Exploring the impact of thickness on the electrical, optical, and structural properties of p-InSb thin films

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Researchers have fabricated non-stoichiometric InSb thin films of varying thicknesses through thermal evaporation. The technique involves depositing nanocrystalline p-InSb semiconducting layers on glass substrates at room temperature using an optimized source material. The resulting p-type InSb films had thicknesses ranging from 150 nm to 450 nm. This study investigated the effect of thickness on the electrical, optical, and structural properties of p-InSb thin films. Structural analysis was conducted using grazing angle X-ray diffraction (GIXRD), which revealed a polycrystalline zinc-blend structure with a preferred orientation along the 220 planes. The research found a peak hole mobility of 2.01E+04 cm²/V-s. A high carrier mobility, a characteristic feature of 2D materials, is essential for the development of advanced optoelectronic and electronic devices.

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1. Introduction

Indium antimonide (InSb) is a crucial semiconductor in technological applications, featuring a direct band gap of 0.17 eV at room temperature and 0.23 eV at 80 K [1]. It possesses a zinc-blend crystal structure with a lattice constant of 6.47 and a dielectric constant of 16.8. These properties, along with their favorable mechanical characteristics, make InSb an ideal material for photonic crystal applications. InSb-based devices can operate at voltages as low as 0.5 V, resulting in minimal power consumption. High-mobility photodetectors for long-wavelength infrared (LWIR) and midwavelength infrared (MWIR) applications employ materials such as InSb and InAs(1-x)Six [2, 3]. InSb distinguishes itself from binary III-V compounds with the highest room-temperature hole and electron mobilities (1260 cm² V⁻¹ s and 10,240 cm⁻² V⁻¹ s, respectively) [4]. This remarkable mobility renders InSb valuable for creating infrared detectors in the 3.5-5 um wavelength range, as well as for electronic and optoelectronic devices [5,6]. Owing to their superior carrier mobility, low effective mass, and large g-factor, high-quality low-dimensional InSb materials are promising for future quantum devices [7]. The semiconductivity of InSb thin films is determined by their composition: p-type behavior is exhibited by antimony-rich films, whereas n-type characteristics are displayed by indium-rich films. N-type InSb thin films have potential applications in bacterial biosensors [8]. The unique properties of InSb make it appropriate for various applications such as high-speed transistors, magnetoresistance devices, speed-sensitive sensors, and Hall sensors [5]. InSb p-n junctions exhibit 100% internal quantum efficiency and demonstrate photovoltaic effects under infrared light [9]. Micro- and nanostructured materials including InSb can be fabricated using various physical and chemical processes. These methods include molecular beam epitaxy, flash evaporation [10], sputtering [11], vacuum evaporation [12], electrospinning [13], chemical oxidative polymerization [14], and chemical and ultrasonic treatments [15-17]. Ast et al. investigated the electrical properties of n-type hydrogenated amorphous silicon films of various thicknesses. They found that thick films (>0.5 μ m) exhibited relatively low resistivity (~1500 Ω -cm) and activation energy (~0.22 eV). In contrast, thin films (<0.5 μm) showed significantly higher resistivity (up to 27000 Ω -cm) and activation energy (up to 0.41 eV). Researchers have attributed this difference to

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the presence of a low-conductivity surface/interface layer in thin films [18]. Lakshminarayana et al. investigated the thickness dependence of the electrical resistivity and activation energy of AgSbTe₂ thin films. Monophase AgSbTe₂ films of various thicknesses were prepared by thermal evaporation on glass substrates. The films exhibited semiconducting behavior and p-type conduction. The activation energy was observed to decrease with increasing film thickness [19]. Shinde et al. investigated the temperature- and thickness-dependent electrical resistances and conductivities of SnO₂ thin films. The authors prepared tin films of varying thicknesses on glass substrates using vacuum evaporation, which were then oxidized to form SnO_2 films. They measured the electrical resistance and conductivity of these films as functions of thickness and temperature. SnO₂ thin films exhibit two distinct conduction mechanisms depending on the temperature range, and their electrical characteristics are significantly influenced by the film thickness, with thinner samples showing higher activation energy values and thicker deposits demonstrating lower transition temperatures [20]. Tripathi et al. investigated the thickness-dependent structural, optical, and electrical properties of Se85In12Bi3 nanochalcogenide thin films. The study utilized various techniques, including DSC, XRD, FESEM, optical absorption, and dc-conductivity measurements. The Se85In12Bi3 nanochalcogenide thin films exhibited an increase in the optical bandgap and activation energy for electrical conduction as the thickness increased, and the absorption coefficient and extinction coefficient decreased with increasing film thickness [21]. Thermal evaporation is an excellent technique for developing semiconductor thin films owing to its simplicity, affordability, precision, high material utilization efficiency, rapid and controlled growth rate, and uniform deposition on substrates. This research focuses on the production of p-type indium antimonide thin films of varying thicknesses using a novel approach. The scientists prepared Antimony-enriched nonstoichiometric InSb powder with a composition of In_{0.35}Sb_{0.65}. The composition of the starting material was optimized based on its electrical, optical, and structural characteristics [22]. Using this starting material, thermal evaporation was employed to synthesize p-InSb thin films with different thicknesses. This study examined how the layer thickness affects the structural, electrical, optical, and surface morphological aspects by utilizing these parameters to optimize the film thickness.

2. Material and methods

The borosilicate glass substrates underwent a thorough cleaning procedure before thin-film application. This process involved a two-hour boil in chromic acid, followed by cleaning with distilled water and an acetone rinse. The samples were then cleaned in an ultrasonic bath with distilled water and dried in an oven at 423 K. P-type InSb thin films with thicknesses ranging from 150 to 450 nm were deposited onto cleaned glass substrates using a vacuum coating unit operating at pressures below 10^{-5} Torr and at ambient temperature. The source material, composed of non-stoichiometric In_{0.35}Sb_{0.65}, was maintained at a fixed distance of 125 mm from the substrate. The deposition rate was controlled by adjusting the electrical current flowing through the boat. A digital film-thickness monitor (DFTM) equipped with a 6 MHz quartz crystal sensor, placed parallel to the substrate, was used to track the film thickness and deposition rate during the process. The film thickness increased with an increase in the deposition time.

Structural characterization of the fabricated films was carried out using a Panalytical X'Pert Pro X-ray diffractometer with Cu K α radiation ($\lambda = 1.5406$ Å). Grazing incidence X-ray diffraction (GIXRD) measurements were conducted at a glancing angle of 1°, and the 2 θ range was scanned from 20° to 60°. Surface morphologies were examined using a Carl Zeiss Gemini SEM-300 field-emission scanning electron microscope (FESEM) equipped with an energy-dispersive X-ray (EDAX) detector. The electrical resistivity of the samples was measured using a standard four-probe technique, which is commonly employed for thin films. This method involved placing four electrical contacts on the sample surface, with two probes acting as current sources and two probes for voltage measurement. This approach eliminates errors caused by probe resistance, spreading resistance, and contact resistance between the metal probes and thin film. To study the Hall effect, a magnetic field perpendicular to the current direction was applied to the p-InSb thin film surface, resulting in the development of a Hall voltage perpendicular to both the current and magnetic fields. An Ecopia HMS -5000 Hall Effect Measurement System was used to measure the Hall effect parameters. The

optical properties of the thin films were analyzed using the absorption spectra recorded using a UVvisible spectrophotometer.

3. Result and discussion

3.1. Grazing incidence X-ray diffraction analysis

The X-ray diffractogram of n-InSb thin films, ranging from 150 to 450 nm in thickness, is shown in Figure 1. The scan was conducted within a 2 θ range of 20–60°. The XRD data were analyzed using the JCPDS data file (06-0208), the XRD data were analyzed. This analysis showed that the p-InSb thin film crystallites were polycrystalline and oriented along two planes: (220) and (311). The XRD patterns indicate a zinc-blend structure with a preferred orientation along the (311) plane for these crystallites. The intensity of the diffraction peak increased as the film thickness increased. For p-InSb films with thicknesses between 150 and 450 nm, the lattice constants (a) were calculated for the (311) plane using Equations 1 and 2. Table 1 presents the results.

$$\frac{1}{a^2} = \frac{(h^2 + k^2 + l^2)}{a^2} \tag{1}$$

$$d_{hkl} = \frac{n\lambda}{2\sin\theta} \tag{2}$$

where d_{hkl} is interplanar spacing and (h k l) is Millar indices.

The grain sizes of the thin films were calculated using a diffractogram and Debye-Scherrer's formula.

$$D = \frac{0.94\lambda}{\beta\cos\theta} \tag{3}$$

where λ is the X-ray wavelength ($\lambda = 1.540598$ Å), θ represents the diffraction angle, and β denotes the full-width at half maximum (FWHM).

The dislocation density (δ) and line strain (ϵ) of the films were calculated using Eqs. 4 and 5, respectively.

$$\delta = \frac{n}{D^2} \tag{4}$$

$$\beta\cos\theta = \frac{\kappa\lambda}{D} + 4\varepsilon\sin\theta \tag{5}$$

where n is a factor that equals unity, yielding the minimum dislocation density.

Table 1 displays the computed values for the grain size (D), dislocation density (δ), and line strain (ϵ) of the p-InSb thin films with thicknesses ranging from 150 to 450 nm, derived from the (311) plane diffraction pattern. The findings revealed that as the film thickness increased from 150 nm to 450 nm, the crystallite size (D) increased from 22.7981 nm to 30.3047 nm. This increase was linked to the rapid expansion of the crystallites at a thickness of 450 nm. Simultaneously, the line strain (ϵ) decreased from 4.171 to 3.129 Line⁻²m⁻⁴, whereas the dislocation density (δ) decreased from 1.924 to 1.082×10^{15} line/m². These reductions in both the line strain and dislocation density, observed as the film approached 450 nm in thickness, also suggested improved crystallinity.



Fig. 1. GIXRD patterns of InSb thin film with different thickness.

Thickness	Grain Size (nm)	Dislocation Density 10 ¹⁵ line/m ²	Lattice parameter (Å)	Strain (ε) Line ⁻² m ⁻⁴
T1 (150 nm)	22	1.924	6.7099	4.171×10^{-3}
T2 (300 nm)	26	1.473	6.7117	3.651×10^{-3}
T3 (450 nm)	30	1.082	6.7126	3.129×10 ⁻³

Table 1. Structural parameter of InSb thin film.

3.2. Field emission scanning electron microscopy

Field-emission scanning electron microscopy (FE-SEM) is a versatile and powerful technique for investigating the microstructural characteristics of thin films.



Fig. 2. FESEM micrographs images (a) surface image of the thin film thickness of 150nm (b) surface image of the thin film thickness of 300 nm (c) surface image of the thin film thickness of 450nm (d) EDS spectra of a non-stoichiometric InSb thin film grown on the glass substrate.

Figure 2 shows FE-SEM images of the fabricated p-InSb thin films, with thicknesses ranging from 150 to 450 nm. Examination of the surface morphology indicated that the p-InSb films were uniform and fully coated on glass substrates. The nanocrystalline nature of the films was evident from their visible morphology in the FE-SEM micrographs. FE-SEM observations revealed that the crystallite dimensions increased as the film thickness increased.

3.3. Electrical properties analysis

Using Equation (6), the electrical resistivity (ρ) of p-InSb thin films with thicknesses between 150 and 450 nm was calculated.

$$\rho = \frac{V \times 2S}{I \times G_7\left(\frac{W}{S}\right)} \tag{6}$$

where $G_7\left(\frac{w}{s}\right) = \frac{2S}{w \log 2}$ is the correction factor, w is the thickness of the thin film, and ρ is the resistivity of the sample.

A steady electric current (I) was introduced through the exterior set of probes, whereas the voltage (V) was measured between the interior pair of probes. The resistivity values are listed in Table 2. The data in Table 2 reveal that the resistivity of the p-InSb thin film decreased from (3.14 - 2.20) ×10¹ ohm-cm as the film thickness increased from 150 to 450 nm. The film with a thickness of 450 nm exhibited the lowest resistivity of $2.20 \times 10^{1} \Omega$ cm. The films demonstrate semiconducting behavior as their electrical conductivity increases with increasing temperature. The relationship between Log10 (ρ) and (1000/T) for p-InSb thin films with thicknesses of 150, 300, and 450 nm is shown in Figure 3a, 3b, and 3c, respectively. The activation energy was determined using the slopes of the curves in Figures 3, and Figure 3d shows the variation with film thickness. As illustrated in Figure 3, the activation energy of the films decreases from 0.674 eV to 0.464 eV as the film thickness increases to 450 nm, owing to the movement of the acceptor level towards the bottom of the conduction band.

$$\sigma_t = \sigma_o exp\left(\frac{-\Delta E_a}{KT}\right) \tag{7}$$

where ΔE_a is the activation energy, K is the Boltzmann constant, T is the absolute temperature, and σ_t is the conductivity at a given temperature.

Hall effect measurements revealed that all InSb thin films exhibited p-type semiconducting characteristics. The carrier concentration in the p-InSb thin films of various thicknesses (150-450 nm) was determined using the Hall coefficient measured at room temperature. Figure 4 (b) shows the correlation between carrier concentration and film thickness. A reduction in the carrier concentration was observed as the film thickness increased from 150 to 450 nm. The p-InSb thin films with a thickness of 450 nm exhibited the lowest carrier concentration of 1.41×10^{13} /cm³. The charge carrier mobility in p-InSb thin films with different thicknesses (150-450 nm) was calculated using the measured values of both the Hall coefficient and resistivity. Figure 4 (d) shows how hole mobility varies with film thickness. As illustrated in Figure 4 (a), the hole mobility increases with film thickness of 450 nm, owing to decreased grain boundary scattering. The highest mobility of 2.01×10^4 was observed at a film thickness of 450 nm, corresponding to a larger grain size. The observed carrier concentration and hole mobility were similar to those of previous measurements of the p-InSb films.



Fig. 3. (a) Plots of Log₁₀ (ρ) versus 1000/T of film thickness 150 nm, (b) Plots of Log₁₀ (ρ) versus 1000/T of film thickness 300 nm, (c) Plots of Log₁₀ (ρ) versus 1000/T of film thickness 450 nm, (d)Variation of Activation energy of different thicknesses of p-InSb thin film.

Thickness	Resistivity (Ohm-cm)	Sheet Resistance (Ω/sq)	Conductivity (S/cm)	Bulk concentration (Cm ⁻³)	R _H (Cm ³ /C)	Mobility (Cm ² /V-s)	Activation Energy (eV)
T1 (150 nm)	3.14E+01	2.09E+05	3.18E-02	4.22E+13	1.48E+05	4.71E+03	0.674
T2 (300 nm)	2.52E+01	0.84E+05	3.97E-02	2.39E+13	2.62E+05	1.04E+04	0.568
T3 (450 nm)	2.20E+01	0.48E+05	4.55E-02	1.41E+13	4.43E+05	2.01E+04	0.464

Table 2.	Electrical	properties	of InSb	thin film	with	different thickness.
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Fig. 4. (a) Variation of Hall coefficient (R_H) with different thicknesses, (b) Variation of Carrier concentration with different thicknesses, (c) variation of thin film resistivity (ρ) with different thicknesses, (d) variation of charge carrier mobility (μ) with different thicknesses.

3.4. Optical properties

Ultraviolet-visible (UV-Vis) spectroscopy is frequently employed to assess the optoelectronic characteristics of InSb thin films by measuring their optical bandgaps. Optical absorption spectra (A) were used to compute the optical bandgaps (Eg) of the InSb films. In particular, the optical absorbance and thickness of the film were calculated using the equation

 $(\alpha) = 2.303 \text{ A/t}$

where (A) is the absorbance, and (t) is the thin film thickness. According to the Tauc theory, InSb is a direct bandgap semiconductor, where hv is the photon energy of optical absorption at the band edge in semiconductors and is employed in the following equation [12–15].

$$\alpha h \nu = A (h \nu - E_g)^n \tag{8}$$

where hv represents the photon energy, α is the absorption coefficient, Eg is the optical bandgap of the InSb thin film, A is the absorption constant, and n = $\frac{1}{2}$ corresponds to a direct-bandgap material.



Fig. 5. (a) Plots of $(ahv)^2$ versus (hv) of film thickness 150 nm, (b) Plots of $(ahv)^2$ versus (hv) of film thickness 300 nm, (c) Plots of $(ahv)^2$ versus (hv) of film thickness 150 nm (d)Variation in the optical band gap for p-type InSb thin films of different thicknesses.

Thickness	Optical Bandgap (eV)
T1	2.4999
(150 nm)	
Т2	2.4901
(300 nm)	
Т3	2.4769
(450 nm)	

Table 3. Variation of optical band gap.

Eg values were determined by extrapolating the linear portion of the curve to its intercept with the energy axis (Figure 5). The calculated energy gap of the InSb thin film decreased from 2.4999 to 2.4769 eV with increasing thickness, as shown in (Table 3). The quantum size effect is likely to be the cause of the shift in the optical bandgap because the bandgap varies linearly with the inverse square of the thickness $(1/t^2)$. It is possible to explain how thickness influences the optical band gap as follows: the optical absorption edge shifts towards higher wavelengths as the thickness of the thin film increases, which causes the transmittance to typically drop and shift to higher wavelengths. Consequently, the optical gap energy decreases.

4. Conclusion

Thermal evaporation was used to create indium antimonide thin films with thicknesses ranging from 150 nm to 450 nm. The films exhibited a polycrystalline structure with average grain sizes between 22.7981 and 30.3947 for thicknesses of 150–300 nm. Hall measurements revealed that the films were p-type, with a carrier concentration of approximately 1.41×10^{13} /cm³ and mobility of approximately $2.01E+04 \text{ cm}^2$ /Vs for a 450 nm thick film. As the film thickness increased, the carrier concentration (n) and resistivity (ρ) decreased, whereas the Hall mobility (μ) increased. The optical bandgap ranged from 2.4999 to 2.4769 eV, which varied with the film thickness. Films with a thickness of 450 nm exhibit superior properties, including the highest hole mobility, lowest resistivity, and highest activation energy.

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