Asian Journal of Chemistry Vol. 5, No. 3 (1993), 644–658

Temperature Dependence of Electrical Conductivity and Thermoelectric Power of In_2Te_3 Single Crystals

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In this paper we present the study of electrical conductivity, Hall coefficient and thermoelectric power (TEP) of In_2Te_3 single crystals. The study covered a wide range of temperature extending from 150–470 K. Measurements of In_2Te_3 indicate p-type conductivity with a hole concentration of 3.16×10^{10} cm^{-3} at room temperature. The energy gap width is found to be 1.01 eV. Conductivity and Hall mobility at room temperature are 0.623×10^{-6} Ω^{-1} cm^{-1} and 1380 cm^2/V. sec. respectively. The mean free time is $\tau_n = 1.106 \times 10^{-16}$ sec. and $\tau_p = 1.07 \times 10^{-15}$ sec. for electrons and holes respectively.

INTRODUCTION

Single-crystal solids have important practical applications in technology. For example, much better frequency stability and lower acoustic losses can be achieved in single crystals than in polycrystalline aggregates. Thus single-crystal piezoelectric crystals, such as quartz, are used for frequency-control elements. Conductivity and mobility requirements dictate the use of single crystals. Semiconductor has created several new demands for single crystals for research and applications.

In_2Te_3 single crystals have been shown to be new materials with attractive characteristics. These compounds recently held the attention of many physicists[1–6]. In this study we have investigated the Hall effect, electrical conductivity and thermolelectric power of In_2Te_3. It is essential to the understanding of the materials and consequently of their practical applications.

EXPERIMENTAL

Preparation of sample

In_2Te_3 single crystal was grown from melt using Bridgman technique[7, 8] in the solid state laboratory at Qena using a new design. The new design is a part of

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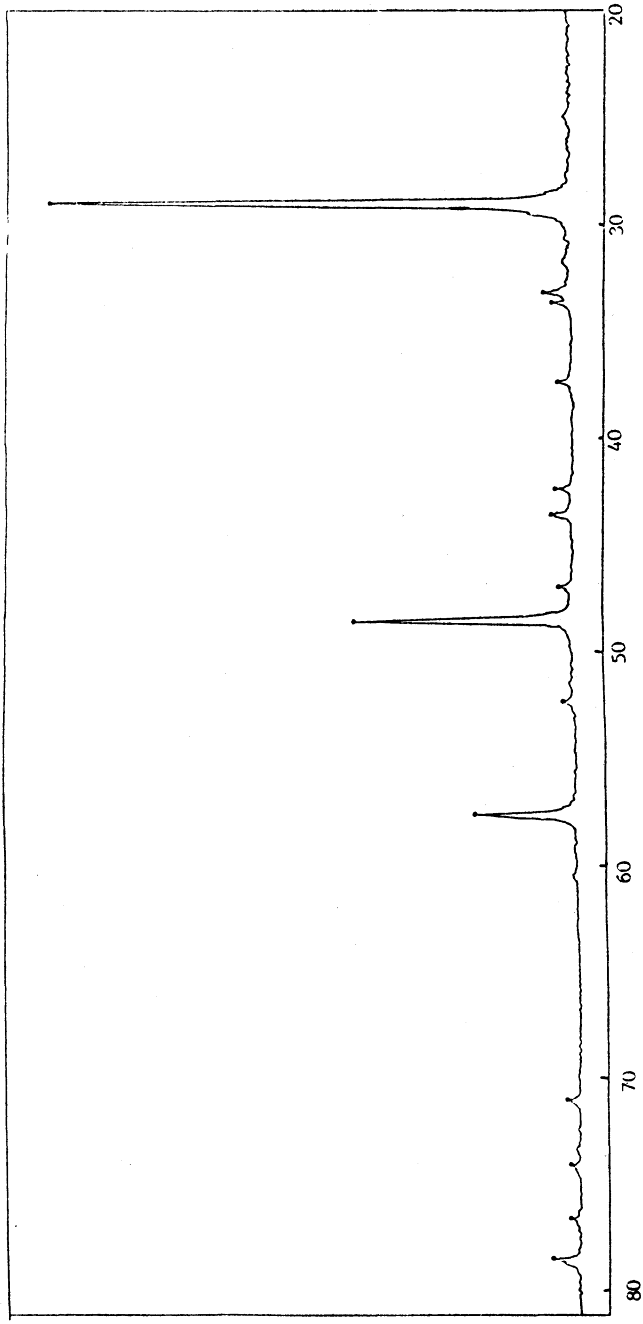

Fig. 1 X-ray diffraction for In_2Te_3 compound.

the UNESCO programme for locally produced equipment for physics research. It demonstrates that the driving force required to move the loaded silica ampoule is equivalent to the decrease of the water level drained in a special container which in turn indicated the rate of motion.

The sample was prepared from high-purity indium (6 N) representing 37.496% and tellurium (5 N) representing 62.504%. The crystal perfection was checked using the X-ray diffraction technique, represented in Fig. 1 . Diffraction for these materials compared with the index data of the American Society for testing materials (ASTM) cards. From these X-ray studies it was evident that the crystals have a high degree of crystallinity indicating that the preparation technique is fairly reliable and satisfactory.

Experimental Arrangement

For studying electrical conductivity and Hall effect, the samples were prepared in a rectangular shape with dimensions $12 \times 4 \times 1\ mm^3$. We used a digital voltmeter, type DT–820 (Univolt), and a multimeter, type ZX–505 (Sanwa), for measuring the voltage and the current, to determine the electrical conductivity.

A field of about 10 kilogauss Oxford type N 177 and a sweep generator unit (SG-3) which had been designed for programming magnets were used for measuring Hall coefficient.

Measurements above temperature were carried out with the help of an electrical insulator heater which supplies its required voltage, gradually, and slowly, from a variance transformer. A temperature below room temperature was achieved using liquid nitrogen, which was introduced in the cryostate container. Measurements were recommended in ASTMF 76, and carried out in a vacuum.

The thermoelectric power was calculated at any temperature by dividing the measured thermo-voltage difference across the crystal by the temperature difference between the hot and cold ends. Then, the thermoelectric power is the e.m.f. per unit temperature drop between the hot and cold ends. It was measured throughout from 140 to 400 K. The temperature of the specimen was measured with the aid of copper-constantan thermocouple.

The ohmic nature of the contacts was verified by recording the current-voltage characteristic. The ohmic contact pressed the conection electrodes on the specimen.

RESULTS AND DISCUSSION

Temperature Dependences of the Electrical Conductivity and Hall Coefficient of In_2Te_3 Single Crystals

The main experimental results of the temperature dependence of electrical conductivity for In_2Te_3 sample with room temperature resistivity 1.44×10^5 Ω cm are plotted in Fig.2. The intrinsic conduction in this crystal appearing in log σ vs. 1000/T curve is 1.06 eV. Our samples under test show semiconducting properties throughout the range of temperature investigated. Fig.2 shows quite clearly that the electrical conductivity rises with the increases of temperature, then passes through an intermediate region in which the carrier concentration is not actually constant. We shall assume that the high temperature conductivity is related to the number of defects which ionized and makes a contribution to the intrinsic conduction. Fig.. 3 shows the dependence of Hall coefficient on

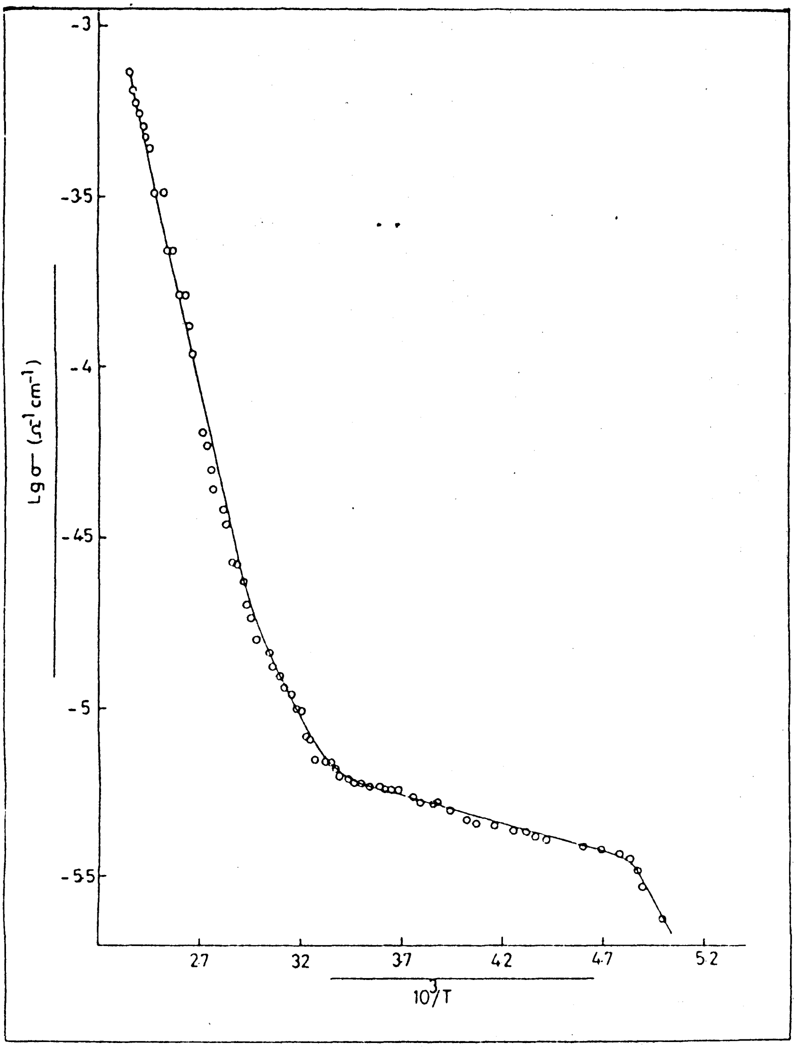

Fig. 2 Electrical conductivity of In_2Te_3 as a function of temperature.

temperature. The positive sign of R_H indicates that the major contribution to conductivity comes from holes. The value of the Hall constant at room temperature is $R_H = 2.4 \times 10^8$ cm^3/C. It is clear from Fig. 3 that the Hall coefficient shows a less rapid dependence on temperature, and the sample exhibits a considerable fall

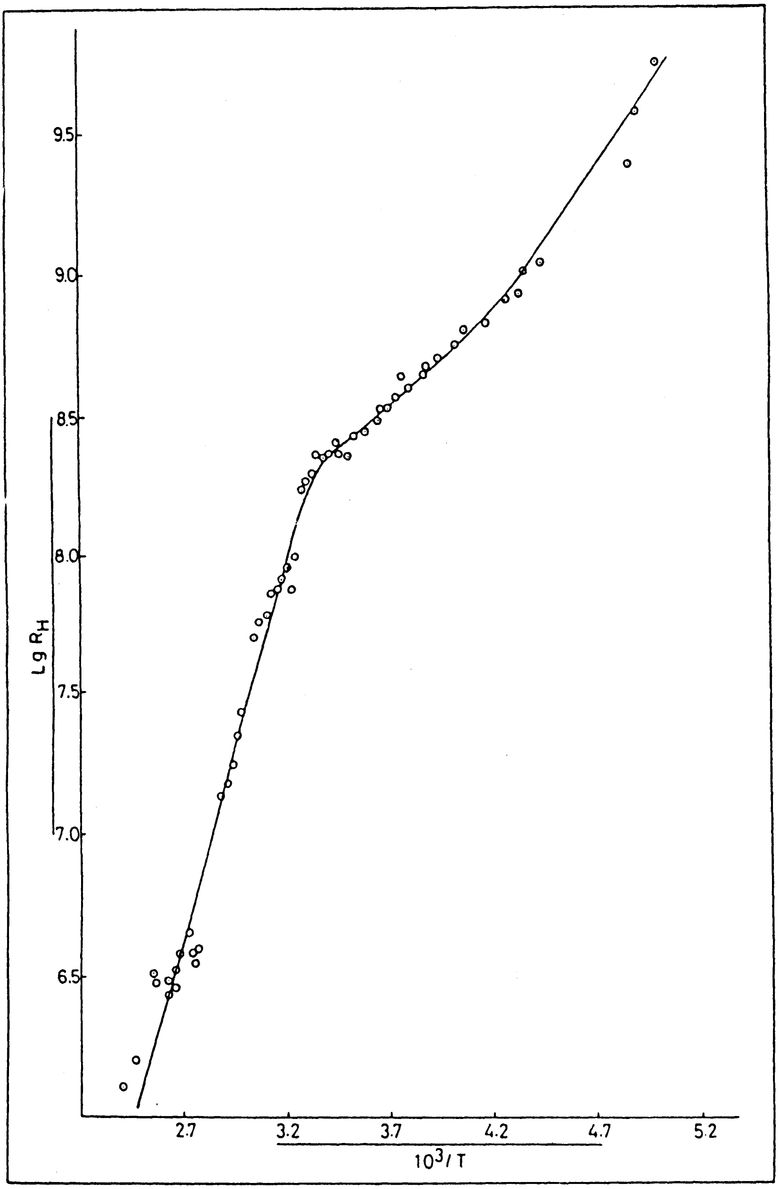

Fig. 3 Effect of temperature on Hall coefficient for In_2Te_3 single crystals.

of the Hall coefficient when temperature is increased till transition region in which the experimental curve for $\log R_H$ versus $10^3/T$ deviates from linearity. In the intrinsic conduction region the Hall coefficient falls more rapidly. Since our experiments show no inversion in the dependences of $\sigma(T)$ and $R_H(T)$, we may conclude that thermal defects in the In_2Te_3 sample create acceptor levels. In Fig. 4

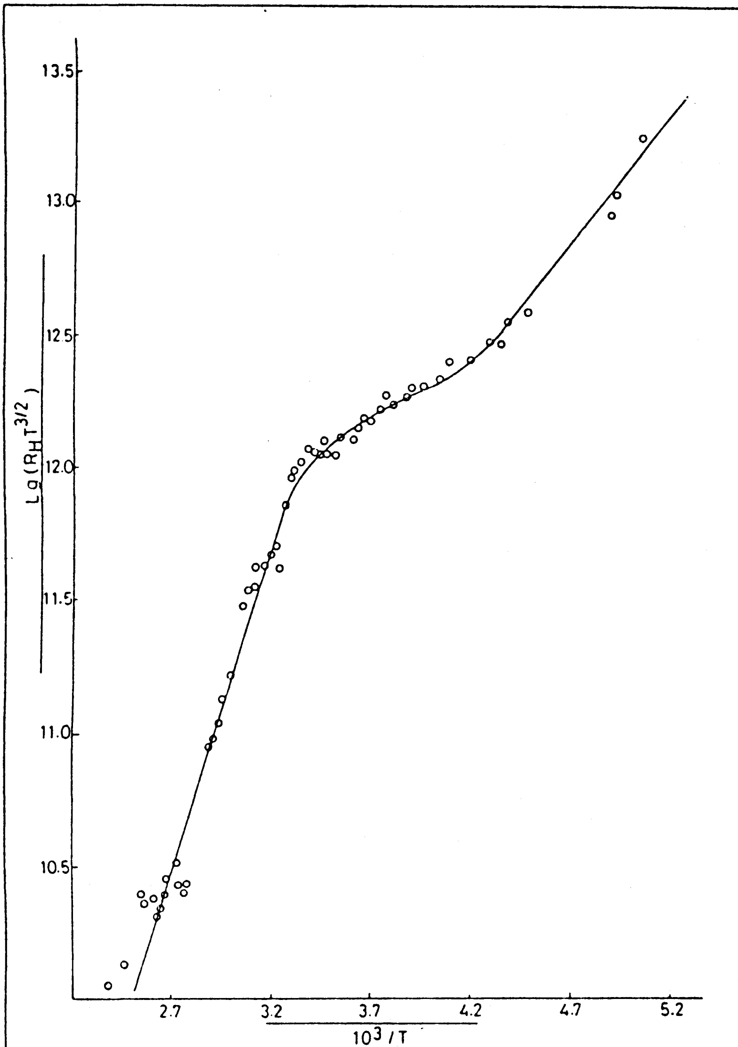

Fig. 4 The relation between $R_HT^{3/2}$ and $10^3/T$ of In_2Te_3 single crystals.

we have plotted $R_HT^{3/2}$ versus the absolute temperature. The band gap energy calculated from the high-temperature slope was 1.01 eV. This is close to the value of the band gap obtained from the optical properties reported by Guizzeffi *et al.*[9] It was found also that the depth of the acceptor centre is 0.426 eV. The variation of Hall mobility with temperature is shown in Fig. 5. Mobility is always seen to increase with decreasing temperature. Thus the mobility of holes in p-type In_2Te_3 has been found to vary as T^{-n} in the whole temperature range under investigation with $\ln \mu \propto n \ln T$, where n = 3.5. This value for n is unusually large

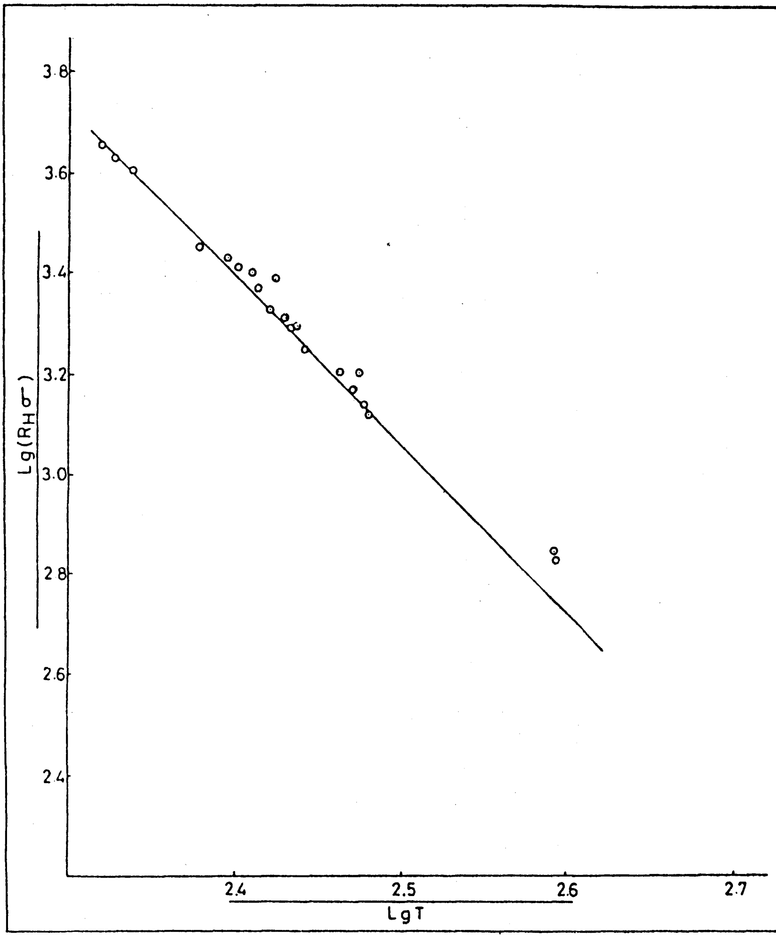

Fig. 5 Temperature dependence of charge carrier mobilities of In_2Te_3 single crystals.

compared with those obtained for impurity and lattice scattering respectively in other semiconductors. However, the variation of mobility with temperature in these defected semiconductors has not been previously reported; there is still insufficient experimental data to throw a clear light upon this behaviour. This behaviour, in our opinion, may be associated with the presence of a high density of stoichiometric vacancies and the creation of defects. The exact nature of defects in these semiconductors remains uncertain, but from structural considerations and also by analogy with III–V compounds, vacancies and anti-site defects are likely to play an important role. Stoichiometric cation vacancies present are themselves not neutral, but their presence is responsible for the easy restoration of radiation ejected atoms into lattice sites across low energy barriers. The room temperature value of the mobility was found to be 1380 cm^2/V sec. The variation of carrier concentration with temperature is shown in Fig. 6. The room temperature concentration is 3.16×10^{10} cm^{-3}. The hole concentration actually increases slowly with a slope of 0.426 eV till it reaches thc intermediate region, in which the concentration is not actually constant, but varies by nearly an order of magnitude. This is probably because the acceptor level is quite deep and the

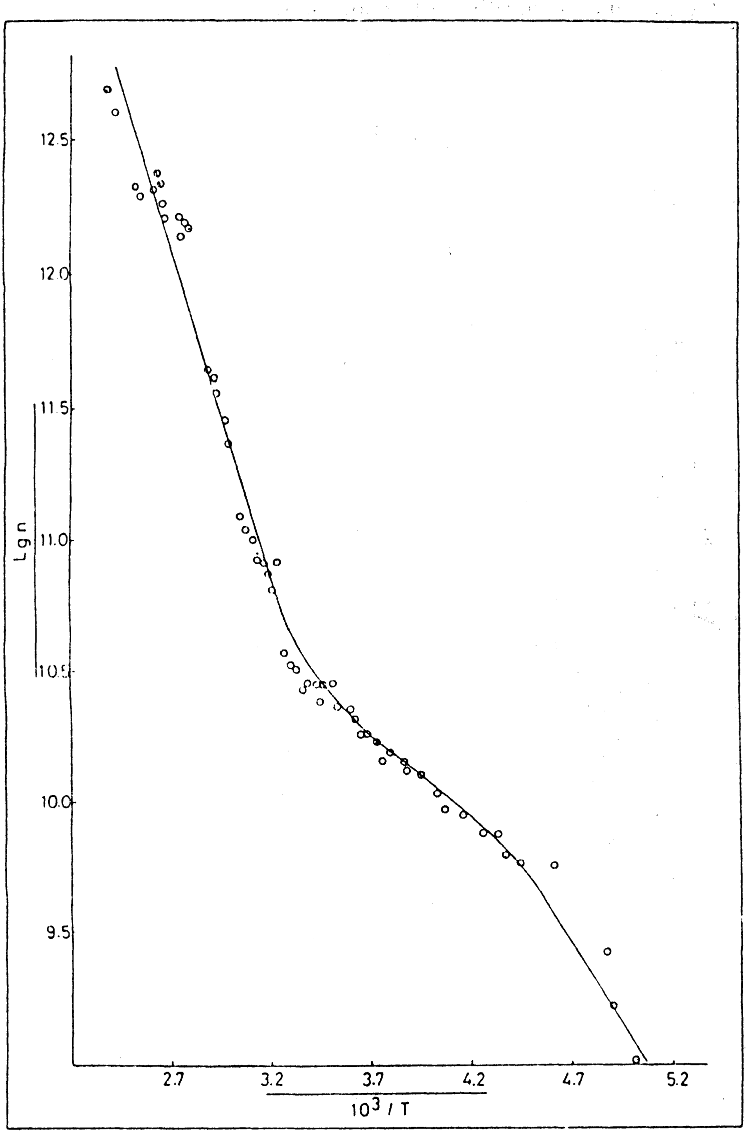

Fig. 6 Dependence of carrier concentration of In_2Te_3 on temperature.

intrinsic concentration is appreciable in this region. In the high temperature region the carrier concentration increases rapidly.

Temperature Dependence of In_2Te_3 Single Crystal

The temperature dependence of the differential emf for In_2Te_3 samples is shown in Fig. 7. Some features of these results may be pointed out: (1) The thermoelectric power grows monotonically with temperature and shows a sharp maximum at

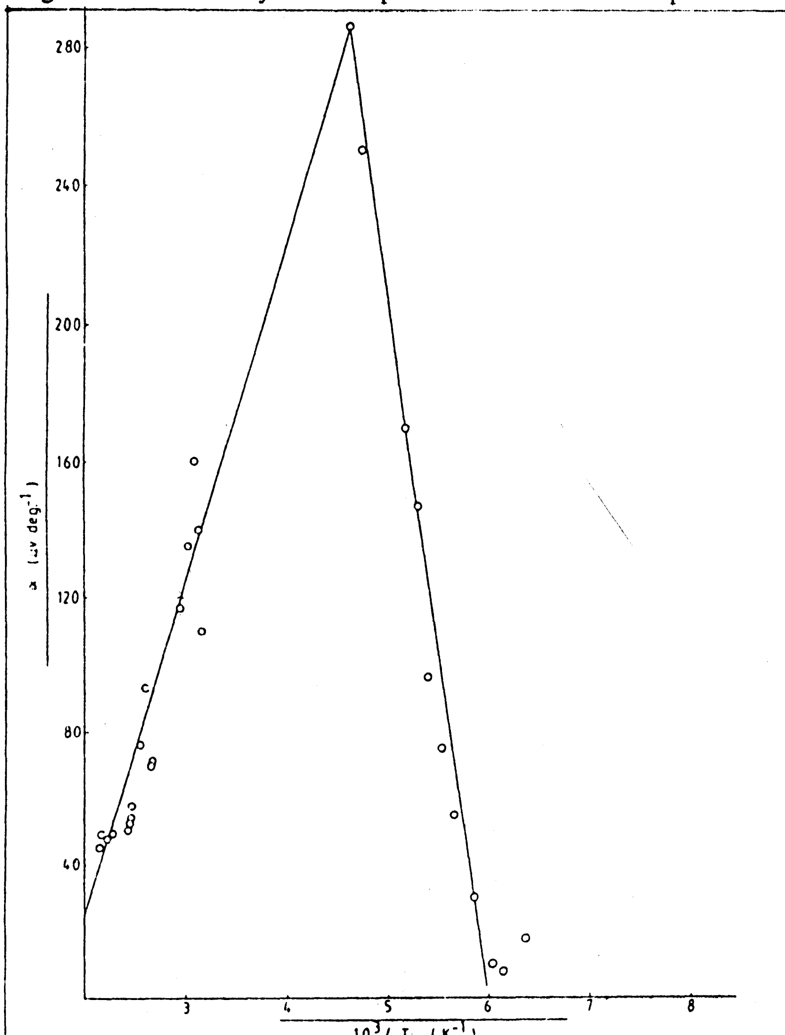

Fig. 7 Variation of thermoelectric power with temperature of In_2Te_3 single crystals.

value of emf 290 μV/K at T equal to 216 K. (2) With a further rise in temperature a rapid fall in the thermal emf is noticeable. (3) The results show that In_2Te_3 samples have positive TEP in the entire temperature range indicating a p-type conductivity of the investigated samples, which is in qualitative agreement with our previous data[10] of Hall coefficient. (4) The room temperature TEP value for In_2Te_3 amounted to 185 μ V/K.

As follows from the expression for the thermal emf of a semiconductor in the intrinsic region[11].

$$\alpha = -\frac{K}{e}\left[\frac{\mu_n - \mu_p}{\mu_n + \mu_p}\left(\frac{\Delta E_g}{2KT} + 2\right) + \frac{3}{4}\ln\frac{m_n^*}{m_p^*}\right]$$

where μ_n and μ_p are the electron and hole mobilities, m_n^* and m_p^* are the effective masses, ΔE_g is the width of the forbidden band. This formula predicts that a plot of α as a function of the reciprocal of the temperature in the intrinsic range should be a straight line with parameters determined $b = \mu_n/\mu_p$ and m_n^*/m_p^*. Fig. 8 shows a plot of α vs $10^3/T$ for p-type In_2Te_3. This linear relation having negative slope

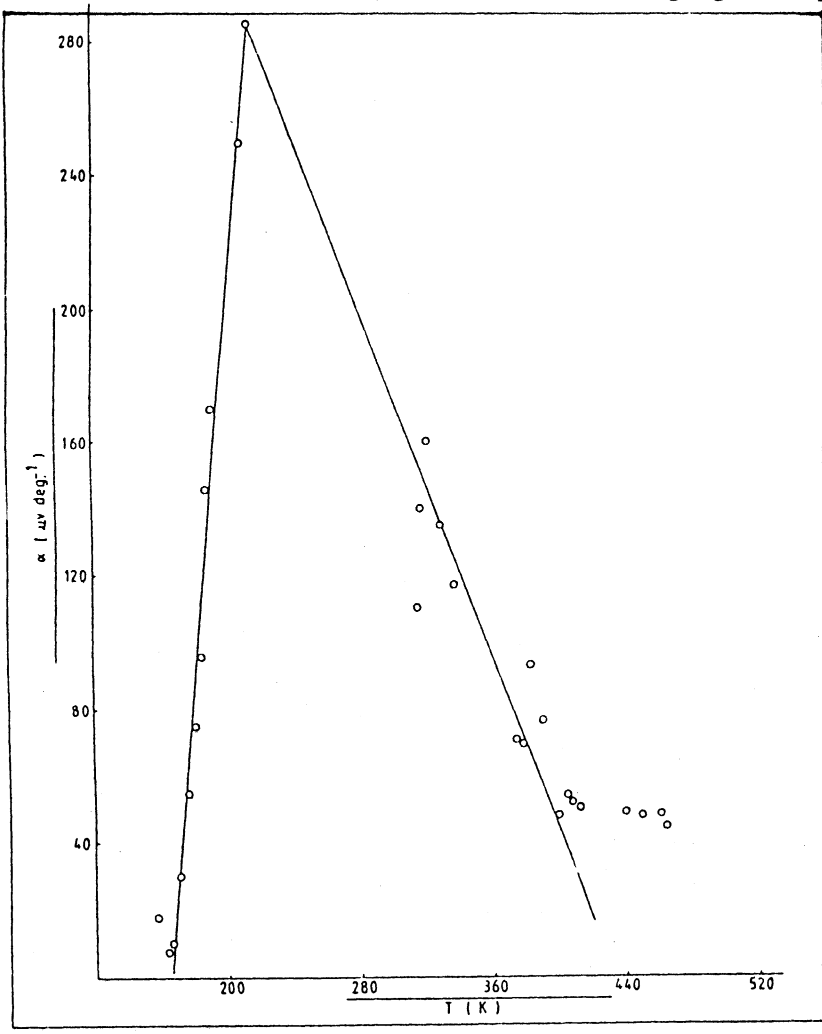

Fig. 8 Thermoelectric power as function of reciprocal absolute temperature for In_2Te_3.

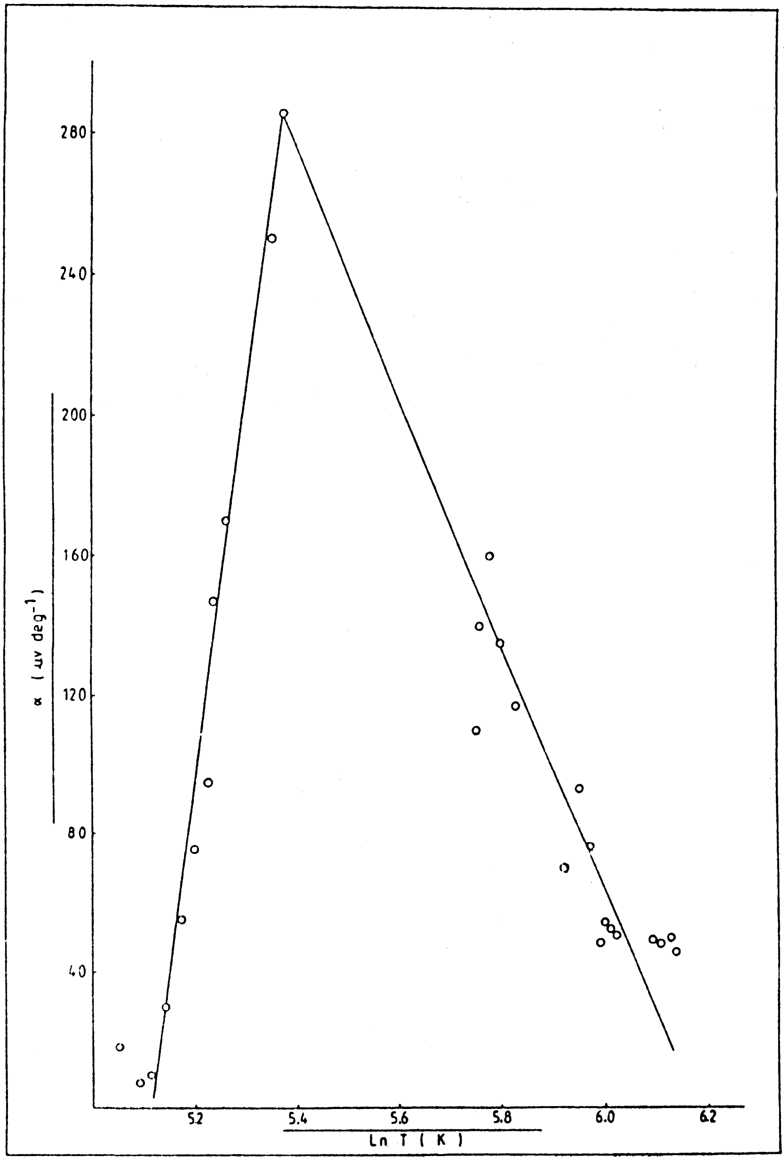

Fig. 9 Relation between α and ln T for In_2Te_3 single crystals.

indicates the increase of α with elevating the surrounding temperature. Knowing ΔE_g from Hall data[10], and assuming that m_n^*/m_p^* does not vary with temperature, it was found that $\mu_n/\mu_p = 1.5$. Thus using $\mu_p = 1380$ cm^2/V sec. at room temperature, $\mu_n = 2063$ cm^2/Vsec. Measurements of the temperature dependence of the electrical conductivity, the Hall coefficient[12] and thermo emf enabled us to find the mean effective masses of the electrons and holes. Their ratio was evaluated from the intercept of the curve to be $m_n^*/m_p^* = 0.37$. This means that the effective mass of hole is approximately three times greater than that of electron.

In the impurity region the following equation could be applied

$$\alpha = \frac{K}{e}\left[2 - \ln \frac{ph^3}{2(2\pi m_p^* KT)^{3/2}}\right]$$

Plotting the above relation between α and ln T we obtain Fig. 9. This figure shows that α increases linearly with the increase of temperature in the temperature range corresponding to the extrinsic conductivity region. Thus the effective mass of holes is evaluated to be 3.50×10^{-30} kg. Combining this value with the above-mentioed results for the ratio m_p^*/m_n^*, one obtains an effective mass of minority carriers of the value $m_n^* = 1.30 \times 10^{-30}$ kg. Using the effective mass values of electrons and holes, the relaxation time for both current carriers can be determined. Its value for holes comes to 3.02×10^{-15} sec. whereas for electrons it is equal to 1.12×10^{-15} sec. The diffusion constant is related to the mobility of charge carriers; its value for holes and electrons can be deduced as $D_p = 34.5$ cm^2/sec. respectively. The diffusion constant as noticed is inversely proportional to the effective mass of holes and electrons. The electron mobility as calculated is much higher than the hole mobility; and this result is acceptable since the hole effective mass is greater than that of electrons.

Another important parameter can be established; this is the diffusion length for holes and electrons. The value of L_p and L_n as deduced was found to be 3.2×10^{-6} cm and 2.4×10^{-6} cm respectively. Fig. 10 represents the dependence of thermoelectric power on the carrier density. We show that α increases sharply at the beginning of the curve, and covers a temperature range (190–215 K) after the value of thermoelectric power decreases with the carrier concentration. The same behaviour was observed when we plotted α, ln σ for In_2Te_3 sample as in Fig. 11. The decrease of the thermoelectric power with the electric conductivity may be due to the decrease of the carrier density in this range (> 215 K). Below 215 K it seems that TEP increases with the electric conductivity. The increases in the value of α in the low conductivity region may be due to the drag of carriers by phonons. The proposed treatment of the experimental data sheds new light on the main physical parameters in In_2Te_3 single crystals. The pronounced parameters obtained from thermopower data gave evidence for practical applications.

CONCLUSION

Measurements of electrical conductivity and Hall coefficient of In_2Te_3 single crystals are performed over the temperature range from 200–416 K. The conductivity throughout the entire temperature range is found to be of p-type. The energy gap is calculated to be 1.01 eV. The Hall mobility at room temperature is estimated as $\mu_H = 1380$ cm^2/ V sec. The electrical conductivity at room tempera-

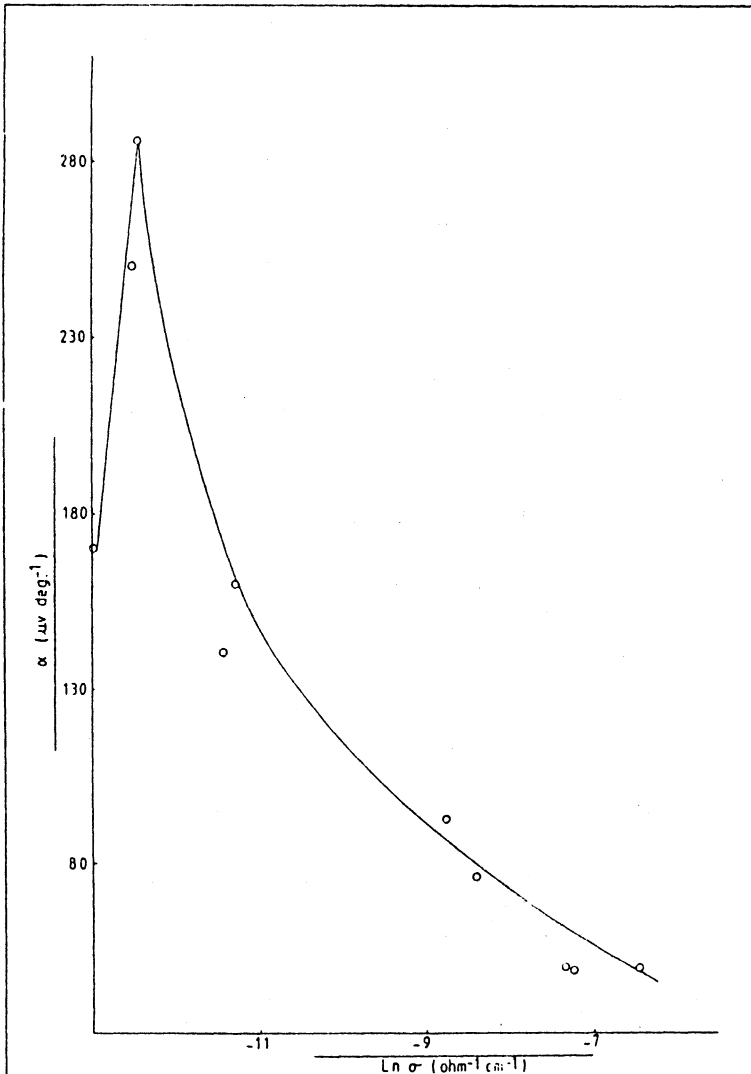

Fig. 10 Dependence of α on the natural logarithm of electrical conductivity for In_2Te_3 single crystals.

ture is equal to $0.623 \times 10^{-6}\ \Omega^{-1}\ cm^{-1}$. The carrier concentration at room temperature is calculated from RH equal to $3.16 \times 10^{10}\ cm^{-3}$.

The thermal e.m.f. of In_2Te_3 single crystals is measured in the temperature from 150–470 K. Thermoelectric power measurements indicate p-type conductivity. The electron mobility is equal to 2063 cm^2/V sec. and hole mobility μ_p = 1380 cm^2/V sec. The effective masses of electron and holes are 1.3×10^{-30}

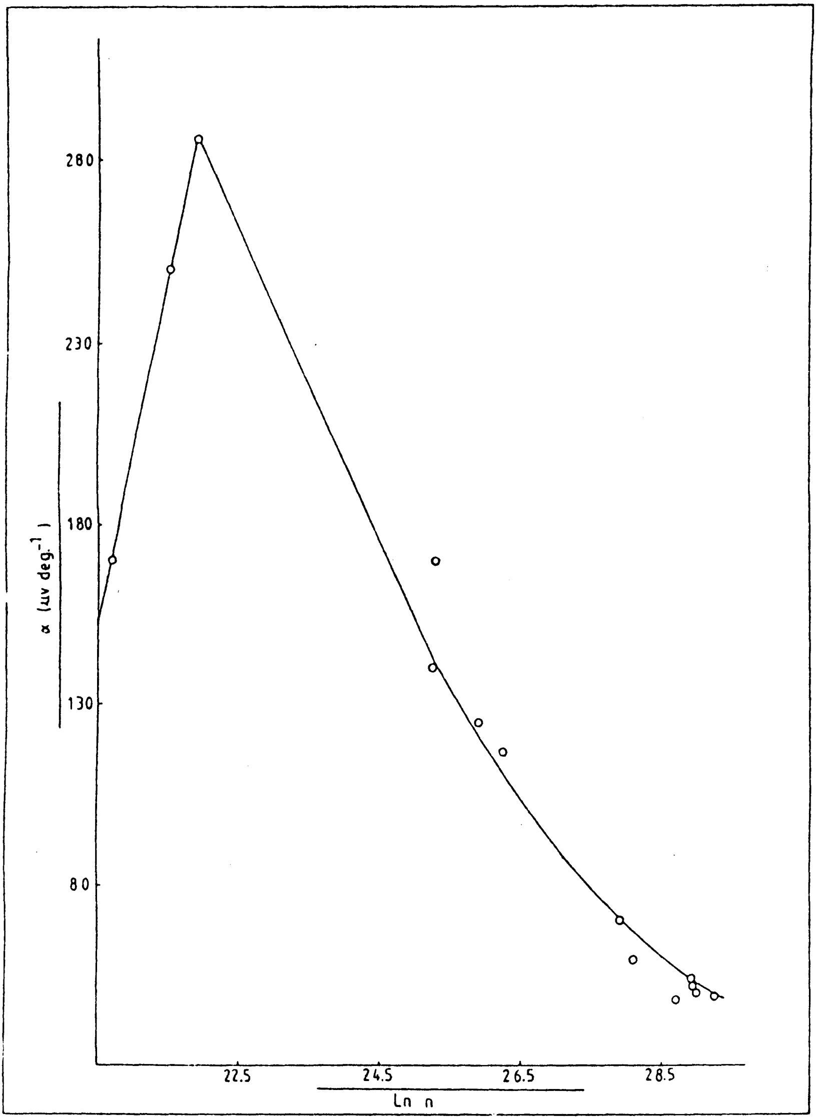

Fig. 11 Dependence of α on concentration of charge carriers for In_2Te_3 single crystals.

and 3.5×10^{-30} kg respectively. The diffusion coefficient for electrons and holes is evaluated to be 51.6 and 34.5 cm^2/sec. respectively. The mean free time between collisions is estimated to be $\tau_n = 1.12 \times 10^{-15}$ sec and $\tau_p = 3.02 \times 10^{-15}$ sec. The diffusion length for electrons and holes is found to be 2.4×10^{-6} and 3.2×10^{-6} cm. respectively.

REFERENCES

1. A.S. Mamedov, K.P. Mamedov, G.Sh. Gasanov, S.B. Bagirov and G.M. Niftiev, Plenum Publishing Corporation, **13**, 1592 (1977).
2. Yu.N. Dmitriev, V.N. Kulik, L.P. Glathinetsku and V.M. Koskin, *Sov. Phys. Solid*, **17**, 2396 (1976).
3. V.I. Belousov, N.F. Vendrikh, A.F. Novoshilov, and A.S. Pashinkin, Plenum Publishing Corporation, **17**, 880 (1981).
4. S. Sen and D.N. Bore, *Solid State Electronics*, **26**, 757 (1983).
5. S. Sen and D.N. Bore, *Solid State Communications*, **50**, 39 (1984).
6. C. Julien, M. Eddrief, M. Balkanski, E. Hatzikranioties and K. Kambas, *Phys. State Sol. (A)*, **88**, 687 (1985).
7. W. Klemm and H.U.V. Vogel, *Z. Anorg. Allg. Chem.*, **5**, 295 (1958).
8. S.A Hussein and A.T. Nagat, *Crystal Research and Technology*, **3**, 284 (1989).
9. G. Guizzeffi, F. Meloni, and A. Baldereshi, 15th Int. Conf. Phys. of Semiconductor, Kyoto, 93 (1980).
10. S.A. Hussein and A.T. Nagat, *Phys. State Sol. (A)*, **114**, K205 (1989).
11. S.A. Hussein, *Cryst. Res. Technol.*, **24**, 635 (1989).
12. V.A. Johnson and K. Lark, *Horovitz Phys. Rev.*, **92**, 2 (1953).

(*Received*: 14 January 1992; *Accepted*: 15 October 1992) AJC–501