Electrical Properties of n-Type InAs†

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Hall coefficient and resistivity were measured as functions of temperature on uncompensated indium arsenide specimens. A room temperature mobility of 30 000 cm^2/volt sec was obtained for a donor concentration of 1.7×10^{16} atoms/cm^3. For this impurity density, no indication of a separation of the donor level from the conduction band was observed.

IN recent investigations to determine better approximations to the lattice mobility in indium arsenide, the resistivity and Hall coefficient of a number of homogeneous n-type specimens of InAs having different impurity concentrations were measured at room temperature. On two of these specimens, measurements were also done as a function of temperature. Results indicate an electron mobility at temperatures below 500°K that is substantially larger than previously reported values.[1,2] The higher mobility is believed to result from a lowered total impurity concentration and possible improvements in the microscopic homogeneity.

The InAs was prepared from high-purity indium[3] and specially purified arsenic.[4] The elements were reacted using the two-furnace method, and the compound was zone melted in a closed tube. Neutron activation analysis indicated sulfur[5,6] to be a troublesome impurity in InAs. The identification was confirmed by establishing equality of segregation rates of the most slowly segregating impurity found in the InAs and that of sulfur which was purposely introduced into a pure ingot. It therefore followed that the first portion of the ingot to freeze contained sulfur and comparatively negligible quantities of other ionized impurities. Specimens of size $1.2\times0.4\times0.3$ cm, containing large crystallites, were cut from the zone-melted ingots. Hall coefficient and resistivity were determined at 300°K on specimens with impurity concentrations ranging from $1.7\times10^{16}/cm^3$ to $3.0\times10^{18}/cm^3$. The electron mobility ($R_H\sigma$) and resistivity of these specimens are shown in Fig. 1. Specimens containing the larger crystallites possessed electron mobility values which fell slightly above the curve, while in the very polycrystalline specimens, the mobility values fell

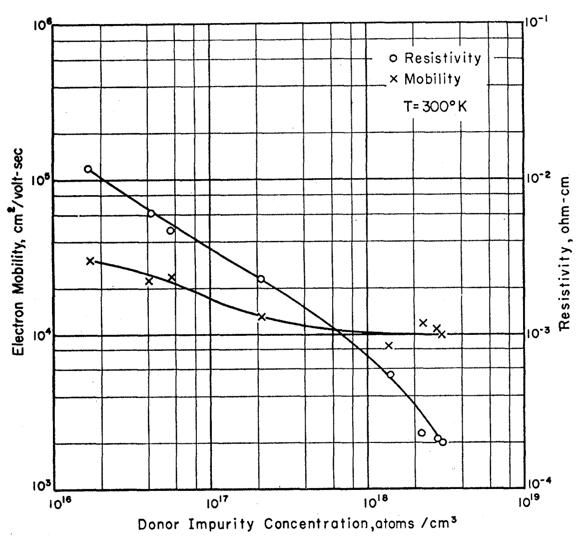

FIG. 1. Mobility and resistivity at room temperature as a function of donor concentration.

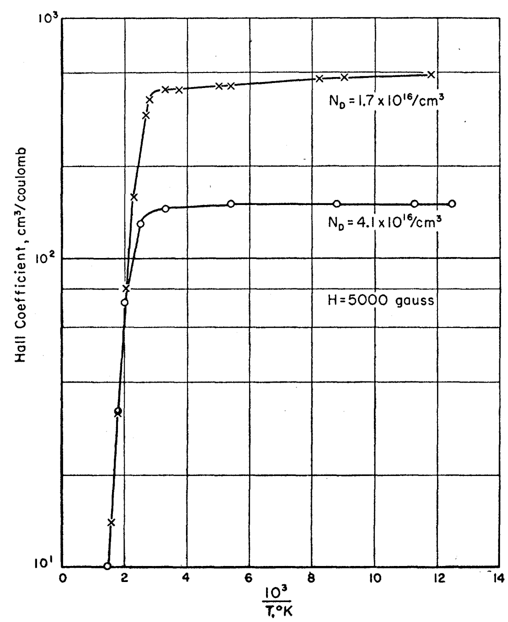

FIG. 2. Hall coefficient as a function of reciprocal temperature for two InAs specimens.

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[1] Folberth, Madelung, and Weiss, Z. Naturforsch. **9a**, 954 (1954).

[2] J. H. Taylor, Phys. Rev. **100**, 1593 (1955).

[3] For information on techniques for analyzing the purity of indium, consult T. C. Harman, J. Electrochem. Soc. **103**, 128 (1956).

[4] Details on the method of purification of the arsenic are being prepared for publication.

[5] The group at Naval Ordnance Laboratory has also found sulfur to be a troublesome impurity in InAs.

[6] Recent measurements on the segregation of impurities in InAs by Schillman give a coefficient of approximately 1.0 for sulfur [E. Schillman, Z. Naturforsch. **11a**, 463 (1956)].

considerably below the curve. It thus follows that the curve shown in Fig. 1 represents a lower limit for the electron mobility in uncompensated InAs with a high degree of crystalline perfection.

The temperature dependence of the Hall coefficient (at $H=5000$ gauss) for two samples having low extrinsic carrier concentrations is shown in Fig. 2. Before analyzing these data, we determined the Hall coefficient as a function of magnetic field strength, using fields ranging from 2000 to 5400 gauss at temperatures of 300°K and 80°K and found R_H to be independent of H. This result confirmed previous calculations that in the extrinsic region the high magnetic field condition is approached at $H=5000$ gauss. Thus, the electron mobility is given by the relation $\mu=R_H/\rho$ and the carrier concentration is $n=1/R_He$.

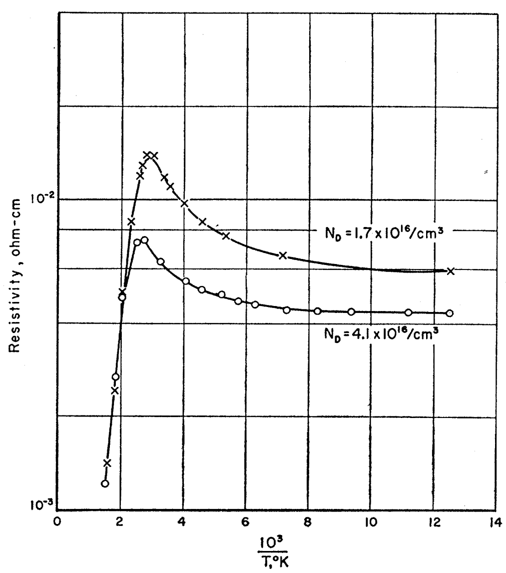

FIG. 3. Resistivity as a function of reciprocal temperature for two InAs specimens.

The resistivity as a function of temperature for the two specimens is shown in Fig. 3. The slope of the curve in the intrinsic region gives a value of 0.21 ev for $W_0/2$. This determination of W_0 agrees with the 0.43 ev obtained by Oswald[7] from optical measurements. Using the optical value for $\Delta W/\Delta T$ of -3.5×10^{-4} ev/°K, one obtains a room temperature band separation of 0.32 ev—a result substantially the same as that obtained from optical data.[7–9]

The electron mobility as a function of temperature[10] for the two specimens is shown in Fig. 4. It is seen that a reduction in impurity concentration from $4.1\times10^{16}/cm^3$ to $1.7\times10^{16}/cm^3$ results in an increased mobility at

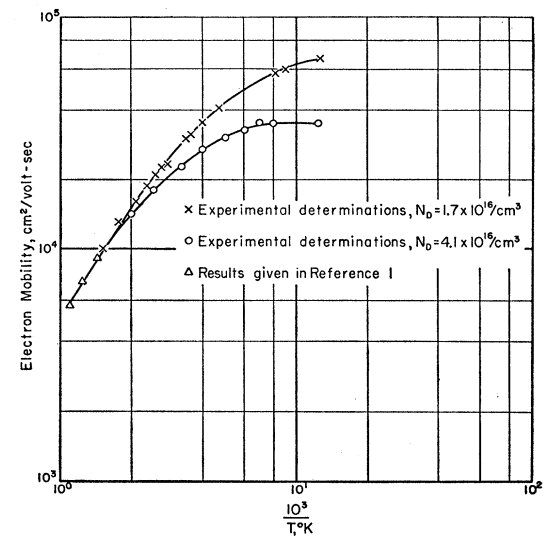

FIG. 4. Electron mobility as a function of reciprocal temperature for two InAs specimens.

temperatures below 500°K. Since impurity scattering is so significant in these specimens, no attempt was made to determine the temperature dependence of the lattice mobility.

The gradual increase in the extrinsic Hall coefficient with decreasing temperature of the sample containing approximately 1.7×10^{16} impurities per cm³ (Fig. 2) led us to wonder whether the donor concentration was low enough for the impurity level to be separated from the conduction band.[8] Dr. Fritzsche of Purdue University was kind enough to provide the answer to this question by carrying out measurements down as low as 1.3°K. The data are shown in Fig. 5. The behavior is very similar to that found in germanium having donor

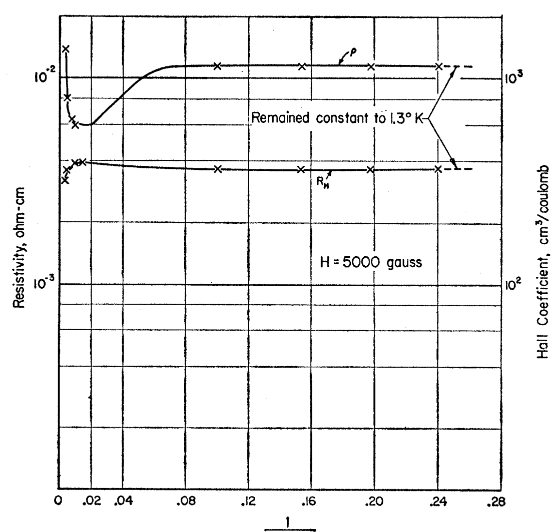

FIG. 5. Behavior of Hall coefficient and resistivity at low temperatures (measurements by H. Fritzsche of Purdue University).

[7] F. Oswald, Z. Naturforsch. **10a**, 927 (1955).
[8] F. Stern and R. M. Talley, Phys. Rev. **100**, 1638 (1955).
[9] H. J. Hrostowski and M. Tanenbaum, Physica **20**, 1065 (1954).
[10] Since the mobility of holes in InAs is less than 0.01 that of electrons (see reference 1), the relationship $\mu_e=R_H/\rho$ is adequate even in the intrinsic region.

concentrations in the 10^{17} range.[11] It thus appears that smaller donor concentrations must be achieved in InAs before the carriers can be frozen out at low temperatures. For a discussion of the contributions of impurity-band conduction in producing Hall effect maxima, the reader is referred to recent publications by Fritzsche[12] and Conwell.[13]

[11] P. P. Debye and E. M. Conwell, Phys. Rev. **93**, 693 (1954).
[12] H. Fritzsche, Phys. Rev. **99**, 406 (1955).
[13] Esther M. Conwell, Phys. Rev. **103**, 51 (1956).

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Magnetic Susceptibility of Dilute Cu Alloys at Low Temperatures

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The temperature dependence of the magnetic susceptibility of a number of dilute copper-tin and copper-iron alloys has been measured between room temperature and 4.2°K. The results indicate an anomalous paramagnetism in the neighborhood of the temperature of the observed resistance minimum in these alloys. Proposed models for the resistance minimum and impurity scattering are reviewed in the light of this new magnetic information.

1. INTRODUCTION

A PHENOMENON of considerable interest in solid state physics is the resistance minimum exhibited in dilute alloys at low temperatures. Since the initial discovery of this effect in gold by de Haas and van den Berg[1] numerous theoretical and experimental papers have appeared.[2,3] Although the occurrence of the resistive minimum appears to follow some order particularly with regard to valence and atomic size of solute present no sound physical explanation has been forthcoming. Perhaps the model that has proved most useful is that proposed by Korringa and Gerritsen.[3] These authors suggest that in order to explain the resistance minimum one needs to suppose that there is a cooperative phenomenon involving the conduction electrons which depends on the existence of localized states at the Fermi level. Unfortunately no theoretical evidence for the *existence* of these states has been found. However it seems certain that some cooperative interaction between conduction electrons and/or impurity ions must be the cause of the resistance minimum.

Since the total magnetic susceptibility of a metal is proportional to the density of states of the conduction electrons at the Fermi level and the spectroscopic state of the impurity ions, valuable information about the resistance minimum should be found through a study of the magnetic properties of alloys exhibiting the anomalous resistive behavior. It was with this in mind that a study of the magnetic susceptibility of these alloys has been started in this laboratory. Although the program is not yet complete, sufficient measurements have been made to make it worthwhile reporting some of the data obtained so far. Magnetic susceptibility measurements have been made on alloys containing impurity ions with unfilled *d* shells (magnetic) and filled *d* shells (nonmagnetic).

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[1] W. J. de Haas and G. J. van den Berg, Physica **1**, 1115 (1934).
[2] D. K. C. MacDonald and W. B. Pearson, Acta Metallurgica **3**, 392 (1955); **3**, 403 (1955). W. B. Pearson, Phil. Mag. **46**, 911 (1955); **46**, 920 (1955).
[3] J. Korringa and A. N. Gerritsen, Physica **19**, 457 (1953).

2. EXPERIMENTAL METHOD

2.1 Technique of Measuring the Susceptibility at Low Temperatures

Susceptibility measurements on metals at low temperatures present three main difficulties.

(a) Since the resistivity of a good conductor at 4.2°K is only about 10^{-3}–10^{-2} of its room temperature value, the problem of electromagnetic damping is quite serious at these low temperatures. In fact Bowers[4] calculated that critical electromagnetic overdamping makes it impossible to measure the susceptibility of a sample with a resistance ratio $R_{4.2}/R_{300}$ of 10^{-3} at temperatures below 30°K. Therefore, in order to obtain reliable results it is important that the sample should not swing freely in the magnetic field.

(b) Since the effects looked for in these alloys are small, it is extremely important that each alloy studied should be examined for ferromagnetic impurity. This

[4] R. Bowers, Phys. Rev. **100**, 1141 (1955).