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Studies on the electrical conductivity, optical absorption and x-ray diffraction in bismuth thin film

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Abstract. Spectroscopically pure bismuth is evaporated onto glass substrates at different substrate temperature using a Hind Hivac coating plant. The electrical conductivity of bismuth thin films, prepared at different substrate temperatures is measured and thermal activation energy is evaluated. From the recorded optical absorption spectrum in the ultraviolet and visible regions optical band gap E_g is determined. X-ray diffractograms are recorded and lattice parameters are determined.

Keywords. Thin film; electrical conductivity; optical absorption; x-ray diffraction.

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1. Introduction

Bismuth is a semimetal. Semimetals are a class of solids which are used to probe the Fermi surface and the band structure of the crystalline solids [1]. The narrow band gap of bismuth and its alloys find applications in Hall effect devices, hyper frequency power sensors, thermopiles and microwave detectors [2]. The electrical, optical and structural studies of bismuth thin films have been reported by many authors [3, 4]. But the studies made earlier on bismuth thin films have large inconsistencies. In this paper a systematic study is reported on the electrical, optical and structural properties of bismuth thin film.

2. Experimental

Thin films of bismuth are prepared by vacuum evaporation of 99.999% pure bismuth (obtained from SISCO) by resistive heating method. The evaporation is carried out from a molybdenum boat at a pressure of 10^{-5} torr. Substrate temperature is varied by a controlled variac arrangement and temperature is monitored by a copper-constantan thermocouple. The thickness of the film is determined by Tolansky's interference technique [5]. Electrical connections are given using silver paste and conductivity measurements have been done using a four probe set-up (DFP-02). The conductivity is measured at regular intervals of 5 K in the temperature range 300–525 K. The uv-visible absorption spectra is recorded using Shimadzu 160A spectrophotometer. The analysis of the spectra yield optical band gap. X-ray diffractogram is recorded using the Regaku x-ray diffractometer.

3. Results and discussion

Figure 1 shows the plot of electrical conductivity (σ) versus temperature for bismuth thin film of different thickness for substrate temperature 30°C. As the temperature increases, conductivity increases which exhibits semiconducting nature for the film. Conductivity measurements are carried out for the films prepared at substrate temperatures 75, 100, 200 and 250°C. Figure 2 shows the plot of electrical conductivity vs temperature for Bi film prepared at substrate temperature 100°C. It is observed that the conductivity increases first, then decreases followed by a sharp increase, in the temperature range 30 to 250°C. The semiconducting region is absent in the cooling cycle. The same behaviour is observed for the films prepared at substrate temperatures of 75, 150, 200 and 250°C. Thin film consists of individual islands which have many of the characteristics of the liquid droplets. As the substrate temperature increases, the contact angle between droplet and substrate decreases and the droplet grows in size. Thus a given amount of material deposited on a substrate at low temperature may be enough to form a continuous film, whereas the same amount of material deposited on a hotter substrate will result in an

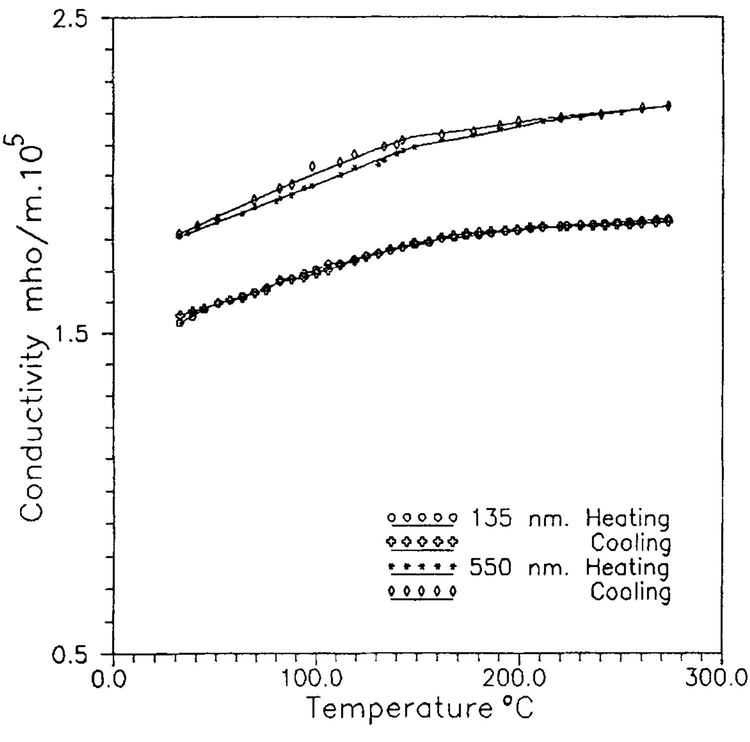

Figure 1. Plot of conductivity (σ) versus temperature (T) for bismuth film coated at room temperature.

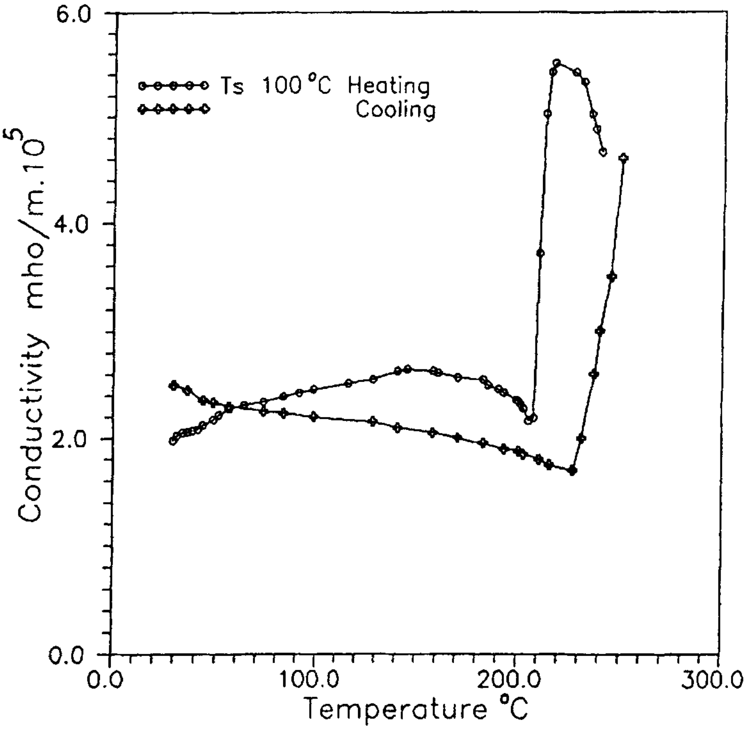

Figure 2. Plot of σ versus T for bismuth film coated at substrate temperature of 100°C.

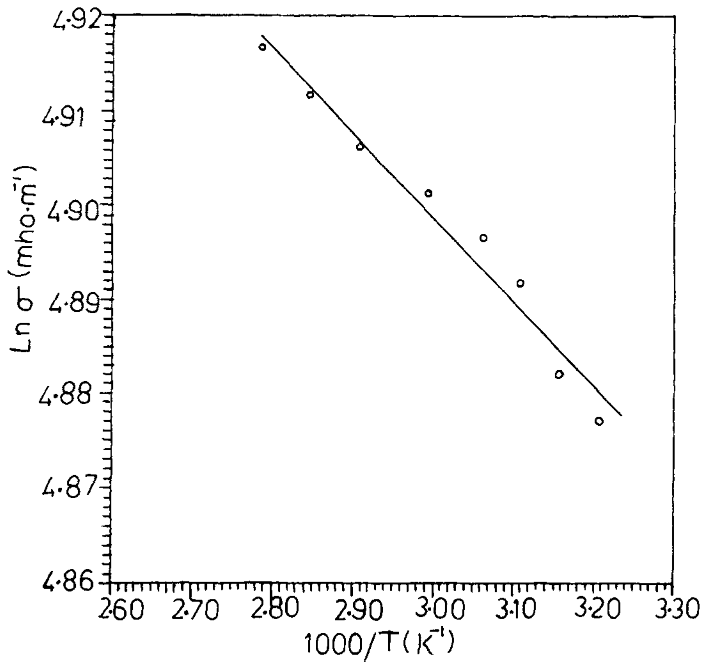

Figure 3. Plot of $\ln \sigma$ versus $1000/T$ for bismuth film.

Table 1. Variation of activation energy with substrate temperature for bismuth thin film.

Substrate temperature °C	Activation energy (meV)
30	15.50
75	10.30
100	7.76
150	6.81
200	6.03
250	5.17

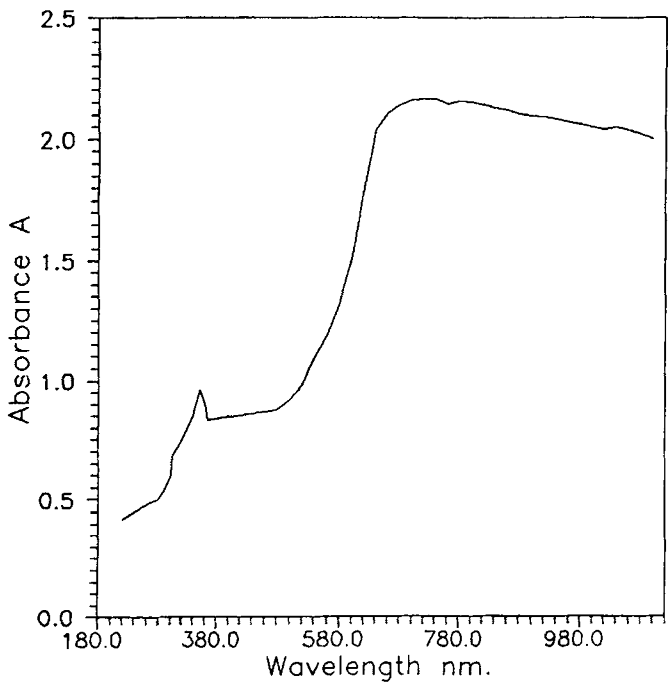

Figure 4. The optical absorption spectrum of Bi film.

island structure. The jumps in conductivity are due to coalesence of islands. Similar results have been observed by Das and Jagadeesh [6] for Bi–Sb alloy films.

Thermal activation energy is related to the electrical conductivity according to Arrhenius relation,

$$\sigma = \sigma_0 \exp[-\Delta E/kT],$$

where σ_0 is a constant, ΔE is the thermal activation energy and k the Boltzmann constant. Graph is plotted with $\ln \sigma$ along y axis and $1000/T$ along x axis as shown in figure 3. From the slope of the graph activation energy is calculated. The effect of substrate temperature on thermal activation energy is shown in table 1.

The uv-visible optical absorption spectrum of bismuth film is as shown in figure 4. The absorbance is high in the visible region. Optical absorption coefficient α is related to

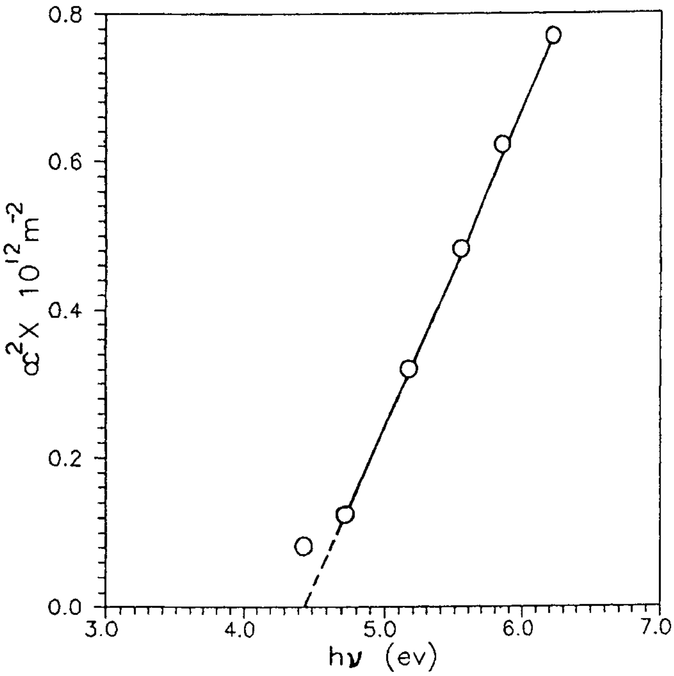

Figure 5. Plot of α^2 versus $h\nu$ for Bi film.

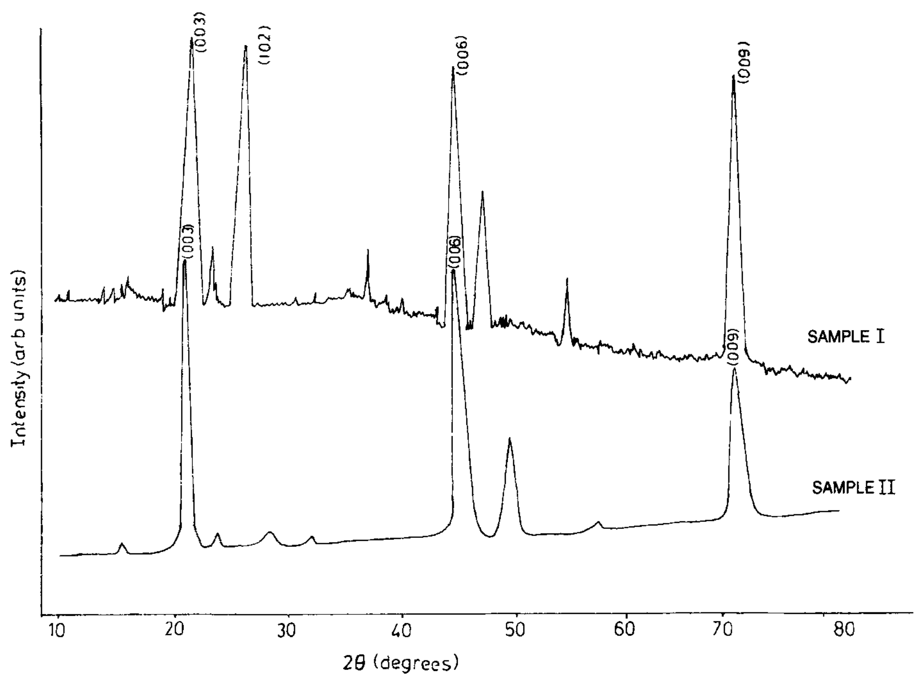

Figure 6. XRD pattern of Bi film at room temperature.

Table 2. Variation of grain size with substrate temperature for bismuth thin film.

Substrate temperature °C	Grain size (nm)
30	18.7
75	72.0
100	62:3
200	60.1
250	47.5

the optical band gap E_g by the relation

$$\alpha = \alpha_0(h\nu - E_g)^n,$$

where $n = 1/2$ for direct allowed transition and E_g is the optical band gap. Graph of α^2 versus $h\nu$ is plotted as shown in figure 5 and is extrapolated to zero absorption to obtain the optical band gap. The optical band gap E_g is obtained as 4.45 eV for bismuth thin film. Similar results have been obtained by Al Houty *et al.* [2] for the energy band gap of bismuth thin film.

X-ray diffractogram is recorded for the bismuth thin film of 200 nm thickness and is shown in figure 6. From the XRD pattern it is evident that bismuth has high degree of preferential orientation with the basal plane parallel to the film plane, indicating strong reflection from (003), (006) and (009) planes [3]. The lattice spacing d is calculated and compared using the standard ASTM data. Lattice constants are obtained for hexagonal bismuth as $a = 4.54$ Å and $c = 11.85$ Å. Grain size (L) of the film is calculated using Scherrer formula [7].

$$L = K\lambda/\eta_{1/2}\cos\theta,$$

where K is a constant equal to 0.9, $\eta_{1/2}$ is the full width at half maximum intensity and θ corresponds to the Bragg angle. The grain size is calculated for the films prepared at different substrate temperatures and is given in table 2.

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