Indian J. Phys., **48**, 332–339 (1974)

Electrical properties of vacuum deposited HgTe films

D. C. BARUA AND K. BARUA

Department of Physics, Dibrugarh University, Assam

(*Received* 28 *April* 1973)

Electrical properties such as activation energy (ΔE), Seebeck coefficient (Q), temperature coefficient of resistance (TCR), Hall coefficient (R_H), Hall mobility (μ_H), etc. of vacuum deposited HgTe films of thickness ranging from 500 Å to 25,000 Å and temperature ranging from 265°K to 420°K have been measured. Resistance measurements of the films at different temperatures yielded two activation energies. Within the thickness range of 4000 Å to 500 Å these two activation energies increase with decreasing thickness. Seebeck coefficient is found to be positive and the value increases with the decrease of film thickness as well as with the decrease of deposition temperature. TCR of these films is a negative quantity and the negative value for each film passes through a maximum. Increase of ΔE with decreasing thickness and the variation of TCR with film thickness and temperature have been explained on the basis of *island structure theory* (Neugebauer 1964). Increase of Seebeck coefficient and the decrease of R_H, μ_H for room temperature deposited as well as for thinner films have been attributed to the high density of defects present in the films. It has been found that the film thickness and the deposition temperature are the dominating parameters for the electrical properties of vacuum deposited HgTe films.

1. INTRODUCTION

Thin films of HgTe are usually prepared by evaporation of the compound or by evaporation of the individual elements in vacuum. II–VI compounds dissociate upon evaporation in vacuum and films prepared by evaporation of the compound actually means the reconstitution of the vapour elements. Elpat'evskaia & Regel (1957) prepared high mobility *n*-type HgTe films and suggested their uses in Hall effect devices. Elpat'evskaia (1958) studied the formation mechanism and some of the electrical properties of HgTe films prepared by both the methods on glass as well as on mica plates. Electrical properties of thin HgTe films were reported by Lagrenaudie (1958). Antcliffe & Krauss (1969) prepared highly perfect HgTe films by vapour phase reaction techniques on semi-insulating CdTe single crystal surfaces and reported some of their transport properties. Film properties depend very much on deposition parameters, stoichiometry and substrates employed. In the present investigation films of progressive thickness were prepared in a single evaporation on glass slides to achieve more or less similar deposition conditions. Some of the electrical properties of these films as a function of film thickness have been described in this paper.

2. EXPERIMENTAL

Highly pure HgTe (99·999% obtained from Koch Light, England) was evaporated from a nichrome coil at $\sim 10^{-5}$ Torr residual pressure and deposited at 27°C, 80°C and 100°C on vacuum baked (300°C) Diamond seal glass slides cut to the size 3 × 1 cm^2. The films thus prepared were annealed at $\simeq$150°C for over two hours. Annealed films showed reversible characteristics.

Films used for Hall measurements were of length 3 cm, breadth 2 mm with Hall probes of width 1 mm. For each temperature Hall measurements were taken by changing the polarity of the magnetic field and the direction of the sample current. The magnetic field used was either 4500 Gauss or 5500 Gauss. Pressure contacts, putting platinum foils over the film surfaces, were used.

The measurements were taken within the temperature range of 265°K to 420°K at a dynamic pressure of $\sim 10^{-2}$ Torr.

The average film thickness was estimated by measuring the area of the film deposit and determining the difference between the weight of the glass slide before and after the film deposition. The density of the deposit was, however, assumed, to be the same as that of the bulk material.

3. RESULTS

The results reported here are for films which showed reversible characteristics even when stored in vacuum for a few days. All the films showed *p*-type conductivity. This was ascertained both from thermoelectric and Hall measurements.

Effect of film thickness and deposition temperatnre on the electrical properties

[*Temperature dependence of resistance and activation energy*

A plot of log$R$ as a function of reciprocal temperature in absolute scale is shown in figure 1. In general each curve consists of two linear portions with a 'break' at a certain temperature. Activation energies for these two linear portions are determined by equating the slopes to $\Delta E/2k$. For the thickness range of 4000 Å to 25,000 Å activation energies are found to be independent of film thickness. ΔE values for room temperature deposited films are about 0·035 eV, 0·07 eV and 80°C, 100°C deposited films are 0·03 eV, 0·06 eV. These two activation energies increase with decreasing thickness in the 4000 Å to 5000 Å range.

II. *Temperature coefficient of resistance (TCR)*

TCR is calculated from the resistance vs temperature graphs for each film at different temperatures using relation

$$\mathrm{TCR} = \frac{1}{\rho}\frac{d\rho}{dT} = \frac{1}{R}\frac{dR}{dT}\,.$$

This parameter is found to be negative. Figures 3 and 4 show the variation of TCR with temperature for different thickness and the variation of TCR with film thickness for 27°C deposited films respectively.

III. *Seebeck coefficient (Q)*

Figure 5 shows thermo emf vs temperature difference curves for six films of different thicknesses. It has been observed that the Seebeck coefficient increases with the decrease of film thickness as well as with the decrease of deposition temperature. The maximum value of Q observed was $\simeq +300\,\mu V/°C$.

IV. *Hall coefficient R_H and Hall mobility μ_H*

Figures 6 and 7 show the variation of R_H and μ_H with film thickness respectively. It is seen that in general R_H increases with the increase of film thickness. The increase of R_H is rapid for 80°C and 100°C deposited films. *Hole* mobility is calculated using relation $\mu_H = R_H.\sigma$, where σ is the measured conductivity of the film. Room temperature deposited films are of low Hall mobility and the value does not vary appreciably with film thickness. High temperature deposited films are with high Hall mobility and the value decreases rapidly with the decrease of film thickness. Carrier concentration p is calculated using relation $p = (R_H.e)^{-1}$, e being the electronic charge. Carrier concentration is found to decrease with the increase of film thickness as well as with the increase of deposition temperature. p lies within the range of 10^{17} cm^{-3} to 10^{19} cm^{-3}.

4. DISCUSSION

The increase of ΔE with the decreasing thickness can be understood from the *island structure theory* based on tunneling of charged carriers between islands separated by few angstroms of distances (Neugebauer & Webb 1962). The theory was reproposed by Neugebauer (1964) and was originally conceived to explain the electrical conduction in ultrathin discontinuous metal films. Gorter (1951) proposed that the activation energy required to move a charge from one metallic island to the next as being proportional to $e^2/\epsilon r$, where e is the charge and r is the linear dimension of the island. This activation energy is equivalent to the electrostatic *binding* energy of the charge to the island. When these charged carriers are excited to at least this energy from the Fermi level there will be tunneling from one island to another. The conductivity of an island structu film is given by

$$\sigma = \left[\frac{A(2m\phi)^{\frac{1}{2}}}{h^2 d}\exp\left\{-\frac{4\pi d}{h}(2m\phi)^{\frac{1}{2}}\right\}\right]\times\left[B\exp\left\{-\frac{e^2/\epsilon r}{kT}\right\}\right]$$

$$= D\left[B\exp\left\{-\frac{e^2/\epsilon r}{kT}\right\}\right]. \qquad \ldots \quad (1)$$

The term D determines the mobility of the charge, which is the quantum mechanical tunneling probability between the islands. Here A and B are constants, ϕ is the potential barrier between the islands corrected for the image forces, m is the effective mass of the charged carriers, ϵ is the dielectric constant of the tunneling medium, d is the inter-island separation, r is the average linear dimension of an island and the remaining symbols have their usual meanings.

For films prepared from semiconducting materials eq. (1) may be modified as,

$$\sigma = D\left[B\exp\left\{-\frac{(2e^2/\epsilon r)+\Delta E_g}{2kT}\right\}\right], \qquad \ldots \quad (2)$$

where ΔE_g is the energy gap of the semiconducting material. From the temperature dependent portion of eq. (2) the activation energy will be

$$\Delta E = (2e^2/\epsilon r)+\Delta E_g$$

At the initial stage of the film growth discrete islands form on the substrate and with the increase of average film thickness these islands grow in size and subsequently merge to give a continuous film. With the decrease of average thickness of the film r decreases and hence the increase of ΔE. Several sets of evaporations were made to prepare films of progressive thickness and it was found that ΔE increases with the decrease of film thickness within the range of 4000 Å to 500 Å. This increase of ΔE with decreasing thickness was due to the complete isolation of the grains. As the film grew above 4000 Å total isolation of the grains became highly unlikely and hence a conduction path with HgTe would therefore be expected. The slightly higher values of ΔE in case of 27°C deposited films might be due to the increased number of grain boundaries.

The presence of two activation energies cannot be explained at present. It may, however, be mentioned that the temperature at which log R vs $1/T$ curves *break* does not remain constant for all the films and hence cannot be attributed to any change of structure or phase of the deposit.

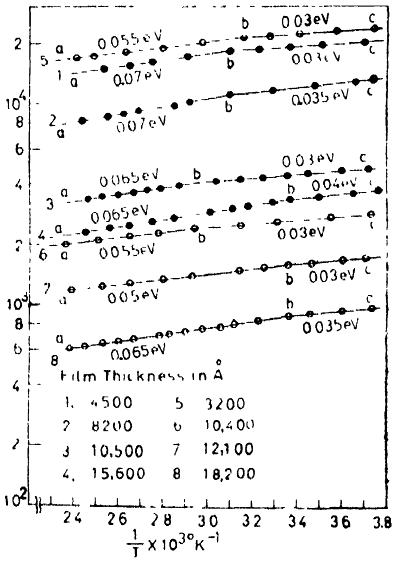

Fig. 1. log R vs $1/T$ curves, 27°C deposition 100°C deposition

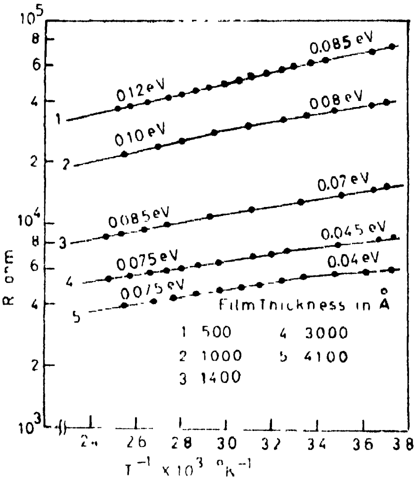

Fig. 2. Increase of ΔE with the decrease of film thickness.

The TCR for films of different thicknesses at 300°K, the temperature of film deposition, can be understood from eq. (2)

$$\text{TCR} = \frac{1}{\rho}\frac{d\rho}{dT} = -\frac{\Delta E}{2kT^2}, \qquad \dots (3)$$

Since in this case the tunneling transmission coefficient D is constant. The values of TCR obtained from relation $\frac{1}{R}\frac{dR}{dT}$ and eq. (3) are shown in figure 4. The variation of TCR with temperature for each film shows a negative maximum. Considering the variation of particle spacing d with temperature which primarily affects the tunneling transmission coefficient D.

$$TCR = \frac{1}{\rho}\frac{d\rho}{dT} = -\frac{dd}{dT}\left[\frac{1}{d} + \frac{4\pi}{h}(2m\phi)^{\frac{1}{2}}\right] - \frac{\Delta E}{2kT^2}. \qquad \dots (4)$$

The decrease or increase of the negative value of TCR will depend on the predominance of one or the other term of the right hand side of the eq. (4).

Room temperature deposited films are usually fine grained polycrystalline and the films deposited at high temperature are normally $1-d$ oriented (Barua & Goswami 1970). Stacking faults, twin boundaries occur less frequently in room temperature deposited films, whereas these defects are more in high temperature deposited films. The higher values of Q in 27°C deposits as well as for thinner films may be due to the increased number of defects, discontinuities etc. present in the films. A similar observation was made for vacuum deposited PbTe films (Goswami & Koli 1966).

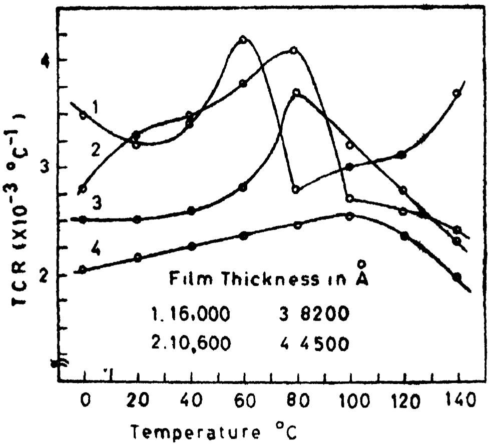

Fig. 3. Variation of TCR with temperature.

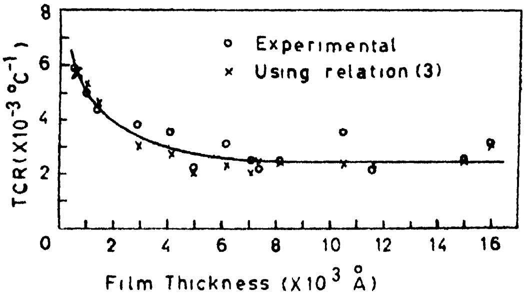

Fig. 4. Variation of TCR with film thickness for 27°C deposited films

Hall coefficient R_H is found to increase with decreasing film thickness, whereas for metallic films R_H is expected to decrease with increasing film thickness (Sondheimer 1952). p-type conductivity observed in HgTe films was due to the Hg vacancies or excess of tellurium, which tend to produce more strongly p-type material. With the increase of film thickness and deposition temperature probably the density of this type of point defect decreases as a result carrier concentration p also decreases. Since $R_H = (p.e)^{-1}$, R_H increases with the increase of film thickness as well as with the increase of deposition temperature.

From classical theory,

$$\sigma = p \cdot \frac{e^-}{mv} \cdot l = p.e.\mu,$$

l being the mean free path of the charge carriers. Due to the decrease of thickness the mean free path of the charge carriers is reduced and hence the value of σ.

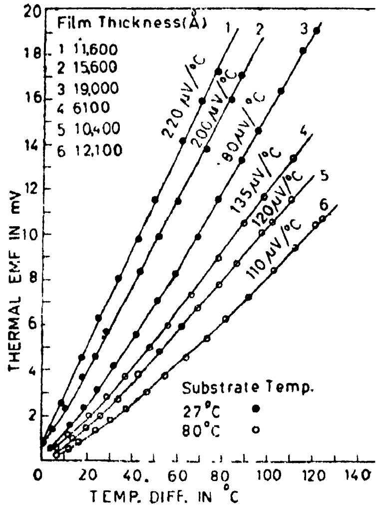

Fig. 5. Thermo e.m.f. vs temperature difference.

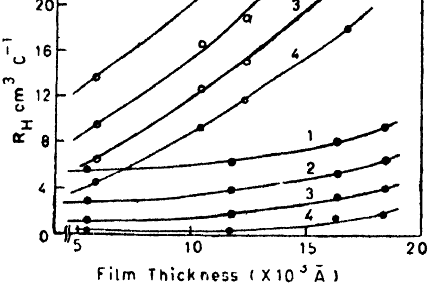

Fig 6. Variation of R_H with film thickness at (1) 0°C, (2) 50°C, (3) 100°Cand (4) 150°C.

The decrease of R_H with film thickness also contributed its part to the decrease of μ_H. The low value of μ_H in case of 27°C deposited films is due to the very high density of structural and chemical defects. The increased density of grain boundaries might have scattered the charge carriers effectively and thus the variation of thickness could play an insignificant role at 0°C. However, at

140°C, μ_H decreases with the decrease of thickness which may be due to the scattering of charged carriers by thermal vibration of lattice etc.

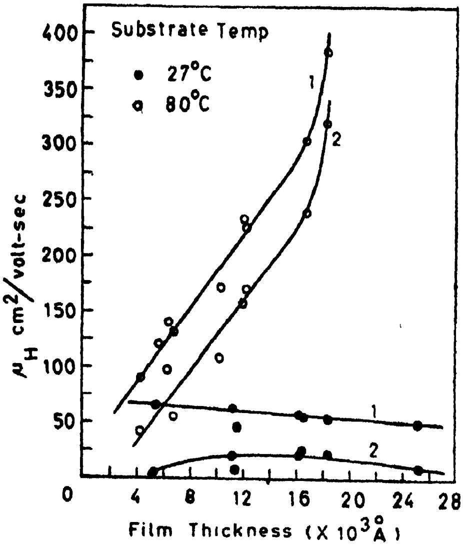

Fig. 7. Variation of μ_H with film thickness at (1) 0°C and (2) 140°C.

It is thus seen that the deposition temperature and the film thickness are the dominating parameters for the electrical properties of vacuum-deposited HgTe films on glass slides.

ACKNOWLEDGMENT

One of the authors (D.C.B.) is grateful to Dibrugarh University for financial support.

REFERENCES

Antcliffe G. A. & Krauss H. 1969 *J. Phys. Chem. Solids* **30**, 243.
Barua K. C. & Goswami A. 1970 *Japanese J. Appl. Phys.* **9**, 705.
Elpat'evskaia O. D. & Regel A. R. 1957 *Zn. Tech. Fiz.* **27**, 45; *Trans. Soviet Phys—Techn. Phys.* **2**, 35.
Elpat'evkaia O. D. 1958 *Zn. Tech. Fiz.* **28**, 2669; *Trans. Soviet Phys.—Tech. Phys.* **3**,-2439.
Gorter C. J. 1951 *Physica* **17**, 778.
Goswami A. & Koli S. S. 1966 *Proc. Int. Symp. on Basic Problem in Thin Film Physics* (Published by Van den Hoeck and Ruprecht, Gottingen), p. 646.
Lagrenaudie J. 1958 *J. Chim. Phys.* **55**, 175.
Neugebauer C. A. 1964 *Physics of Thin Films*, vol. 2, Academic Press Inc., New York.
Neugebauer C. A. & Webb M. B. 1962 *J. Appl. Phys.* **33**, 74.
Sondheimer E. H. 1952 *Advances in Phys*, **1**, 1.