conduction is due to a thermally activated process. From the Hall measurement, it is found that In_2O_3 films are n-type electrical conductivity with carrier concentration of order of 10^{19} cm^{-3}. High optical transparency is obtained in visible and infrared regions. Optical band gap of these thin films was calculated and found 3.34 eV, 3.69 eV, respectively for the two films. These characteristics of In_2O_3 films of low resistivity, high transparency, high absorption coefficient and wide band gap make them suitable candidate for technological applications such as antireflection coating for solar cells and opto-electronic devices as mentioned in previous section.

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