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Mobility analysis in plastically deformed CdTe single crystals

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Mobility, d.c. Hall effect and d.c. conductivity studies have been done on deformed and undeformed samples of n-type CdTe in the temperature range 77 to 300 K. The Hall coefficient studies have suggested that acceptor centres are introduced during the formation and motion of dislocations. The mobility variation with temperature of the deformed samples has shown a peak at the higher temperature side. The dislocation mobility (μ_D) deduced from the observed mobilities of deformed and undeformed samples has shown two regions, Region 1 being independent of temperature and Region 2 having a linear increase with temperature. The observed rate of change of μ_D with temperature from Region 2 and the rate deduced from the simple analysis suggested by the authors are found to be almost equal. The dislocation density at room temperature is estimated using the dislocation scattering mobility and the Dexter and Seitz model. These values are comparable with those observed from etching studies within the experimental errors.

1. Introduction

Dislocations in semiconductors are considered to have a charged core and these core states are associated with dangling bonds [1, 2]. Duga [3] has measured the dislocation effects on the electrical properties of n-type InSb produced by plastic bending. Gatos and Lavine [4] on the other hand have found that the electrical properties of InSb measured at 77 K depend markedly on the type of dislocations introduced during the bending process. They have concluded that indium and antimony dislocations introduce acceptor and donor levels respectively. Recently Nagabhooshanam and Hari Babu [5] have also studied the conductivity and Hall mobility variations with temperature on plastically deformed n-InSb. These measurements at low temperatures showed that the carrier concentration changes were very small, but the mobilities were reduced considerably. The results were interpreted by assuming that equal concentrations of indium- and antimony-type dislocations were introduced during the deformation process. Mihara [6] and Mihara and Ninomiya [7] measured the mobilities of both types of dislocation in several compound semiconductors, using a double etching method, and succeeded in showing that α dislocations move faster than β dislocations. Photoplastic effect and conductivity studies were made by Buch and Ahlquist [8] in compressed CdTe crystals. The observed changes in conductivity always corresponded to a shift of the Fermi energy towards the conduction band. This change was attributed to the creation of excess tellurium dislocations (donors).

Recently, Svoboda and Klier [9] have studied conductivity and photoconductivity on plastically bent p-type CdTe samples. They have concluded that the acceptors increase on increase in the dislocation density. But a systematic study on the mobilities of charge carriers was not done in deformed CdTe single crystals. With a view to investigate the nature of dislocations formed due to plastic deformation in CdTe crystals and their influence on transport properties, studies of the Hall effect, conductivity and mobility have been undertaken. The temperature coefficient of mobility of charge

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carriers due to dislocations was estimated by two methods and were found to be almost equal. The dislocation density calculated from etching studies was found to agree with the calculated density by means of the Dexter and Seitz model.

2. Experimental details

n-type CdTe single crystal slices perpendicular to the $\langle 1\,1\,0\rangle$ axis were cut into regular bars and etched for 10 sec in a solution containing 10 ml HNO_3, 20 ml H_2O and 4 g $K_2Cr_2O_7$. The etched samples were observed under an optical microscope and found to be free from work damage [10]. This sample is referred to as C000. Using the standard five-probe technique in vacuum, the Hall coefficient R_H and the conductivity σ were measured on C000 in the temperature range 77 to 300 K. The sample was then removed from the cryostat and plastically deformed by means of indentations with a diamond pointer attached to an NU–2 microscope. After every 50, 100 and 160 indentations (these samples are referred to as C050, C100 and C160) the R_H and σ measurements were carried out. Care was taken to see that indentations were distributed uniformly. This method of plastic deformation avoids the removal of ohmic contacts during the deformation process. The details of deformation, the vacuum cryostat and the experimental arrangement are given elsewhere [5, 11].

3. Results and discussion

The variation of conductivity with temperature (log σ against $1/T$) for the four samples C000, C050, C100 and C160 are shown in Fig. 1. It can be seen that there is a considerable amount of change in the conductivity due to deformation. The conductivity decreases in both intrinsic and extrinsic regions with increase in plastic deformation. An excess decrease in the extrinsic region is also observed when compared to the intrinsic region.

The temperature variation of Hall coefficient (corresponding to a magnetic field of 0.75 T) for Samples C000, C050, C100 and C160 is shown in Fig. 2. It can be seen from the figure that (a) the R_H values of C050, C100 and C160 differ considerably from C000 at all temperatures under investigation; (b) R_H decreases with increase in deformation; (c) in each sample R_H decreases with increase in temperature, the decrease being rapid in the extrinsic region and gradual in the intrinsic region.

Fig. 3 shows the variation of mobility with temperature (log μ against log T) for Samples C000, C050, C100 and C160. It can be observed that (a) the electron mobility decreases steadily as the deformation progresses, and (b) the mobility difference between deformed and undeformed crystals is more at low temperatures than at room temperature.

Unlike the case of plastically deformed InSb

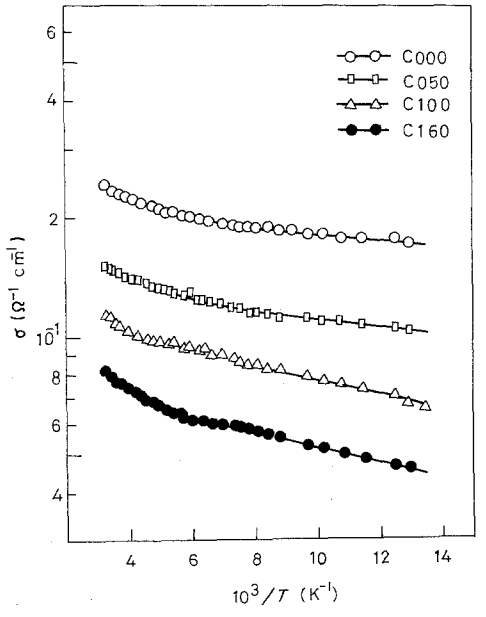

Figure 1 Temperature variation of the d.c. conductivity (log σ against $1/T$) for four samples of n-type CdTe.

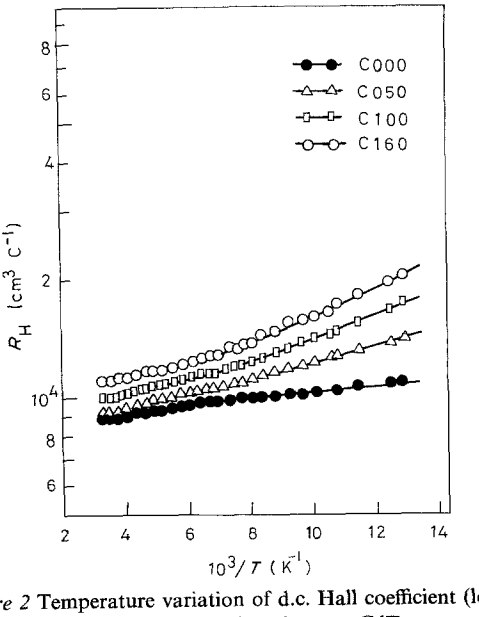

Figure 2 Temperature variation of d.c. Hall coefficient (log R_H against $1/T$) for four samples of n-type CdTe.

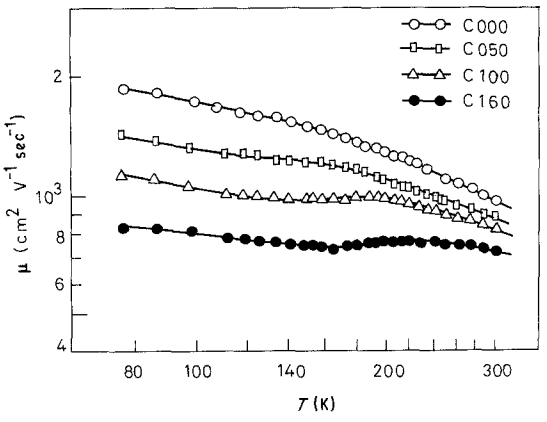

Figure 3 Temperature dependence of observed Hall electron mobility (log μ against log T) for four samples. In Sample C000, a maximum is not observed.

[5], a considerable change in the Hall coefficient is found as the deformation proceeds. This probably is due to the creation of charged acceptor centres during the formation and motion of α and β dislocations introduced with plastic deformation. Svoboda and Klier [9] in p-type CdTe have also suggested the creation of acceptor centres with the introduction of dislocations. These centres were later attributed by them to cadmium vacancies. The same type of charged acceptor centres were also suggested by other workers [12, 13] in n- and p-type InSb due to plastic deformation. The change observed in the Hall coefficient due to deformation may then be due to acceptor centres attributed to cadmium vacancies. The large decrease in conductivity due to deformation also supports this.

The effect of these dislocations will be more on the mobility of charge carriers rather than on Hall coefficient for two reasons:

(a) Hall coefficient varies inversely with the charge carrier concentration n which is equal to N_D–N_A, where N_D and N_A are donor and acceptor concentrations respectively.

(b) Mobility is more closely related to the total impurity concentration N_I, where $N_I = N_D + N_A$.

It is also possible that a small amount of trapping at these dislocations may occur [14]; this is observable only in the specimens containing 1×10^{14} charge carriers per cm^3, which is true here.

It can also be seen from Fig. 3 that the mobility corresponding to Samples C050, C100 and C160 shows a slight maximum in the range 140 to ~ 300 K, whereas this is not observed in the underformed sample C000. A similar result was observed by the authors [5] in plastically deformed n-InSb, by Duga *et al.* [15] in uniaxially compressed bulk InSb, and by Wieder [14] in InSb films prepared by flash evaporation.

The temperature dependence of the electron mobility in these samples will be interpreted by using the model proposed by Dexter and Seitz [16], according to which scattering of charge carriers by the deformation potential associated with stationary edge dislocation is possible. The dislocation scattering according to them is characterized by the mobility μ_D and is given by

$$\mu_D = \beta T \tag{1}$$

where

$$\beta = \frac{32}{3\pi}\left(\frac{1-\nu}{1-2\nu}\right)^2 \frac{k_B \hbar}{\varepsilon^2 \lambda^2 N}\left(\frac{e}{m^*}\right) \tag{2}$$

The parameters involved in the above equation along with their values are given in Table I.

TABLE I Values of parameters used in calculations

Parameter	Value taken	Reference
ε = energy associated with dislocation	6.01 eV	[17]
ν = Poisson's ratio	0.1866	[18]
λ = lattice parameter	0.6481 nm	[19]
e = electron charge	1.60×10^{-19} C	
m^* = electron effective mass	$0.0963\, m_0$	[20]
ϱ = density	6.06 g cm^{-3}	[21]
$\hbar$ = Planck's constant	6.5821×10^{-16} eV sec	
k_B = Boltzmann constant	8.615×10^{-5} eV K^{-1}	
T = absolute temperature		
N = dislocation density		

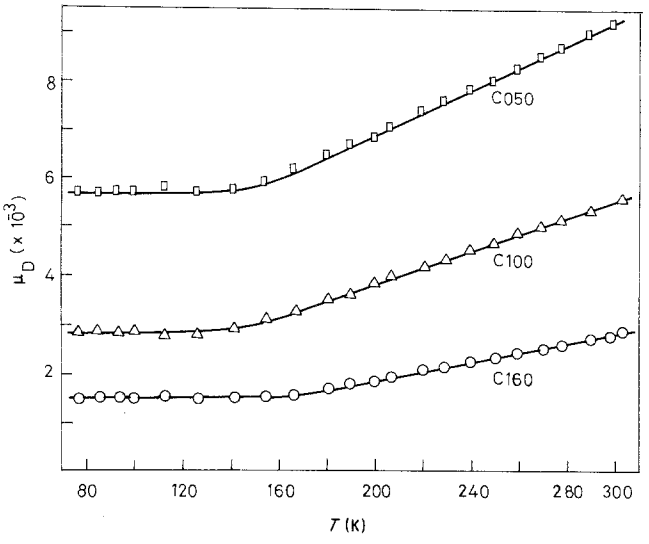

Figure 4 Temperature dependence of the dislocation mobility (μ_D against T) of Samples C050, C100 and C160. Two regions are seen. Region 1 is independent of temperature and Region 2 has a linear variation with temperature.

The experimentally measured mobility of an undeformed μ and deformed μ' are related with the dislocation mobility μ_D by

$$\frac{1}{\mu'} = \frac{1}{\mu} + \frac{1}{\mu_D} \tag{3}$$

The addition of inverse mobilities in this manner is an approximation with $\langle\tau^2\rangle/\langle\tau\rangle^2 = 1$. The error in using Equation 3 is quite small [22].

Using the experimental values of μ', μ and Equation 3, μ_D is computed at different temperatures for the three deformed samples. Fig. 4 gives the variation of μ_D with temperature for Samples C050, C100 and C160. For all these samples μ_D has two regions, as in the case of InSb [5]. Region 1 extends from 77 to 140 K and Region 2 from 140 K to room temperature. The value of β for each deformed sample is calculated from Region 2 and is found to decrease with the increase in deformation.

The value of β can also be obtained using the peak temperature T_0 (where mobility is maximum in the range 140 to 300 K). To relate β with T_0, the following simple analysis is proposed. Combining Equations 1 and 3 we have

$$\frac{1}{\mu'} = \frac{1}{\mu} + \frac{1}{\beta T} \tag{4}$$

Differentiating this equation with respect to temperature

$$-\frac{1}{\mu'^2}\frac{\partial\mu'}{\partial T} = -\frac{1}{\mu^2}\frac{\partial\mu}{\partial T} - \frac{1}{\beta T^2} \tag{5}$$

At $T = T_0$, $\partial\mu'/\partial T = 0$. Therefore Equation 5 can be modified as

$$\beta = -\left.\frac{\mu^2}{T^2\dfrac{\partial\mu}{\partial T}}\right|_{T=T_0} \tag{6}$$

Hence, β values for the three deformed samples C050, C100 and C160 are calculated by substituting μ and $\partial\mu/\partial T$ for the pure sample C000 at the corresponding peak temperatures of the deformed samples in Equation 6. The observed and calculated values of β along with the peak temperatures of the deformed samples are tabulated in Table II. The calculated and experimental values are almost identical. The slight difference between them is because of the initial assumptions made in deriving the expression for μ_D.

TABLE II Calculated parameters for samples

Sample	Measured T_0 (K)	β($cm^2 V^{-1} sec^{-1} K^{-1}$)		μ_D($cm^2 V^{-1} sec^{-1}$) at 300 K	N (per cm^3) at 300 K	
		From Equation 6	From Region 2 (Fig. 4)		From μ_d values	From etch-pit counting
C050	155	22.92	22.134	9.24×10^3	1.2668×10^9	1×10^9
C100	190	16.32	16.171	6.50×10^3	2.1283×10^9	2×10^9
C160	220	9.52	9.276	2.79×10^3	4.1956×10^9	3.2×10^9

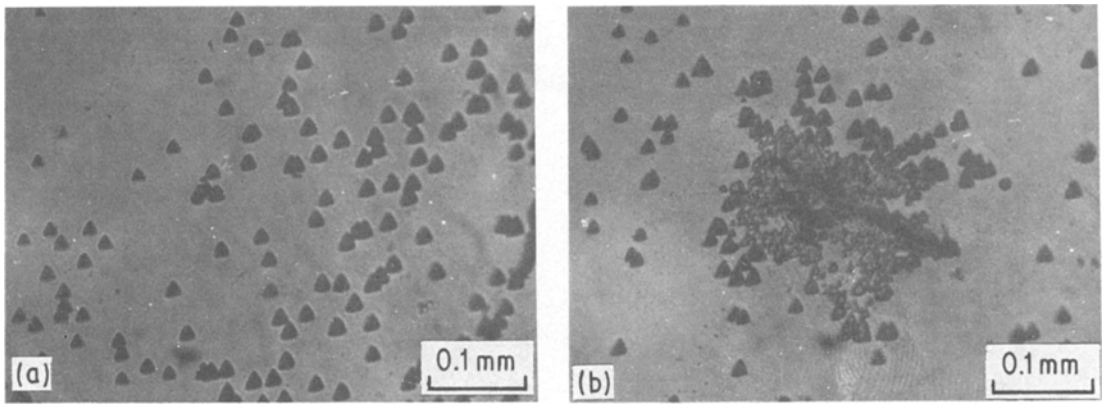

Figure 5 (a) Etch pits on freshly cleaved CdTe; (b) etch pits around an indentation on CdTe.

The fresh dislocation density as a function of dislocation mobility is given by

$$N = \frac{32}{3\pi}\left(\frac{1-\nu}{1-2\nu}\right)^2 \frac{k_B T\hbar}{\varepsilon^2\lambda^2\mu_D}\left(\frac{e}{m^*}\right) \quad (7)$$

Substituting the values of μ_D at room temperature in the above equation, the fresh dislocation densities have been calculated for the three deformed samples and are given in Table II.

The dislocation density was also calculated by the etch-pit counting method on a number of freshly cleaved and indented CdTe samples. The etchant employed was slightly modified EAg–1 (10 ml conc. HNO_3 + 20 ml H_2O + 4 g $K_2Cr_2O_7$ + 10 ml 40% $AcNO_3$) as suggested by Inoue *et al.* [23]. Photomicrographs of etch pits on both freshly cleaved and indented samples are shown in Figs. 5a and b respectively. We have roughly observed 5×10^5 dislocations on a freshly cleaved sample and 500 dislocations per indentation on an indented sample. The dislocation densities introduced in Samples C050, C100 and C160 are also given in Table II. The order of the densities is same when compared to the order observed by Duga [24] on bent samples. The values obtained from etching studies are almost comparable with those obtained from mobility studies using the Dexter and Sietz model [16].

4. Conclusions

(a) The method of plastic deformation is simple and easily controllable.

(b) This type of plastic deformation gives similar results as that of plastic bending.

(c) The small change in the Hall coefficient after deformation is because of the creation of charged acceptor centres (cadmium vacancies) during the formation and motion of α and β dislocations.

(d) In all deformed samples, the variation of mobility with temperatures has a maximum at the higher temperature side. β (the rate of change of dislocation mobility with temperature) observed from the μ_D against T plot and the one calculated by using T_0 are almost the same.

(e) The dislocation density calculated by the Dexter and Seitz mechanism agrees with an etch-pit density determined chemically.

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References

1. W. SHOCKLEY, *Phys. Rev.* **91** (1953) 228.
2. W. T. READ, *Phil. Mag.* **45** (1954) 775.
3. J. J. DUGA, PhD thesis, Ohio State University (1960).
4. H. C. GATOS and M. C. LAVINE, *J. Phys. Chem. Solids* **14** (1960) 169.
5. M. NAGABHOOSHANAM and V. HARI BABU, *Bull. Mater. Sci.* **3** (1981) 415.
6. M. MIHARA, PhD thesis, University of Tokyo (1971).
7. M. MIHARA and T. NINOMIYA, *J. Phys. Soc. Jpn.* **25** (1968) 1198.
8. F. BUCH and C. N. AHLQUIST, *J. Appl. Phys.* **45** (1974) 1756.
9. M. SVOBODA and E. KLIER, *Czech. J. Phys. (B)* **22** (1972) 725.
10. M. INOUE, I. TERAMOTO and S. TAKYANAGI, *J. Appl. Phys.* **34** (1963) 404.
11. M. NAGABHOOSHANAM, PhD thesis, Osmania University, Hyderabad, (1982) p. 160.

12. A. P. KRASNOV and Y. A. OSIPYAN, *Sov. Phys. Solid State* **20** (1978) 1025.
13. *Idem, ibid.* **21** (1979) 430.
14. H. H. WIEDER, *Solid State Electron.* **9** (1966) 373.
15. J. J. DUGA, R. K. WILLARDSON and A. C. BEER, *J. Appl. Phys.* **30** (1959) 1798.
16. D. H. DEXTER and F. SEITZ, *Phys, Rev.* **86** (1952) 964.
17. D. KRANZER, *Phys. Status Solidi* (a) **26** (1974) 11.
18. R. D. GREENOUGH and S. B. PALMER, *J. Phys.* (*D*) **6** (1973) 587.
19. A. J. STRAUSS, "Proceedings of International Symposium on CdTe", Strasbourg, 1977, p. 167.
20. A. L. MEARS and R. A. STRADLING, *Solid State Commun.* **7** (1969) 1267.
21. B. R. NAG, "Electron transport in Compound Semiconductors" (Springer-Verlag, Berlin, 1980) p. 372.
22. B. SEGALL, M. R. LORENTZ and R. E. HALSTEAD, *Phys. Rev.* **129** (1963) 2471.
23. M. INOUE, I. TERAMOTO and S. TAKAYANAGI, *J. Appl. Phys.* **33** (1962) 2578.
24. J. J. DUGA, *ibid.* **33** (1962) 169.

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