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Research Article

Structural, Electrical, and Optical Properties of PbTe Thin Films Prepared by Simple Flash Evaporation Method

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Lead telluride (PbTe) films have been prepared on glass substrates by flash evaporation method. Structure of the film is found to possess stable face-centered cubic (fcc) NaCl phase in which the grains predominantly grow in the direction of (200) plane. The calculated grain size was in the range 19 nm. The electrical resistivity as a function of temperature was measured using four-probe technique. The electrical conductivity was calculated, and the value is found to be from 67.11 to 344.82 S/cm in the temperature range 303–453 K. The value of mobility was evaluated, and it is found to be 0.329×10^{-3} $cm^2 \cdot V^{-1} S^{-1}$. An optical study reveals that the PbTe thin films exhibit large blue shift. The optical constants such as absorption coefficient and refractive index have been estimated, and the results are discussed.

1. Introduction

Lead telluride belongs to the group $A^{IV}B^{VI}$ semiconductors which crystallize in the FCC NaCl- type structure at ambient conditions. The unusual characteristics of lead salts, such as narrow band gap $E_0 \sim 0.3$ eV whose temperature coefficient is positive, the high dielectric constant, and the large carrier mobility, make them unique among polar semiconductors and have important applications in many fields, such as infrared detectors, light-emitting devices, more recently as infrared laser in fiber optics, thermoelectric materials, solar energy panel, and window coatings [1–8]. Recently, other specific low-dimensional structures such as multiple quantum-well systems, super lattices, and quantum dots have attracted much attention in various fields such as infrared sensor arrays, vertical cavity surface emitting laser, thermoelectricity, self-organized semiconductor nanostructures, and persistent low-temperature photoconductivity [9]. Various methods have been utilized to prepare PbTe thin films such as thermal evaporation [10], RF magnetron sputtering [11], pulsed laser evaporation [12], electrodeposition [13], and hot-wall epitaxy [14]. However, not much work has been reported on flash evaporated PbTe thin films. Hence, in the present investigation, the structural, electrical, and optical properties of flash evaporated PbTe thin film were studied. The flash evaporation method is facile, cost-effective, clear, easy to control, and can produce uniform films of high purity under varied experimental conditions. The temperature dependence on resistivity was examined, and the prepared PbTe thin films exhibit an enhancement in electrical conductivity. The effect of temperature on the current passing through the PbTe thin film was studied in order to evaluate the mobility of charge carriers. From optical analysis the band gap was determined which exhibits large blue shift.

2. Experimental Details

PbTe thin films were prepared by flash evaporation technique onto ultrasonically cleaned glass substrates at a pressure of 9×10^{-6} mbar using 12A4D Hind Hivac Coating unit. The powder was gradually dropped onto a preheated molybdenum boat through a controllable vibratory spiral feeder. The evaporation rate was maintained as 15–20 Å/Sec. The thickness of the film was measured using a quartz crystal thickness monitor during deposition, and it is found to be 50 nm. The deposition time was 15–20 mins. Pure aluminum

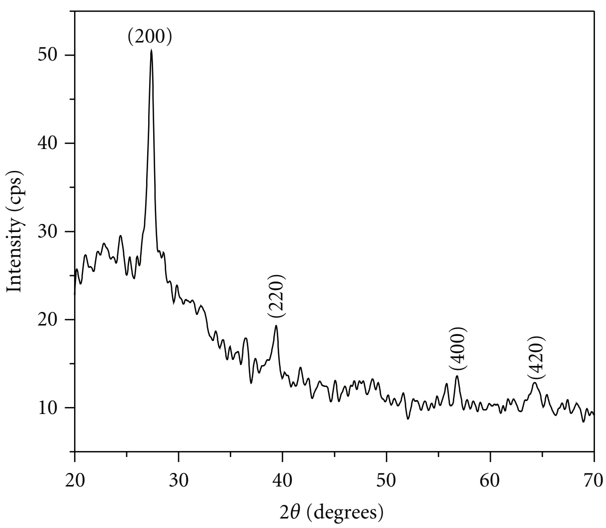

Figure 1: X-ray diffractogram of PbTe thin film.

was first evaporated onto precleaned glass substrates through suitable mask to form a base electrode. The PbTe was then evaporated from molybdenum boat through a controllable vibratory spiral feeder to form a dielectric layer. An aluminum counter electrode was evaporated as top electrode, so as to form Al/PbTe/Al (MSM) structure. The deposited film was uniform, pinhole-free, and strongly adherent to the substrate. The structure of the film was analyzed by an X-ray diffractometer with CuK_α radiation (λ = 1.5406 Å). JFOL JSM-6330f Scanning Electron Microscope was employed in the present study to analyze the surface morphology of PbTe thin film. Electrical resistivity measurements as a function of temperature in the range 303–463 K were performed on PbTe thin film using a four-probe resistivity setup. For the current measurements, the dc bias voltage was provided by power supply and the current was recorded by digital milliammeter as a function of temperature in the range 303–383 K. Optical investigations were performed using spectrophotometer (Jasco Corp, V-570) which allows measurement in the spectral range 200–2500 nm with 1 nm resolution.

3. Results and Discussion

The crystal structure of PbTe films was investigated by X-ray diffraction. Figure 1 shows the X-ray diffraction pattern of PbTe film of thickness 50 nm. The presence of characteristic peaks in the diffractogram indicates fcc NaCl-type structure (JCPDS card no: 77-0246) with preferential orientation along (200) plane. The grain size was evaluated using Scherrer's formula, and the value is 19 nm. The lattice constant deduced from the XRD analysis is to be 6.484 Å which is in good agreement with the standard value (6.454 Å). The micrograph of flash evaporated PbTe thin film is shown in Figure 2. It reveals that the prepared film is smooth, uniform, and pinhole-free.

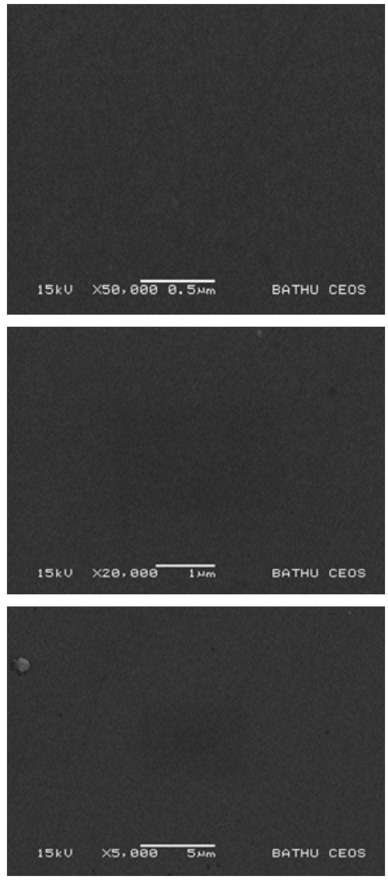

Figure 2: SEM image of PbTe thin films.

Electrical resistivity measurements were made in the temperature range 303–453 K by four-probe method. The resistivity has been plotted as a function of temperature for the film of thickness 50 nm and shown in Figure 3. The resistivity of the PbTe thin film varies from 1.49 to 0.29 $\times 10^{-2}$ ohm-cm. From the resistivity values, the electrical conductivity was calculated, and the value is found to be from 67.11 to 344.82 S/cm in the temperature range 303–453 K which is higher than the reported value of Wan and others [15] for PbTe nanocubes. This implies that the PbTe thin films prepared by flash evaporation method exhibit an enhancement in electrical conductivity. This may be due to that the prepared film has small crystallite size (19 nm from XRD). It was observed that the carriers were strongly non degenerate and hence the resistivity decreases with increase in temperature. The observed exponential decrease of resistivity with temperature clearly explains that the prepared PbTe thin film is semiconducting in nature. The activation energies can be evaluated from the graph plotted between log ρ versus $1/T$ and presented in Figure 4. The activation energies calculated from the above plots are given in Table 1. These values are in the range 0.2–0.22 eV, and it can be seen that the activation energy decreases with increase in current. PbTe thin film studied in the present work exhibit, negative temperature coefficient of resistance which suggests their semiconducting nature.

Table 1: Variation of activation energy with current.

Current I (μA)	Activation energy (eV)
1	0.220
4	0.216
6	0.207

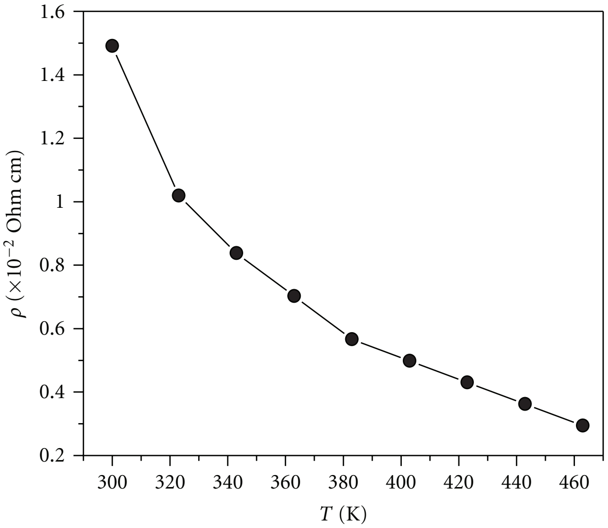

Figure 3: Variation of resistivity with temperature.

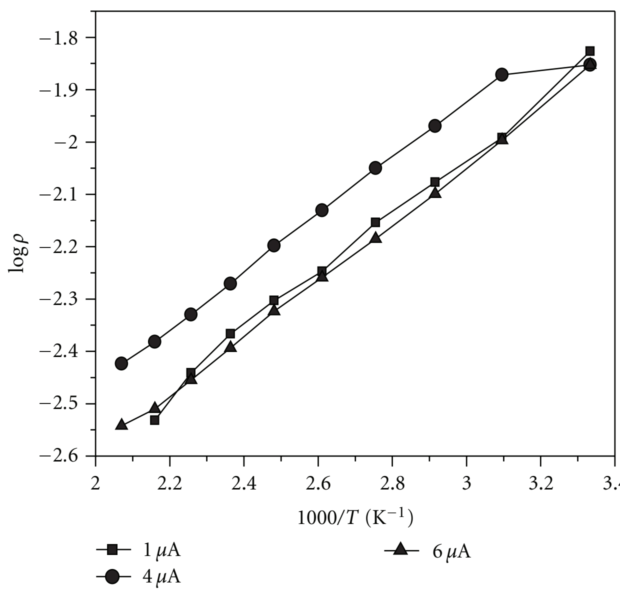

Figure 4: Plot of log ρ versus $1/T$.

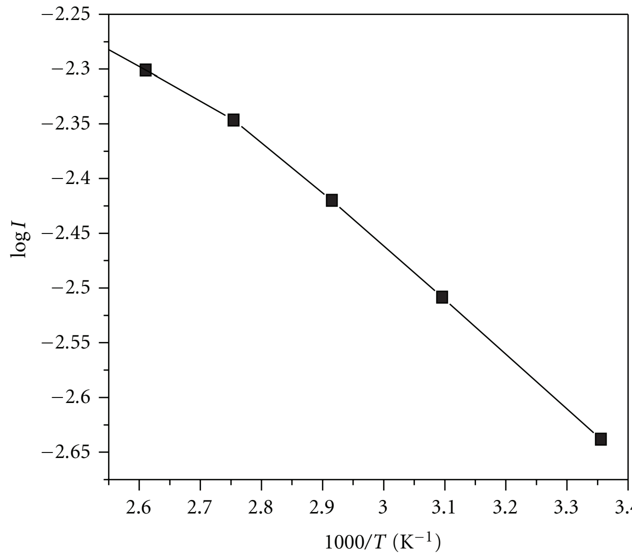

Figure 5: Temperature dependence of current.

The logarithm of current is plotted against the reciprocal of absolute temperature and is shown in Figure 5. The current varies with temperature in accordance with the relation

$$I = I_0 \exp\left(\frac{-\Delta E}{KT}\right). \quad (1)$$

The plot is straight line indicating that conduction in the film is through thermally activated process. The current increases with the increase in temperature showing the semiconducting nature of the film. The activation energy is evaluated from the slope, and the value is 0.181 eV. The mobility of electrons in PbTe thin film was estimated from the relation [16] as follows:

$$I_0 = \frac{q\mu N_d A V}{d}, \quad (2)$$

where q is the electronic charge, μ the mobility, N_d the donor (or acceptor) density $\approx 10^{18}\,\text{cm}^{-3}$, V the voltage, d the electrode separation, A the area, and I_0 the current at zero temperature determined from Figure 5. The value of mobility is evaluated, and it is found to be $0.329 \times 10^{-3}\,\text{cm}^2 \cdot \text{V}^{-1}\text{S}^{-1}$. This low value of mobility is an indication of a localized state conduction, which is limited by the scattering on the barriers among crystallites. Similar observation was reported by M. I. AbdEl-Ati for PbTe thin films [17].

The absorption coefficient, optical band gap, and refractive index are the most significant parameters in chalcogenide thin films. UV-visible absorption spectroscopy is a powerful technique to explore the optical properties of semiconducting nanocrystalline thin films. The optical transmittance spectrum of PbTe thin film was measured at room temperature. From the transmittance spectrum we can evaluate the absorption coefficient with the aid of the expression

$$\alpha = \frac{2.303 \log_{10}(1/T)}{t}, \quad (3)$$

where t is the thickness of the film, and T the transmittance of the film. The variation of the absorption coefficient as a function of wavelength for PbTe film is shown in Figure 6. It is observed that the absorption coefficient is high ($\sim 10^7\,\text{cm}^{-1}$) and decreases with wavelength.

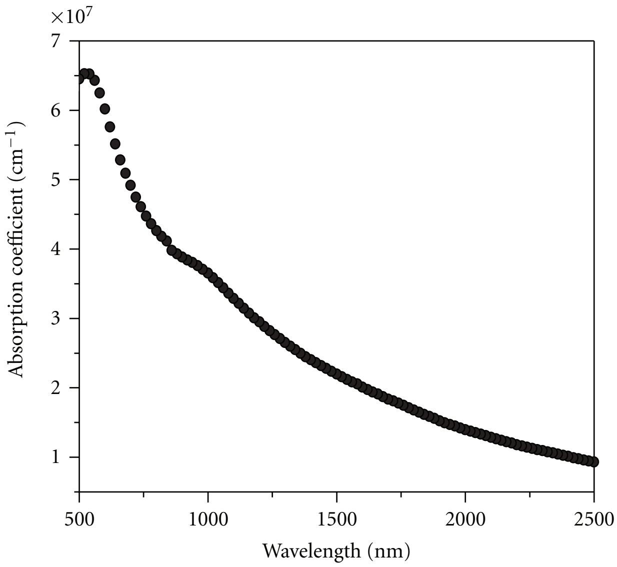

FIGURE 6: Variation of absorption coefficient on wavelength.

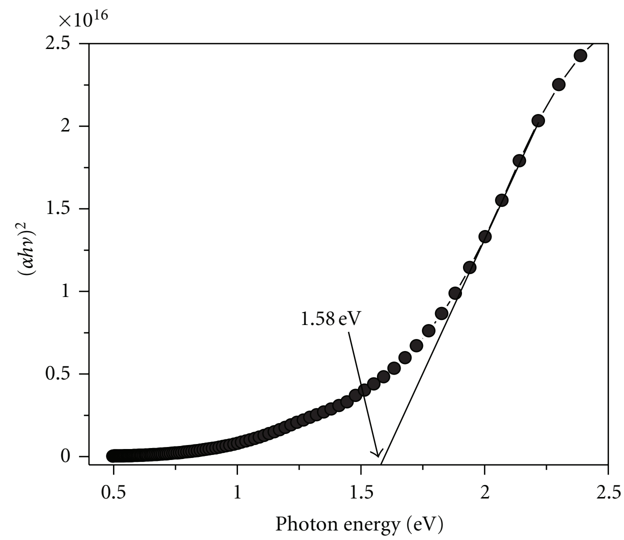

FIGURE 7: Tauc plot for determination of band gap.

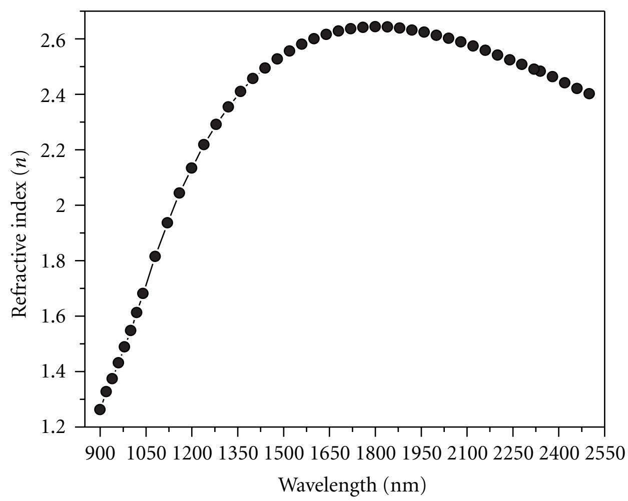

FIGURE 8: Spectral distribution of the refractive index of PbTe thin film.

The electronic transition between valence band and conduction band is given by

$$\alpha h\nu = A\left(h\nu - E_g\right)^p, \quad (4)$$

where A is a constant, α the absorption coefficient, E_g the energy gap, ν the frequency of the incident radiation, and "h" the Planck's constant. The exponent p is 0.5 for direct allowed transitions, 1.5 for direct forbidden transitions, 2 for indirect allowed transitions, and 3 for indirect forbidden transitions. The variation of $(\alpha h\nu)^2$ with $h\nu$ is shown in Figure 7. The presence of single slope in the curve suggests that the prepared PbTe thin film is single phase in nature, and the type of transition is direct and allowed. Extrapolation of the linear portion of the plot to the energy axis yielded the direct band gap value 1.58 eV which is greater than the bulk value (0.32 eV). A blue shift of the absorption onset of about 1.26 eV compared to the bulk PbTe material (0.32 eV) can be noticed in prepared PbTe thin film. This result is a direct consequence of the quantum confinement effect associated with the small particle size or ultrathin film thickness. The quantum confinement effect in polycrystalline PbTe thin films has also been observed by Wang et al. [18] due to the small grain size of the film, and also they reported that the observed band gap is direct.

The knowledge of accurate values of wavelength dependence of refractive index of chalcogenide thin film is very important for both fundamental and technological point of view. Moreover, the refractive index is necessary for the design and modeling of optical components and optical coating such as interference filters. Refractive index of the film is determined from the following relation [19]:

$$n = \frac{\left(1 + R^{1/2}\right)}{\left(1 - R^{1/2}\right)}. \quad (5)$$

Figure 8 represents the spectral distribution of the refractive index for the investigated films. Refractive index of the PbTe thin film varies from 1.26 to 2.64. Refractive index of the film increases from 900 nm to 1841 nm and then the refractive index found to decrease with the increase in wavelength.

4. Conclusion

The absorption coefficient is high, and the band gap of direct type is blue shifted due to quantization effect. The film exhibits polycrystalline nature and has a rock salt structure. The low resistivity and high value of electrical conductivity of the film indicates that the thermoelectric properties of PbTe thin films can be enhanced. The electrical conduction and activation energy of the film suggest that electrical conduction is through a thermally activated process. The observations are quite encouraging, and it may lead to new directions for device applications.

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