MAGNETORESISTANCE AND HALL EFFECT IN ORIENTED SINGLE CRYSTAL SAMPLES OF *n*-TYPE INDIUM ANTIMONIDE

C. H. Champness

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C. H. CHAMPNESS

ABSTRACT

Measurements have been made on the angular dependence of the magnetoresistance effect and the Hall effect on oriented *n*-type indium antimonide samples. The measurements were taken at room temperature and liquid air temperature using a magnetic field strength of about 5000 gauss. Besides evidence of inhomogeneity, the results show directional dependence of the longitudinal magnetoresistance. The largest value was found in the ⟨100⟩ direction. This can be explained if, in addition to electrons at the central minimum, there is some filling of the ⟨111⟩ minima in **k** space.

1. INTRODUCTION

While a large amount of work has been done on the galvanomagnetic properties of *n*-type indium antimonide, there appears to have been no detailed rotational study using oriented single crystal specimens. Possibly one reason for this is that it was thought that such work would not show up anything special because cyclotron resonance and preliminary magnetoresistance experiments had indicated that, unlike germanium, the conduction band electrons of indium antimonide had an isotropic effective mass. However, it is instructive to review briefly some of the experiments supporting the idea of spherical energy surfaces.

The observation of cyclotron resonance carried out by Dresselhaus, Kip, Kittel, and Wagoner (1955) was isotropic under a rotation in a (100) plane. This indicates that at the temperature of the experiment, namely 4° K, spherical energy surfaces prevail. In the room temperature cyclotron resonance experiments of Burstein *et al.* (1956) and of Keyes *et al.* (1956) rotation of the crystals was not carried out. Hence isotropy at room temperature has not been definitely established.

So far as magnetoresistance is concerned, the first angular dependence was studied by Pearson and Tanenbaum (1953) on a polycrystalline sample which was *p*-type below 175° K. This work showed that the magnetoresistance almost vanished when the current (I) and the magnetic field (H) were parallel. Measurements on *n*- and *p*-type single crystal samples at room temperature and 77° K were later carried out by Tanenbaum, Pearson, and Feldman (1954); the samples were cut with their current axes along the [100] and the [110] directions. They reported that they obtained the same results as on the polycrystalline material but no published curves of these particular measurements have appeared. Other workers, however, have found that the magneto-

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resistance does not fall to zero when I and H are parallel. Work on degenerate polycrystalline material by Mansfield (1955) showed that the longitudinal magnetoresistance could be an appreciable fraction of the transverse effect. Work on two single crystal unoriented samples by Frederikse and Hosler (1957) showed in one case a longitudinal magnetoresistance which was positive at small fields but became negative as the magnetic field was increased; the other sample showed a positive effect for I parallel to H but underwent changes of sign to negative and then back to positive values as the angle between I and H was increased. Using pulsed fields up to 180 kilogauss, Haslett and Love (1959) found longitudinal magnetoresistance values up to 25 at 78° K. At this temperature they found that no "freeze out" effects occurred (Keyes and Sladek 1956). Both Frederikse and Hosler and Haslett and Love state that the non-zero longitudinal magnetoresistance can be explained on the basis of a quantum transport treatment such as that of Argyres and Adams (1956). It is difficult to believe that this is so, at least as far as room temperature is concerned. At this temperature and a field of 10^4 gauss, the reduced Landau splitting energy $\hbar\omega_c/kT$ would only be about 0.15, taking as the effective mass ratio a "room temperature" value of 0.03. Here ω_c is the cyclotron resonance angular frequency, T is the absolute temperature, $\hbar$ is Planck's constant divided by 2π, and k is Boltzmann's constant.

According to Herman (1955), the band structure of indium antimonide should be similar to that of the group four elements with minima in **k** space at the center of the reduced zone, along the $\langle 100\rangle$ axes and along the $\langle 111\rangle$ axes (see Fig. 1). To explain the cyclotron resonance experiments at 4° K, it

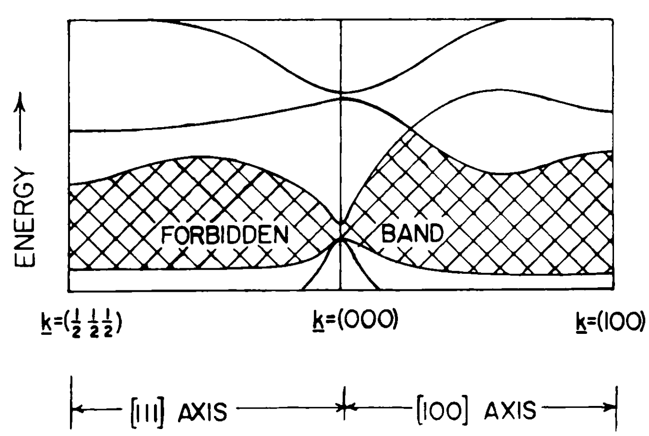

FIG. 1. Schematic energy band diagram for indium antimonide (after Herman 1955).

is supposed that the central minimum must lie below the other minima; the non-central minima are therefore assumed to be unpopulated at low temperatures. Two questions arise. Firstly, how does the presence of an impurity band affect the picture and secondly do the non-central valleys become populated at higher temperatures?

In order to throw some light on these questions, some magnetoresistance measurements were made at room temperature and liquid air temperature on oriented single crystal samples. The measurements were made as a function of the angle θ between I and H using the same method as that described by

Pearson and Suhl (1951) on germanium. Specifically, the special point of interest was to find the magnitude of the longitudinal magnetoresistance and to see if it was directionally dependent. Some possible evidence for deviation from perfectly spherical energy surfaces was found by Bate, Willardson, and Beer (1959). They found a hump in the variation of the Hall coefficient with magnetic field. However, it is learned (private communication) that this effect may have been due to inhomogeneity in the samples.

2. SAMPLES

Three samples were cut from a single crystal of *n*-type indium antimonide with long axes in the [100], [110], and [111] directions. The other faces of the samples were cut as in Fig. 2. The sample dimensions were approximately

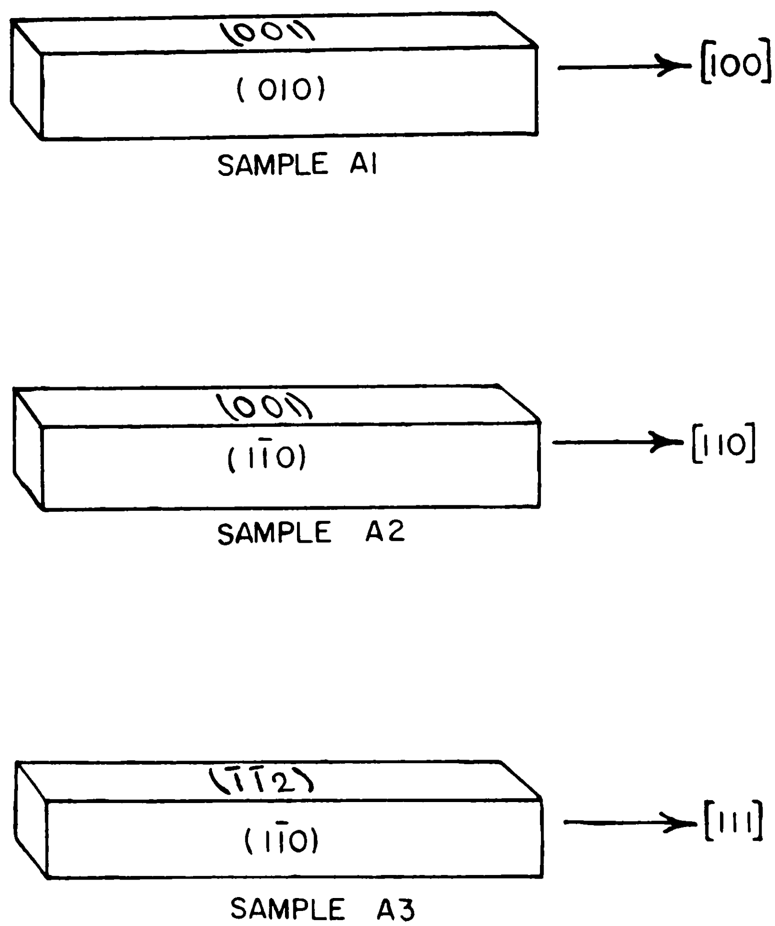

FIG. 2. The orientations of the three samples used for measurement.

$7\times1\times1$ mm. The material was kindly supplied by the Minneapolis Honeywell Research Center. Figures for the Hall coefficient, conductivity, and Hall mobility taken from the measurements described later are shown in Table II. The mobilities can be roughly accounted for taking into account impurity scattering with 3×10^{15} as the number of impurity centers/cc from the liquid air Hall coefficient. There is therefore no appreciable compensation present.

3. METHOD OF MEASUREMENT

Each of the samples was mounted in a special sample holder consisting of a micarta rod with a double flat filed at one end. The sample was mounted in a slot cut at right angles to the axis of the rod (Fig. 3). The ends of the sample were indium soldered to two small screws tapped in the base of the slot. The screws were made from thin brass wire using a watchmaker's die. Short lengths of platinum wire 0.003 in. in diameter and coated with indium were used for

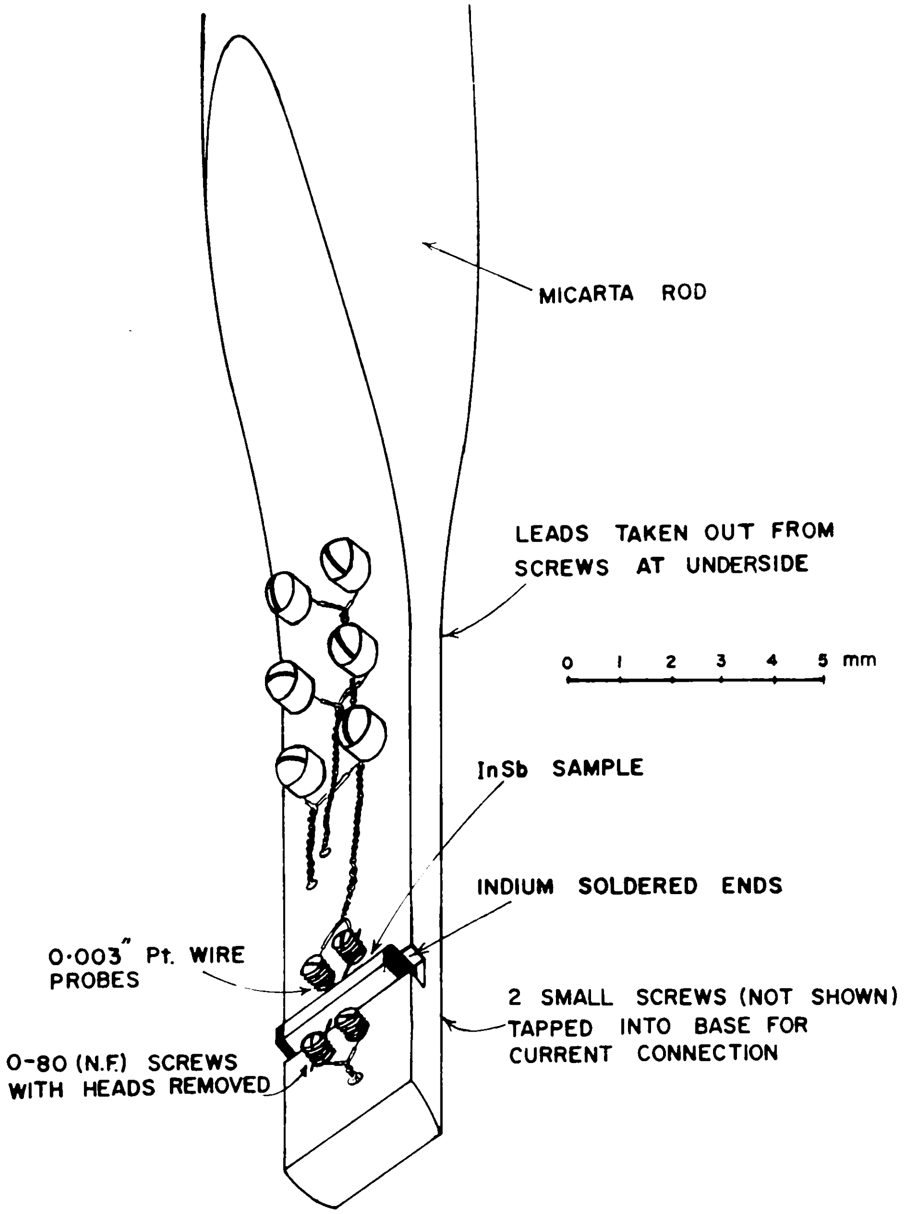

FIG. 3. Sample holder used in the measurements.

the potential probes. These were threaded through small transverse holes drilled in 0–80 (N.F.) screws using watchmakers' drills. The heads of the 0–80 screws were sawn off and screwdriver slots cut in the stems. By twisting the screws in the holder, it was possible for the platinum wires to make contact with the sides of the sample. Good electrical contact was ensured by discharging a 2.5-μf condenser at 50 volts between each probe and one end of the sample.

Four probes were used on each sample so that two conductivity and two Hall readings could be taken. The sample holder was mounted vertically between the poles of a rotatable 6-in. electromagnet. Alignment of the long sample axis (current axis) with the magnetic field was done by eye. With the sample fixed, the electromagnet could be rotated round it so as to obtain any angle θ between I and H (Fig. 4).

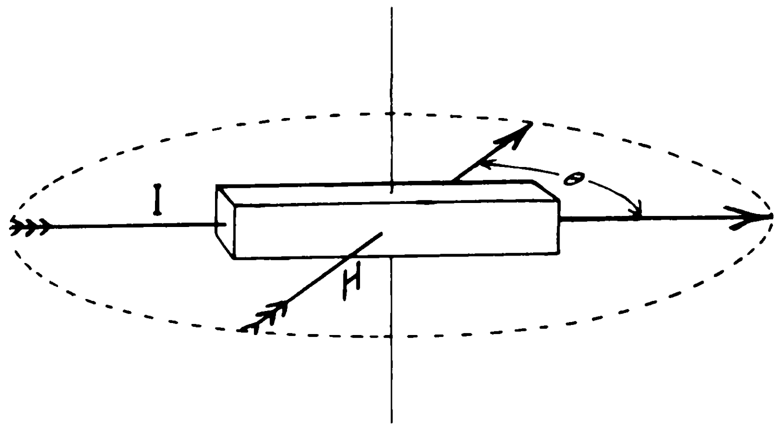

FIG. 4. Schematic diagram showing the position of the probes and the angle of rotation of the magnetic field.

A constant current (I) of about 10 ma at room temperature and 1 ma at liquid air temperature was passed through the sample and four potential difference readings were taken at a time using a Leeds and Northrup K.2 potentiometer. To avoid thermoelectric effects, the current was reversed through the sample. To distinguish clearly between the magnetoresistance and the Hall effects, the magnetic field was also reversed for each set of readings. Because of this field reversal, it was only necessary to make the measurements over an angle of 180° of rotation.

Measurements were also made of the variation of the Hall coefficient, transverse magnetoresistance, and longitudinal magnetoresistance with magnetic field strength up to 4880 gauss. The results of this part of the work will be reported in a later publication.

4. EXPERIMENTAL RESULTS

4.1. Angular Dependence of Magnetoresistance

The variation of the magnetoresistance ratio $\Delta\rho/\rho_0$ with the angle θ is given in Figs. 5, 6, 7, and 8 for the three samples; measurements in two planes of rotation of H were carried out on sample A2. Here ρ_0 is the zero field resistivity and $\Delta\rho$ is the increase in the resistivity due to a magnetic field. In the measurements, the magnetic field was maintained at 4880 gauss.

The experimental curves in Figs. 5 to 8 show the following general features:

(*a*) The magnetoresistance is not zero when I and H are apparently parallel at $\theta = 0°$.

(*b*) The positions of the minima in general deviate from $\theta = 0°$.

(*c*) The magnetoresistance values at the minima are not zero.

(*d*) Negative values occur for some of the minima at room temperature as well as at liquid air temperature.

(*e*) Negative values do not occur together on the two sets of probes; if one pair gives a negative value the other pair gives a positive one at the same temperature.

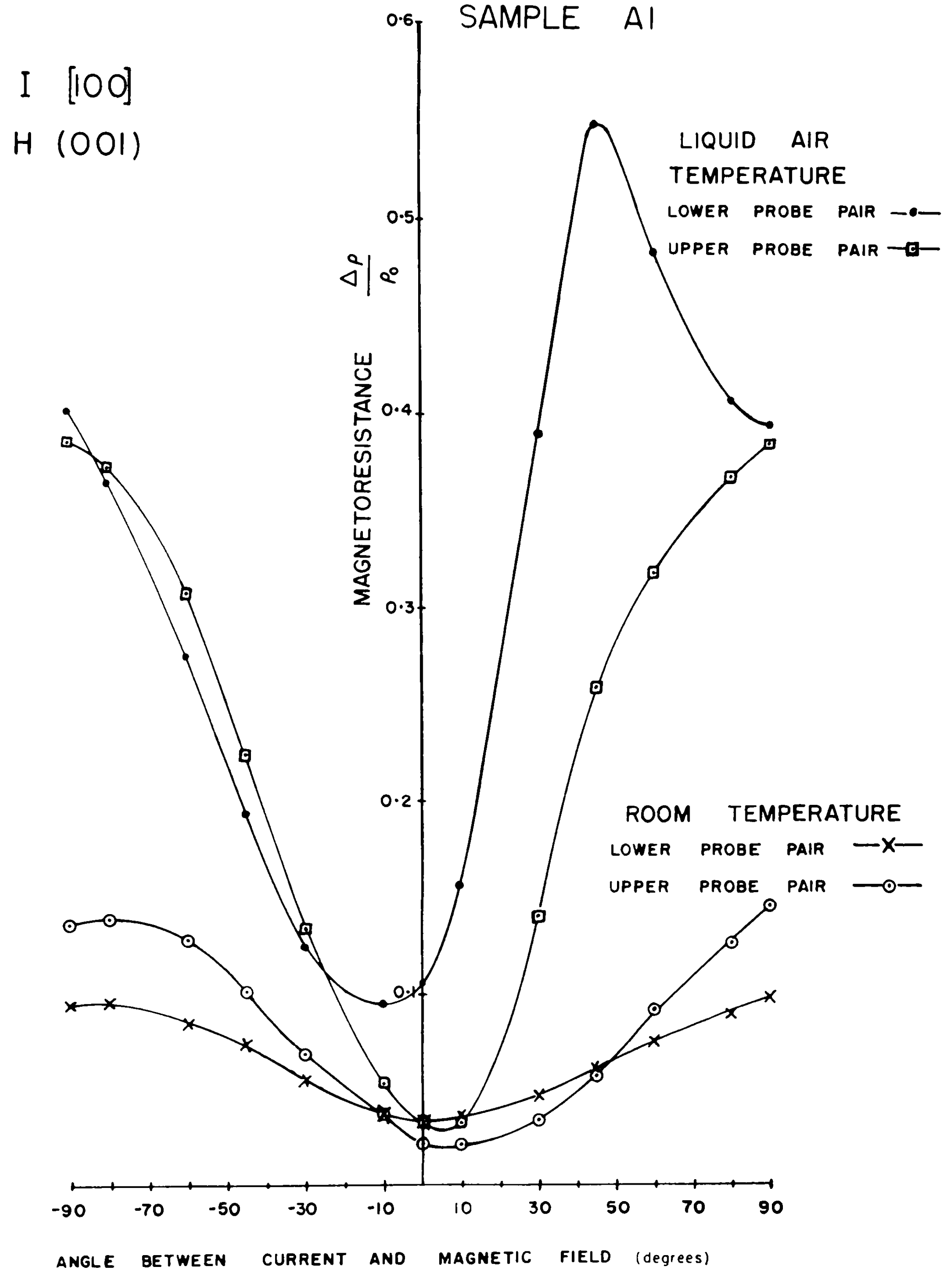

FIG. 5. Variation of the magnetoresistance in the [100] direction of sample A1 with rotation of the magnetic field (4880 gauss) in an (001) plane.

(*f*) The maxima in general are displaced in the same direction as the corresponding minima. Most of the minima are displaced to the right of the origin.

(*g*) The values at the minima for the [100] sample (A1) are larger than for the other cases. In particular, no negative magnetoresistance is observed either at room or at liquid air temperature on this sample.

(*h*) There are no subsidiary minima near $\theta = 0°$, such as were observed by Frederikse and Hosler (1957).

(*i*) Apart from the above-mentioned deviations, the curves have roughly the shape of a $\sin^2\theta$ curve, which would ideally correspond, for weak fields, to spherical energy surfaces.

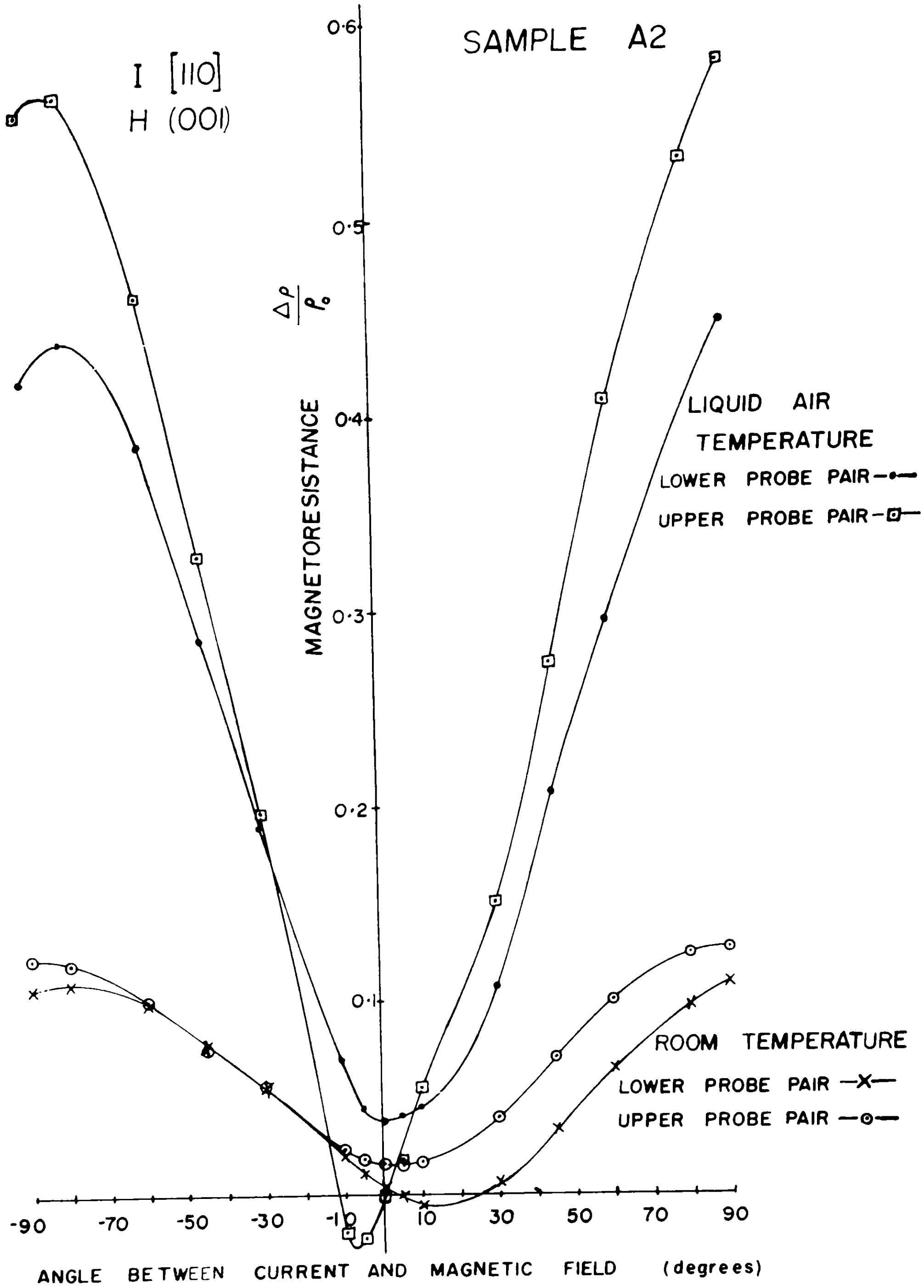

FIG. 6. Variation of the magnetoresistance in the [110] direction of sample A2 with rotation of the magnetic field (4880 gauss) in an (001) plane.

TABLE I

Average magnetoresistance values at 4880 gauss on three oriented samples

		Transverse magnetoresistance $\Delta\rho/\rho_0$			Longitudinal magnetoresistance $\Delta\rho/\rho_0$		
Sample	Current direction	Room temp. (298° K)	Liq. air temp. (77–90° K)	Magnetic field direction	Room temp. (298° K)	Liq. air temp. (77–90° K)	Magnetic field direction
A1	[100]	0.116	0.46	[010]	0.028	0.061	[100]
A2	[110]	0.117	0.51	[$1\bar{1}0$]	0.0045	0.01	[110]
		0.110	0.41	[001]	0.008	−0.02	[110]
A3	[111]	0.105	0.30	[$\bar{1}\bar{1}2$]	−0.006	0.0075	[111]

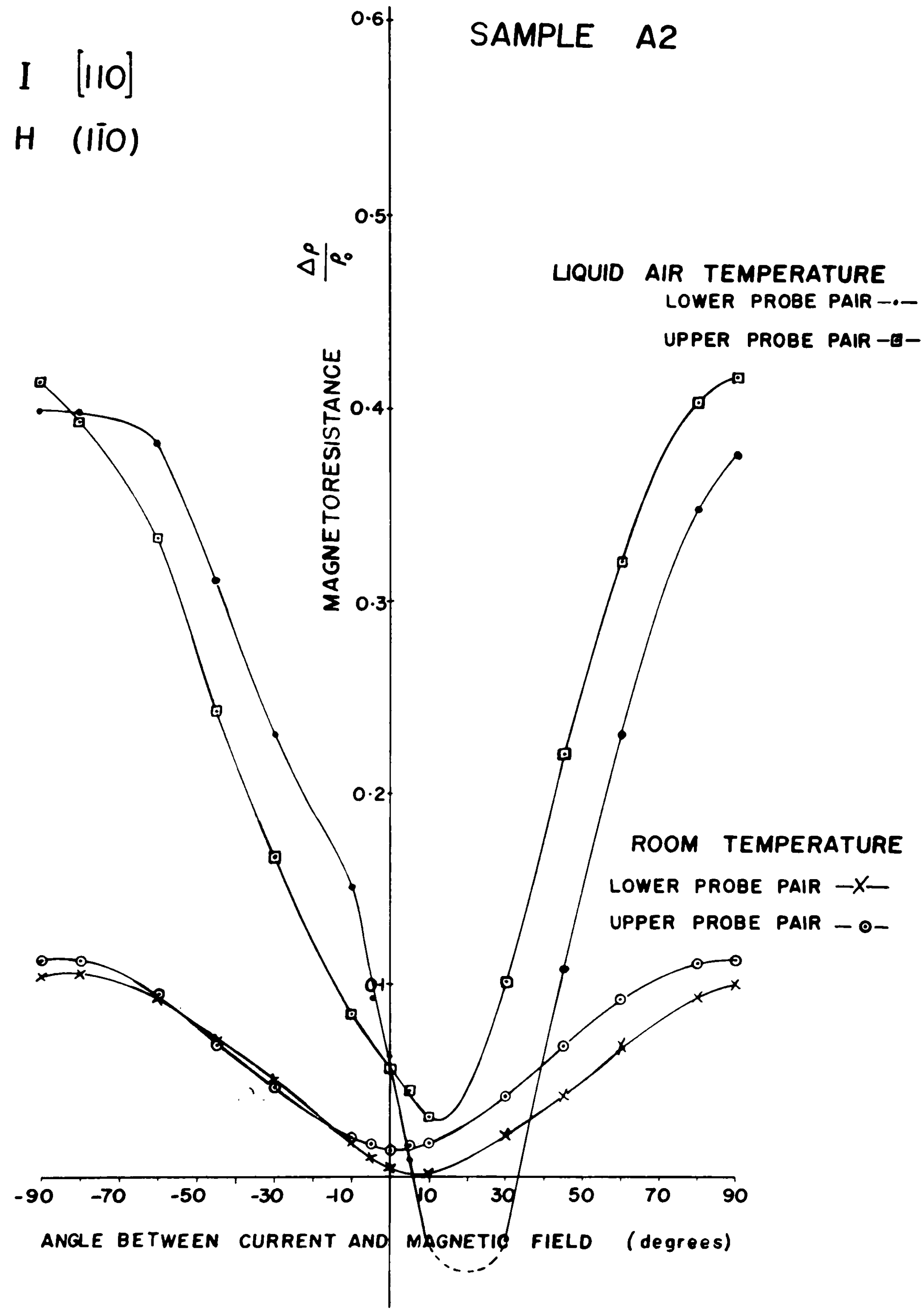

FIG. 7. Variation of the magnetoresistance in the [110] direction of sample A2 with rotation of the magnetic field (4880 gauss) in a $(1\bar{1}0)$ plane.

For the longitudinal magnetoresistance, values were taken at the minima rather than at $\theta = 0°$. Table I shows these values together with the transverse magnetoresistance values averaged, in both cases, for the two sets of probes. It is clearly seen from the table that the longitudinal effect is largest in the [100] direction both at room temperature and at liquid air temperature. The smallest effect is not so clearly shown; it is apparently in the [111] direction at room temperature and in the [110] direction at liquid air temperature. The transverse effect does not appear to show any marked dependence on direction.

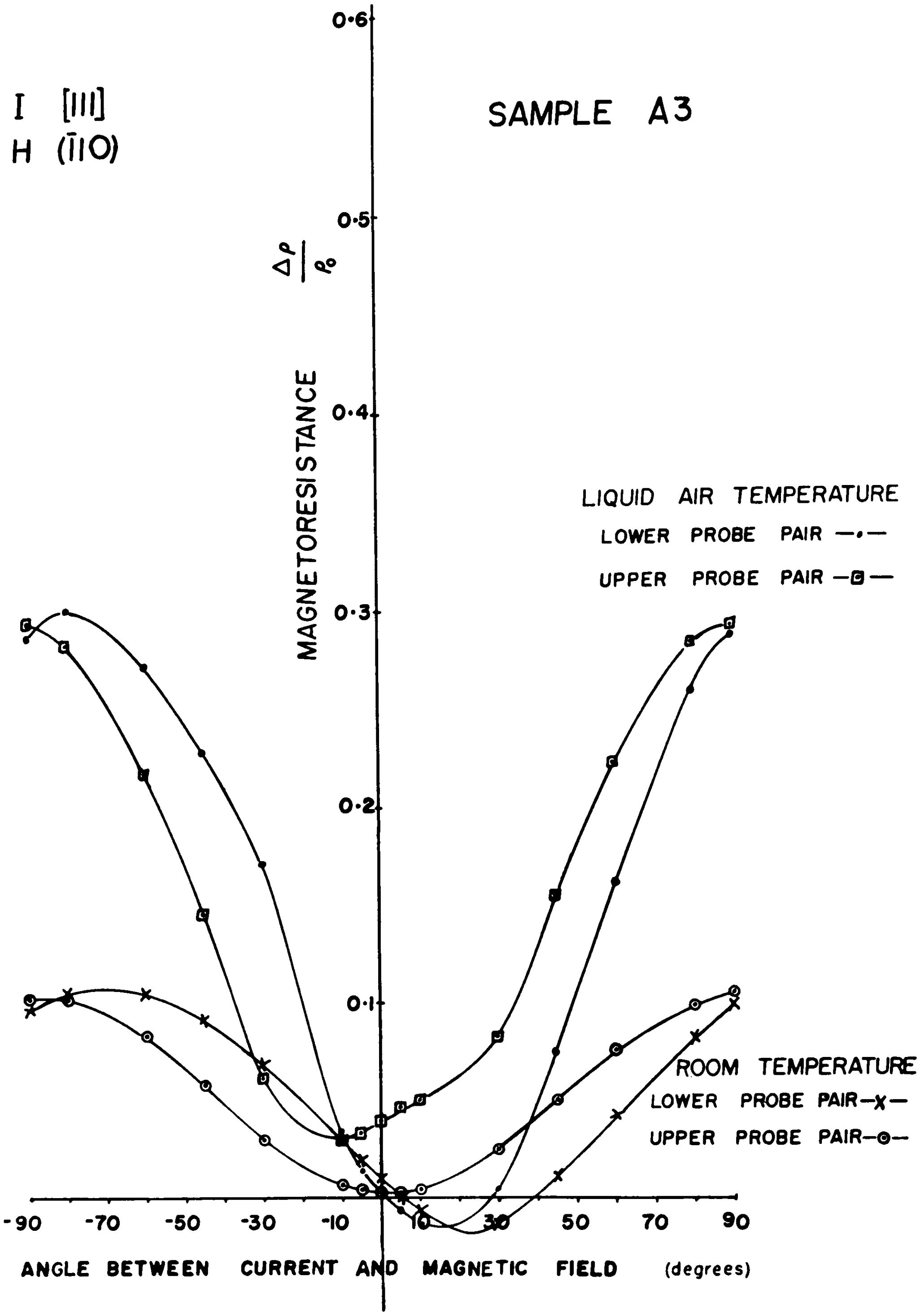

FIG. 8. Variation of the magnetoresistance in the [111] direction of sample A3 with rotation of the magnetic field (4880 gauss) in a $(\bar{1}10)$ plane.

4.2. Angular Dependence of Hall Effect

From the readings, values of the quantity $10^8 V_H t/IH$ cm^3/coulomb were worked out (V_H is the Hall potential difference measured across the sample in volts, I is the sample current in amperes, H is the magnetic field in oersteds, and t is the sample thickness in centimeters). This quantity, which could be called the reduced Hall voltage, is equal to the Hall coefficient (R_H) when I and H are perpendicular to each other. Ideally it would be equal to $R_H \sin \theta$. It is plotted against θ for the three samples in Figs. 9, 10, 11, and 12 corresponding respectively to the previous four sets of magnetoresistance data in

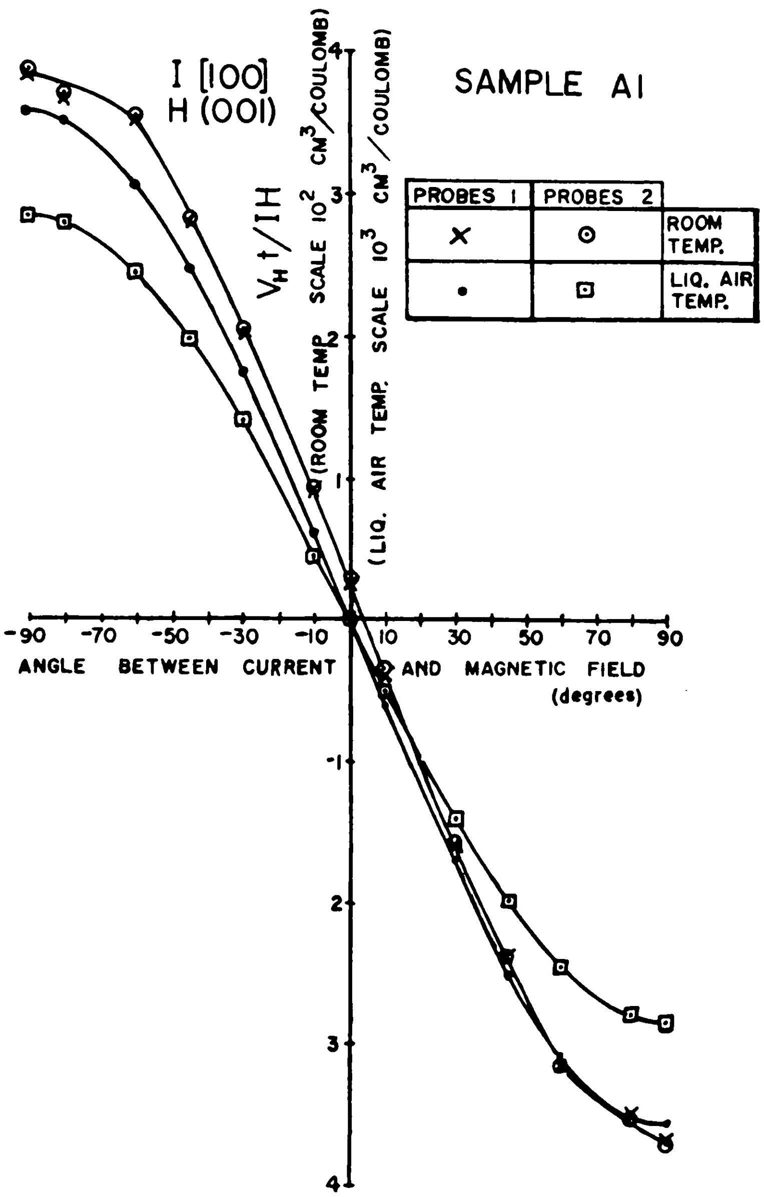

FIG. 9. Variation in sample A1 of the reduced Hall voltage $10^8 V_H t/IH$ for current in the [100] direction with rotation of the magnetic field (4880 gauss) in an (001) plane.

Figs. 5, 6, 7, and 8. The curves show the following features:

(*a*) The variation with angle appears to be as sin θ.

(*b*) The Hall zeros occur much closer to $\theta = 0°$ than the corresponding magnetoresistance minima; the largest deviation is about 6° whereas the largest magnetoresistance deviation is about 25°.

(*c*) The results on the two sets of probes agree well at room temperature.

(*d*) At liquid air temperature, the Hall voltages on the two pairs of probes differ from each other by something like a third. Hence, there is a gradient of electron concentration, at this temperature, of about a third or so in the distance of a probe spacing, which is about 0.15 cm.

The averaged values of the Hall coefficient for the two pairs of probes are given in Table II, together with (zero field) conductivity and Hall mobility values. The conductivities in the three samples are not exactly the same. That in the [100] direction (A1) is rather less than the others. The difference ought not to be directly connected with crystal directions because the cubic symmetry

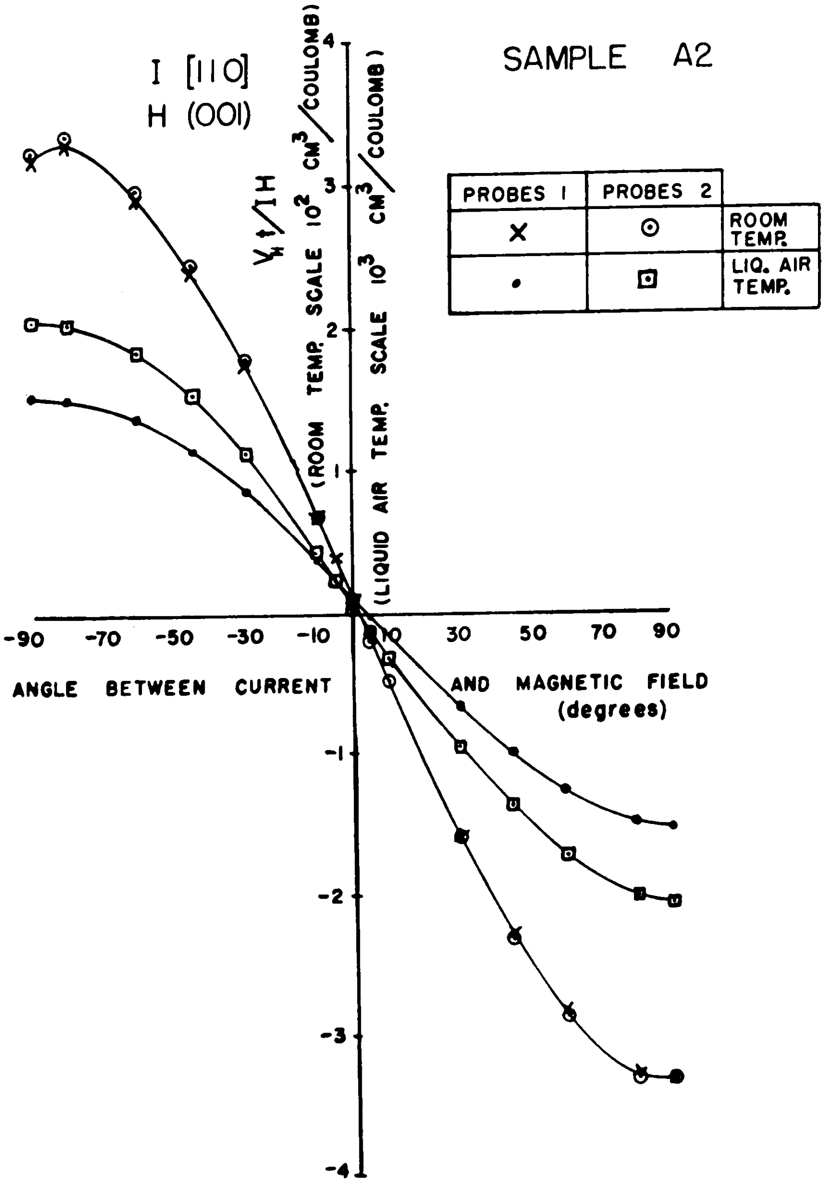

FIG. 10. Variation in sample A2 of the reduced Hall voltage $10^8 V_H t/IH$ for current in the [110] direction with rotation of the magnetic field (4880 gauss) in an (001) plane.

of the zinc blende lattice implies isotropic conductivity in the absence of external fields. It is rather a matter of an actual difference in the samples themselves. It is clear from the table, in fact, that the conductivity in sample A1 is lower than the other two samples because both the electron concentration and the mobility are smaller; the reason for these two things being smaller is, however, not known.

5. DISCUSSION

According to Herring (1955), the longitudinal magnetoresistance vanishes along the principal axes of an ellipsoidal energy surface in **k** space. An array of ellipsoids along the ⟨100⟩ axes, as in silicon for instance, would give a zero effect along the three directions [100], [010], and [001]. For ellipsoids arrayed along other axes, it would not be possible to find directions which would be parallel to all the principal axes at the same time and so there would be no

TABLE II

Average conductivity and Hall coefficient values on three oriented samples

Sample	Current direction	Conductivity σ: σ at room temp. (Ω^{-1} cm^{-1})	Conductivity σ: σ at liq. air temp. (Ω^{-1} cm^{-1})	Conductivity σ: Face on which probes were placed	Hall coefficient R_H at H = 4880 gauss: R_H at room temp. (cm^3/coulomb)	Hall coefficient R_H at H = 4880 gauss: R_H at liq. air temp. (cm^3/coulomb)	Hall coefficient R_H at H = 4880 gauss: Magnetic field direction	Hall mobility: $R_H\sigma$ at room temp. (cm^2/v sec)	Hall mobility: $R_H\sigma$ at liq. air temp. (cm^2/v sec)
A1	[100]	164	28.2	(001)	-3.7×10^2	-3.18×10^3	[010]	6.07×10^4	8.97×10^4
A2	[110]	199	55	(001)	-3.3×10^2	-1.79×10^3	$[1\bar{1}0]$	6.57×10^4	9.85×10^4
		197	53	$(1\bar{1}0)$	-3.3×10^2	-1.77×10^3	[001]	6.50×10^4	9.38×10^4
A3	[111]	209	53	$(\bar{1}10)$	-3.15×10^2	-1.77×10^3	$[\bar{1}\bar{1}2]$	6.58×10^4	9.38×10^4

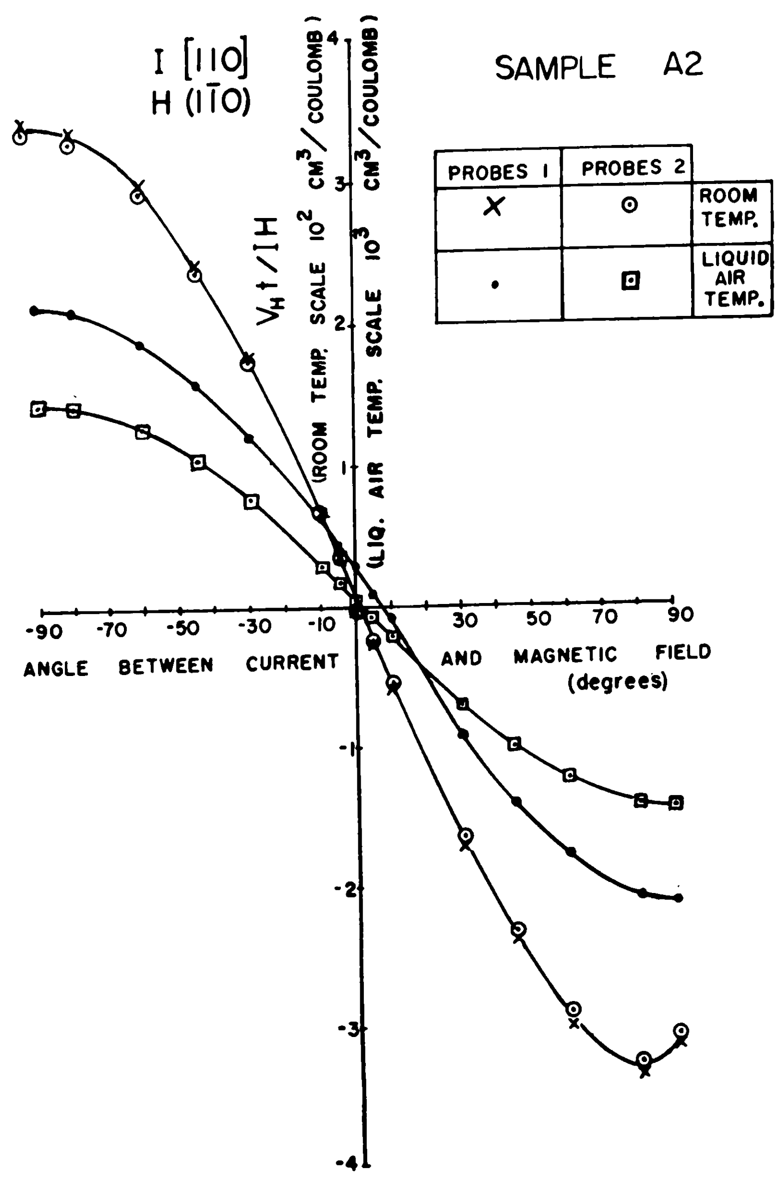

FIG. 11. Variation in sample A2 of the reduced Hall voltage $10^8 V_H t/IH$ for current in the [110] direction with rotation of the magnetic field (4880 gauss) in a (1$\bar{1}$0) plane.

directions of zero magnetoresistance. However, the longitudinal magnetoresistance would be a minimum for certain directions which are nearly parallel to principal ellipsoidal axes. Conversely, the longitudinal magnetoresistance would be a maximum for those directions which are the most skew to the principal axes. Consideration of the theoretical results of Shibuya (1954) for just the ⟨100⟩, ⟨110⟩, and ⟨111⟩ directions shows that of these the directions of greatest magnetoresistance are the ⟨111⟩ directions for a model (*a*) with ellipsoids along ⟨100⟩ axes, ⟨100⟩ or ⟨110⟩ for (*b*) ellipsoids along ⟨110⟩ axes, and ⟨100⟩ for (*c*) ellipsoids along ⟨111⟩ axes.

The experimental results shown in Table I appear, from the above considerations, to be consistent with a model in which the energy surfaces consist of a central sphere and a set of ellipsoids along the ⟨111⟩ directions. In other words, the band structure is that postulated by Herman (1955) with the ⟨111⟩ minima low enough to be populated, at least above liquid air temperature. This assumed model would predict (Glicksman 1958) for weak fields in the ⟨100⟩,

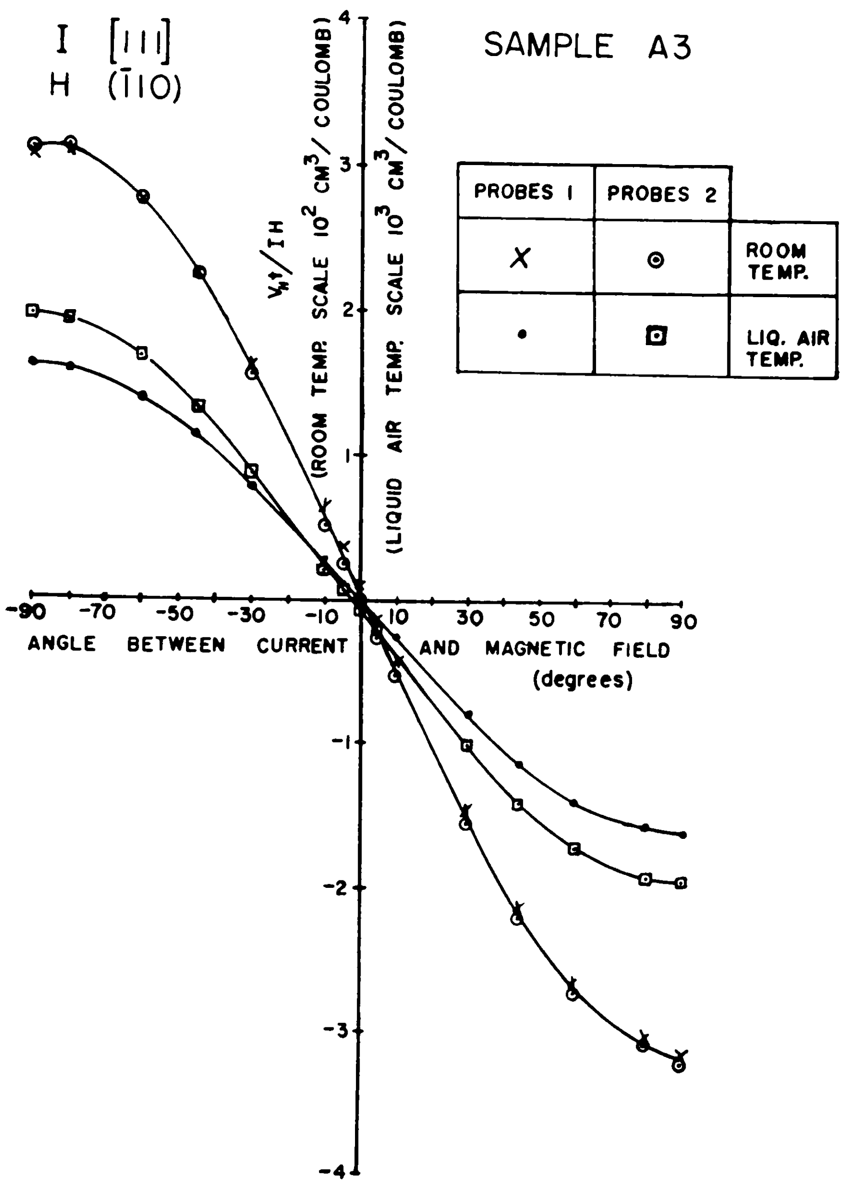

FIG. 12. Variation in sample A3 of the reduced Hall voltage $10^8 V_H t/IH$ for current in the [111] direction with rotation of the magnetic field (4880 gauss) in a $(\bar{1}10)$ plane.

$\langle 110 \rangle$, and $\langle 111 \rangle$ directions longitudinal magnetoresistance values in the ratio 6:3:2 respectively.* For strong fields, the relative values would depend to a certain extent on K, the ratio (Abeles and Meiboom 1954) of the longitudinal to the transverse mass for the electrons in the ellipsoids. For instance, taking the saturation longitudinal magnetoresistance coefficients worked out by Shibuya (1954, in this paper $K = 1/r$), we find the relative values are approximately 10:6:3 for $K = 0.5$ and 8:3:3 for $K = 2$. The transverse magnetoresistance in this model would be almost entirely due to the central spherical energy surfaces. This is borne out by the fact that the transverse values given in Table I appear to have no significant directional dependence. It should be mentioned that anisotropy in the relaxation time could also explain the observed results.

The impurity band in indium antimonide would have to be taken into

*The ratio would be $b+c+d : b+c+d/2 : b+c+d/3$ with $b+c = 0$ using the notation of Glicksman (1958).

account in inferring band structure from the experimental data. It is not known how this could be done but one could hazard a guess that the impurity band would have an isotropic average mass and would "add" to the central minimum.

In addition to the trends shown in Table I, the results exhibit marked evidence of inhomogeneity in the samples. This is shown up by the effects (*b*), (*d*), (*e*), and (*f*) of Section 4.1 and effects (*b*) and (*d*) of Section 4.2. Further evidence for inhomogeneity is the fact that sometimes, in the taking of the potentiometer measurements, the relative values of the readings at zero magnetic field would change order in going from room temperature to liquid air temperature. The deviations of the magnetoresistance minima from $\theta = 0°$ cannot be due to error in alignment because the Hall zeros occur much nearer the origin. For the same reason deviations cannot be due predominately to currents flowing in directions not parallel to the sample axis. However, the negative effects can be explained on the basis of the following idealized model. Let us suppose a sample consisted of two halves of different conductivity joined together as in Fig. 13. The current in the absence of a magnetic field

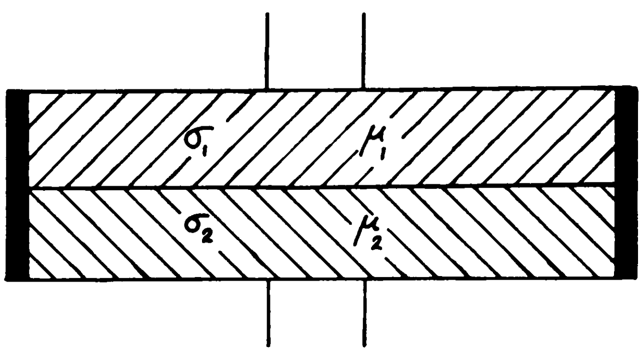

FIG. 13. Hypothetical sample with one half having a different conductivity from the other half. Redistribution of the current in such a sample in the presence of a magnetic field could lead to an apparent negative magnetoresistance.

would divide itself in the ratio of the conductances of the two halves. Now in the presence of a magnetic field the current would redistribute itself. For instance, if the upper part had a higher mobility than the lower part, it would have a larger magnetoresistance effect and so it would receive less current in the presence of a magnetic field. The lower half would at the same time receive more current. Thus the probes on the upper half would show an apparent increase in the magnetoresistance and those on the lower half would show a reduced or even a negative apparent magnetoresistance. In fact the samples have probably a more complex form of conductivity inhomogeneity than the one just considered but the same general effect would occur.

It is possible that the observed anisotropy in the longitudinal magnetoresistance could also be due in some way to inhomogeneity and not to band structure. However, the larger longitudinal effect in sample A1 cannot be attributed to a larger mobility. Table II shows in fact that the Hall mobility is smaller than for the other two samples. Furthermore, the transverse effect in this sample is not significantly different from the values on the other two samples. Nevertheless, it is hoped to repeat, in the near future, measurements on another [100] sample cut from the same ingot. Definite existence of the anisotropy cannot be really decided upon until such measurements have been made on a number of n-type indium antimonide crystals.

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