Electrical, optical and structural properties of indium-antimonide (In-Sb) bilayer film structure

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Received 10 January 2003; revised 11 December 2003; accepted 13 April 2004

The indium-antimonide having small band gap is an important material for IR detectors and sources. The In-Sb thin film was deposited on glass substrate in the high vacuum chamber at pressure $10^{-5}$ torr. The samples were annealed for three hours on two different temperatures. The electrical resistivity decreases with increasing temperature, shows the semiconducting behaviour. The optical band gap varies from 0.22 to 0.23 eV with annealing temperature. The observed positive thermoelectric power indicates that In-Sb thin films were p-type in nature. The Rutherford back scattering analysis shows that the inter-diffusion concentration varies with temperature and X-ray diffraction pattern shows the improvement of crystallinity with annealing temperature.

[Keywords: In-Sb, Band gap, electrical resistivity, optical band gap]

IPC Code: C 03 B 25/00

1. Introduction

Among the compound semiconductors, InSb with small band gap, is of interest in the application of high speed infrared detectors due to the high electron mobility of 76000 cm$^2$/Vs. Hence the study on the deposition of indium-antimonide thin film is interesting for fabricating devices such as antenna-coupled infrared detectors$^1$ and photo-electronic$^2$ and magnet-electric$^3$ conversion devices.

In order to obtain InSb films there are several deposition methods like a flash evaporation$^4$ r.f sputtering$^5$ MBE$^6$ and CVD$^7$ are used. The vacuum evaporation technique is however easy but inferior, because element may decompose during evaporation. In-Sb bilayer structure has been deposited on glass substrate to study the effect of annealing on electrical, optical and structural properties of deposited thin films.

2 Experimental Details

The samples were prepared by thermal evaporation method using Hind High vacuum unit at pressure $10^{-5}$ torr. The high purity indium (99.99%) powder and pure antimony powder (98.5%) obtained from the BDH Chemicals Ltd., Poole England, are places in two different boats in the vacuum unit at pressure $10^{-5}$ torr. The glass substrate was placed in the substrate holder above the boats carrying materials. The material first evaporated indium and latter antimony to get bilayer of In-Sb thin films. The deposited films were annealed at pressure $10^{-5}$ torr for three hours to interdiffuse In and Sb elements to each other for different constant temperature. The FTIR spectrophotometer used to record transmission spectra of In-Sb annealed thin film samples. Electrical resistivity and thermo-electric power measurements by using standard techniques. The Rutherford back scattering (RBS) spectra were recorded at Indian Institute of Physics, Bhubaneshwar (India) to confirm compositional variation and interdiffusion with temperature in bilayer structure of In and Sb elements to each other. The thickness was measured by gravimetric method. The observed thickness of In and Sb in bilayer was 2000 and 2200 Å, respectively.

3. Results and Discussion

3.1 The resistivity of In-Sb thin films

Figure 1 shows the variation of resistivity with reciprocal of temperature for two samples, they are annealed at 331 and 351 K in vacuum up to three hours at pressure $10^{-5}$ torr. The thin films samples annealed at different temperatures for three hours at $10^{-5}$ torr pressure because of heat treatment of bilayers result in the interdiffusion and reaction between the
components, accompanied by the consequent nucleation and growth phases. The resistivity decreases with temperature in both the cases. The negative coefficient of temperature shows the semiconducting behaviour of the films. The thermal activation energy of films was obtained by following formula

\[ \rho_t = \rho_0 \exp(-\Delta E/KT) \]  

where, \( \rho_t \) is resistivity at any temperature; \( \rho_0 \) is resistivity at room temperature; \( \Delta E \) is activation energy and \( K \) is Boltzmann constant.

The activation energy obtained for the sample annealed at 331K was \( \Delta E_a = 1.56 \text{ meV} \), which was very low in comparison to band gap of material. This shows the conduction at this temperature due to transformation from impurity levels, lying within the band gap of this film (In-Sb), to the valence band. The value of activation energy at temperature 351 K was \( \Delta E_a = 19.5 \text{ eV} \), slightly higher but less than band gap which again proves the possibility of the presence of acceptor like levels within the band gap.

### 3.2 Thermo electric power

The thermo electric power (TEP) measurements were carried out on annealed samples of InSb, by using integral temperature method. In this method, the temperature of one end was varied and temperature of other was kept constant. The induced e.m.f. was recorded.

The thermoelectric power was calculated as

\[ S(t) = \Delta V/\Delta T \]  

where, \( \Delta V \) is thermo EMF and \( \Delta T \) is the temperature gradient and the positive sign of the TEP suggest that conduction should occur predominantly due to holes. This p-type conduction is achieved either by cation vacancies or anion interstitials. The InSb has mainly metallic covalent bonds with vacancies acting as accepters which are responsible for p-type nature. The temperature dependence of thermoelectric power of films is shown in Fig. 2 for films annealed at two different temperatures. These graphs show that the thermoelectric power increases with temperature. The variation of TEP with temperature in our case may be explained on the basis of defect state model. It may be considered that during the TEP measurements the thermal gradients established changes the density of charged defect state by capturing electrons and holes. The motion of the electron and holes can take place through process of diffusion. The variation of thermoelectric power at different temperature may also indicate phase transformation during the inter-diffusion of multilayers.

![Fig. 1](image1.png)  
Variation of resistivity with reciprocal of temperature for InSb bi-layer thin films at temperature 331 K and 351 K

![Fig. 2](image2.png)  
Variation of thermoelectric power vs \( 10^3/T \) (a) annealed InSb bi-layer at 331 K (b) annealed InSb bi-layer at 351 K
The $10^3/T$ versus thermoelectric power also indicates that thermoelectric power increase linearly with increasing temperature, which agrees with the behaviour expected of a typical non-degenerate semiconductor. Table 1 gives the hopping activation energy at 331 and 351 K.

The thermo power activation energy and conductivity activation energy were not found to be equal. Which shows that transport mechanism for above-mentioned temperature are due to variable range hopping in the localized states near the fermi-level. The thermo-power activation energy is less than the band gap of material, therefore it also confirms the presence of acceptor levels within the band gap.

It is also observed that 0.4 μm thick films of In-Sb show $p$-type conduction in the extrinsic temperature range by Masaaki. The values of $(E_v-E_f)$ from TEP slope for both annealing temperatures were found to be 0.48 and 0.56 mV, respectively.

3.3 Optical Band Gap

Thin films samples were isochronal annealed at different constant temperatures in vacuum system for three hours at pressure $10^{-5}$ torr. The transmission spectra of In-Sb thin films were taken at room temperature with the help of FTIR spectrometer.

The optical energy band gap of thin films was calculated by using Tauc relation:

$$\alpha h\nu = A(h\nu - E_g)^n$$  ... (2)

where, $h\nu$ = photon energy; $\alpha$ = absorption coefficient; $E_g$ = optical band gap; $A$ = constant; $n = \frac{1}{2}$ for direct band gap material and 2 for indirect band gap material.

Since the material is with direct band gap, the extrapolation of straight-line to $(\alpha h\nu)^2 = 0$ axis gives the value of energy band gap. In annealed films the optical absorption edge is produced by transitions between two state densities, both of which rapidly change as a function of energy and which corresponds to the valence and conduction band edges for the ideal stable continuous random network structure Connell et al. It was observed that the band gap varies with annealing temperature of these samples, it may be due to change in the inter-diffusion ratio of In and Sb interface at different temperatures. The observed band gap in our case was found to vary from 0.22 to 0.23 eV for temperature range 331-351 K, respectively. The increasing band gap can be explained on the basis of the reduction in the number of unsaturated defects, decreases in the density of localized states in the band structure and consequently increase in the optical band gap with increasing annealing temperature.

3.4 X-ray Diffraction Measurements

The X-ray diffraction patterns, the increase of InSb films deposited 4200 Å thickness by bilayer method and annealed in vacuum at pressure $10^{-5}$ torr for three hours at two different temperatures were taken. The deposited films show the amorphous nature but after annealing the InSb films show the (202) and (311) peaks in the range of diffraction angle 31 - 71º. These results indicate the crystallinity as well as grain size of films after annealing. The increased grain size with doping of Sb in case of CdSe thin films was observed by Masumdar et al. These observed results were in agreement with XRD pattern observed for InSb with variation of substrate temperature by Masaaki et al. But in the present case we annealed the InSb bi-layer structure instead of substrate temperature and found the similar crystallization pattern as shown in Fig. 3, also observed that the re-crystallized area shows preferred

<table>
<thead>
<tr>
<th>Temperature (K)</th>
<th>Thermo-power activation ($\Delta E_s$)</th>
<th>Conductivity activation ($\Delta E_a$)</th>
<th>Hopping activation ($\Delta E_h$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>331</td>
<td>0.19 eV</td>
<td>1.56 meV</td>
<td>0.1885 eV</td>
</tr>
<tr>
<td>351</td>
<td>0.22 eV</td>
<td>19.5 meV</td>
<td>0.2105 eV</td>
</tr>
</tbody>
</table>

Fig. 3 — X-ray diffraction of InSb thin films (a) as deposited (b) annealed InSb bilayer at 331 K (b) annealed InSb bi-layer at 351 K
(220) orientation, and the film was found to have a two phase character of InSb-In (101) and (202) peaks of indium which is in full agreement with earlier observations \(^\text{14,15}\) and also agree well with XRD and SEM results of Okimura et al \(^\text{16}\). These type of films like InSb-In, are usually obtained as higher magneto resistance effect \(^\text{17}\). The increase in the intensity of peaks with annealing temperature shows the formation of InSb at interface of bilayer structure. This is in the agreement with Cruz et al \(^\text{19}\) who observed that in case of Te/Cd bilayer structure, the XRD pattern of a glass/Te/Cd films annealed at different temperature shows peaks of CdTe cubic structure. These peaks grow slowly with increasing annealing time and extra peaks of Cd and Te are due to free elements and established that bilayer structure annealing with temperature from the CdTe structure.

3.5 Rutherford Back Scattering Spectrometry

Rutherford back scattering spectrometry assisted by channeling facility is being successfully employed for quantitative information about stoichiometry and structure of interfaces doped semiconductor as a function of depth. The RBS is single rapid, sensitive and non-destructive depth profiling technique and is most suitable for quantitative analysis, however the chemical information is obtained from a depth of 1000 Å and spatial resolution is of the order of 10 Å. Figure 4 shows the normal yield versus channel spectra in which the In-Sb peaks are shifted downward with annealing temperature, Which shows that the inter-diffusion of bi-layer structure of In and Sb increases with temperature.

These results also support our resistivity, presented thermoelectric power, optical band gap and XRD analysis presented in this paper. This is in agreement with Holloway et al. \(^\text{18}\) for Ti-Si layer structure where the reduced peak to valley ratio indicates the significant inter-diffusion of elements. They had also observed the micro structural changes in Ti-Si multilayered during the thermal annealing by using RBS and XRD techniques. The total mass transport of one element into another depends critically on the grain size and the grain boundary structure. As the temperature increases, the interaction of diffusing atoms with the host atoms leads to grain boundary migration, which leads to the generation of vacancies and network of dislocations \(^\text{23}\). Such defect formation is quite often associated with compound formation. In the Cu/Au \(_3\) system, for example, the vacancy concentration associated with the formation of AuCu and Cu\(_3\)Au alloys is located at the Cu sublattice \(^\text{24}\). The complete intermixing of Cu and Au occurs at 400 °C observed by Peter et al. \(^\text{25}\). The compound formation and complete intermixing analysis is under progress.

4 Conclusions

1 The electric resistivity can be used to understand phase transformation in bi-layer structure.
2 The positive sign of TEP confirm the P-type nature of Indium antimonide.
3 The transportation of carrier may be through hopping mechanism.
4 The band gap measurements confirm the variation of elemental concentration in the bi-layer interface with temperature.
5 The XRD measurement shows the improvement of crystallinity of annealed samples.
6 RBS analysis indicates the elemental variation of concentration in the interface with annealing temperature.

References