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Preparation of Al–Sb semiconductor by swift heavy ion irradiation

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Abstract. Al–Sb bilayer thin films having various thicknesses were deposited by thermal evaporation on ITO-coated conducting glass substrates at a pressure of 10^{-5} torr. These films were irradiated by Ag^{12+} heavy ions of energy, 160 MeV, with a fluence of $2{\cdot}2 \times 10^{13}$ ions/cm^2, to get aluminum antimonide semiconductor. Rutherford back scattering and optical band gap data confirmed mixing of bilayer to form the semi-conducting system.

Keywords. Thin films; Al–Sb; ion irradiation; absorption; RBS; optical band gap.

1. Introduction

The III–V group semiconductors have great importance due to their applications in various electro-optic devices like P–N junction diode, transistors, high efficiency solar cell, infrared detectors, photon detectors etc. Aluminum antimonide is a promising semiconducting material for high temperature applications specially for high efficiency solar cells, transistors and P–N junction diode due to its large band gap (1·62 eV) (Herczog *et al* 1958; Yu *et al* 1995). The Al–Sb is normally synthesized by co-melting a mixture with given stoichiometry. However, its application in a device form needs it in thin film form. The properties of Al–Sb in thin films will vary with composition due to its variation while vacuum evaporation. A well defined composition of Al–Sb can be formed in thin film form by stack elemental layer deposition and their intermixing. A low energy ion beam irradiation causes a ballistic mixing due to elastic collision cascades. Therefore, nuclear energy loss is considered to be responsible for ion beam mixing as Avasthi *et al* (1999) and Mayer *et al* (1981) have shown that the number of atoms in the mixed region is proportional to the nuclear energy loss and ion fluence. Irradiation of solids with swift heavy ions often results in material modifications like structural changes, plastic deformation, or alteration at the phase composition. The observation of ion tracks in quartz and other insulators as well as the damage observed in semiconductors and metals indicate that a vivid motion of atoms must have taken place in a small cylinder along the ion's path (Klaumiinzer and Stolterforth 1998). Thermal spikes were used to explain the high mixing effects due to nuclear stopping observed at lower ion energies (Bolse 1994; Nastasi and Mayor 1994). In the thermal spike model (Seitz and Kochler 1956), one assumes first thermalization at the electronic system within some 10^{-12} s and an energy transfer to the lattice via electron–phonon coupling within a few 10^{-12} s depending on the material and the energy deposed by the ion. The temperature in the surroundings at the ion path may significantly exceed the melting point and a liquid cylinder of some nm in diameter is formed, which subsequently is rapidly quenched to the ambient temperature within a few tens to a few hundreds of ps. Due to the high cooling rate, a non-equilibrium material is found in the ion track.

Ion beam (210 MeV I ions and 230 MeV Au ions) mixing in Fe/Si and CuO/glass system observed by Avasthi *et al* (1999) suggested that on the basis of different recoil spectra ion beam mixing increases with the increase in electronic energy loss. Dufour *et al* (1993) have shown that the mixing at the interface can also be induced by the large electronic excitations of high energy heavy ions with the atoms in the sample. Ion beam mixing in Fe/Si and Ta/Si bilayer observed by Dhar *et al* (2003) suggested that on the basis of RBS analysis, in case of Fe/Si system, the ion (Ar^{1+}–Ar^{8+}) charge was observed to have an effect on the mixing rate, but in case of Ta/Si system there was no effect on the charge state of sputtering and a thermal mixing rate was observed in the case of Ta/Si system. The mass production of electronic devices such as galvanomagnetic sensors still depend on the process of thin film deposition on low cost insulating substrates, using a simple vacuum evaporation technique. The basic aim of this paper is to understand the interdiffusion reaction kinematics of bilayer structure with control manner ion beam mixing technique and RBS analysis.

In this paper, we present the method of preparation of Al–Sb in thin film form as a semiconductor and charac-

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terization by optical absorption and Rutherford back scattering spectroscopy.

2. Experimental

2.1 *Sample preparation*

The samples of Al–Sb were prepared by thermal evaporation method using vacuum coating unit at a pressure of 10^{-5} torr. The high purity aluminum (99·99%) thin foils and pure antimony powder (99·5%) obtained from BDH Chemicals, Pool, England, were placed in two different boats at a pressure of 10^{-5} torr. The conducting glass substrates were placed in the substrate holder above the boats carrying materials. The antimony having thicknesses 1000 Å, 1500 Å, 2000 Å was first evaporated and later aluminum of constant thickness deposited over these films to get Al–Sb bilayer structure. The thickness was measured by quartz crystal thickness monitor.

2.2 *Irradiation*

These films were irradiated by Ag^{12+} ions of energy, 160 MeV, with a fluence of $2{\cdot}2 \times 10^{13}$ ions/cm^2 in General Purpose Scattering Chamber at the Nuclear Science Centre, New Delhi, to get homogenous mixture of Al–Sb semiconducting system.

2.3 *Absorption spectra*

The absorption spectra of as deposited and ion irradiated thin films were carried out in the wavelength range 360–860 nm with the help of a Hitachi Spectro Photometer Model-330.

2.4 *Rutherford backscattering spectra*

The RBS data have been recorded at the Ion Beam Laboratory, Institute of Physics, Bhubaneswar, using Pelletron facility with alpha particle beam (He^{2+}) of 3·0 MeV, while the back scattered alpha particles were recorded at an angle of 160° using a surface barrier detector.

2.5 *Optical micrograph*

The optical micrographs were observed with the help of Labomade optical microscope at 40×10 magnification and microscope was kept in reflection mode.

3. Results and discussion

3.1 *Optical properties*

Figures 1 and 2 show the graph between wavelength vs absorption of as deposited and ion irradiated thin films, respectively having a constant thickness (3000 Å) of aluminum over different thicknesses (1000, 1500 and 2000 Å). The optical absorption of as deposited samples do not show any sharp absorption edge, however, the effect of increasing thickness is larger at lower wavelength region indicating partial crystallization of Al and Sb. The absorption spectra (figure 2) of irradiated samples show a sharp absorption edge around 700 nm. The variation in absorption spectra is due to variation in intermixing at the surface. This is similar to the behaviour observed by Singh *et al* (2004) in case of transmission of Zn–Se bilayer structure with rapid thermal annealing. In the case

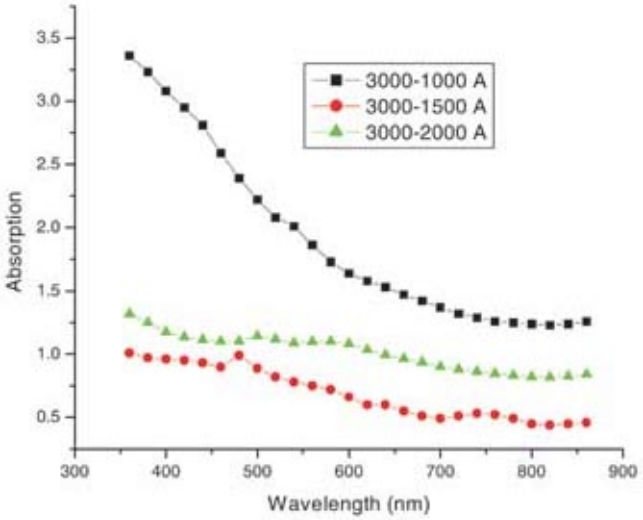

Figure 1. Wavelength vs absorption of as deposited Al–Sb bilayer thin films of thicknesses, 3000–1000 Å, 3000–1500 Å and 3000–2000 Å.

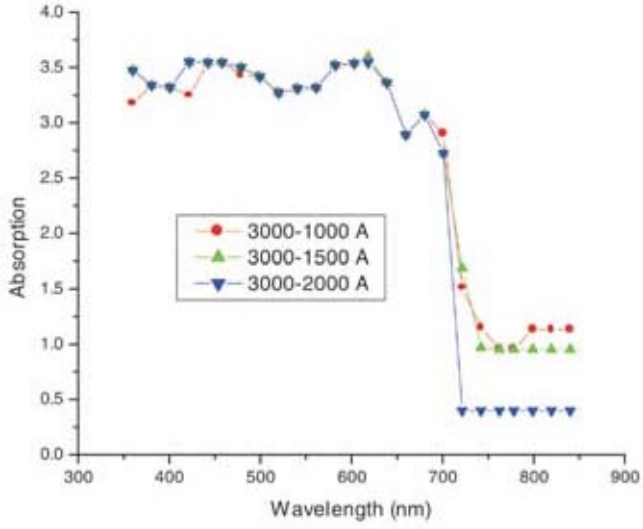

Figure 2. Wavelength vs absorption of ion beam irradiated Al–Sb bilayer thin films of thicknesses, 3000–1000 Å, 3000–1500 Å and 3000–2000 Å.

of Al–Sb for ion irradiation, mixing occurs due to thermal heating, which is supported by our optical micrograph in which droplets occur due to mixing.

3.2 *Optical band gap*

The optical band gap of these films have been calculated using the relation (Tauc 1974)

$$\alpha\, h\nu = A\,(h\nu - Eg)^n,$$

where, $h\nu$ is the photon energy, α the absorption coefficient, Eg the band gap, A a constant and, $n = 0{\cdot}5$ for direct band gap material, $n = 2$ for indirect band gap material. The Al–Sb is an indirect band gap material, so, in the present work, we have taken $n = 2$ for calculation. Figure 3 shows the photon energy vs $(\alpha\, h\nu)^{1/2}$ for Al–Sb thin films. This graph shows the value of optical band gap for ion beam irradiated films which have been given in table 1. The optical band gaps nearly agree with the reported band gap (1·62 eV) (Rittner *et al* 1954; Herczog *et al* 1958; Yu *et al* 1995). The variation observed in samples having different thicknesses is due to non-uniform mixing of Al and Sb.

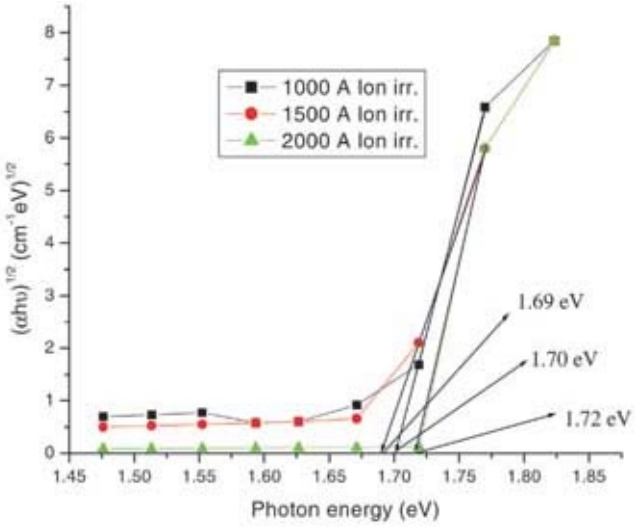

Figure 3. Photon energy vs $(\alpha h\nu)^{1/2}$ of ion beam irradiated Al–Sb thin films for thicknesses, 3000–1000 Å, 3000–1500 Å and 3000–2000 Å.

Table 1. Variation of optical band gap with thickness of the Al–Sb bilayer thin film.

Thickness (Å) of Al–Sb films	Band gap of ion irradiated films (eV)
3000–1000	1·70
3000–1500	1·69
3000–2000	1·72

3.3 *Rutherford backscattering analysis*

Rutherford backscattering (RBS) energy spectrum of alpha particles is based on energy loss due to collisions between atomic nuclei. It measures the number and energy of ions, backscattered from a beam by atoms in the near-surface region of a sample as the beam collides with the sample (targeted). It is a single rapid, sensitive and non-destructive depth profiling technique. From figures 4–6, we observe that the peaks of ion irradiated films shifted towards higher energy side. The energy loss of alpha particle is due to reduction in passage in top Al-layer. The observed reduction in the number of alpha particles could

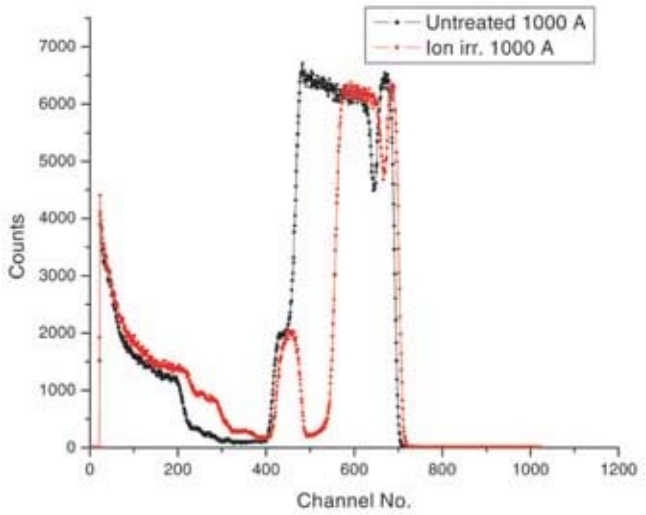

Figure 4. Rutherford backscattering spectra of as deposited and ion beam irradiated Al–Sb thin film of thickness, 3000–1000 Å.

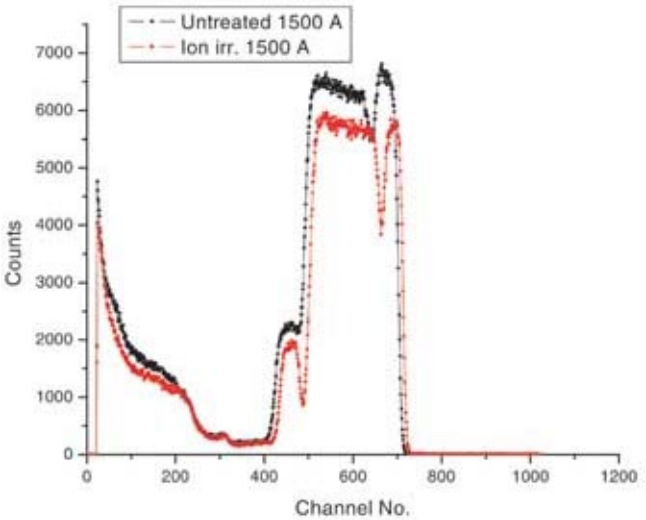

Figure 5. Rutherford backscattering spectra of as deposited and ion beam irradiated Al–Sb thin film of thickness, 3000–1500 Å.

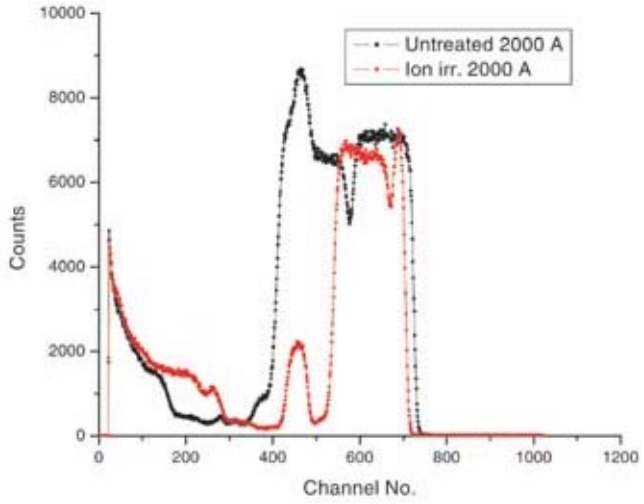

Figure 6. Rutherford backscattering spectra of as deposited and ion beam irradiated Al–Sb thin film of thickness, 3000–2000 Å.

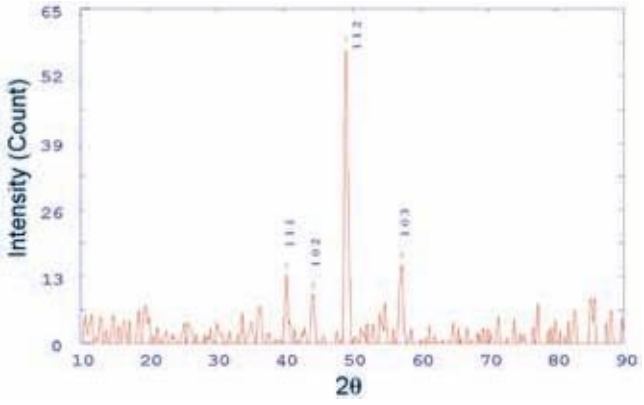

Figure 7. X-ray diffraction pattern of as deposited Al–Sb bilayer thin film of thickness, 3000–1500 Å.

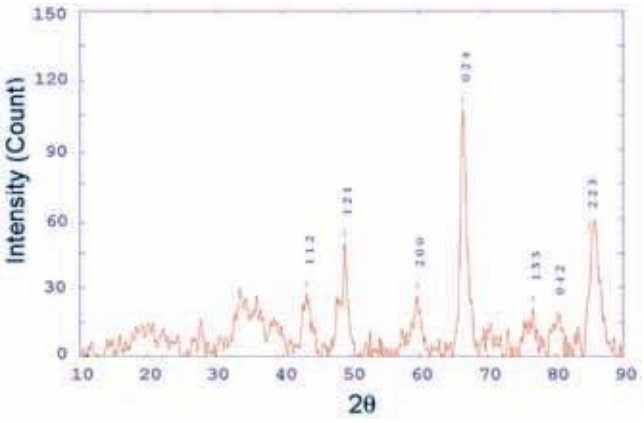

Figure 8. X-ray diffraction pattern of ion irradiated Al–Sb bilayer thin film of thickness, 3000–1500 Å.

be due to distribution of Sb atoms into Al-layer due to mixing. It means that the Al and Sb inter-diffuse with each other by ion beam irradiation.

In a comparative study of figures 4, 5 and 6 for as deposited (with ion beam mixed) Al–Sb bilayer thin films, samples having thicknesses, 3000–1000 Å and 3000–2000 Å, show more shifting of peaks towards higher energy side compared to sample having a thickness of 3000–1500 Å, but in this sample peaks are more diminished compared to other samples i.e. the top layer of aluminum seems to diffuse into antimony side and mixing is affected at each thickness. Hence, it confirms that ion beam irradiation process is useful to prepare Al–Sb semiconductor in thin film form. This was also confirmed by our optical band gap data. Our results of ion beam mixing agree with Dhar *et al* (2003) who suggest that in case of Fe/Si, the ion of Ar^{8+} is useful for mixing. The mixing of Fe/Si was also observed by Avasthi *et al* (1999) with heavy ion beam of Au having a fluence of $8{\cdot}8 \times 10^{13}$ ions/cm^2. The peaks were broadened as well as reduced in intensity. The X-ray reflectivity and Mössbauer spectroscopic analysis have also been carried out by Gupta *et al* (1999) to confirm mixing by ion beam irradiation. These observations well agree with Holloway and Sinclair (1987) and Singh and Vijay (2004).

In our case, to check the mixing effect, thickness was taken as a variable function. The mixing was found to be near constant with thickness that was confirmed by our optical band gap data and shifting in RBS peaks. The reduction of lower edge of Al peak and front edge of Sb shows the intermixing of interface.

3.4 *X-ray diffraction study*

X-ray diffraction spectra (figures 7 and 8) have shown Al–Sb bilayer thin films having a thickness of 3000–

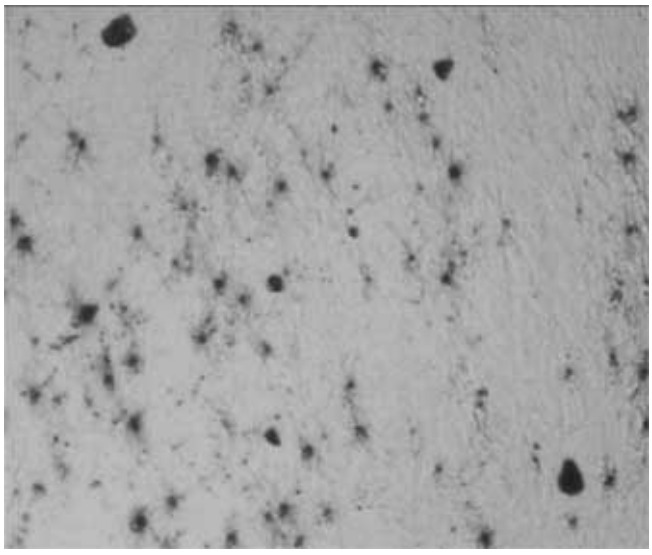

Figure 9. Microphotograph of as deposited Al–Sb bilayer thin film of thickness, 3000–1500 Å.

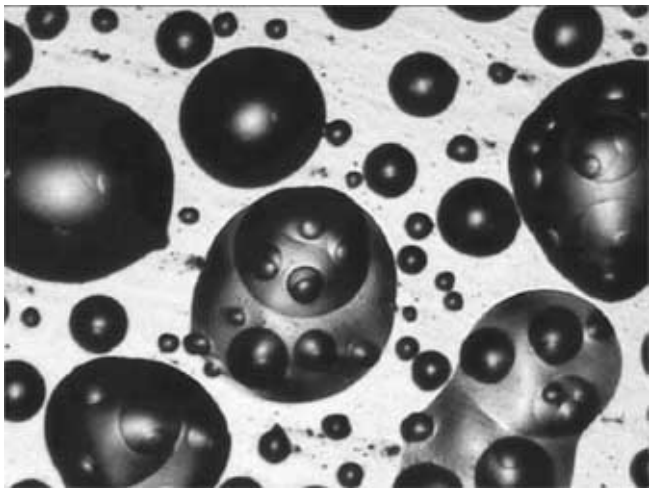

Figure 10. Microphotograph of ion irradiated Al–Sb bilayer thin film of thickness, 3000–1500 Å.

1500 Å. In as deposited sample the major peak for aluminum was found at 49·039°, 112 and other peaks was for antimony (Sb). After ion irradiation peaks were found at 48·993°, 59·652°, 66·369°, 76·753° and 80·275°. The *hkl* values for these peaks are (121), (200), (024), (133) and (042), respectively, which indicate the formation of crystalline AlSb compound in ion irradiated sample. Intensity of major peak in ion irradiated sample also decreases due to mixing of bilayer system. Similar effects for rapid thermal annealing was also observed by Singh *et al* (2004).

3.5 *Optical micrograph*

The optical micrograph of thin film having thickness, 3000–1500 Å, is shown in figures 9 and 10 before and after ion irradiation, where the effect of SHI has resulted into breakage of uniform film into circular droplets of diameter ≈1–10 μm, which indicates mixing occurs due to thermal heating by ion irradiation.

4. Conclusions

(I) The Ag^{12+} ion can be used for Al–Sb mixing to prepare semiconductor.

(II) Swift heavy ion irradiation process provides approximately same band gap of our samples that also indicates different phase formations with thickness due to large diffusion at interface.

(III) Swift heavy ion irradiation may be used to control the phase transformation.

(IV) The X-ray diffraction study also confirms formation of AlSb by ion irradiation.

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