Effect of Pressure on the Electrical Properties of Indium Antimonide*

DONALD LONG
University of Pennsylvania, Philadelphia, Pennsylvania
(Received March 24, 1955)

The electrical resistivity and Hall coefficient of indium antimonide have been measured as a function of pressure to 2000 atmospheres at 0°C, 24.3°C, and 54.3°C. The sample was p-type at low temperatures and became intrinsic with respect to the type of conductivity-temperature variation at about 220°K. It was found that the resistivity and Hall coefficient both increase exponentially with pressure, but at different rates, the resistivity curves having the greater slopes. The experimental results indicate an increase in the energy gap of 14.2×10^{-6} ev/atmosphere and a decrease in the electron mobility of 14 percent for 2000 atmospheres pressure at room temperature.

INTRODUCTION

INDIUM antimonide is one of a series of semiconducting compounds formed between elements of columns IIIB and VB of the periodic table. The lattice has the zincblende structure and therefore exhibits cubic symmetry.

This paper presents the results of measurements of the effect of pressure on the resistivity and Hall coefficient of a sample of InSb which was intrinsic at the temperatures of the experiments and p-type below about 220°K. It was found that the energy gap increases linearly with pressure and that there is an accompanying decrease in the electron mobility.

APPARATUS AND MEASUREMENTS

The hydrostatic-pressure vessel used in these experiments was constructed of nonmagnetic stainless steel, and the lower section in which the sample was located could be placed in a temperature bath between the pole-pieces of a magnet. Electrical leads passed out of the vessel through a plug in the top. Tri-cresyl phosphate was used as the pressure-transmitting fluid, and the pressure was measured by a Bourdon-tube gauge. A thermocouple junction was placed next to the sample inside the pressure vessel to measure the temperature.

Electrical lead wires of copper were soldered to the sample with pure indium. The resistivity was measured by the usual four-probe potentiometric method. The Hall voltages were read from a Leeds and Northrup indicating dc microvolt amplifier. All thermomagnetic effects except the Ettingshausen were eliminated from the Hall voltage readings by reversing the current and magnetic field directions and taking the appropriate averages. The Ettingshausen effect has the same current and field dependence as the Hall effect and so cannot be eliminated in this way. Thermocouples were soldered to the sample in the Hall probe positions, and an attempt was made to measure an Ettingshausen temperature difference due to the magnetic field under the same experimental conditions present inside the pressure vessel. No such temperature difference was detected, however, and thus no correction for the Ettingshausen effect was necessary in the Hall voltage readings. Changes in the sample dimensions with pressure were not taken into account in any case, since the compressibility of InSb is as yet unknown; however, the effects of any such changes would undoubtedly be negligible.

The experimental results are shown in Fig. 1 in which log resistivity and log Hall coefficient are plotted against the pressure at three different temperatures. The resistivity and Hall coefficient both increase exponentially with pressure but at different rates, the resistivity rate being the larger at each temperature.

An auxiliary experiment in which the Hall coefficient was measured as a function of temperature from liquid

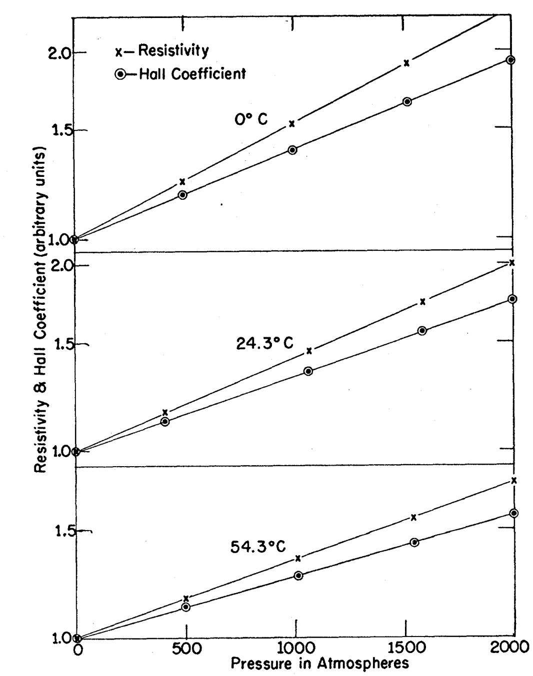

FIG. 1. Resistivity and Hall coefficient *versus* pressure for InSb. The zero-pressure actual values of resistivity and Hall coefficient are as follows:

Temp. °C	Resistivity (Ω cm)	Hall coeff. (cc/coul)
0	1.13×10^{-2}	547
24.3	0.670×10^{-2}	294
54.3	0.387×10^{-2}	153

* Work supported by a contract with the Office of Naval Research.

air to room temperature was also performed in order to determine the density of impurity holes in the sample and the electron-hole mobility ratio. These data are shown in Fig. 2 and are typical of the behavior of p-type InSb. The impurity density p_0 as found from the value of the Hall coefficient in the extrinsic range,

$$R_{\rm ext}=-\frac{3\pi}{8}\frac{1}{p_0 e}, \tag{1}$$

was 3.26×10^{15} per cm^3. A mobility ratio c of 32 was found from the condition that the Hall coefficient pass through a maximum in the negative region, *viz.*,

$$R_{\rm max}/R_{\rm ext}=(c-1)^2/4c. \tag{2}$$

Other important properties of InSb are listed in Table I, including an electron mobility of about 40 000 cm^2/volt-sec for the sample used in these experiments.

The Hall *vs* pressure data were taken using the rather small magnetic field of 870 gauss in order to minimize the field dependent term of the Hall coefficient. Simple theory[1] predicts that this term should be approximately $0.4u_n^2H^2\times10^{-16}R$, which for a mobility of 40 000 cm^2/volt-sec and a magnetic field of 870 gauss would have a value of $0.05R$, where R is the zero-field Hall coefficient. The Hall coefficient of the sample was measured as a function of field strength from 870 gauss down to 290, but no measurable field dependence was observed. Thus, the value at 870 gauss must closely approximate the zero-field Hall coefficient. In order to verify that any small field dependence had no effect on the results, the Hall *vs* pressure experiment was repeated at 24.3°C using a field of 290 gauss. The same slope was obtained on the log Hall coefficient *vs* pressure plot as that for the measurements at 870 gauss.

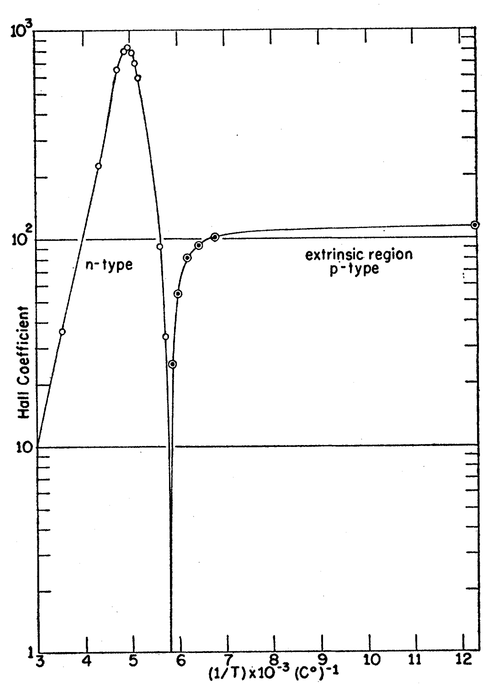

FIG. 2. Hall coefficient *vs* inverse temperature for InSb.

TABLE I. Properties of InSb.

Energy gap at room temperature	0.18 ev,[a] 0.16 ev[b]
Electron mobility at room temperature	~40 000 cm^2/volt-sec
Mobility ratio	32
Electronic effective mass	$0.03m_0$,[a] $0.04m_0$;[b] where m_0 is the true mass

[a] O. Madelung and H. Weiss, Z. Naturforsch **9a**, 527 (1954).
[b] Breckenridge, Blunt, Hasler, Frederikse, Becker, and Oshinsky, Phys. Rev. **96**, 571 (1954).

INTERPRETATION OF MEASUREMENTS

Because of the extremely small effective mass of an electron in InSb it is possible for a sample to become degenerate at relatively low conduction electron concentrations. For an effective mass of $0.03m_0$ classical statistics may be used with accuracy in the analysis if the density of conduction electrons does not exceed about 2×10^{16} per cm^3; the criterion used is that the Fermi level should not lie closer than $2kT$ below the bottom of the conduction band. This condition is satisfied in the experiments at 0°C and 24.3°C. Even though it is not quite satisfied at the higher temperature, the error involved in using classical statistics should not be significant.

It is possible to explain the experimental results in terms of decreases in the density and mobility of the conduction electrons with the application of pressure to the sample, and to relate these decreases in turn to increases in the energy gap and the electronic effective mass. The conductivity and Hall coefficient are expressed as functions of the carrier densities and mobilities by the following two equations:

$$\sigma=e(n\mu_n+p\mu_p), \tag{3}$$

$$R=-\frac{3\pi}{8e}\frac{nc^2-p}{(nc+p)^2}, \tag{4}$$

where the factor $3\pi/8$ is used in (4) because Harman *et al.*[2] have shown that thermal scattering dominates InSb above 125°K. The constant value of the Hall coefficient over a wide range of temperatures in the extrinsic range indicates that nearly all the acceptor impurities become ionized at a very low temperature, and for this case it is possible to make the substitution, $p=n+p_0$, into the above equations which then become

$$\sigma=e\mu_p[n(c+1)+p_0]\simeq ne\mu_n\left[1+\frac{p_0}{n(c+1)}\right], \tag{3a}$$

$$R=-\frac{3\pi}{8e}\frac{n(c^2-1)-p_0}{[n(c+1)+p_0]^2}\simeq-\frac{3\pi}{8e}\frac{1}{n}\left[1-\frac{2p_0}{nc}\right], \tag{4a}$$

[1] A. H. Wilson, *The Theory of Metals* (Cambridge University Press, Cambridge, 1936).

[2] Harman, Willardson, and Beer, Bull. Am. Phys. Soc. **30**, No. 2, 9 (1955).

TABLE II. Results.

Temperature °C	$(\partial E_g/\partial P)_T$ ev/atmos	$(\Delta u_n/u_{n0})P=2000$ atmos	$(\Delta m_n/m_{n0})P=2000$ atmos
0	$+(14.2\pm0.3)\times10^{-6}$	-0.16	-0.060
24.3	$(14.2\pm0.3)\times10^{-6}$	0.14	0.053
54.3	$(13.1\pm0.4)\times10^{-6}$	0.12	0.046

where the approximations are valid because of the high mobility ratio in InSb and because in these experiments n was always greater than p_0.

The value of n at any pressure is calculated by using Eq. (4a) from the measured value of R at that pressure and the values of p_0 and c, providing the assumption is made that c does not vary with pressure. It is evident though from the above approximate expressions for σ and R that a change in c would not produce an appreciable effect anyway.

An expression for μ_n at any pressure is obtained by multiplying (3a) by (4a) and neglecting terms which are very small. The result is,

$$\sigma R=-\frac{3\pi}{8}\mu_n\left[1-\frac{p_0}{n(c+1)}\right]\left(1-\frac{1}{c}\right). \qquad (5)$$

Now, according to Bardeen and Shockley,[3] μ_n is related to the electronic effective mass in the thermal scattering range by the following equation:

$$\mu_n=\frac{(8\pi)^{\frac{1}{2}}eh^4}{3(kT)^{\frac{3}{2}}}\frac{c_{ii}}{E_1{}^2m_n{}^{5/2}}, \qquad (6)$$

where c_{ii} is the elastic constant in the direction of propagation of thermal vibrations, and E_1 is the change in energy gap per unit dilation. No data are available on the change in c_{ii} with pressure in InSb. Lazarus[4] has measured the changes in elastic constants with pressure for KCl, NaCl, CuZn, Cu, and Al. Only in KCl and NaCl, which are strongly ionic crystals, did any elastic constant change by more than 1.5 percent for 2000 atmospheres, the changes in these crystals being as large as 6 percent. It seems probable that in InSb, which is only slightly ionic, the change is not much greater than 1.5 percent. This change is small compared to the approximately 14 percent decrease of mobility of InSb. A change in E_1 would represent the existence of a nonlinear change in the energy gap, but this is unlikely because of the true exponential nature of the data. Thus, it can be assumed that the observed decrease in mobility of InSb is the result of an increase in the electronic effective mass, the magnitude of which is then determined from Eqs. (5) and (6).

The energy gap is related to the free carrier densities and effective masses at a temperature T by the following equation.

$$n(n+p_0)=4(2\pi kT/h^2)^3(m_nm_p)^{\frac{3}{2}}\exp(-E_g/kT). \qquad (7)$$

[3] J. Bardeen and W. Shockley, Phys. Rev. **80**, 72 (1950).
[4] D. Lazarus, Phys. Rev. **76**, 545 (1949).

The change in energy gap due to the application of a pressure P to the sample is then calculated from the equation below, which follows from (7), where the values of n and m_n at zero and high pressure are obtained by the methods previously described.

$$\Delta E_g=-kT\left[\ln\left(\frac{n_p}{n_0}\right)+\ln\left(\frac{n_p+p_0}{n_0+p_0}\right)\right]+\tfrac{3}{2}kT\ln\left(\frac{m_{np}}{m_{n0}}\right). \qquad (8)$$

No allowance has been made for a change in the effective mass for holes, since it cannot be deduced from the data. Further justification for this procedure is that the mass of the holes is nearer that of the free electron mass and should be less sensitive to pressure. The calculated values of $(\partial E_g/\partial P)_T$ are given in Table II along with the corresponding values of $(\Delta\mu_n/\mu_{n0})$ and $(\Delta m_n/m_{n0})$ for 2000 atmospheres pressure.

The lower value of $(\partial E_g/\partial P)_T$ at 54.3°C may be due to the onset of degeneracy at this temperature. The apparent value of $(\partial E_g/\partial P)_T$ would be lower than the true one when degeneracy is present in InSb, because the conduction band empties as the energy gap increases thereby decreasing the difference in energy between the bottom of the conduction band and the lowest state into which an electron may be excited. The variation in the fractional changes in electron mobility at the different temperatures might be explained either as a true effect or as the result of neglecting any variation of mobility ratio with pressure when calculating μ_n from Eq. (5). It can be seen from (5) that a decrease in c would tend to bring the three mobility decrease values into closer agreement.

ACKNOWLEDGMENTS

The author wishes to express his gratitude to Professor Park H. Miller, Jr., of the University of Pennsylvania for his guidance and assistance during the course of this work. Thanks are also due to Dr. R. G. Breckenridge of the National Bureau of Standards for providing the sample of InSb, to Mr. John Bowen of Pressure Products Industries for assisting in the design and construction of the high-pressure system, and to Professor H. B. Callen of the University of Pennsylvania for several suggestions regarding interpretation of the results.