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Electrical Properties of Thermal Evaporated Bismuth Telluride Thin Films.

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Abstract: Bismuth Telluride films (Bi_2Te_3) were fabricated using thermal evaporation technique in a vacuum better than 10^{-5} torr onto glass substrate. The study of electrical properties of Bi_2Te_3 thin films was carried out in the thickness range of about 50-300 nm and temperature range 300-470K. The electrical conductivity was found to increase with thickness of the films and temperatures. The activation energy was decreased with film thickness while the grain size was increased with the thickness. The temperature co-efficient of resistance (TCR) was obtained negative that indicates nonmetallic behavior. The Hall co-efficient, carrier mobility, carrier concentration, mean free path and mean free time were also studied. These results suggest that the investigated films are semiconducting in nature.

Keywords: Topological insulator, Fuch-Sondheimer theory, Hall Effect measurement.

1 Introduction

Bismuth Telluride is a narrow gap semiconductor and it is one of the best performing materials in the point of view of thermoelectric properties [1-2]. Recently, researchers have reported this material as a topological insulator [3-6] that behaves as an insulator in its interior while surface contains conducting states.

The emerging possibilities of topological insulator may further accelerate the changing of future device. Therefore, this material has become of particular interest in recent years because of its potential application. Literature reports indicate that bismuth telluride thin films have been prepared by a number of techniques by many researchers. These include radio frequency magnetron sputtering [6], flash evaporation [7], pulsed laser deposition [8], molecular beam epitaxy (MBE) [9]. Most of the reports address thermoelectric and structural aspect of the film emphasizing the prospect of the films in their efficiency. Although there are number of investigations on the thermoelectric and structural properties of this material, there are few systematic studies on the electrical properties on the films.

Hence there is a need to study the electrical properties. The thickness and temperature dependence of conductivity, activation energy are studied. The Hall co-efficient, carrier life time, mean free path were also studied.

2 Experimental

Bismuth Telluride films (Bi_2Te_3) have been prepared by thermal evaporation of Bismuth Telluride powder from a tantalum boat in E306 vacuum coating system onto glass substrate held at room temperature. Films of various thicknesses have been deposited for electrical and optical measurements onto glass substrates with 1×1 cm^2 size. The thickness was measured by the Tolansky Interference method. Thickness of these samples was about 50 to 300 nm, respectively. Electrical conductivity measurements as a function of temperature was carried out in the temperature range of 300-470K. The Hall co-efficient was determined by using conventional DC method.

3 Results and Discussions

The variation of conductivity and sheet resistance as a function of film thickness has been studied and is shown in fig. 1. It is seen from the graph that the values of the conductivity increases with increasing film thickness. The thickness dependence of conductivity corroborates the Fuchs-Sondheimer size effect theory [10-11]. The value of the sheet resistance decreases with film thickness. This is due to the fact that lattice defects and electron scattering decreases with film thickness.

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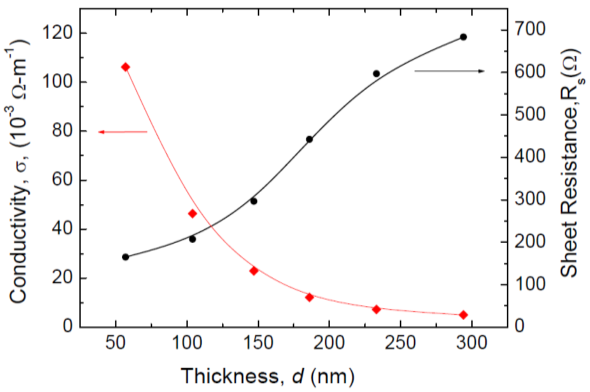

Fig.1 The variation of conductivity and sheet resistance of Bi_2Te_3 films with thickness.

Electrical conductivity was also measured as a function of temperature in the range of 300-470K. Fig.2 shows the variation of conductivity with temperature for the as-deposited films. It is observed from the graph that the conductivity increases with temperature for all films. This type of variation indicates the nonmetallic behavior of the films. The increase in conductivity with temperature may be attributed to the intrinsic conduction-taking place in semiconductor films. It is also seen from the graph that the conductivity of the thinner film is less than that of the thicker ones.

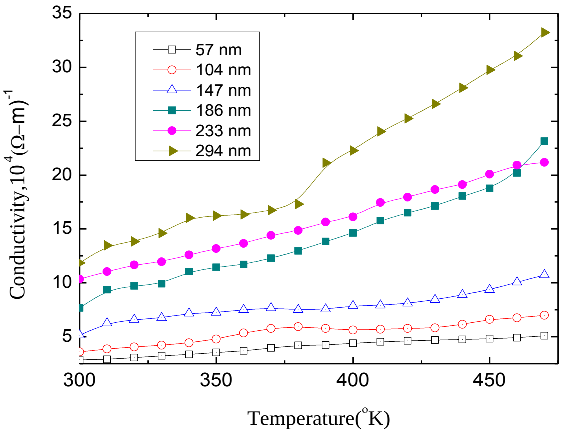

Fig.2 The variation of conductivity of Bi_2Te_3 films with temperature.

The temperature co-efficient of resistance (TCR) with temperature is calculated at the same way as reported elsewhere and plotted in fig. 3. Although there is not systematic variation of TCR. It is evident that for all the films the TCR is negative that indicates the semiconducting property. The activation energy and grain size as a function of film thickness was estimated. The activation energy is related with film conductivity and given by the relation [12].

$$\sigma = \sigma_0 \left(\frac{\Delta E}{K_B T} \right) \tag{1}$$

Where σ_0 is the conductivity at 273K and K_B is the Boltzmann constant and T is the absolute temperature. Equation (1) can be written as

$$\Delta E = \left\{ \frac{\ln \sigma}{1/T} \right\} \times 2K_B \tag{2}$$

The activation energy is calculated from the slope of the $ln\sigma$ vs. $1/T$ curves using the above equation. A thin film consists of planer array of many small discrete particles of islands of linear dimension r having dielectric constant ε. According to Neugebauer and Webb, the activation energy may be expressed in terms of r, e, and ε [12],

$$\Delta E = \frac{e^2}{\varepsilon . r} \tag{3}$$

From this equation, the grain size can be expressed as,

$$r = \frac{1.44}{\varepsilon . \Delta E} \text{ nm.} \tag{4}$$

Fig.4 shows the variation of activation energy and grain size with film thickness. As the conductivity was changed continuously with temperature, the conduction was occurred by an activated process. It is seen that the activation energy decreases with increasing film thickness while the grain size increases with the film thickness. This variation follows Gorter model [13] satisfactorily and consistent with the other reports. According to Gorter, the grain size increases when the thickness of the film increases. At 100nm thickness film, the grain size was estimated of about 3 nm.

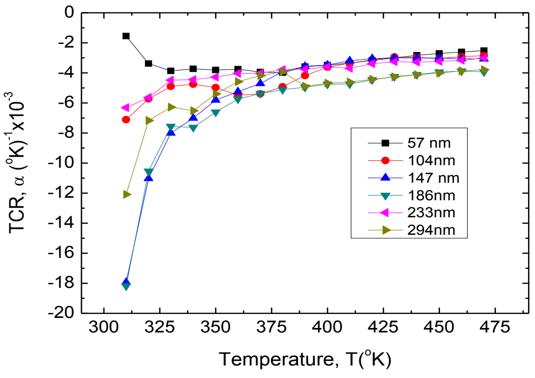

Fig.3 The temperature co-efficient of resistance (TCR) of Bi_2Te_3 thin films of various thicknesses.

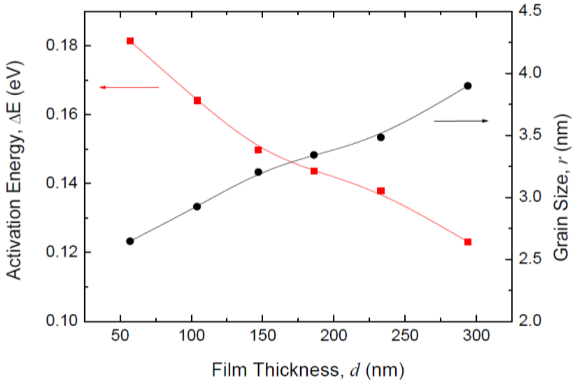

Fig.4 The activation energy and grain size of Bi_2Te_3 thin films as a function of thickness.

The thickness variations of Hall Effect measurement were carried out for the as-deposited films. The Hall co-efficient of a thin film was measured by the use of Van der Pauw's method. The carrier concentration and mobility was also estimated from the Hall Effect measurement. The Hall Effect measurement on these films shows a positive Hall co-efficient indicating p-type carrier. The thickness dependent Hall co-efficient follows that galvanometric size effect theory. The variation of Hall co-efficient, carrier mobility, carrier concentration, mean free path and mean free time with film thickness are represented in fig. 5 and fig. 6. The figure interpret that Hall co-efficient decrease with thickness while carrier mobility, carrier concentration, mean free path, and mean free time increases with film thickness. The magnitude of carrier concentration is in the order of 10^{19}/cc that signifies high order of carrier concentration. The increase in carrier mobility may be partly due to size effect as well as effects of structural defect [14].

The defects namely impurity centers, voids and grain boundaries are of higher order in the case of thin films. In the higher thickness the defect concentration will certainly decrease due to partial removal of defect by filling up the voids and other imperfections. Hence, the continuity of the films crystallites' obtained better. Therefore, carrier mobility of the films was increased with thickness. As carrier mobility was increased with thickness, the mean free path and mean free time were also increased with thickness.

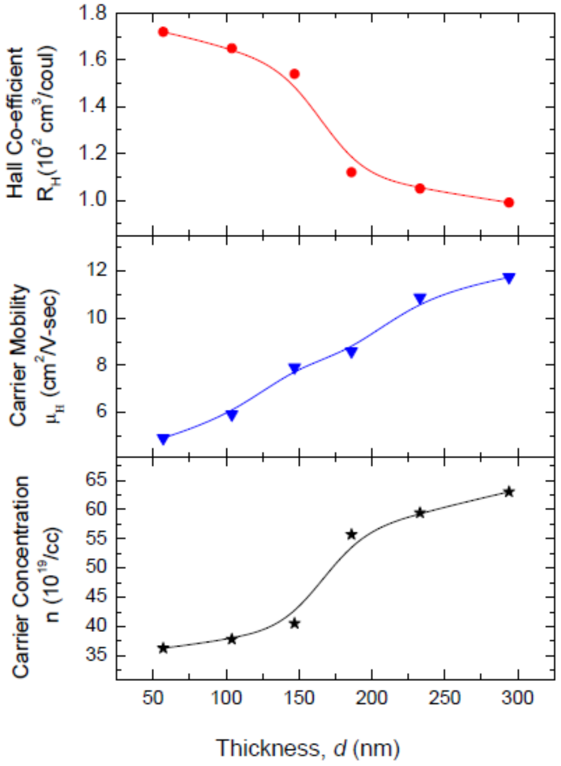

Fig.5 The Hall co-efficient, carrier concentration and carrier mobility of Bi_2Te_3 thin films as a function of thickness.

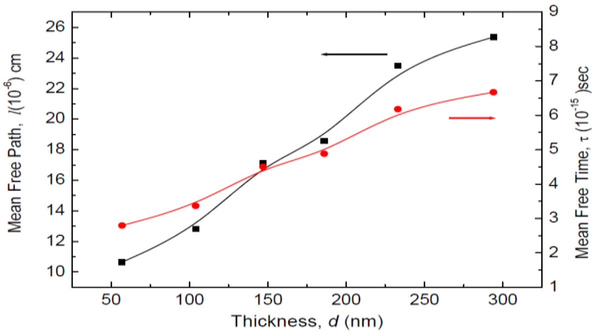

Fig.6 The mean free path and mean free time of Bi_2Te_3 thin films with the variation of thickness.

4 Conclusion

The study of electrical properties of Bi_2Te_3 thin films have been carried out in the thickness range 50-300nm and temperature range 300-470K. The electrical conductivity was found to decrease with thickness of the films while sheet resistance was increased with the same. At 100nm thickness, the conductivity was obtained about $35\times10^{-3}\ \Omega\text{-}m^{-1}$ and sheet resistance was about 200Ω. The conductivity was increased with temperature and the increment was more in the thicker films. The thickness dependent conductivity and sheet resistance at room temperature follows Fuch-Sondheimer theory. The temperature coefficient of resistance of films is found to be negative and these results indicate that Bi_2Te_3 is a nonmetal. The activation energy of Bi_2Te_3 films is found to lie in the range from 0.12-0.18 eV. The Hall Effect measurement on these films shows a positive Hall co-efficient and high order of carrier concentration. The results suggest that the investigated films were semiconducting in nature.

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