Galvanomagnetic Effects of *n*-InSb below 1°K*

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Some galvanomagnetic properties of *n*-InSb have been measured in the temperature range 4–0.4°K with donor concentrations between 2.6×10^{15} and 7.5×10^{13} cm^{-3}. The electrical conductivity in zero magnetic field indicated the lack of freeze-out for all donor concentrations measured. The transverse magnetoresistance of samples with donor concentrations of 7.5×10^{13} and 1.0×10^{14} cm^{-3} showed a saturation in magnetic fields less than 10 kOe, provided that the temperature was less than 1°K. At temperatures above 1°K, the saturation was not observed in any of the samples in magnetic fields up to 16 kOe. A possible interpretation of the saturation effect is given by assuming a hydrogen-molecule model of the impurities and by taking the dominant scattering mechanism to be due to neutral impurities.

1. INTRODUCTION

THE electrical conductivity of *n*-InSb has been measured by Putley[1] in the temperature range 2–4°K. It does not decrease as predicted by a theoretical model which works well for other semiconductors such as *n*-type germanium and silicon.

The usual model that is assumed for donor impurities is a hydrogenlike atom. The ionization energy from such a model is the energy necessary to excite an electron from its lowest bound state into the conduction band. If this energy is much less than kT, where k is Boltzmann's constant and T is the absolute temperature, then most of the electrons should be bound to the impurity ion. The ionization energy can be calculated from the Bohr theory[2] by inserting the values of the effective mass and the dielectric constant. The ionization energy is given by

$$E=e^4m^*/2h^2\epsilon^2,$$

where e is the electronic charge, m^* is the isotropic effective mass, ϵ is the dielectric constant, and h is Planck's constant divided by 2π. For InSb, m^* is equal to $0.013m_e$, where m_e is the electron mass and $\epsilon=16$. Therefore $E=6.9\times10^{-4}$ eV. Now 6.9×10^{-4} eV corresponds to the thermal energy at approximately 8°K. Certainly at temperatures of the order of 4°K, the ionization energy should be detectable. Putley, however, found that at temperatures as low as 1.5°K and for a donor concentration of 5×10^{13} cm^{-3} no indication of an ionization energy was seen. These results indicate that the donor energy levels are merged with the conduction band.

In the experiments reported here, freeze-out was not observed at temperatures as low as 0.35°K and for donor concentrations down to 7.5×10^{13} cm^{-3}. A saturation of the transverse magnetoresistance was found at temperatures below 1°K for the lower concentrations. For the impurity concentrations and magnetic fields for which saturation was observed, the quantum limit condition $\hbar\omega\gg\epsilon_F$ has been satisfied, where ω is the cyclotron frequency and ϵ_F is the Fermi energy. The results and possible interpretations are discussed in Sec. 3.

2. EXPERIMENTAL TECHNIQUES

The polycrystalline *n*-InSb was received in cylindrical form with each item weighing approximately 20 g. Table I gives the excess donor concentration n, the Hall mobility μ, and the conductivity σ, all measured at 76°K.

The samples were sliced into rectangular bars with a diamond-edged wheel. They then were etched in CP-3, a modified solution of CP-4, without bromine. The samples were then rinsed in distilled water, etched again, and again rinsed in distilled water.

The electrical contacts were made with indium solder that had been doped with 1.7% tellerium. The tellerium was added to the indium solder so that the contacts would be heavily doped *n*-type. This was done to avoid *p-n* junctions between the contact and the crystal. The soldering was done with a pencil soldering iron operated from a Variac. Before an experiment was undertaken, the ohmicity of the contacts was checked at 76 and 4°K. Only those samples which exhibited ohmic behavior were used.

The lowest temperature achieved was 0.35°K. The refrigerator used was a bath of liquid He^3 connected to a vacuum pump which reduced the vapor pressure, and hence the temperature, of the bath. A bath of pumped liquid He^4 was used to cool and liquify the He^3 gas. A schematic drawing of the cryogenic system is shown

TABLE I. Properties of InSb samples.

Sample	n (cm^{-3})	μ (cm^{2}V^{-1} sec^{-1})	σ (Ω^{-1} cm^{-1})
2	4.6×10^{14}	9.1×10^5	...
4	7.5×10^{13}	3.1×10^5	3.70
5	1.0×10^{14}	3.2×10^5	5.21
6	2.6×10^{15}	1.4×10^5	57.5

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[1] E. H. Putley, Proc. Phys. Soc. (London) **73**, 280 (1959).
[2] R. B. Leighton, *Principles of Modern Physics* (McGraw-Hill Book Co., New York, 1959), pp. 72–75.

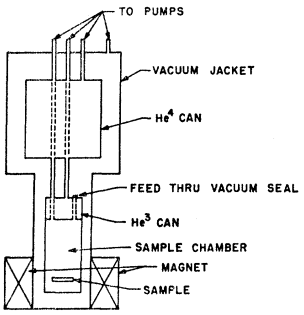

FIG. 1. Cryostat schematic (not to scale).

in Fig. 1. Helium exchange gas was used in the appropriate chambers to attain cooling and thermal equilibrium.

Temperatures were determined by measuring the vapor pressure of the liquid-helium baths. A mercury manometer and an oil manometer were attached to both the He^3 and the He^4 systems. A thermocouple vacuum gauge was installed in each system; these guages were used for the lower pressures attained. It was possible to determine the temperature from the vapor pressure of both the He^3 and the He^4 systems for temperatures between 1.1 and 2.5°K. The temperatures so obtained agreed to within 1%.

The magnetic fields were produced with a superconducting magnet with NbZr wire. The diameter of the wire, including the copper sheath, was 0.011 in. A calculation[3] of the homogeneity of the magnetic field showed that the field decreased by less than 1.5% within a distance of 1 cm either side of center. The maximum magnetic field obtainable was approximately 16 kOe.

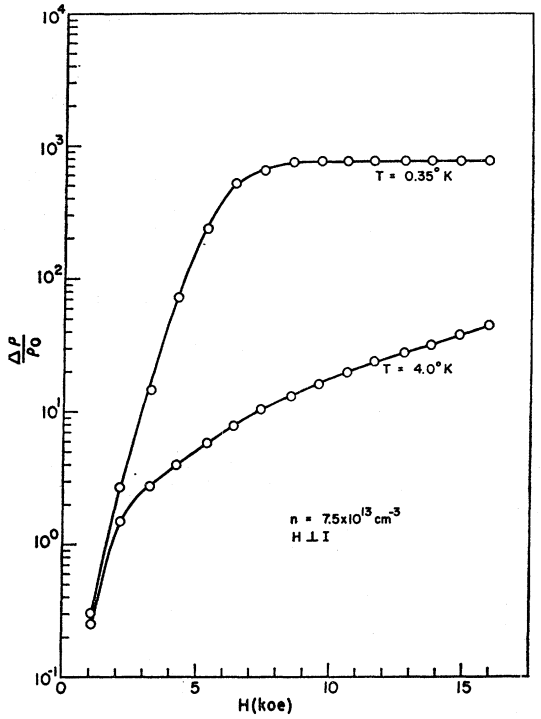

FIG. 3. Transverse magnetoresistance as a function of magnetic field for sample 4 showing saturation at 0.35°K but not at 4.0°K.

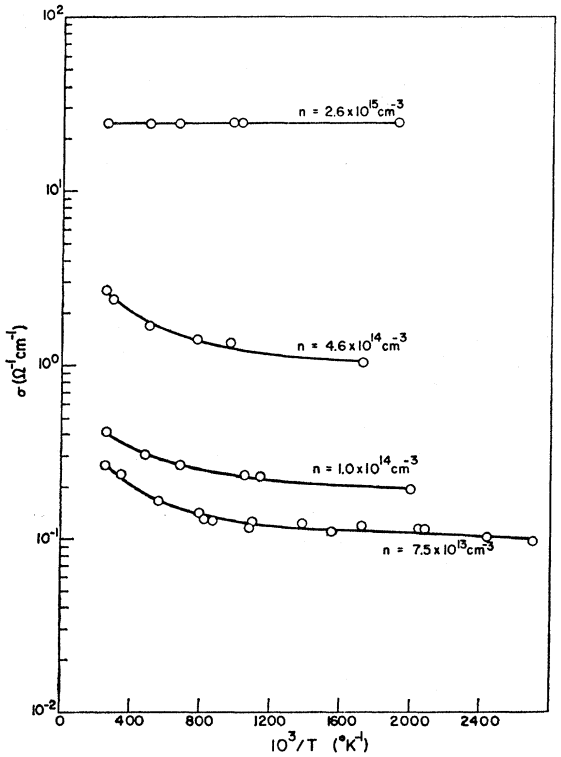

FIG. 2. Zero-field conductivity plotted against reciprocal temperature.

A direct current technique was used for all measurements reported. A battery in series with a large resistor and the sample provided a small measuring current. The chosen magnitude of the current was such that hot electrons effects were not a factor. The electric field in the sample caused hot-electron effects if it exceeded approximately 20 mV/cm at the lower temperatures.

3. DISCUSSION OF RESULTS

The conductivity curves in Fig. 2 show that freeze-out is not taking place at the temperatures and donor concentrations measured. The temperature independence of the conductivity in the sample with a donor concentration of 2.6×10^{15} cm^{-3} conceivably could be due to wave-function overlap. The overlap would cause the impurity band to be merged with the conduction band. It is improbable that the overlap could account for the lack of freeze-out in the samples with donor concentrations of the order of 1.0×10^{14} cm^{-3}. The data presented are consistent with the screening-effect

[3] K. S. W. Champion, Proc. Phys. Soc. (London) **B63**, 795 (1950).

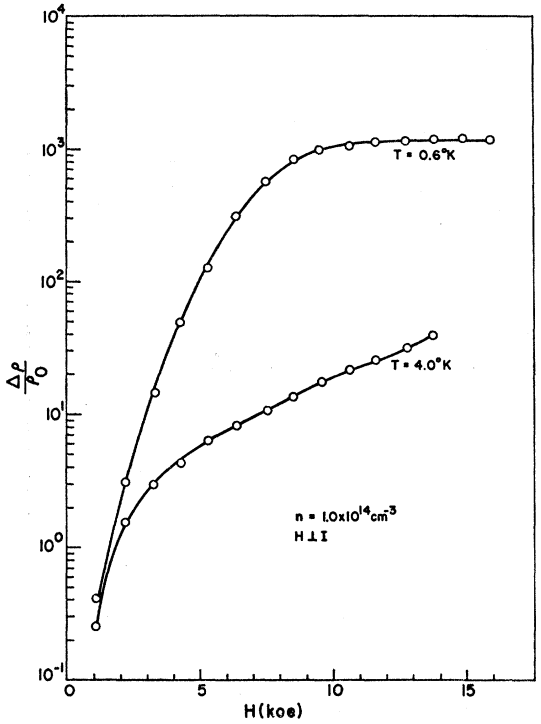

FIG. 4. Transverse magnetoresistance as a function of magnetic field for sample 5 showing saturation at 0.6°K but not at 4.0°K.

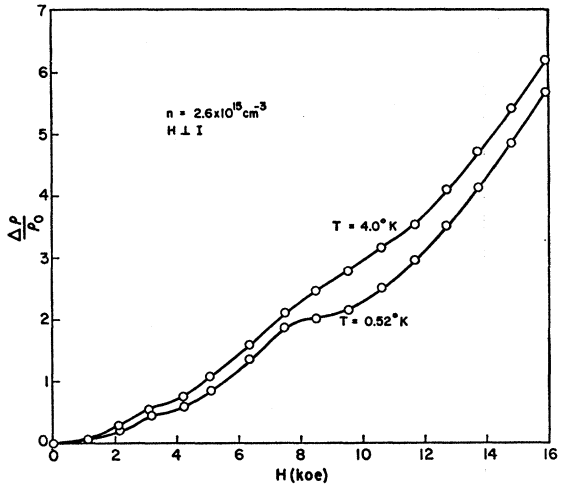

FIG. 5. Transverse magnetroesistance as a function of magnetic field for sample 6 showing oscillatory behavior.

model discussed by Li.[4] At 0.3°K, the calculated ionization energy has gone to zero for donor concentrations above about 6.1×10^{13} cm^{-3}. Therefore, if the screening model is correct, one would not expect the freeze-out to occur in any sample measured in this work.

The transverse magnetoresistance curves shown in Figs. 3 and 4 reveal a new behavior in n-type InSb that has not been previously reported. A very definite saturation in the magnetoresistance as a function of magnetic field was observed for temperatures below 1°K. The effect was seen in the samples with donor concentrations of 7.5×10^{13} and 1.0×10^{14} cm^{-3}, respectively. An entirely different behavior was observed for a donor concentration of 2.6×10^{15} cm^{-3} as shown in Fig. 5.

The saturation of the magnetoresistance would not be expected to occur if the normal magnetic freeze-out effect is operative. However, the calculations of Miller[5] on a hydrogen-molecule model of donor impurities in n-InSb indicate that even at 0°K there will be a fraction of donor electrons in the conduction band at these magnetic fields of the order of 10^{-8}. This is due to the fact that the exclusion principle causes the singly ionized state of two donors close enough together to be the state of lower energy if the magnetic field is high enough to cause alignment of the electron spins. This provides a mechanism for the resistivity to remain orders of magnitude smaller than otherwise expected as the field is increased. The explanation of the complete saturation can only be accomplished through detailed calculations. While not all scattering mechanisms lead to saturation of the relaxation time with increasing mag-

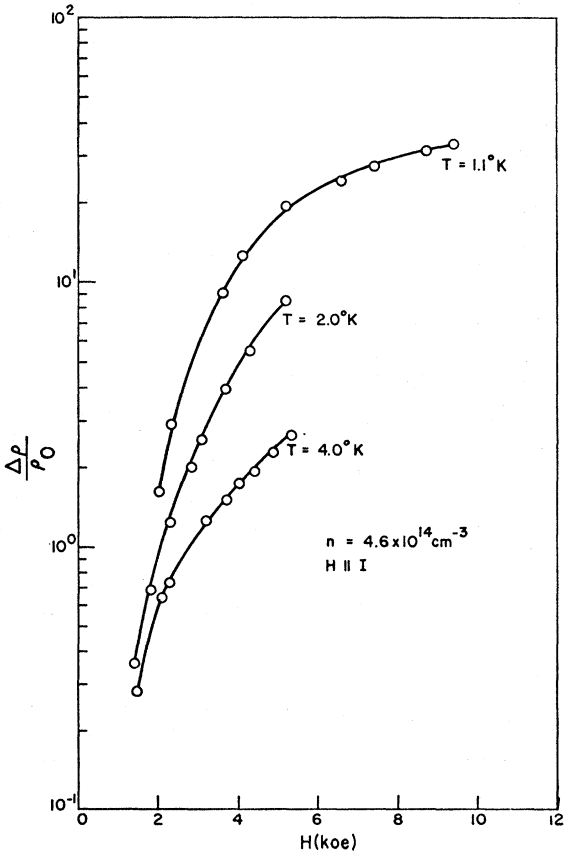

FIG. 6. Longitudinal magnetoresistance of sample 2.

[4] S. P. Li, dissertation, University of Colorado, 1966 (unpublished).

[5] S. C. Miller, Phys. Rev. 133, A1138 (1964).

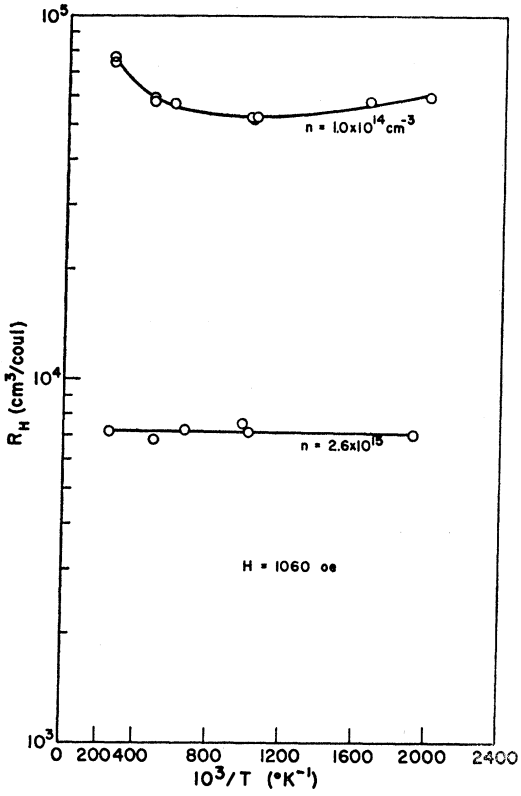

FIG. 7. Hall coefficient plotted against reciprocal temperature for samples 5 and 6.

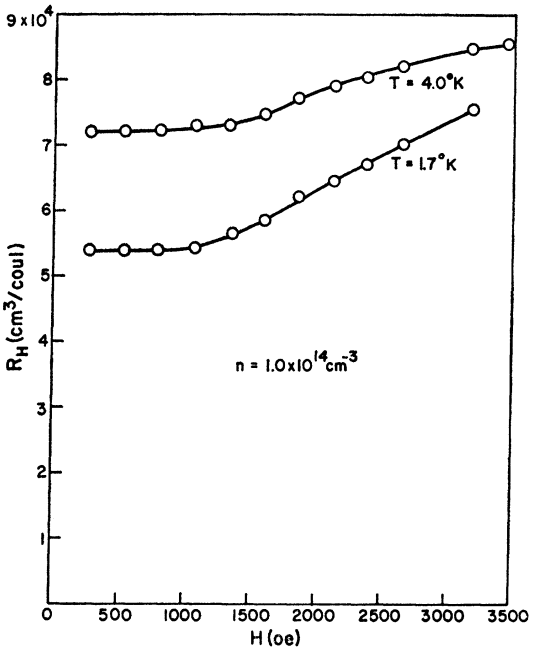

FIG. 8. Hall coefficient plotted against magnetic field for sample 5.

netic field, impurity scattering, which is expected to dominate at these temperatures, should lead to saturation.[6]

The oscillatory magnetoresistance effect in the sample with a donor concentration of 2.6×10^{15} cm^{-3} has been observed by several groups.[7,8] It is explained by a variation of the density of allowed states near the Fermi level. There was no evidence of a saturation taking place.

The longitudinal magnetoresistance curves in Fig. 6 show that the magnitude is much less than for the transverse case. Classically, the longitudinal magnetoresistance vanishes for a material having a spherical energy band. InSb is known to have an almost spherical energy band. Consequently, the low value of the longitudinal magnetoresistance was due to the sphericity of the band. It was difficult experimentally to align the sample exactly parallel to the magnetic field. Therefore, a part of the magnetoresistance could be due to a transverse component.

The Hall coefficient as a function of temperature is shown in Fig. 7. There was no temperature dependence of the Hall coefficient in the sample with a donor concentration of 2.6×10^{15} cm^{-3}. This was interpreted to mean that the number of electrons in the conduction band was constant. The behavior of the Hall coefficient with a donor concentration of 1.0×10^{14} cm^{-3} was quite puzzling. There was an initial decrease as the temperature was decreased. As the temperature was lowered further, the Hall coefficient increased slowly. Such behavior is not clear from a one-band model of the conductivity. Therefore, a more complicated model of the conduction process is indicated. Sladek[9] has reported work where a two-band model was used to analyze results.

The Hall coefficient was measured in a magnetic field of 1060 Oe. The true Hall coefficient should be measured in vanishingly small magnetic fields. The data in Fig. 8 showed that the Hall coefficient remains constant for magnetic fields up to about 1500 Oe. These data justified the use of a measuring magnetic field of 1060 Oe.

ACKNOWLEDGMENTS

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[6] E. N. Adams and T. D. Holstein, J. Phys. Chem. Solids **10**, 254 (1959).
[7] Y. Kanai and W. Sasaki, J. Phys. Soc. Japan **11**, 1017 (1956).
[8] H. P. R. Frederikse and W. R. Holser, Phys. Rev. **108**, 1146 (1957).
[9] R. J. Sladek, J. Phys. Chem. Solids **5**, 157 (1958).