# EFFECT OF SUBSTRATE TEMPERATURE ON THE PROPERTIES OF VACUUM EVAPORATED THIN InSb FILMS

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***Abstract:*** *Indium Antimonide (InSb) thin films were deposited onto well cleaned glass substrate at different substrate temperatures (323K, 373K and 473K) by vacuum evaporation technique using InSb compound as a source material. The characteristics of the films such as composition, microstructure and electrical properties were investigated in terms of substrate temperature. X-ray diffraction studies confirmed the polycrystallinity of the films and the films show preferential orientation along the (111) plane. The particle size, dislocation density and strain were evaluated. The particle size increases with the increase of substrate temperature, which was found to be in the range 14.32 to 33.35 nm. Hall measurements indicate that the films were p-type, having carrier concentration* $\cong 10^{17} cm^{-3}$ *and Hall mobility (0.42 - 7.10)* $\times 10^3$ $cm^2/Vs$ *for the film thickness of 300 nm. It is observed that the carrier concentration decreases and Hall mobility increases with the increase of substrate temperature. The sheet resistance is found to decrease with the increase of substrate temperature. The Hall mobility decreased with the increase of the film thickness and the maximum Hall mobility of 1.34* $\times 10^4$ $cm^2/Vs$ *was obtained for the films the thickness of 1000 nm and the substrate temperature of 473K.*

***Keywords:*** *Indium antimonide (InSb), thin films, vacuum evaporation, Hall effect, crystal structure, stoichiometry, carrier concentration, Hall mobility.*

## 1. Introduction

Many compound semiconductors which have large carrier mobility and small band-gap have attracted much attention for the fabrication of electronic devices. Among various potential candidates, Indium Antimonide (InSb) has the highest mobility of $7.8 \times 10^4$ $cm^2/Vs$ and small band-gap of 0.17 eV at room temperature, and thus it is the best material available for magnetic-filed sensing devices such as Hall sensors and magnetoresistors [1], speed-sensitive sensors [2] and magnetic sensors [3]. Many reports are available on the growth of InSb thin films using techniques such as molecular beam epitaxy (MBE), metalorganic chemical vapour deposition and vacuum evaporation. Of all the methods used to prepare InSb films, vacuum evaporation is the very simple and inexpensive technique and can be used for large area deposition [4].

Thin films of InSb prepared by conventional vacuum evaporation techniques have difficulties in maintaining the stoichiometry because of large differences in vapour pressures of In and Sb [5]. This problem of non-stoichiometry could also be addressed properly by optimizing the conditions of evaporation. The present article explains the effect of substrate temperature on the structural and electrical properties of thin InSb films by vacuum evaporation.

## 2. Experimental Procedure

Thin films of InSb were deposited by evaporating high purity (99.999%) InSb compound onto well-cleaned glass substrates maintained at different substrate temperatures ($T_s$) 323, 373 and 473K at a pressure of less than $10^{-5}$ Torr. Corning 7059 glass was used as a substrate with a mask for electrical measurements. The alumina coated tungsten basket was used to evaporate InSb compound. The distance between source material and substrate was about 10 cm. The source temperature and thus the deposition rate (0.5 – 20 nm/s) were adjusted by changing the electrical current flow and the flow time. In this study, the deposition rate was evaluated by thickness monitor using a quartz crystal sensor (CRTM-5000), set-up near the substrate. During deposition, the film thickness was always measured by the thickness monitor, and the film of 300 nm was prepared for measurement.

The structural analysis was made using X-ray diffractometer (JEOL-JDX-35 HS) with $CuK_\alpha$ radiation ($\lambda$ = 1.542 Å) at 40 kV and 300 mA in the scanning angle ($2\theta$) from $20^o$ to $80^o$. The surface morphology of the films was observed by a field emission scanning electron microscope (FE-SEM). The chemical composition of the deposited films was examined by X-ray fluorescence (XRF) (RIX 2000, Rigaku) and electron probe micro analyzer (EPMA-8705, Shimadzu).

The various electrical parameters such as Hall mobility ($\mu_H$), carrier concentration ($N_H$), Hall coefficient ($R_H$) and sheet resistance ($R_s$) were determined adapting Van der Pauw technique. A

standard four-probe method was used to measure the resistivity of the deposited films. The measurements were carried out at room temperature under a magnetic field of 1.0 T and passing a current of about 5 mA through the films.

## 3. Experimental Results and Discussions

The electrical and structural properties of the deposited films depend strongly on the source temperature and the substrate temperature [4]. In general, deposited InSb films tend to deviate from stoichiometry because the vapour pressures of Sb and In differ remarkably from each other. To obtain a stoichiometric film it should be needed to determine the optimum deposition condition such as deposition rate. From this view point, several investigations were made for the films at various deposition rate and thus the optimum deposition condition was determined.

In order to determine the crystallinity of the deposited films, several samples were examined by XRD. The results of three typical InSb samples deposited at 0.5, 5 and 10 nm/s are shown in Fig. 1. The film thickness was about 300 nm with polycrystalline structure.

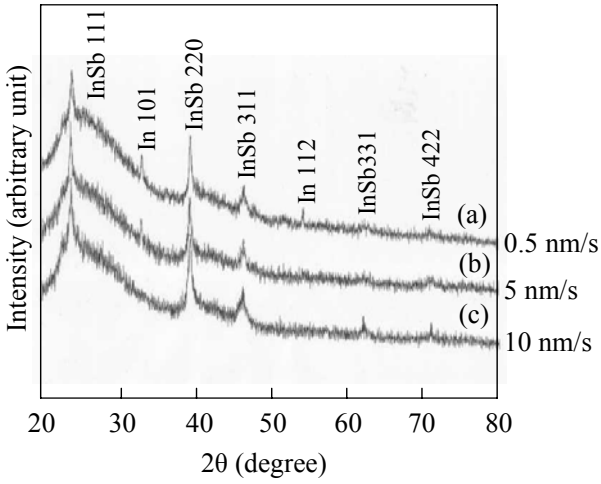



Figure 1: X-ray diffraction results of InSb films prepared at various deposition rates but have the same thickness of 300 nm.

Figure 1(a) shows the result for a film deposited at 0.5 nm/s, which contains two phases: InSb phase with peaks 111, 220, 311 and In phase with two minor peaks 101, 112. The InSb peaks become much stronger, but In peak decreases gradually with increasing deposition rate. In the film deposited at 5 nm/s, In 112 peak disappeared but a weak In 101 peak still remains. All In peaks disappeared completely for the film deposited at 10 nm/s. Moreover, two additional peaks (331 and 422) for the InSb are clearly seen in this film, and the other InSb peaks appeared with appreciable intensities. The films deposited at higher deposition rates than 10 nm/s, showed a similar but less sharp X-ray profile than that of the film deposited at 10nm/s. The results support that the film deposited at the optimum rate 10 nm/s is highly stoichiometric.

The composition ratio of these as-deposited films was analyzed by XRF. Figure 2 shows the dependence of Hall mobility and composition ratio of the films on the deposition rate. It is clear from the figure that the value of the ratio Sb/(In+Sb) is (50±1)% when the film deposited at 10 nm/s. On the contrary, the ratio was found as small as 35% when the film deposited at 0.5 nm/s. For more confirmation, some samples were analyzed by EPMA. The composition ratio obtained by EPMA was the same (≅ 50%) as that of XRF analysis. The Hall mobility also shows the maximum value for the film deposited at 10 nm/s. The same composition has been observed for other three films deposited at the substrate temperatures of 323, 373 and 473K. The above results indicate that the stoichiometric film can be obtained at the optimum deposition rate of 10 nm/s. Therefore, we determined that 10 nm/s is an optimum deposition rate in the present study.

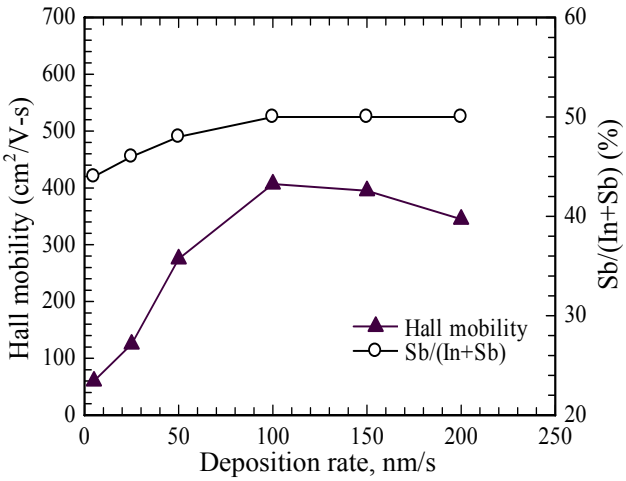



Figure 2: Dependence of Hall mobility and composition ratio on deposition rate of as-deposited film.

Figure 3 depicts the X-ray diffractogram for the films deposited at different substrate temperatures. The spectra confirm the crystalline nature of the prepared film. XRD measurement of the grown material at different substrate temperature showed agreement with ASTM data and JCPDS-ICDD No. 6-208 (Int. diff. data 1990). The crystallites in a

polycrystalline material normally have a crystallographic orientation different from that of its neighbours. The orientation of the crystallites, called the preferential orientation, may be randomly distributed with respect to some selected frame of reference. From the XRD patterns of InSb films, it has been observed that the structure films are found to be cubic with predominant orientation along the (111) direction. The results are in comparable with films prepared by other techniques [6]. It is concluded that the polycrystalline InSb film can be grown highly oriented along the (111) direction by vacuum evaporation technique. From the XRD profiles, the inter-planner spacing $d_{hkl}$ was calculated for the (111) plane using the Bragg's relation.

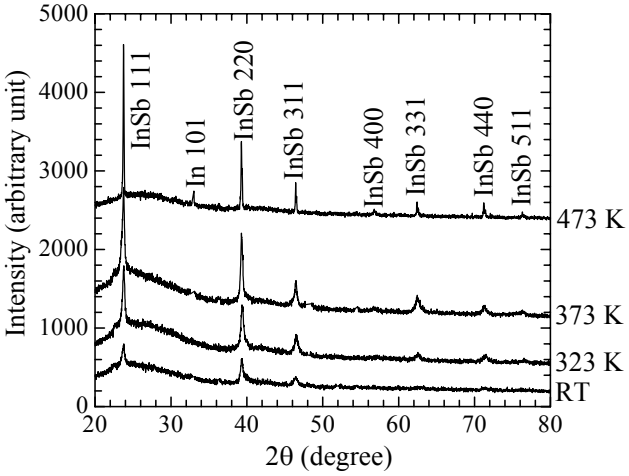
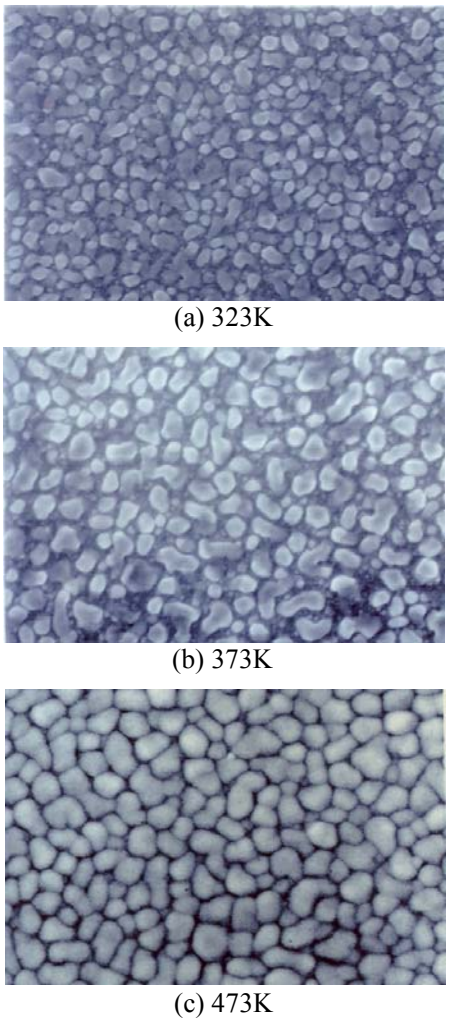



Figure 3: X-ray diffraction results of films deposited at different substrate temperatures.

The crystallite size (D), strain value (ε), dislocation density (δ) and the lattice constant of the film were calculated at different substrate temperatures and the results are shown in Table 1. It has been observed that the crystallite size increases with increase of substrate temperature which may be due to the decrease in strain value. Such an increase of particle size with increase of substrate temperature has also been reported by Masahiro et al. [4]. The increase in particle size with substrate temperature may be due to the coalescence of small crystallites. The dislocation density decreases with the increase of substrate temperature. Since dislocation density and strain are the manifestation of dislocation network in the films, the decrease in dislocation density indicates the formation of high-quality films at higher substrate temperatures [4]. This is possibly because of the fact that when the substrate is kept at higher temperature, the dislocations get more thermal energy and have a higher mobility. At room temperature three peaks of InSb (111, 220 and 311) are observed and they increase with the increase of substrate temperature. Other two peaks such as (331) and (440) for InSb are also observed in the films deposited at higher substrate temperatures and they become sharp as the substrate temperature increases. These results indicate that the crystallinity is improved in the film deposited at higher substrate temperatures. This is in good agreement with the results observed by Masahiro et al. [4] and Senthilkumar et al. [7].



(a) 323K

(b) 373K

(c) 473K

Figure 4: SEM micrographs of the films deposited at the substrate temperatures of (a) 323K, (b) 373K and (c) 373K. Film Thickness: 300 nm.

Table 1 Structural parameters of InSb thin films

| $T_s$ (K) | Particle size D (nm) | Dislocation density δ ($\times10^{15}$ lin/m$^2$) | Strain ε ($\times10^{-3}$ lin$^{-2}$m$^{-4}$) | Lattice constant a ($\times10^{-10}$ m) | Lattice spacing d ($\times10^{-10}$ m) |
|---|---|---|---|---|---|
| R.T | 14.32 | 4.87 | 4.94 | 6.59 | 3.81 |
| 323 | 23.25 | 1.84 | 2.53 | 6.52 | 3.77 |
| 373 | 26.65 | 1.40 | 1.69 | 6.50 | 3.75 |
| 473 | 33.35 | 0.89 | 1.25 | 6.48 | 3.74 |

Table 2 Electrical measurements of InSb thin films

| $T_s$ (K) | Hall mobility ($\mu_H$) $\times10^3$ cm$^2$/Vs | Carrier Conc. ($N_H$) $\times10^{17}$/cm$^3$ | Hall coefficient ($R_H$) $\times10^3$/ Coul | Sheet Resistance, ($R_s$) (Ω/cm$^2$) |
|---|---|---|---|---|
| R.T | 0.42 | 92.4 | 0.67 | 142.6 |
| 323 | 3.94 | 14.0 | 4.46 | 88.4 |
| 373 | 5.65 | 10.9 | 5.73 | 72.3 |
| 473 | 7.10 | 8.2 | 7.62 | 58.9 |

Figure 4 shows the SEM micrographs of the films deposited at substrate temperatures of (a) 323K, (b) 373K and (c) 473K. A large number of small grains are observed in the film deposited at the substrate temperature of 323K (Fig. 4a). The grain size increased as the substrate temperature increased as shown in figure 4(b), and 4(c). Morphological study showed good agreement with the XRD crystallinity anlysis. From XRD data, relatively small amplitude of each diffraction peak was observed for the film deposited at room temperature.

The small grain sizes and strains were suspected to be the cause of the small amplitude. As the substrate temperature increases, stronger and sharper diffraction peaks were observed. This was thought to result mostly from the grain growth, which released strains, partly from homogenization, which increased the amounts of the stable phases present in the films. Furthermore, it gives rise to even stronger diffraction intensities for some diffraction peaks, namely, the InSb (111), In (101), InSb (220) and InSb (311), indicates the improvement of crystallinity. The improvement of crystallinity and grain growth with the increase of substrate temperature also indicates the improvement in electrical characteristics.

## 4. Electrical Characterization

Table 2 gives the results of Hall effect measurements obtained in the present investigation. The decrease in sheet resistance with the increase in the substrate temperature is due to the increase in mobility of the charge carriers as a result of increase in preferred orientation. The calculated results are in agreement with the observations on InSb films by earlier workers [4, 7]. The Hall effect measurements show that the films exhibit p-type conductivity.

Figure 5 shows the dependence of Hall mobility and carrier concentration of the deposited films on the substrate temperature. The carrier concentration decreases and the Hall mobility increases with the increase of substrate temperature. The observed behavior at lower $T_s$ is associated with an increase in the number of their structural defects [8]. The Hall mobility values obtained are lower than that of bulk InSb [9], but higher than those of other films [7, 10], which may be due to density of dislocations.

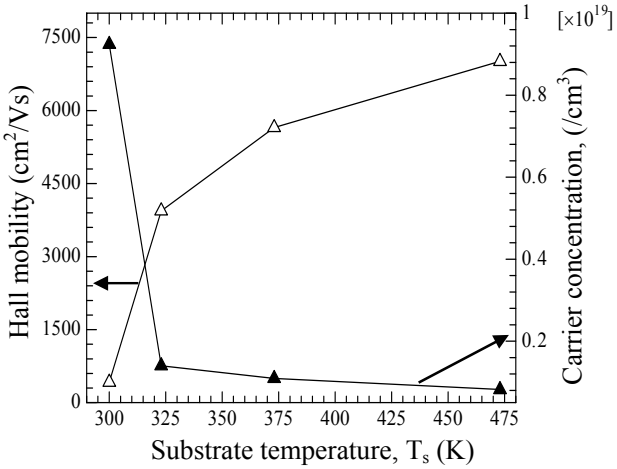



Figure 5: Dependence of Hall mobility and carrier concentration on substrate temperature.

The Hall mobility depends on the film thickness [4]. As expected from the present measurements a highest Hall mobility of $1.34 \times 10^4$ cm$^2$/Vs was found for InSb films of thickness 1000 nm.

Measurements on some thicker films (thickness above 1000 nm), showed that the mobility was approximately constant regardless of higher film thickness.

## 4. Conclusion

Thin InSb Films were deposited onto well-cleaned glass substrate at various substrate temperatures by rapid vacuum evaporation technique. The composition ratio of the deposited film was analysed by using XRF and EPMA and was found to be (50 ± 1) %. XRD, XRF and electrical measurements revealed that the film deposited at 10 nm/s is highly stoichiometric. X-ray diffraction studies confirmed that the films have polycrystalline in nature and the films showed preferential orientation along the (111) plane. The increase of peak intensity of (111) plane with increase in substrate temperature was observed. The microstructural parameters were calculated for the films and the values are in good agreement with the previous reports. Hall measurement studies indicate that the films were p-type, having carrier concentration $\cong 10^{17}$ $cm^{-3}$ and Hall mobility (0.42 – 7.1) $\times 10^3$ $cm^2/Vs$. The Hall mobility increased with increasing film thickness with a maximum of 1.34 $\times 10^4$ $cm^2/Vs$ for a thick film deposited at 473K.

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