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Galvanomagnetic properties of plastically deformed InSb single crystals

M NAGABHOOSHANAM and V HARI BABU
Solid State and Materials Science Laboratories, Department of Physics, Osmania University, Hyderabad 500 007, India

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Abstract. The dc Hall effect, dc conductivity and mobility have been studied on deformed and undeformed samples of *n*-type InSb from liquid nitrogen temperature to room temperature. These studies have shown that the Hall coefficient values of deformed samples do not differ much from undeformed sample, but a considerable amount of change was observed in mobility, suggesting that equal number of donor and acceptor type dislocations are introduced during the deformation process. In addition the mobility variation of the deformed samples with temperature has shown a peak in 170–300°K range. The dislocation mobility (μ_D) is deduced from the observed mobilities of deformed and undeformed samples. The plot μ_D *vs* T has two regions, region 1 being independent of temperature and region 2 having a linear increase with temperature. The β factor obtained from region 2 is found to be almost equal to the one calculated from Dexter and Seitz model. The dislocation densities at room temperature are also calculated for the deformed samples using the above model.

Keywords. dc Hall coefficient; dc conductivity; mobility; deformation; dislocations; dislocation mobility.

1. Introduction

It is a well-known fact that plastic deformation alters the electrical properties of semiconductors. For example, deformation in silicon (Zhurkin *et al* 1967; Staunton and Pollak 1967) and Germanium (Komatsubara and Tagsugi 1965; Cuevas and Fritzsche 1967; Fritsche 1962) has produced changes in the carrier mobility, life time and carrier concentration by orders of magnitude. Recently (Yasuda *et al* 1978) have established that uniaxial stress will also produce change in the dielectric properties of anti-ferroelectric materials. InSb, which can be easily grown into single crystals, was subjected to plastic deformation and influences of magnetic field and temperature on galvanomagnetic properties were studied (Kaila 1977; Galvanov and Obuknov 1973). This semiconductor on slight deformation produces an appreciable density *i.e.*, about 10^7 dislocations/cm^2 (Kaila 1977). Furthermore the behaviour of certain galvanomagnetic coefficients are very sensitive to the presence of the dislocations. Recently the authors (Nagabhooshanam and Hari Babu 1980) have studied the effect of dislocations on galvanomagnetic properties of InSb single crystals, dislocations being created during the annealing process. In the present work we report dc Hall coefficient and dc conductivity measurements done from liquid nitrogen temperature to room temperature on *n*-type InSb crystals before and after applying anisotropic uniaxial stress along [111] direction. The stress was applied with a diamond indentor at regular intervals of distance on both sides of the n-InSb single crystal at room temperature. The mobility due to the scattering of charge carriers by the dislocations has been found to be temperature independent till a particular temperature, and increases linearly thereafter. The temperature coefficient of the dislocation scattering mobility for the second region was determined and compared with the value determined by using Dexter and Seitz model (Dexter and Seitz 1952) for stationary edge dislocations. These two values are almost comparable.

2. Experimental details

The n-InSb crystals were obtained from Electronics Corporation of India Limited, Hyderabad. Slices perpendicular to the c-axis were cut from the boule. From these slices, samples of rectangular bar geometry of about $8 \times 4 \times 0{\cdot}75$ mm^3 were cut and then lapped with fine grains of carborandom. The work damage at the surface during sawing and lapping was removed by chemical etching. The etchant consisted of 40 parts lactic acid + 10 parts HNO_3 + 5 parts HF + 15 parts H_2O and the time of etching was about 30 secs. To the dried crystal five ohmic contacts were made (2 current contacts and 3 voltage contacts) with dots of high purity indium at 200°C in a 10^{-5} torr vacuum. The size of indium contacts was about 0·5 mm in diameter while the current contacts were spread over the entire cross-section of the sample.

After observing the Hall coefficient and conductivity with temperature the sample was indented at the room temperature with a diamond pointer attached with the Universal Microscope (Carl Zeiss, Zena) to produce plastic deformation. The load applied was 100 g and the time of indentation being 10 sec. each. For every 50, 100 and 150 indentations the observations were made from liquid nitrogen temperature (77°K) to the room temperature (300°K). Care was taken to see that indentations made are equidistant. This method of producing plastic deformation avoids removal of ohmic contacts during deformation process.

Five probe technique was used to measure the Hall coefficient (R_H) and conductivity (σ) of the samples, one probe being kept common for the measurements of R_H and σ. Measurements were made from liquid nitrogen temperature to the room temperature by mounting the sample on a copper block (with electrical insulation) in a cryostat in which heating of the sample was achieved by conduction through the copper block. The cryostat is kept exactly in the middle of the pole caps of the 6 inch electromagnet and it was made sure that the sample is under the action of a uniform magnetic field. The magnetic field was measured by a differential Gaussmeter. The Hall voltage and the voltage across the current leads were measured by means of a Phillips dc microvoltmeter at different currents through the sample. Every time the direction of the current through the sample and the direction of the magnetic field were changed, and the Hall voltages were measured. The average of these four measurements is taken for the Hall coefficient calculations. The temperature measurements were made by means of a copper constantan thermocouple, one of its junction being kept at 0°C.

3. Results and discussion

The variation of Hall coefficient with temperature (log R_H *vs* $1/T$) for the four *n*-type InSb samples, having indentations zero (pure), 50, 100 and 150 (hereafter referred as sample S1, S2, S3 and S4) are shown in figure 1 corresponding to a magnetic field of 7·5 kG. It is seen from the figure that the R_H values of S2, S3 and S4 do not differ much from S1. It is also seen that R_H value decreases slowly with the increase in temperature up to a certain temperature and thereafter decreases rapidly. This behaviour is typical for a degenerate extrinsic semiconductor.

Figure 2 shows the temperature dependence of conductivity of S1, S2, S3 and S4. It is seen that there is a considerable amount of change in the conductivity due to deformation.

The variation of mobility with temperature for the four samples is shown in figure 3. It is observed that the electron mobility decreases steadily as the deformation progresses. The mobility difference between deformed and undeformed crystals is more at liquid nitrogen temperature and is less at room temperature.

The near constancy in the values of R_H, in the extrinsic region and the difference in mobility between deformed and undeformed crystals indicate that the donor and acceptor concentrations introduced during deformation process are almost equal as

(i) the Hall coefficient varies inversely with the charge carrier concentration (n) and $n = N_D - N_A$, where N_D and N_A are donor and acceptor concentrations.
(ii) mobility is more closely related to the total impurity concentration (N_I) *i.e.* $N_I = N_D + N_A$.

These dislocations are nothing but the rows of atoms with unsaturated dangling bonds on the edges of extra half planes created throughout the body of the crystal. When

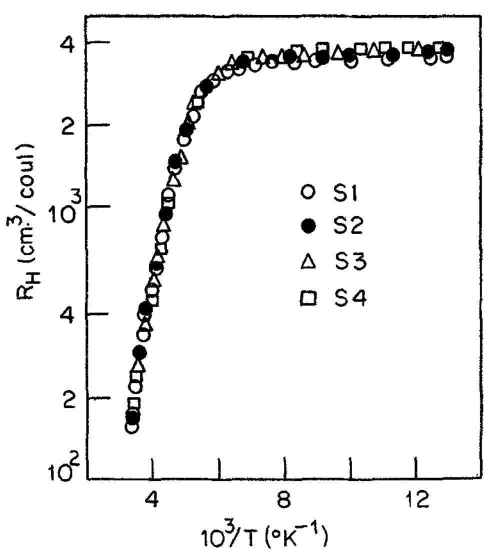

Figure 1. Temperature variation of dc Hall coefficient (log R_H *vs* $1/T$) for the four samples S1, S2, S3 and S4 of *n*-type InSb.

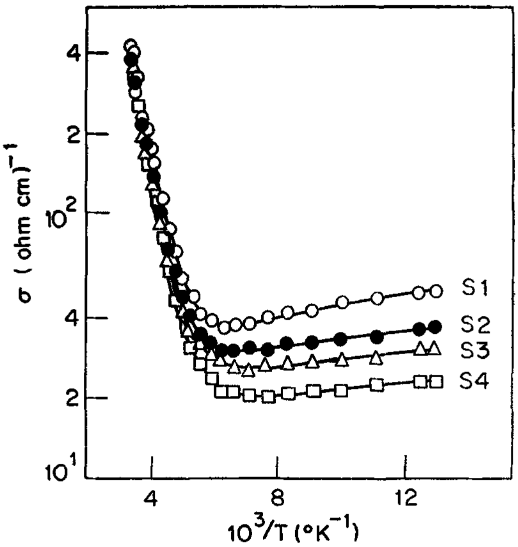

Figure 2. Temperature variation of the dc conductivity (log σ *vs* $1/T$) for the four samples S1, S2, S3 and S4 of n-type InSb.

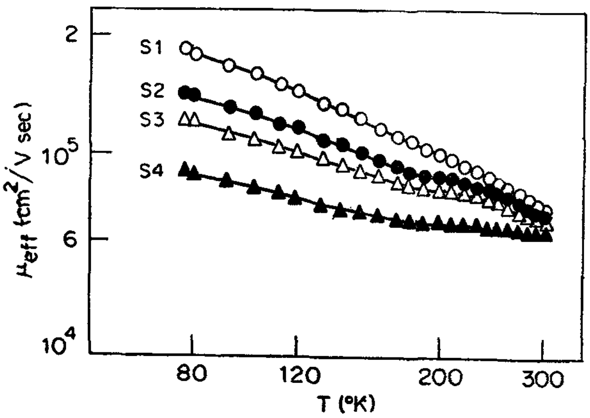

Figure 3. Temperature dependence of the observed Hall electron mobility (log μ_{eff} *vs* log T for S1, log μ'_{eff} *vs* log T for S2, S3 and S4) in the four samples S1, S2, S3 and S4. In sample S1, maxima is not observed.

In atoms are at the edge of the extra half planes, there are no excess of electrons and such a row will create an acceptor level in the forbidden gap. When Sb atoms form these rows, each atom has a saturated electron pair and the dislocations should introduce a donor level. These dislocations are called respectively In and Sb type and have been effectively observed to exhibit both donor and acceptor behaviour (Bell *et al* 1960; Duga 1962). It is also possible that a small amount of trapping at these dislocations may occur and is observable only in the specimens of higher purity. This effect was found to be of only 1% in specimens containing 1×10^{14} charge carriers per cm^3 (Duga *et al* 1959). As our original sample (S1) contains carrier concentration of $1{\cdot}6 \times 10^{16}$ cm^3, this effect can almost be neglected.

It is also seen from figure 3 that the mobility corresponding to samples S2, S3 and S4 show slight maximum in the range 170 ~ 300°K which was also observed by Duga in uniaxially compressed bulk InSb (Duga *et al* 1959) and by Wieder in InSb thin films prepared by flash evaporation (Wieder 1966). This maximum was not observed in the undeformed sample S1.

The temperature dependence of the electron mobility in these samples will be interpreted in terms of the model proposed by Dexter and Seitz according to which, scattering of charge carriers by the deformation potential associated with stationary edge dislocations is possible. For simplicity the polar nature of the InSb lattice, electron hole scattering as well as the impurity scattering will be neglected. Lattice scattering will be characterized by a mobility μ_L and a relaxation time τ_L and dislocation scattering will be represented by a mobility μ_D and a relaxation time τ_D. The experimentally measured mobility μ_{eff} is related to μ_L and μ_D by

$$\frac{1}{\mu_{\text{eff}}} = \frac{1}{\mu_L} + \frac{1}{\mu_D}, \tag{1}$$

The value of μ_D is given by

$$\mu_D = (e/m^*)\,\tau_D, \tag{2}$$

where m^* is the effective mass of the charge carriers and τ_D is defined as (Wieder 1966)

$$\tau_D = \frac{32}{3\pi}\left(\frac{1-\nu}{1-2\nu}\right)^2 \frac{kT\hbar}{\epsilon^2\,\lambda^2\,N}. \tag{3}$$

The parameters involved and their values in (3) are given in table 1. Substituting the equation for lattice mobility

$$\mu_L = 1{\cdot}09 \times 10^9 \times T^{-1{\cdot}68}, \tag{4}$$

Table 1. Parameters involved in equation (3) and their values.

Parameters	Values taken	Reference
ϵ = Energy associated with the dislocation	6·4 eV	Ehrenreich 1957
ν = Poisson's ratio	0·4	Wieder 1966
λ = Lattice spacing	6·48 Å	Wieder 1966
m_n^* = Electron effective mass	0·0139 m_0	Johnson and Dickey 1970
m_p^* = Hole effective mass	0·42 m_0	Pidgeon and Brown 1966
T = Absolute temperature		
N = Dislocation density		
$\hbar$ = Planck's constant	$1{\cdot}0546 \times 10^{-27}$ erg sec	
k = Boltzmann constant	$8{\cdot}615 \times 10^{-5}$ eV/°K	

as given by Hrostowski (Hrostowski *et al* 1955) and (2) and (3) in (1), one gets

$$\frac{1}{\mu_{\text{eff}}} = \frac{T^{1\cdot 68}}{1\cdot 09 \times 10^9} + \frac{1}{\beta T}, \tag{5}$$

where

$$\beta = \frac{32}{3\pi}\left(\frac{e}{m^*}\right)\left(\frac{1-\nu}{1-2\nu}\right)^2 \frac{k\hbar}{\epsilon^2 \lambda^2 N}. \tag{6}$$

Taking the derivative of (5) with respect to T, maximizing the resultant expression and solving for β, we get

$$\beta = 6\cdot 49 \times 10^8 \, T_0^{2.68}, \tag{7}$$

where T_0 is the peak temperature in the mobility versus temperature plot. The peak temperature values and the calculated β values of the deformed samples are tabulated in table 2.

For each of the three specimens S2, S3 and S4, μ_D as a function of temperature is calculated using the measured mobility values of deformed (μ'_{eff}) and undeformed (μ_{eff}) samples using the relation

$$\frac{1}{\mu'_{\text{eff}}} = \frac{1}{\mu_{\text{eff}}} + \frac{1}{\mu_D}. \tag{8}$$

The variation of μ_D with temperature can be seen in figure 4. For samples S2, S3 and S4, μ_D variation has two regions, region 1 which extends from 77°K$\sim$170°K, where μ_D is almost constant and region 2 from 170°K to room temperature where μ_D increases linearly. Experimentally measured values of β from the region 2 are also given in table 2. The arrived values of β using (7) more or less agree with the experimental values. The slight difference in them is because of the initial assumptions.

From (2) and (3) we get the dislocation density as

$$N = \frac{32}{3\pi}\left(\frac{1-\nu}{1-2\nu}\right)^2 \frac{k T \hbar e}{\epsilon^2 \lambda^2 \mu_D m^*}, \tag{9}$$

Table 2. Peak temperatures, values of β obtained by two methods, dislocation mobility and dislocation density of three samples S2, S3 and S4.

Sample No.	Measured T_0	β(cm^2/V-sec/°K) From Equation (7)	β(cm^2/V-sec/°K) From region 2 of figure 4	μ_D (cm^2/V-sec) at 300°K	N(per cm^3) at 300°K
S2	190	$5\cdot 07 \times 10^2$	$6\cdot 12 \times 10^2$	$1\cdot 2934 \times 10^6$	$2\cdot 9668 \times 10^8$
S3	225	$3\cdot 22 \times 10^2$	$3\cdot 04 \times 10^2$	$7\cdot 4684 \times 10^5$	$5\cdot 1380 \times 10^8$
S4	280	$1\cdot 79 \times 10^2$	$1\cdot 36 \times 10^2$	$4\cdot 3452 \times 10^5$	$8\cdot 8311 \times 10^8$

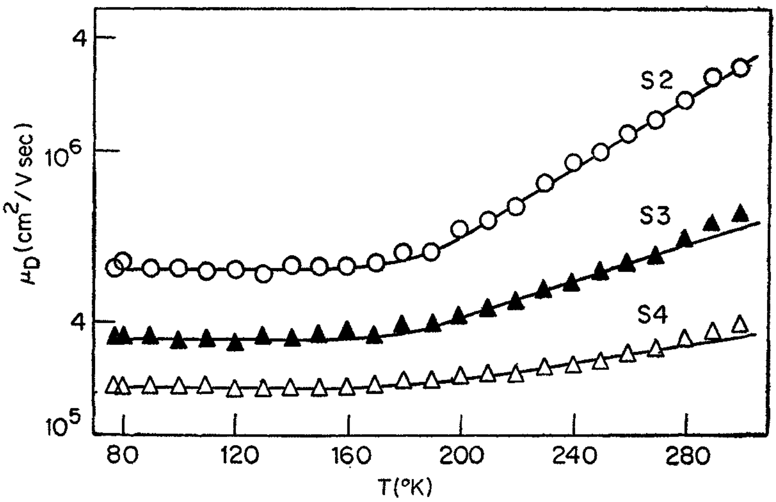

Figure 4. Temperature dependence of the dislocation mobility (μ_D *vs* T) of the three samples S2, S3 and S4. Two regions 1 and 2 are seen. Region 1 is independent of temperature and region 2 has a linear variation with temperature.

and substituting the value of μ_D at room temperature in this equation, dislocation densities have been calculated for the three samples and are given in table 2. Their order of magnitude are same as those observed by Duga (1962). Finally it is concluded that by this simple method of plastic deformation one can introduce dislocations in a controlled manner and study the effect of dislocations on galvanomagnetic properties.

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