Magnetoresistance and Hall effect in n-type indium antimonide in the magnetic freeze-out region

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Magnetoresistance and Hall effect in n-type indium antimonide in the magnetic freeze-out region

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Abstract. Measurements on n-type indium antimonide down to 0·3 K are described of the resistivity in a magnetic field (0–40 kG) both parallel and perpendicular to the current, and of the Hall effect. Increases of resistivity by a factor of 10^{10} are observed before the resistivity becomes too high to measure provided special care is taken over the preparation of the surface of the specimen. A saturation of resistivity with increase of magnetic field is sometimes observed and this is attributed to the effect of a conducting surface layer. The resistivity approximates to the form $\rho^{-1} = \rho_{01}^{-1} \exp(-E_1/kT) + \rho_{03}^{-1} \exp(-E_3/kT)$. The E_1 region is identified with magnetic freeze-out and the E_3 region with electrons hopping between donor centres. Good agreement is obtained between theory and experiment for the magnetic field dependence of ρ_{03}.

1. Introduction

Indium antimonide with an excess of donor centres does not exhibit freeze-out of the electrons from the conduction band on to the donor centres as the temperature is lowered provided it is not heavily compensated. This is because the donor centres have such a low activation energy and such a large radius that their energy levels merge with the conduction band. When a magnetic field is applied the donor activation energy E_D increases and the radius of the donor centres decreases (Yafet, Keyes and Adams 1956, referred to as YKA). For moderate fields the resistivity is still quasi-metallic, being independent of temperature down to 1·5 K or lower but there is a critical field when a metal–non-metallic transition occurs (Ishida and Otsuka 1977). For donor concentrations up to 10^{15} cm^{-3} the critical field is less than 10 kG for samples having a compensation ratio of a half. For fields greater than the critical field freeze-out occurs either as the temperature is reduced or as the magnetic field is increased since this causes a further increase in the donor activation energy. Work described here is primarily concerned with the non-metallic range. Many papers have already been published covering this region but there have been discrepancies in the experimental results and differing interpretations of results.

In the non-metallic region the conductivity tensor $\boldsymbol{\sigma}$ is due to a combination of $\boldsymbol{\sigma}_c$ due to conduction by the electrons remaining in the conduction band and $\boldsymbol{\sigma}_i$ due to conduction by electrons hopping between donor centres. The components of the current

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density $\boldsymbol{J}$ in terms of the electric field $\boldsymbol{E}$ with the magnetic field along the z-axis are given by

$$\begin{aligned} J_x &= \sigma_{xx}E_x + \sigma_{xy}E_y \\ J_y &= \sigma_{yx}E_x + \sigma_{yy}E_y \\ J_z &= \sigma_{zz}E_z \end{aligned} \tag{1}$$

where

$$\sigma_{xx} = (\sigma_{xx})_c + (\sigma_{xx})_i \text{ etc.}$$

Experiments provide values for the components of the resistivity tensor

$$\begin{aligned} E_x &= \rho_{xx}J_x + \rho_{xy}J_y = \rho_\perp J_x - RBJ_y \\ E_y &= RBJ_x + \rho_\perp J_y \\ E_z &= \rho_{zz}J_z = \rho_\parallel J_z \end{aligned} \tag{2}$$

where

$\rho_{xx} = \rho_\perp$ = resistivity in a tranverse magnetic field
$\rho_{xy} = -\rho_{yx} = -RB$
$\rho_{zz} = \rho_\parallel$ = resistivity in a longitudinal magnetic field
R = Hall coefficient, B = magnetic field.

Hence the components of the conductivity tensor are obtained using

$$\begin{aligned} (\sigma_{xx})_c + (\sigma_{xx})_i &= \rho_\perp^{-1}[1 + (RB\rho_\perp^{-1})^2]^{-1} \\ (\sigma_{xy})_c + (\sigma_{xy})_i &= -RB\rho_\perp^{-2}[1 + (RB\rho_\perp^{-1})^2]^{-1} \\ (\sigma_{zz})_c + (\sigma_{zz})_i &= \rho_\parallel^{-1}. \end{aligned} \tag{3}$$

It is not possible to determine independently the individual contributions to the conductivity tensor and it is difficult therefore to separate out the conduction electron contribution in order to follow the freeze-out of the electrons over a wide range of concentrations to find the donor activation energy. Mansfield (1971) assumed that the component $(\sigma_{xy})_i$ which is determined by the Hall effect is negligible because conduction amongst the donors is by hopping and there is evidence from other materials that the Hall effect due to hopping is much less than that produced by a band process. In this case the electron concentration can be obtained from

$$ne/B = RB\rho_\perp^{-2}[1 + (RB\rho_\perp^{-1})^2]^{-1} \tag{4}$$

and the donor activation energy E_D derived using

$$\frac{n(N_A + n)}{N_D - N_A - n} = N_c \exp\left(\frac{-E_D}{kT}\right). \tag{5}$$

The donor activation energy so obtained is less than the theoretical values deduced by YKA. The discrepancy may be due to a combination of the effect of screening (Ortenberg 1973) and of the spread of energies of the donor levels (Dyakanov *et al* 1969). Robert *et al* (1973) used this method for analysing their results on indium antimonide using magnetic fields up to 200 kG. The donor activation energy was deduced, not from (5) but by making

use of the approximation that E_D is proportional to $B^{1/3}$ and by plotting $\log(n/B)$ versus $B^{1/3}$. This approximation should be satisfactory at very high fields. They also obtained similar agreement between experimental and theoretical values of E_D.

The resistivity with a longitudinal field has also been used to determine the free-electron concentration. It has two advantages, firstly its reciprocal gives the conductivity σ_{zz} directly and secondly $(\sigma_{zz})_c$ is greater than $(\sigma_{zz})_i$ over a greater range of magnetic fields and temperatures than the corresponding transverse components σ_{xx} because for the latter $(\sigma_{xx})_c$ is reduced by a term $(1 + (\omega_c\tau)^2)^{-1}$ which has a large effect in this case since $\omega_c\tau \gg 1$. Mansfield and Ahmad (1970) assumed $(\sigma_{zz})_c \gg (\sigma_{zz})_i$ and that the mobility u of the free electrons is constant. Then n and E_D can be calculated using $\sigma_{zz} = neu$. The values of E_D obtained were closer to the YKA values but this method may not be so reliable because it assumes a mobility independent of magnetic field.

Measurements on the resistivity tensor are not the only method of investigating the donor activation energy. Optical measurements are also available. There are two types of investigations. Firstly, optical absorption and photoconductivity in the far infrared have been investigated giving clear evidence that a large magnetic field localises the donor centres and gives rise to an activation energy which agrees with theory (Kaplan 1969). These measurements also show absorption due to electrons being raised to excited states as well as being raised to the conduction band and the excited levels could also be interpreted theoretically. The second type of optical experiment is based on cyclotron resonance. Kaplan *et al* (1973) observed resonant absorption of both the electrons in the conduction band and electrons in the impurity centres. Their relative populations could be observed as the magnetic field was changed. The relative population of electrons in impurity centres and the conduction band has also been observed to vary when an electric field is applied (Oka and Narita 1970). The field causes excitation of electrons from donor centres to conduction band and this is shown by the relative changes in absorption maxima due to impurity and conduction band transitions on the Landau ladder of energy levels.

The investigations on transport properties quoted so far assume the exponential decrease of carrier concentration and also the increase of longitudinal resistivity with T^{-1} are simply due to an activation energy which is identified with the donor activation energy. Now experiments on a number of semiconductors at low temperature show that the resistivity can be represented by the expression (Fritzshe 1955)

$$\sigma = \rho^{-1} = \rho_{01}^{-1} \exp(-E_1/kT) + \rho_{02}^{-1} \exp(-E_2/kT) + \rho_{03}^{-1} \exp(-E_3/kT). \tag{7}$$

This equation has been applied to the resistivity of indium antimonide in a magnetic field but because of the tensor form of the resistivity it is only valid for the longitudinal resistivity. On a logarithmic plot of the resistivity against reciprocal of the temperature successive linear regions are observed with activation energies E_1, E_2 and E_3. Each of these regions has been interpreted as being due to a different process so that the total conductivity is the sum of contributions from each process. Thus the E_1 region has been associated with conduction due to electrons excited from donor levels to the conduction band with energy $E_1 = E_D$, E_2 with excitation of electrons to extended conducting states and E_3 with an activated hopping process (The use of a logarithmic plot to determine E_1 etc will be valid provided the energies are sufficiently different; a simple check shows that this is the case here).

Ferre *et al* (1975) measured the transverse resistivity over a similar range of temperatures and magnetic fields as Mansfield and Ahmad and Robert *et al* but they attributed

the dominant linear part of the log(ρ) versus T^{-1} plot to the E_2 region, that is excitation to extended states instead of with the donor activation energy. This led Pepper (1976) to point out that the common pre-exponential term ρ_{02} for different magnetic fields which Ferre *et al* observed is in good agreement with the minimum metallic conductivity estimated by Mott (1972). In fact applying equation (7) to the transverse resistivity is not valid since $(RB\rho_\perp^{-2})^2 > 1$ and consequently from equation 3 $\rho_\perp^{-1} \neq \sigma_{xx}$. Furthermore a common intercept on the resistivity axis could be explained as the saturation resistivity obtained when all the carriers are excited into the conduction band provided the mobility is independent of the transverse magnetic field, which is approximately the case for ionised impurity scattering (Adams and Holstein, 1959). It is possible that the upper (Hubbard) band overlaps the conduction band giving $E_2 = E_1 = E_D$ but from the cyclotron resonance studies and from measurements presented here the excited electrons appear to have a mobility appropriate to electrons in the conduction band.

Below the E_1/E_2 regions impurity conduction occurs and for low donor concentration, which applies here, the donor centres are localised and conduction occurs by hopping. At very low densities of donors an electron hops between donors without being affected by neighbouring hops. In this case according to Shklovskii and Efros (1971) and to Pollak (1970) the conductivity is determined by the Coulomb interaction energy between a majority and minority ion with $E_{Coul} = e^2/Kr$ where K is the dielectric constant and r the average intermajority distance. Shklovskii and Efros show that the activation energy E_3 is given by $\theta e^2/Kr$ where $\theta = 1{\cdot}6$ but a lower value of θ is suggested by Knotek and and Pollak (1974). For a higher density of donors Knotek and Pollak suggest that neighbouring hops may affect each other and may be correlated. In this case the activation energy is reduced below E_{Coul} by an amount dependent on the density of donors. The transition density N_C from uncorrelated to correlated hops is determined by

$$N_C = (4/3\pi R_C^3)^{-1} = \frac{3}{4\pi}\left(\frac{2KkT}{\theta a e^2}\right)^{3/2} \tag{8}$$

where a is the Bohr radius of the impurities.

Measurements on p-type germanium by Gadzhiev and Shlimak (1973) and Knotek (1977) show such a decrease in E_3 with increase in the concentration of acceptors, the majority dopant in this case. Furthermore an increase in E_3 is observed on application of a magnetic field which was interpreted as due to a reduction in the amount of correlation in the hopping process.

The pre-exponential term ρ_{03} is determined by the overlap of neighbouring majority ion wavefunctions and here there are two cases depending on the strength of the magnetic field. Mikoshiba (1962) and Shklovskii (1973) have considered the case for moderate fields when the percolation paths are not altered and the expression they obtain agrees with the work on p-type germanium. For strong magnetic fields when the percolation paths are affected Shklovskii (1973) has shown that

$$\rho_{03} = \rho_0 \exp(\lambda^2 a_B N_D)^{-1/2} \tag{9}$$

where $a_B = a[\ln(a/\lambda)^2]^{-1}$, $\lambda^2 = c\hbar/eB$. The transition between moderate and strong fields is given by (Gadzhiev and Shlimak)

$$B_c = \frac{\sqrt{24}\, c\hbar}{aet} N_D^{1/3} \qquad t = 0{\cdot}8\text{–}0{\cdot}9. \tag{10}$$

For indium antimonide the strong field condition applies for $B > 1500$ G when $N_D =$

$4 \times 10^{14}\,\mathrm{cm}^{-3}$ and corresponding lower values of N_D. The authors are unaware of results which are in satisfactory agreement with (9). Gershenzon *et al* (1974) have studied hopping conduction in n-type indium antimonide and for low magnetic fields obtained agreement with the Mikoshiba–Shklovskii formula. Their measurements were on two highly compensated samples which have abnormally large activation energies and which have been the subject of a separate series of investigations (Yaramenko 1975). These specimens agreed roughly with (9). A third specimen was studied which was highly compensated with $N_D - N_A = 5{\cdot}8 \times 10^3\,\mathrm{cm}^{-3}$ and which is similar to the specimens considered here. This specimen had a resistivity which was only weakly dependent on magnetic field below 1 K. This is at variance with the results obtained here and the weak field dependence may be due to the effect of a conducting surface layer. This is discussed later.

Equation (9) is based on a wavefunction for the donor centres given by

$$\psi = C \exp\left(- \frac{x^2 + y^2}{4\lambda^2} - \frac{|z|}{a_B} \right). \tag{11}$$

The corresponding expression for a donor centre wavefunction of the type used by YKA

$$\psi = (2\pi^{3/2} a_\perp^2 a_\parallel)^{-1/2} \exp\left(- \frac{x^2 + y^2}{4a_\perp^2} - \frac{z^2}{4a_\parallel^2} \right) \tag{12}$$

is

$$\sigma = \sigma_0 \exp[-0{\cdot}337 (N_D a_\perp^2 a_\parallel)^{-2/3}]. \tag{13}$$

In some materials a fourth temperature range is observed below the E_3 region when the resistivity increases less rapidly as the temperature is reduced than expected for an activated process. At these temperatures it is considered that variable range hopping occurs in which nearest neighbour hopping is replaced by hopping to more remote centres. Mott (1969) initially considered this case and the theory has been developed for a large magnetic field by Shklovskii (1973) for donor wavefunctions given by (11) and Suprapto and Butcher (1975) for wavefunctions given by (12). The results can be expressed as

$$\rho = \rho_0 \exp(T_0/T)^x \tag{14}$$

where for

$B = 0$	$x = \frac{1}{4}\ T_0 = s_1 (g a^3 k)^{-1}$
B large and ψ given by (11)	$x = \frac{1}{3} T_0 = s_2 (g \lambda^2 a_B k)^{-1}$
B large and ψ given by (12)	$x = \frac{2}{5}\ T_0 = s_3 (g a^2 a k)^{-1}$

where g is the density of states at the Fermi level and s_1, s_2 and s_3 are constants. (There is an error in Shklovskii's paper which gives $x = \frac{1}{2}$ instead of $\frac{1}{3}$.)

The possibility that the electrons in a semiconductor might freeze-out into a Wigner lattice due to the effect of a magnetic field, provided the density is low enough, was suggested by Durkan *et al* (1968) and has been considered further by March and Care (1971) and Kleppmann and Elliott (1975). Such a Wigner transition would cause a change from a conducting to nonconducting state with a characteristic activation energy. Mention has already been made of the transition from quasi-metallic to activated conductivity observed by Ishida and Otsuka but their explanation in terms of an Anderson transition seems satisfactory. Furthermore in the non-metallic region the activation energies E_1 and E_2 seem to be in satisfactory accord with YKA and E_3 with models for hopping conduction.

Returning to the weak dependence of resistivity on magnetic field below 1 K observed by Gershenzon *et al*, a similar result was obtained by Walton and Dutt (1977) who observed only a relatively small change in conductivity as the magnetic field was changed from 20 to 62 kG at 0·5 K and as the temperature was changed from 1 to 0·3 K in a field of 25 kG for a specimen with $N_D - N_A = 4 \times 10^{13}$. Specimen A3 used in this work having similar impurity content has a resistivity which changes by a factor 10^3 for a magnetic field variation from 12 to 26 kG at 0·9 K and by a similar factor as the temperature is reduced from 1 to 0·3 K with $B = 12$ kG. Ferre *et al* and also Fantner *et al* (1976) have both observed saturation of ρ for large fields and in the low temperature range. It is suggested here that as the bulk resistivity becomes very high due to freeze-out effects the specimen resistance may be limited by conduction through a surface layer. A low temperature conductivity has been observed in GaSb by Nerou *et al* (1976) to limit the resistance as the temperature is reduced in the same sort of manner.

2. Experimental details and results

Bar-shaped single crystals ($3 \times 3 \times 12\,mm^3$) were cut from boat-grown indium antimonide with the bar cut perpendicular to the direction of growth for uniformity of dopant concentration. During the investigation it became clear that the preparation of the surfaces of the specimens was very important. Initial results were obtained which did not reproduce the freeze-out expected from previous work and this was attributed

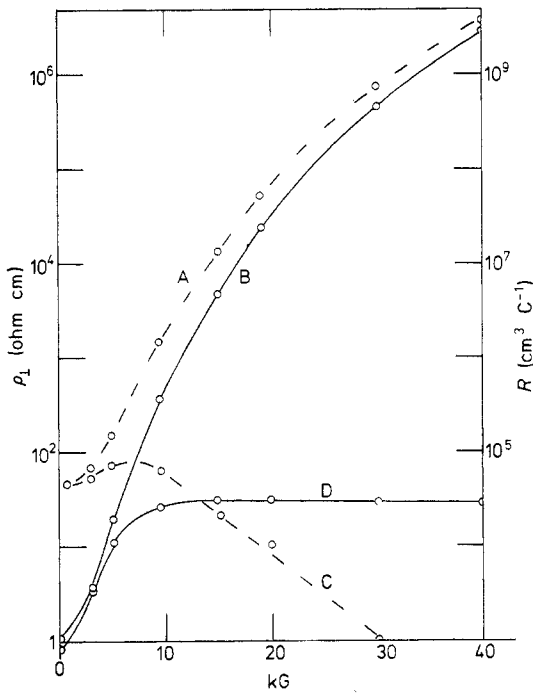

Figure 1. Curve A and B are the Hall coefficient and transverse resistivity for specimen A9 when etched after soldering current leads. Curves C and D are obtained after current leads resoldered with no subsequent etching, and heated to 60° C for 2 hours. Broken curve—Hall coefficient; full curve—transverse resistivity.

to a surface layer providing a conducting path which limited the resistance of the specimen. This layer appeared to have a resistance independent of the magnetic field. A layer appeared to be formed when leads were soldered to the specimen due probably to the increase in temperature required for soldering. To eliminate the layer the specimen was initially etched with CP4 and current leads soldered to the ends of the specimen. The ends were then coated with a protective layer of nail varnish and the specimen re-etched. Potential probes were now spot-welded to the sides of the specimen by condenser discharge. The effect of applying this procedure to specimen A9 is shown in figure 1. Curves A and B are the Hall coefficient and transverse resistivity of specimen A9 with sample preparation as described. Curves C and D were obtained by resoldering the sample with no subsequent etching and after heating to approximately 60°C for 2 hours. Following the routine of etching the specimens after soldering the current leads was not always successful in preventing a conducting layer from forming. When it is successful, however, the resistance of the specimen increases indefinitely with magnetic field until, at low temperatures, the resistance becomes too high to measure. Starting with a specimen having a relatively high carrier concentration such as A1 ($(N_D - N_A) = 1{\cdot}1 \times 10^{15}$) a change in resistivity by a factor of 10^{10} to 10^{11} could be measured.

A ^{3}He cryomagnetic system fitted with a charcoal adsorption pump and superconducting magnet provided temperature down to 0·3 K and magnetic fields to 40 kG. With the magnet in the persistent mode providing a constant field the resistivity was measured at frequent intervals as the temperature was lowered. The process was repeated with the magnet reversed. Regular checks were made to ensure that the electric field was low

Table 1.

Specimen:	A1	A2	A3	A4	A9
$N_D - N_A$ (10^{14} cm^{-3})	11	5·7	0·64	0·29	1·4
N_D (mobility) (10^{14} cm^{-3})	17	15	1·8	2	4
N_D (equation 9) (10^{14} cm^{-3})	19	16	4·7	3·4	6·3
N_D (equation 13) (10^{14} cm^{-3})	12	11	3·0	2·1	3·6
Activation energy E_3 (meV)					
B = 5 kG			0·12		
7·5			0·18	0·16	0·11
10			0·24		0·18
12·5			0·28	0·16	
15		0·09	0·30		0·27
20	0·09	0·16			
25	0·14				
30	0·17				
35	0·27	0·30			
40	0·32				
E_{coul} (meV)	1·73	1·66	0·82	0·85	1·07

E_D = donor activation energy (meV) (specimen A9)

B (kG)	9·5	15	19	30	40
Experimental using (5) and (6)	0·94	1·48	1·80	2·26	2·35
Yafet, Keyes and Adams	2·05	2·40	2·60	2·95	3·20

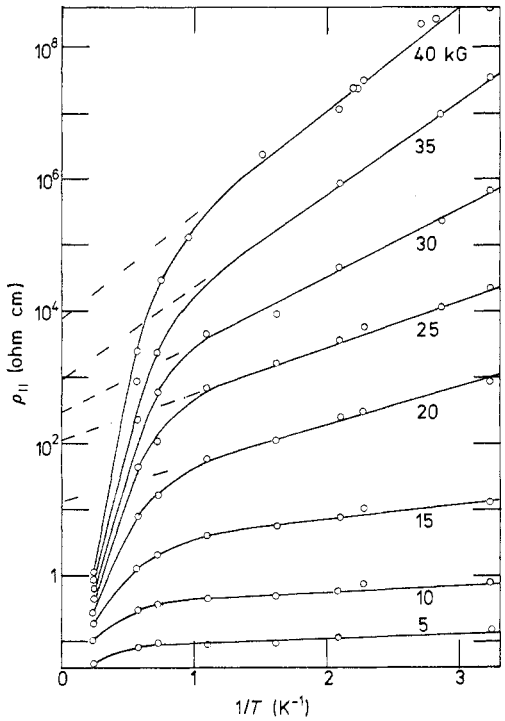

Figure 2. Longitudinal resistivity of specimen A1 for different values of B (in kG).

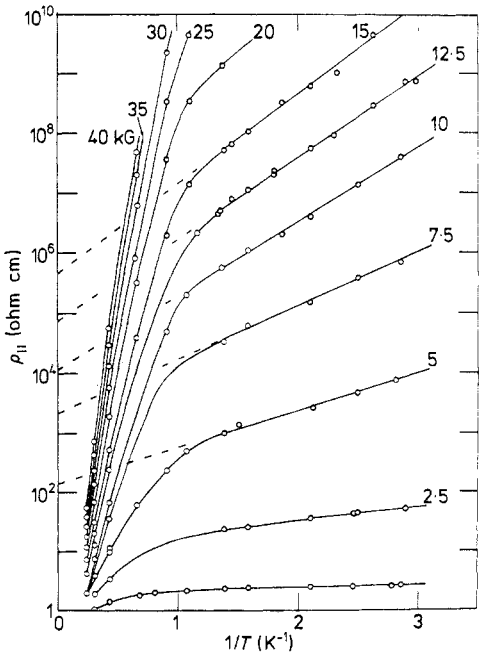

Figure 3. Longitudinal resistivity of specimen A3

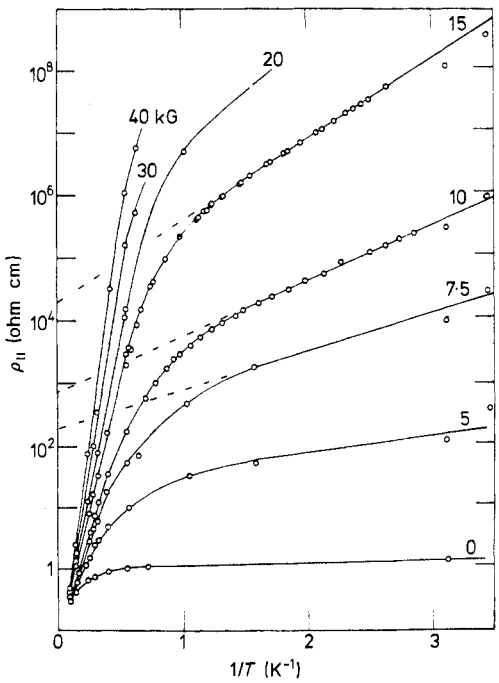

Figure 4. Longitudinal resistivity of specimen A9.

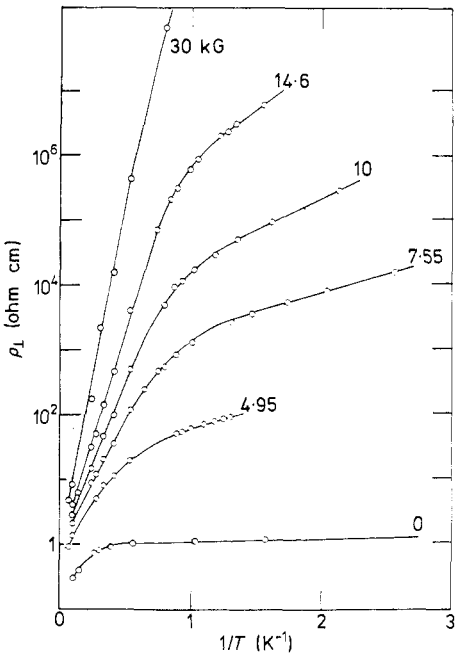

Figure 5. Transverse resistivity of specimen A9.

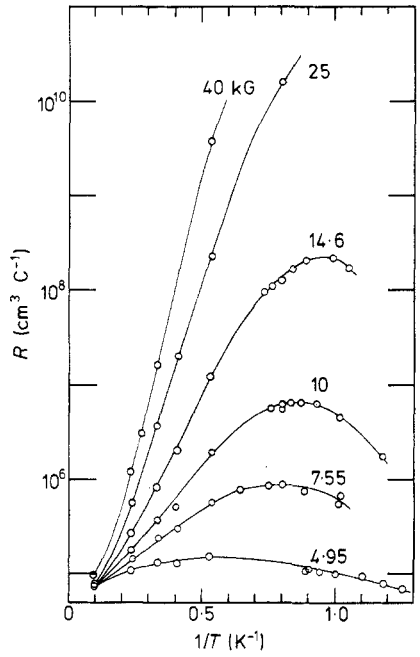

Figure 6. Hall effect of specimen A9.

enough for the specimen to be ohmic. Several weeks were required to complete the measurements in some cases and during that period the specimen was kept at a temperature below 77 K. Most of the results were made on the resistivity with a longitudinal magnetic field but for specimen A9 the transverse resistivity and Hall effect were also measured. The effect of a surface conducting layer on the Hall effect was very large but with suitable precautions the Hall effect increased to over 10^{10} cm^3 C^{-1} for a large magnetic field.

A list of the specimens investigated is given in table 1. Values of $N_D - N_A$ were determined from the Hall coefficient measured at 77 K and $N_D + N_A$ from measurements of the conductivity in the temperature range 10–40 K where impurity scattering dominates and the Brooks–Herring theory can be used. Figures 2, 3 and 4 illustrate representative results for the longitudinal resistivity of specimens A1, A3 and A9. Figure 5 shows the transverse resistivity and figure 6 the Hall effect for specimen A9.

3. Interpretation of results

3.1. Freeze-out region

In the temperature range 1 K to 10 K the concentration of electrons in the conduction band has been calculated by deducing σ_{xy} from $\rho_\perp$ and R using (4) and the donor activation energy from (5). The results are shown in the table and agree well with previous work (Mansfield, Robert *et al*). The discrepancy between the YKA values of E_D and those derived here are probably due to the effect of screening of the donor centres and to the spreading of the donor energy levels.

Using the free-electron concentration obtained from the transverse effects the longitudinal conductivity can be calculated using the theory of Argyres and Adams (1956).

This has already been applied to indium antimonide by Mansfield and Ellis (1976) at higher temperatures. The conductivity is given by (non-degenerate case)

$$(\rho_{\|})^{-1} = \sigma_{zz} = \frac{2^{3/2}(kT)^{3/2}K^2[2 + 3/b]n}{\pi^{3/2}\sqrt{m^*}e^2N_1}$$

where N_1 = number of scattering centres, $b = 6Km^*(kT)^2/\pi n\hbar^2e^2$.

The longitudinal resistivity can be calculated without any adjustable parameters and the agreement between the calculated and measured values, shown in figure 7, is excellent and gives strong support to the hypothesis that E_1 is simply the donor activation energy and is not the energy required to excite the electrons to a band of extended states as suggested by Ferre *et al.* The upper Hubbard band must either merge with the bottom of the conduction band where, because of the effect of the magnetic field, the density of states is very high so that the additional levels do not have an appreciable effect, or be separated from the band and electrons are predominantly excited to the conduction band.

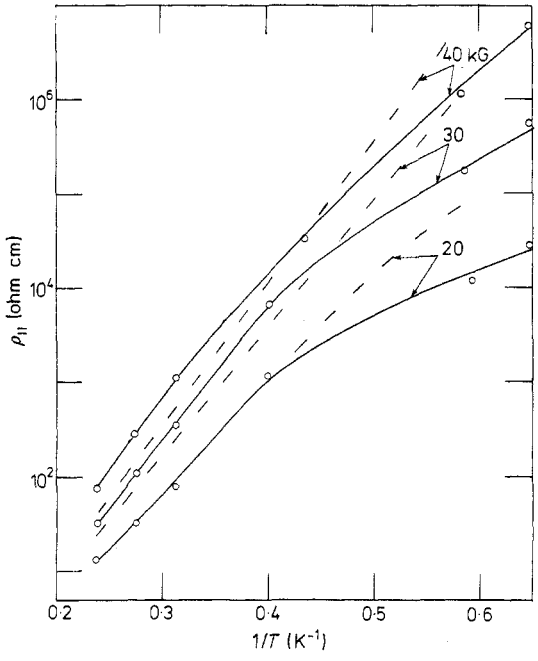

Figure 7. Longitudinal resistivity of specimen A9: measured—full curves; theoretical—broken curves.

3.2. Impurity conduction

In the temperature range 1 to 0·3 K

$$\sigma = (\rho_{03})^{-1}\exp(-E_3/kT)$$

and the values of E_3 are given in table 1. Also given in table 1 is the Coulomb interaction energy (e^2/Kr) which is approximately expected if uncorrelated hopping occurs. E_3 increases as the magnetic field is increased but is much smaller than the Coulomb energy. This is similar to the results on p-type germanium obtained by Knotek and is explained by the effect of correlation of the hopping process. The E_3 region was sufficiently well

defined to allow extrapolation of $T^{-1} \rightarrow 0$ to determine ρ_{03}. Figure 8 shows the magnetic field dependence of ρ_{03} expected from expressions (9) and (13) and table 1 shows the donor concentration N_D obtained from these two expressions. Both expressions are in reasonable agreement with experiment. The donor concentration deduced from equation (13) is in slightly better agreement with the concentrations obtained from mobility measurements.

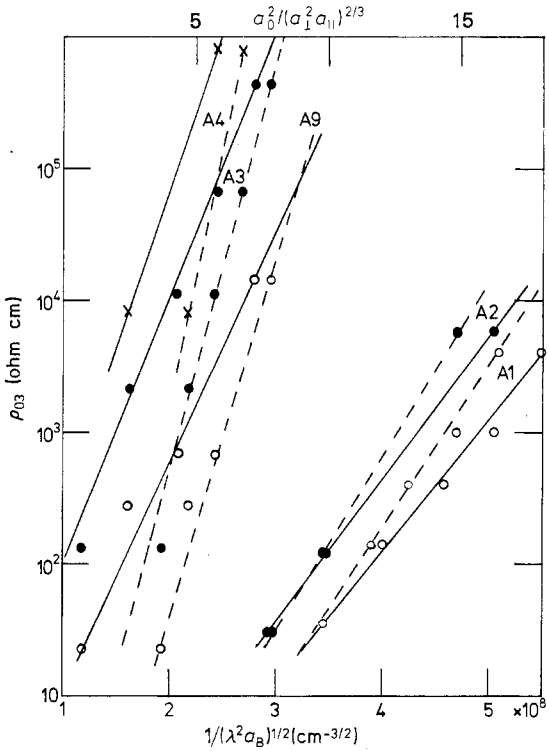

Figure 8. Resistivity ρ_{03} as a function of (*a*) $(\lambda^2 a_B)^{-1/2}$ (full curves), (*b*) $a_0^2(a_\perp^2 a_\parallel)^{-2/3}$ (broken curves).

4. Conclusion

The effect of the magnetic freeze-out of electrons from the conduction band to donor centres in indium antimonide can be masked by a surface conducting layer and considerable care must be taken over the preparation of the surfaces of specimens. With suitable precautions the resistivity and Hall effect increased beyond the range of measurement in this investigation and further measurements using differently shaped specimens would be interesting. For example higher resistivities could be determined by abandoning the potential probe method and using a disc shaped sample. Such a sample could have a guard ring to eliminate altogether the effect of a surface layer. One surface of the disc could have a uniform inner circular contact A surrounded by, but separate from, a guard ring contact G, the whole of the other surface being covered by contact B. With A and G at the same potential the current flowing to A when different potentials are applied to B will give the resistivity of the disc defined by the contact A and the effect of conduction through the side of the disc will be eliminated.

The results in the magnetic freeze-out region confirm previous results obtained by Mansfield and Robert *et al.* Below the freeze-out region conduction is by activated hopping and the activation energy increases with magnetic field. The activation energy is much less than the Coulomb interaction energy suggesting that correlated hopping occurs which decreases the activation energy. Increasing the magnetic field reduces the amount of correlation and increases the activation energy. The pre-exponential factor agrees satisfactorily with theoretical expressions derived for the strong magnetic field region where the percolation paths are affected by the field. Expressions derived from different types of donor wavefunctions yield similar results.

Acknowledgments

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