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D.c. galvanomagnetic properties in a heavily compensated single crystal of n-type CdTe

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Experimental data on d.c. galvanomagnetic properties, namely the Hall coefficient R_H, the low-electric-field d.c. conductivity σ and the Hall mobility μ_H, in a heavily compensated single crystal of n-type CdTe in the temperature range 77 to 300 K have been analysed, firstly on the basis of a simple one-band model involving normal free-electron conduction, and secondly on the basis of a two-band model involving normal free-electron conduction along with impurity-band conduction. The analysis provides evidence for a significant contribution of impurity-band conduction to the transport phenomena at temperatures below $\sim$150 K. This conclusion is further substantiated by transverse magnetoresistance measurements and the observed dependence of d.c. conductivity on the electric field. From the analysis of these data, the average hopping distance R in the impurity band is calculated, and it is found to increase with decrease of temperature. The relative contributions of normal free-electron conduction and impurity-band conduction to the d.c. galvanomagnetic properties are estimated at different temperatures.

1. Introduction

Cadmium telluride (CdTe) has become the subject of intensive investigations because of its many interesting properties [1, 2] and applications [2–10]. It has been a promising material for γ-ray detectors, scintillator detectors, laser windows, electro-optical modulators in the infrared, and solar cells. The high potential of this material has drawn considerable attention to further research on the electrical and optical properties of this material. The d.c. galvanomagnetic properties, namely Hall coefficient, low electric field d.c. conductivity, Hall mobility, transverse magnetoresistance, electric-field dependent d.c. conductivity, etc. have proved to be very powerful tools in understanding electrical transport in this material. Single crystals of CdTe can be grown in both n- and p-type forms, which makes it accessible to a wider range of electrical measurements. De Nobel [11] measured the d.c. galvanomagnetic properties of single crystals of both n- and p-type CdTe. A maximum Hall mobility of about 1200 $cm^2 V^{-1} sec^{-1}$ was observed at 170 K in the n-type crystals. The temperature dependence of the Hall mobility at higher temperatures did not clearly show one particular type of scattering mechanism, and de Nobel suggested a combination of acoustic mode and polar optical mode scattering mechanisms to explain this behaviour. Similar inferences were drawn by de Nobel as to the scattering of holes in p-type CdTe. Yamada [12] investigated the Hall mobilities in moderately pure single crystals of n-type CdTe, but he did not refer to the scattering mechanism. The highest mobilities achieved in his n-type crystals were higher than those of de Nobel, the maximum being 1500 $cm^2 V^{-1} sec^{-1}$ at 90 K. Segall *et al.* [13], in an extensive study of n-type CdTe prepared under a variety of growth conditions, were able to conclude that, in the purest samples, the polar optical mode scattering was predominant down to 100 K. Below that temperature, ionized impurity scattering became dominant and caused the mobility to eventually decrease, giving a maximum value of 57 000 $cm^2 V^{-1} sec^{-1}$ at 30 K. It is, therefore, obvious that there is a necessity for understanding the basic transport in this material at different stages of purity.

The present paper reports measurements of the temperature dependence of the Hall coefficient R_H, the low electric field d.c. conductivity σ, and the Hall mobility μ_H, the magnetic-field dependence of transverse magnetoresistance $\Delta\varrho/\varrho$, and the electric-field dependence of d.c. conductivity $\sigma(E)$ in a heavily compensated single crystal of n-type CdTe in the temperature range 77 to 300 K. Firstly, R_H, σ and μ_H have been analysed on the basis of a simple one-band model involving only the normal free-electron conduction mechanism, and the donor ionization energy E_D and the donor and acceptor concentrations N_d and N_a are estimated. The analysis of the experimentally observed Hall mobility μ_H has been done by taking into account various scattering mechanisms in the conduction band, namely polar optical mode scattering, ionized impurity scattering, piezoelectric scattering and deformation potential scattering. A significant discrepancy between the theoretically calculated and experimentally observed Hall mobilities has been observed in the low-temperature region, and this has led to the rejection of the simple one-band model. The discrepancy has been explained by the introduction of a two-band model involving a hopping conduction mechanism in

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the impurity band along with the normal free-electron conduction mechanism. Evidence for this effect has also been provided by analysing the experimentally observed transverse magnetoresistance and electric-field dependent d.c. conductivity. The values of the average hopping distance, R, in the impurity band have been estimated at different temperatures.

2. Experimental details

The single crystal of n-type CdTe used in the present investigation was grown from the melt in the $\langle 1\,1\,1 \rangle$ direction by using the zone melting technique described by de Nobel [11]. Samples of rectangular bar geometry of size about 6.0 mm × 1.5 mm × 1.0 mm were cut from the grown crystal boule. One of the cut as-grown samples was annealed in molten cadmium of 5N purity for about 400 h at 850° C to remove the compensating impurities and native acceptor defects. For annealing, the sample and metallic cadmium were kept in an evacuated quartz ampoule which was kept in the hot zone of a high temperature furnace. Subsequent analysis of the electrical properties made on the sample showed that while the conductivity of the as-grown sample improved considerably, the sample was still highly compensated, showing that the sample was not optimally annealed.

Before making the ohmic contacts, the sample was lightly ground with fine-grained abrasive powder (3 μm silicon carbide). This was followed by chemomechanical polishing with a solution of acetone, alcohol and distilled water. The sample was then etched in a solution of one part HF, one part HNO_3 and two parts distilled water for a two-minute period. After etching, the sample was treated by boiling in 50% NaOH solution for 1.5 min followed by washing in distilled water.

Ohmic contacts on the etched sample were provided by diffusing high-purity indium at 250° C in an inert atmosphere of high-purity argon. The voltage contacts measured 0.5 mm in size, whereas the current contacts spread over the entire end cross-sections of the sample. The ohmic nature of the contacts was verified by the observed linearity of the current–voltage characteristics throughout the temperature range of interest. The temperature dependence of the Hall coefficient R_H and the low electric field d.c. conductivity σ, the magnetic-field dependence of the transverse magnetoresistance $\Delta\varrho/\varrho$ and the electric-field dependence of the d.c. conductivity $\sigma(E)$ were measured by the five-probe technique [14] (with one voltage probe taken as common in the standard six-probe technique) in the temperature range 77 to 300 K, by mounting the sample in a double-walled metal vacuum cryostat [15].

The Hall voltage was measured with an accuracy of about 1.0% with a Keithley d.c. nanovoltmeter. Including the errors in the measurement of the magnetic field and the sample current, the error in the measurement of Hall coefficient R_H is estimated to be about 2.0%. The conductivity σ was measured to an accuracy of about 1.5%, and so the overall maximum error in the measurement of Hall mobility μ_H is estimated to be about 3.0%.

3. Experimental results and discussion

Firstly, the simple one-band model involving only the normal free-electron conduction mechanism has been applied to analyse the experimental data on Hall coefficient R_H, low electric field d.c. conductivity σ and Hall mobility μ_H. The contributions of all the scattering mechanisms (namely polar optical mode scattering, ionized impurity scattering, piezoelectric scattering and deformation potential scattering) limiting the mobility of the conduction-band electrons have been estimated and combined by Matthiessen's rule to give the resultant conduction-band Hall mobility μ_{Hc}. There is no mechanism left in the conduction band to account for the discrepancy between experimentally observed and calculated Hall mobilities μ_H, μ_{Hc}. Secondly, therefore, admitting the inadequacy of the simple one-band model, we have switched over to the two-band model involving the two non-interacting conduction processes operating in the conduction and impurity bands, respectively. The experimental data on R_H, σ and μ_H have been reanalysed by assuming their two-band expressions, and impurity-band and conduction-band contributions to them have been estimated. Evidence for the existence of impurity-band conduction has been provided by analysing the experimental data on transverse magnetoresistance $\Delta\varrho/\varrho$ and electric-field dependent d.c. conductivity $\sigma(E)$. We may now elaborate these two analytical approaches.

3.1. Analysis on the basis of a simple one-band model

The temperature dependence of the Hall coefficient R_H at a typical magnetic field of 3 kG (0.3T) and in the temperature range 77 to 300 K is shown in Fig. 1. The value of R_H was found to be independent of the magnetic field. It is observed from Fig. 1 that R_H decreases with increase of temperature over the entire temperature range, initially at a faster rate and thereafter at a slower rate, reaching almost saturation near room temperature. Using a simple one-band model, which involves only the normal free-electron conduction, we have calculated the concentration of the conduction-band electrons, n_c, by using the equation

$$n_c = r_H(eR_H)^{-1} \quad (1)$$

where the temperature dependence of the Hall scattering factor r_H, as suggested by Devlin [16], has been applied. Having calculated n_c over the entire temperature range, we have fitted the results by the following charge-neutrality equation [17] for a non-degenerate compensated semiconductor with a single donor level of concentration N_d and with compensation by acceptors of concentration N_a, using the method of least squares and adjusting E_D for best fit:

$$\frac{n_c\,(n_c + N_a)}{N_d - N_a - n_c} = gN_c \exp\,(-E_D/k_B T) \quad (2)$$

In this equation N_c is the effective density of states in the conduction band, $g = 1/2$ is the donor level degeneracy factor, k_B the Boltzmann constant, T the absolute temperature and E_D the donor thermal ionization energy. At higher temperatures all the donors

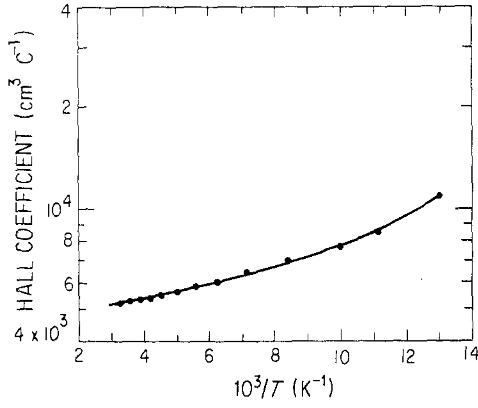

Figure 1 The temperature dependence of observed Hall coefficient R_H in a heavily compensated single crystal of n-type CdTe.

are ionized and the concentration of the conduction-band electrons, n_c, equals $(N_d - N_a)$. At low temperatures, where n_c is less than N_a, the above equation has been best fitted to the Hall coefficient data of Fig. 1 to determine E_D, which is found to be about 10 meV. A value of (0.11 ± 0.01) m_0 [18], where m_0 is the free-electron mass, has been used for the effective mass m^* of the free electrons. The donor and acceptor concentrations have been estimated to be 1.67×10^{16} and $1.55 \times 10^{16} \text{cm}^{-3}$, respectively.

The temperature dependence of the low electric field d.c. conductivity σ in the temperature range 77 to 300 K is shown in Fig. 2. It is observed that, initially, the conductivity σ increases with increase of temperature, reaches a maximum value and then decreases with further increase of temperature. At low temperatures, since both the concentration and the mobility of the conduction-band electrons increase with increase of temperature, as indicated by Figs. 1 and 3, the conductivity σ continues to increase with temperature. However, the mobility, after reaching a maximum value, starts decreasing with temperature and, thus, the conductivity σ attains a maximum value. At higher temperatures, the concentration of the conduction-band electrons increases at a much reduced rate and the conduction is effectively determined by the mobility, and therefore σ falls with increasing temperature.

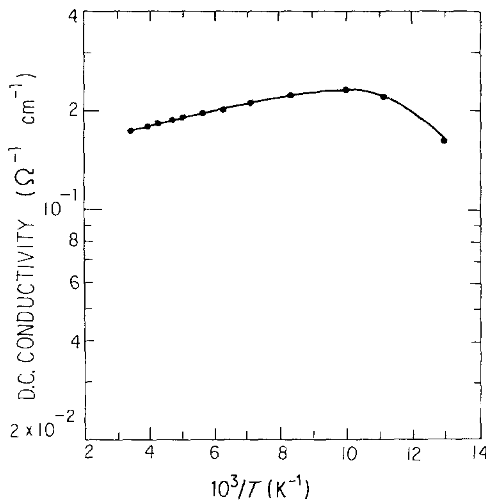

Figure 2 The temperature dependence of observed d.c. conductivity σ in a heavily compensated single crystal of n-type CdTe.

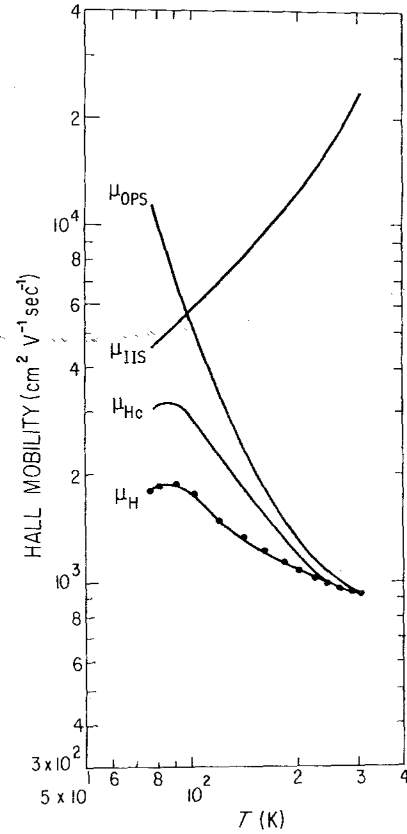

Figure 3 The temperature dependence of observed Hall mobility μ_H and its theoretically calculated components μ_{IIS}, μ_{OPS} and μ_{Hc} in a heavily compensated single crystal of n-type CdTe.

Fig. 3 depicts the temperature dependence of the Hall mobility $\mu_H(= R_H\sigma)$. It is seen that, initially, μ_H increases slightly with increase of temperature, reaches a maximum value and then falls with a further increase of temperature. An attempt has been made to explain this behaviour on the basis of the various possible scattering mechanisms which limit the mobility of the conduction-band electrons. The slight increase of mobility observed at low temperatures is due to the dominance of ionized impurity scattering, whereas the decrease of mobility observed at higher temperatures is due to the dominance of polar optical mode scattering. The ionized impurity scattering and polar optical mode scattering increase and decrease, respectively, with temperature over the entire temperature range. The other scattering processes, namely piezoelectric scattering and deformation potential scattering, also limit the mobility of the conduction-band electrons but, as shown below, their role is found to be comparatively insignificant over the entire temperature range.

Polar optical mode scattering operates over the entire temperature range through the coupling of electrons to the associated electric field of the polarization wave [19, 20]. A measure of the extent of coupling is the so-called polaron coupling constant α, which is defined by

$$\alpha = \frac{e^2}{\hbar}\left(\frac{m^*}{2\hbar\omega_l}\right)^{1/2}\left(\frac{1}{K_\infty} - \frac{1}{K_s}\right) \quad (3)$$

where $\hbar\omega_l = 0.0212$ eV [21] is the energy of the longitudinal optical phonons, and K_∞ and K_s are the optical and the static dielectric constants, respectively. The

temperature dependence of K_s is given [22] by

$$K_s(T) = K_s(0)(1 + \lambda T) \quad (4)$$

where $K_s(0) = 10.31$ is the static dielectric constant extrapolated linearly to 0 K and $\lambda = 2.27 \times 10^{-4}$ K^{-1} is a constant for the material. It has been pointed out by Rode [23] that K_s/K_∞ is independent of temperature, and keeping this in view we have obtained the temperature dependence of K_∞ by using the value of K_s/K_∞ at room temperature. The value of K_∞ at room temperature has been taken to be 7.6 [11]. The polaron coupling constant α has been calculated over the entire temperature range, and it is found to be 0.37 at room temperature. The low value of α is indicative of a weak coupling. Under such a weak coupling, the mobility μ_{OPS} for polar optical mode scattering has been calculated by using the formula for non-degenerate semiconductors given by Howarth and Sondheimer [24], i.e.

$$\mu_{OPS} = \frac{1}{2\alpha\omega_l}\frac{e}{m^*}\frac{8}{3\pi^{1/2}} Z^{-1/2}\,\psi(Z)\,(\exp Z - 1) r_H \quad (5)$$

where the reduced reciprocal temperature Z is the quotient of the Debye temperature $\Theta_D = \hbar\omega_l/k_B$ and temperature T and $\psi(Z)$ is a function which has been evaluated by Howarth and Sondheimer and generalized by Ehrenreich [25]. The values of μ_{OPS} calculated by using Equation 5 are indicated in Fig. 3.

Ionized impurity scattering results from either the impurities or the lattice defects generated by non-stoichiometry of the compound. The coulombic field of an ionized defect deflects the electrons from their paths in a way that depends on the sign of the charge on the scattering centre. This scattering is important, especially at low temperatues, that is when the thermal motion of the atoms is small. It has a very small, but not negligible, contribution to the mobility at room temperature. The mobility μ_{IIS} for ionized impurity scattering has been estimated over the entire temperature range by using the Brooks–Herring formula [26] for non-degenerate semiconductors, that is

$$\mu_{IIS} = \frac{2^{7/2}(4\pi\varepsilon_0 K_s)^2 (k_B T)^{3/2} r_H}{\pi^{3/2} e^3 (m^*)^{1/2} N_I \ln[6m^*(k_B T)^2 4\pi\varepsilon_0 K_s/\pi e^2 \hbar^2 n'(2 - n'/N_I)]} \quad (6)$$

where

$$n' = n_c + \left(1 - \frac{n_c + N_a}{N_d}\right)(n_c + N_a) \quad (7)$$

is the effective screening concentration and

$$N_I = N_a + N_d \quad (8)$$

is the total ionized impurity concentration. The temperature dependence of the static dielectric constant K_s and the Hall scattering factor r_H have been taken into account for calculating μ_{IIS} over the entire temperature range. These calculated values of μ_{IIS} are shown in Fig. 3.

In CdTe, where the bonds are partly ionic and the unit cell does not contain a centre of symmetry (zinc-blende structure), the carriers may be scattered by the longitudinal acoustic waves due to "piezoelectric scattering" [27–29]. The mobility μ_{PES} due to piezoelectric scattering is given by

$$\mu_{PES} = \frac{16(2\pi)^{1/2}\hbar^2\varepsilon_0 r_H}{3e(m^*)^{3/2}(k_B T)^{1/2}}\left(\sum_{\text{modes}}\frac{\langle K^2\rangle}{K_s}\right)^{-1} \quad (9)$$

where K^2 is the piezoelectric electromechanical coupling coefficient. This formula has been employed to evaluate μ_{PES} over the entire temperature range. $\Sigma_{\text{modes}}(\langle K^2\rangle/K_s)$ has been taken to be 3.27×10^{-5} for this purpose. The μ_{PES} values are found to be several hundred times larger than the observed Hall mobility values. This is indicative of the insignificant role played by the piezoelectric scattering mechanism. The room-temperature Hall mobility for this scattering is about 1.08×10^6 $cm^2\,V^{-1}\,sec^{-1}$.

Deformation potential scattering arises from changes in the band-gap due to the local dilatational strains associated with acoustic modes. The following formula, as proposed by Bardeen and Shockley [30] for long-wavelength acoustic modes, has been employed to calculate the mobility μ_{DPS} due to deformation potential scattering:

$$\mu_{DPS} = \frac{2(2\pi)^{1/2} e\hbar^4 (d_s v_l^2) r_H}{3E_{1c}^2 (m^*)^{5/2}(k_B T)^{3/2}} \quad (10)$$

where d_s is the density, v_l the average longitudinal sound velocity and E_{1c} the deformation potential of dilatational strain for the conduction band. The term $(d_s v_l^2)$ has been evaluated by using the elastic constants as measured by McSkimin and Thomas [31]. An estimated value of 2 to 3 eV for E_{1c}, as in the experiments of Thomas [32] on the behaviour of exciton spectra in CdTe under uniaxial stress and those of Langer [33] on studies of the optical properties of the band edge under pressure, has been used in the calculations. The mobilities due to this type of scattering also have been found to be a few hundred times larger than the corresponding observed mobilities over the entire temperature range, so this mechanism also does not play a significant role. The room-temperature Hall mobility for deformation potential scattering is estimated to be about 1.05×10^5 $cm^2\,V^{-1}\,sec^{-1}$.

Having estimated the mobilities for the various scattering mechanisms operating significantly in the conduction band over the entire temperature range, we have combined them by using Matthiessen's rule to obtain the resultant conduction-band Hall mobility μ_{HC}. Thus

$$\frac{1}{\mu_{Hc}} = \frac{1}{\mu_{OPS}} + \frac{1}{\mu_{IIS}} \quad (11)$$

The temperature dependence of μ_{Hc} is shown in Fig. 3. It is seen that the observed and the calculated mobilities μ_H, μ_{Hc} are in good agreement from room temperature to about 240 K, but below 240 K μ_{Hc} is significantly larger than μ_H. The discrepancy between the two

mobilities is found to increase with decrease of temperature.

Since all the scattering mechanisms limiting the mobility of the conduction-band electrons have been taken into account, there is no mechanism left in the conduction band to account for the discrepancy between the observed and calculated mobilities below 240 K. This has forced us to reject the simple one-band model, which involves only normal free-electron conduction.

3.2. Analysis on the basis of a two-band model

The discrepancy between the observed and calculated mobilities has been attributed to the presence of some conduction mechanism operating in yet another band besides the various scattering mechanisms operating in the conduction band. The simple one-band model has, therefore, been replaced with a two-band model which involves two non-interacting conduction processes acting in parallel, one in the conduction band and the other in the impurity band. For doping concentrations of the order of $10^{16}\,cm^{-3}$, as in our case, the wave functions of the electrons in the adjacent impurity atoms overlap, and the discrete impurity levels broaden to form impurity band [34]. According to Conwell [35] the behaviour of very impure material at low temperatures can be accounted for by a combination of both the conduction processes operating in the impurity and conduction bands. A very large effective mass and a low mobility are the characteristics of impurity-band conduction. Since the temperatures are not too low, sufficient phonon energy is available and a thermally assisted hopping conduction between the nearest localized electron states is expected. This process involves the movement of an electron from one localized state to the other with the emission or absorption of a phonon. Compensation, i.e. the presence of acceptors, is a necessity for the process. The acceptors accept electrons from a certain proportion of the donors, thus allowing an electron localized on one donor to "hop" to a nearby ionized donor, leaving the first donor ionized and the second donor deionized. The application of an electric field to the material enhances the probability of a jump toward the lower potential. The result is a net charge flow. Theories in this regard were given by Miller and Abrahams [36] and Mott and Towse [37] and are in good agreement with the experimental results.

If the conduction processes are assumed both in the impurity band and the conduction band, the following two-band expressions [37] can be used for the conductivity σ, the Hall coefficient R_H and the Hall mobility μ_H:

$$\sigma = \sigma_c + \sigma_i = en_c\mu_c + en_i\mu_i \qquad (12)$$

$$R_H = \left(\frac{\sigma_c}{\sigma}\right)^2 R_{Hc} + \left(\frac{\sigma_i}{\sigma}\right)^2 R_{Hi} \qquad (13)$$

$$\mu_H = \left(\frac{\sigma_c}{\sigma}\right) \mu_{Hc} + \left(\frac{\sigma_i}{\sigma}\right) \mu_{Hi} \qquad (14)$$

Here σ_c, n_c, μ_c, μ_{Hc}, R_{Hc} are the conduction-band conductivity, the concentration of conduction-band electrons, the conduction-band drift mobility, the conduction-band Hall mobility and the conduction-band Hall coefficient, respectively, and σ_i, n_i, μ_i, μ_{Hi}, R_{Hi} are similar quantities for the impurity band. We have best-fitted these expressions to the experimental data. The constraint that $(n_c + n_i)$ is a constant independent of temperature and equal to the concentration of the conduction-band electrons at room temperature (since impurity-band conduction vanishes at room temperature) has been applied. μ_{Hc} has again been taken to be the conduction-band Hall mobility arising significantly from polar optical phonon scattering and ionized impurity scattering. Thus, the conduction-band and impurity-band components of the conductivity σ, the Hall coefficient R_H and the Hall mobility μ_H have been separated out. These components have been included in Figs. 4, 5 and 6.

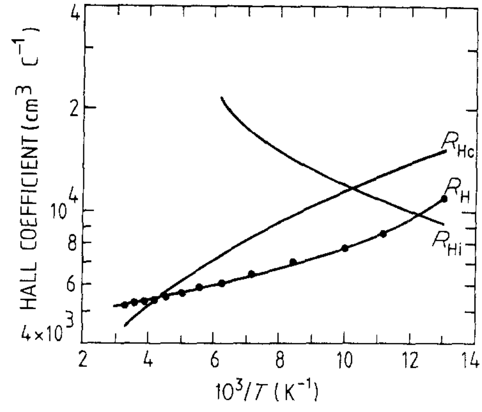

Figure 4 The temperature dependence of theoretically calculated components R_{Hc}, R_{Hi} of the observed Hall coefficient R_H in a heavily compensated single crystal of n-type CdTe.

Fig. 4 shows the temperature dependence of R_{Hc} and R_{Hi}. It is observed that the concentration of the impurity-band electrons, n_i, decreases with increase of temperature, whereas the concentration of the conduction-bands electrons, n_c, increases with increase of temperature. At high temperatures, n_i is reduced to extremely small values relative to n_c, thereby indicating that the impurity-band conduction almost vanishes. This is because at high temperatures a very large

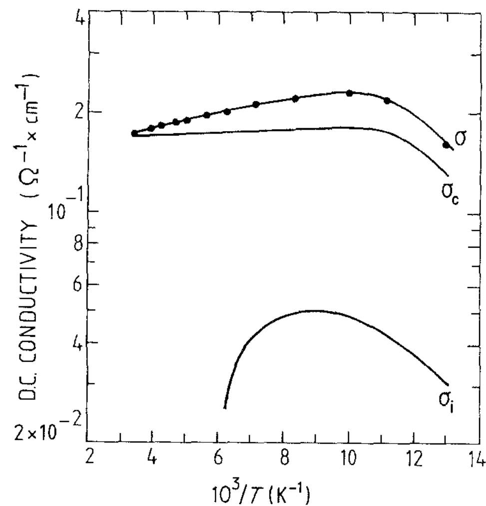

Figure 5 The temperature dependence of theoretically calculated components σ_c, σ_i of the observed d.c. conductivity σ in a heavily compensated single crystal of n-type CdTe.

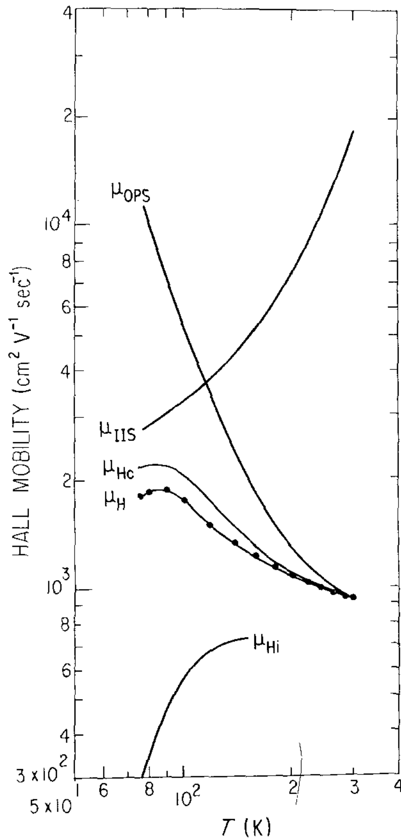

Figure 6 The temperature dependence of theoretically calculated components μ_{IIS}, μ_{OPS}, μ_{Hc} and μ_{Hi} of the observed Hall mobility μ_{H} in a heavily compensated single crystal of n-type CdTe.

number of impurity-band electrons go to the extended states (conduction band).

The temperature dependence of the conductivity components σ_c and σ_i is shown in Fig. 5. While the temperature dependence of both the components is similar in character, σ_i is about an order of magnitude smaller than σ_c. At higher temperatures, σ_i is reduced to extremely small values relative to σ_c and the latter falls off very slowly with increase of temperature. The contribution σ_i, arising from thermally assisted hopping between nearest localized states, is given [38] by

$$\sigma_i = \sigma_{i0} \exp(-\Delta W_i/k_B T) \tag{15}$$

where ΔW_i is the hopping energy and σ_{i0} is the impurity band conductivity in the limit $1/T \to 0$. The hopping energy ΔW_i has been estimated to be about 14 meV.

Fig. 6 represents the temperature dependence of the Hall mobility components μ_{Hc} and μ_{Hi}. It is found that the impurity-band Hall mobility μ_{Hi} is of the activation type in the low-temperature region, in accordance with the relation

$$\mu_{\text{Hi}} = \mu_{\text{Hi0}} \exp(-\Delta W_{\text{Hi}}/k_B T) \tag{16}$$

where μ_{Hi0} is the mobility in the limit $1/T \to 0$ and ΔW_{Hi} is the mobility activation energy for impurity-band electrons. The mobility activation energy is found to be about 19 meV.

TABLE I Values of the exponent s in expression $\Delta\varrho/\varrho \propto H^s$ for a heavily compensated single crystal of n-type CdTe at various temperatures

T(K)	77	100	150	200	250	300
s	1.31	1.49	1.52	1.68	1.80	1.98

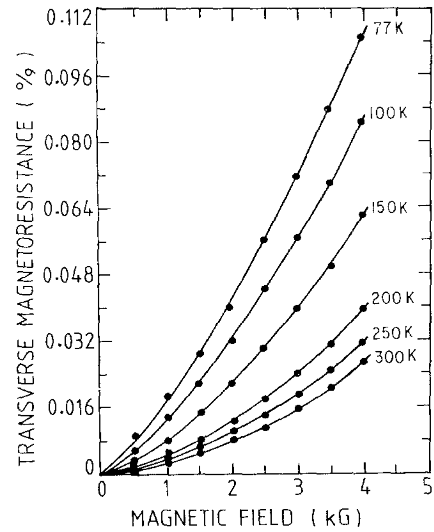

Figure 7 The magnetic-field dependence of the observed magnetoresistance, $\Delta\varrho/\varrho$, in a heavily compensated single crystal of n-type CdTe at temperatures 77, 100, 150, 200, 250 and 300 K. $1\,\text{G} = 10^{-4}\,\text{T}$.

The magnetic-field dependence of the transverse magnetoresistance (TMR), that is $\Delta\varrho/\varrho$, at some typical temperatures in the range 77 to 300 K is shown in Fig. 7. The solid curves represent least-squares fits to the experimental data. The TMR is found to be positive over the entire temperature range and obeys the relation

$$\Delta\varrho/\varrho \propto H^s \tag{17}$$

The values of the exponent s for various temperatures have been estimated and are shown in Table I. The values are in increasing order with increase of temperature. At higher temperatures, the TMR exhibits nearly the square-law behaviour expected for free-electron conduction. However, at lower temperatures the TMR deviates from square-law behaviour, with values of s diminishing to 1.31 at 77 K, thereby indicating the existence of impurity-band conduction besides the normal free-electron conduction.

Fig. 8 shows the electric-field dependence of the d.c. conductivity $\sigma(E)$ at various constant temperatures from 77 to 140 K. It is observed that the $\sigma(E)$ at each constant temperature increases with increase of the

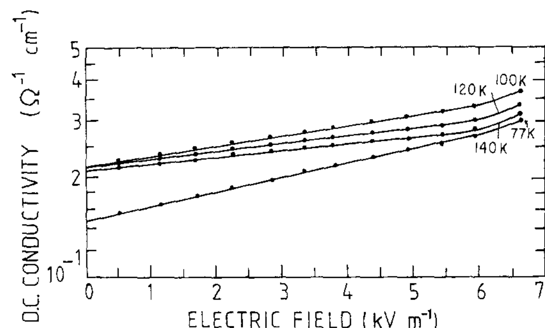

Figure 8 The electric-field dependence of the observed d.c. conductivity $\sigma_{(E)}$ in a heavily compensated single crystal of n-type CdTe at temperatures 77, 100, 120 and 140 K.

TABLE II Values of the average hopping distance R in a heavily compensated single crystal of n-type CdTe at various temperatures

T(K)	77	100	120	140
$R(\mu m)$	0.71	0.62	0.60	0.53

applied electric field. This shows the presence of impurity-band conduction along with the normal free-electron conduction. The observed increase in $\sigma(E)$ with the applied electric field cannot be attributed to the Poole–Frenkel effect [39, 40] since the observed data cannot be fitted with a log $\sigma(E)$ against $E^{-1/2}$ variation. It was shown by Hill [40] that if the coulombic centres are situated in the impurity band so close together that their electric fields overlap, the d.c. conductivity $\sigma(E)$ is given by

$$\sigma(E) = \sigma(0) \exp (eER/k_B T) \quad (18)$$

where $\sigma(0)$ is the d.c. conductivity for zero electric field and R is the average hopping distance for the carriers. The observed variation of d.c. conductivity $\sigma(E)$ with the applied electric field can be best fitted with the relation derived by Hill up to a field of about $6.0\,kV\,m^{-1}$. The deviations at higher electric fields may be due to Joule heating in the sample.

The average hopping distance R, as calculated at various temperatures by using Hill's relation (Equation 18), is listed in Table II. It is noteworthy that R decreases with increase of temperature. As explained by Mott [41, 42], this is because when the temperature is lowered, the number of phonons available for absorption decreases and the carriers do not possess sufficient energy to hop to nearest-neighbour sites, which may involve a large energy change. Indeed, the hopping transitions take place to sites corresponding to nearly the same energy level, although such sites may be situated at larger distances, resulting in larger values of R at lower temperatures. The estimated values of R are in agreement with the results of Ryvkin and Shlimak [43] obtained in highly doped and heavily compensated single crystals of germanium.

4. Conclusions

We come to the conclusion that in a heavily compensated single crystal of n-type CdTe the compensating impurities play a significant but not a dominating role in shaping the conductivity and carrier mobility in the temperature range of interest. The conduction, being composite in nature, takes contributions from the carriers both in the conduction band and the impurity band. A two-band model successfully explains the discrepancy between the observed Hall mobility and the theoretically calculated conduction-band Hall mobility. The existence of impurity-band conduction is confirmed by transverse magnetoresistance measurements and the observed electric-field dependence of d.c. conductivity.

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