Investigating the Hall Effect in Indium Antimonide

Thorin Bristow
9917340
School of Physics and Astronomy
University of Manchester
This expermient was performed in collaboration with Hermione Warr.
(Dated: December 20, 2019)

The properties of an undoped crystal of impure indium antimonide (InSb) were investigated using Hall effect measurements. Resistance, Hall coefficient and magnetoresistance were measured as a function of temperature in the range 77-380K. The energy gap, E_g, of the InSb sample was found to be $(0.257 \pm 0.002)eV$; the concentration of impurities $N_D = (5.1 \pm 0.5) \times 10^{-19} m^{-3}$.

I. INTRODUCTION

Semiconductor physics has revolutionised the modern world through the invention of numerous devices, including computers, colour television screens and solar cells [1]. In this experiment the electrical properties of indium antimonide (InSb) were investigated using the Hall effect. The structure type of InSb was first reported by Liu and Peretti in 1951 who identified it as zincblende with a lattice constant of $0.648nm$ [2]. It is known to have a high electron mobility, making it a useful material in galvanomagnetic device applications [3].

The Hall effect was first discovered in 1879, when Edwin Hall observed that when an electrical current passes through a sample placed in a magnetic field, a potential proportional to the current and to the magnetic field develops across the material in a direction perpendicular to both the current and magnetic field [4].

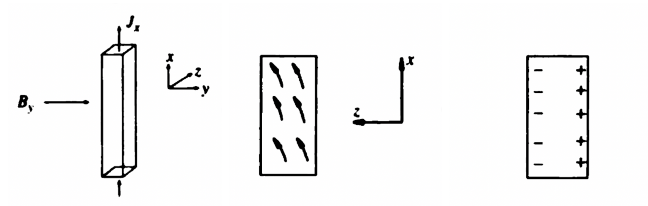
A. Semiconductors

Semiconductors are materials with conductivites between those of metals (of the order $10^7(\Omega m)^{-1}$) and insulators (as low as $10^{-26}(\Omega m)^{-1}$), whose conductivities rise with temperature [5]. Electrons are only mobile in a certain energy band called the *conduction band*. For *intrinsic* semiconductors, the conduction band is vacant at absolute zero temperature and is separated by an energy gap E_g from the filled *valence band*. This energy gap is called the *band gap* and is the difference in energy between the lowest point in the conduction band and the highest point of the valence band. As the temperature is increased, electrons are thermally excited from the lower energy valence band to the conduction band, leaving a vacant orbital called a "hole" [6]. *Holes* are empty states with an effective positive charge. Both electrons and holes contribute to electrical conductivity.

Semiconductor crystals are usually "impure" and contain a small fraction of foreign atoms. An impurity atom which can give up a negative carrier is called a *donor* because it "donates" an electron; an impurity atom which can produce a hole is called an *acceptor* because it "accepts" an electron. A crystal with a small concentration of donor impurities will have a majority of negative carriers; such a material is called an "n-type" semiconductor. Similarly, a material with an excess of positive carriers is called a "p-type" semiconductor. When a donor or an acceptor impurity is added to a semiconductor, we say that the material has been "doped" [7] and refer to this type of semiconductor as *extrinsic*. Correspondingly, an *intrinsic* semiconductor is one where the conductivity is due to the intrinsic properties of the material, that is, there are an equal number of electrons and holes ($n = p$).

B. The Hall effect

The Hall effect is an experimental phenomenon which the free electron theory fails to explain in *some* metals [8].



(a) (b) (c)

FIG. 1: The Hall effect. Schematic diagram showing the experimental geometry (a); deflection of electrons due to the Lorentz Force (b); change in charge density producing an electric field across the sample (c) [5].

Suppose we have a block of semiconductor material with a current $\mathbf{j}$ flowing through it in the x-direction (Fig.1a). Now we apply a magnetic field $\mathbf{B}$ to the block at a right angle to the current, in the y-direction. The moving charge carriers, having velocity $\mathbf{v}$, will experience a magnetic force $q(\mathbf{v} \times \mathbf{B})$. If the current carriers are electrons they are deflected as shown in figure 1b. Since the average drift velocity is either in the $-x$ or $+x$ direction, depending on the sign of the charge carrier, the average magnetic force on the moving charges will be in the *same direction*. A few of the charges flow to the $+z$ face producing a surface charge density, leaving an equal and opposite surface charge density on the opposite face (Fig.1c). Due to this redistribution of charge density, a transverse electric field $\mathbf{E}_H$ known as the *Hall field* is set up. Under steady conditions, the electrical forces from this induced field exactly cancel the magnetic forces (on average) so that a steady current flows [7] in the x-direction.

The charges on the $+z$ and $-z$ surfaces produce a potential difference across the block which can be measured with a voltmeter. The sign of the potential difference registered on the voltmeter depends on the sign of the charge carriers responsible for the current. The Hall field is given by

$$\mathbf{E}_H = R_H \mathbf{B} \times \mathbf{j}. \tag{1}$$

This is the Hall effect, and R_H is known as the Hall coefficient [8]. The Hall coefficient depends only on the density of carriers, provided that carriers of one sign are in a large majority, and is given by

$$R_H = \begin{cases} -1/ne & \text{for electrons} \\ +1/pe & \text{for holes} \end{cases}, \tag{2}$$

where e is the fundamental electronic charge and is positive. Furthermore, it can be shown that

$$V_H = \frac{\mathbf{j} \times \mathbf{B}}{net}, \tag{3}$$

where V_H is the Hall voltage, n is the density of charge carriers and t is the thickness of the semiconductor sample. Measurement of the Hall effect is therefore a convenient way of determining experimentally the density of carriers in a semiconductor.

II. EXPERIMENT

To take Hall effect measurements, an undoped sample of indium antimonide of dimensions $22mm \times 5mm \times 0.85mm$ was mounted on a cold finger inside a cryostat with a liquid nitrogen bath, vacuum insulation, heaters and thermocouples. A magnetic field was provided by an iron-cored electromagnet (Fig.2) and monitored by a commercial Hall probe. Specialised apparatus was used to systematically cycle through the voltage measurements via the voltmeter; also allowing for the sample current to be set. A heating device was used to power the heating element to raise the sample temperature. A temperature range of 77K (liquid nitrogen temperatures) to 380K was achieved. A device used to adjust the strength of the magnetic field allowed us to vary the field from zero to approximately 0.73T, the values were recorded using a digital Gaussmeter. A computer interface was used to record the various voltages.

Measurements were taken at 14 different temperatures, using a range of magnetic field strengths at each temperature. Graphs of sample voltage V_S against sample current I_S, as well as Hall voltage V_H against $I_S \times B$ (cf. (3)), were plotted for each value of temperature and magnetic field strength. From these, the resistance of the sample, as well as its charge carrier concentration, was calculated.

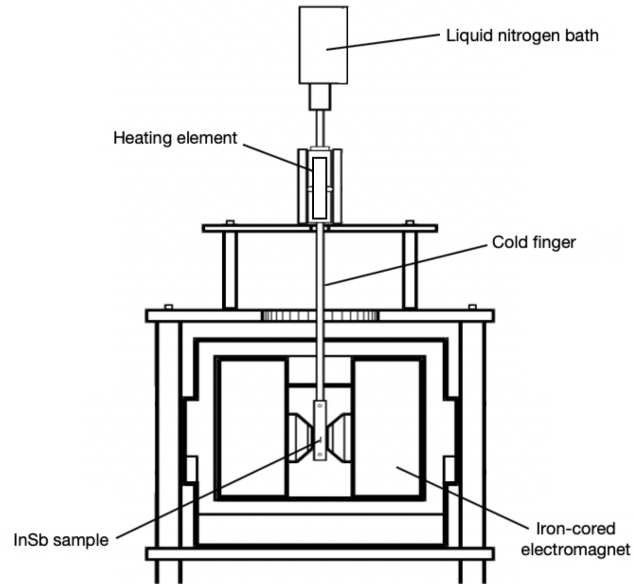


FIG. 2: Schematic of the experimental set-up.

III. RESULTS

With increasing temperature, the sample transitioned from extrinsic to intrinsic behaviour in the region of 150K.

At temperatures much higher than those at which the impurity atoms are ionised, the dopant charge carriers are negligible in comparison to the concentration of charge carriers excited from the valence band. Thus the semiconductor behaves as an intrinsic semiconductor at high temperatures. In the intrinsic regime, the density of charge carriers follows the relationship

$$n = T^{\frac{3}{2}} \exp\left\{-\frac{E_g}{2k_B T}\right\}, \tag{4}$$

where n is the charge carrier density, T is the temperature of the semiconductor, E_g is the energy gap and k_B is the Boltzmann constant. Consequently, by plotting

$$\ln\left(\frac{n}{T^{\frac{3}{2}}}\right) \tag{5}$$

against inverse temperature, we find a straight line in the intrinsic region of the semiconductor from which the energy gap can be determined by applying a linear fit (Fig.3) [9]. A value of $(0.257 \pm 0.002)eV$ was calculated for the energy gap, the error having been derived from

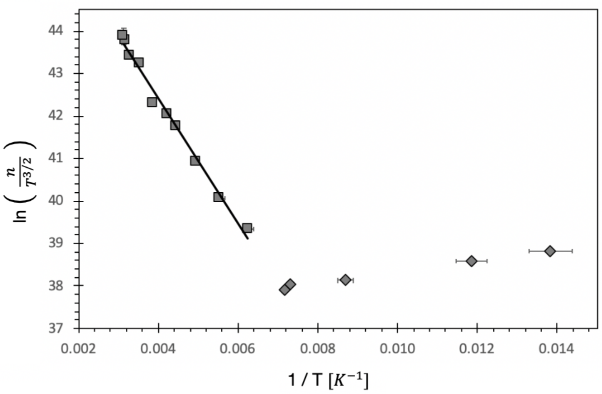


FIG. 3: Above 150K the intrinsic region of the semiconductor is marked with squared plots, with a linear fit applied. The extrinsic region is marked with diamond points.

the error on the weighted line of best fit. This was not wholly in agreement with the accepted value of $0.18eV$ at room temperature [3], although the energy gap has been shown to be strongly temperature dependent [10], which may offer some explanation.

The impurity concentration, N_D, of the sample was calculated by taking the weighted average of the charge carrier concentration in the extrinsic region of figure 3 giving a value of $5.1 \times 10^{-19} m^{-3}$. The uncertainty in charge carrier concentration, n, was taken from the errors of the gradient on the plots of V_H against $I_S \times B$ combined in quadrature with the error on the thickness of the sample, t. The uncertainty on the impurity concentration was calculated as $0.5 \times 10^{-20} m^{-3}$, using the standard deviation of values from the average, which was approximately 20% larger than combining them in quadrature. This provided a more accurate value for the uncertainty, although it may indicate that not all sources of error were accounted for.

The primary source of uncertainty that was successfully accounted for was the random error on the Hall voltage which was determined by varying the sample current for zero magnetic field. Similarly, the uncertainty on the sample voltage was found by setting the sample current to zero and varying the magnetic field. The standard deviation of these points provided the uncertainty on both the Hall voltage and sample voltage.

IV. CONCLUSION

The sample of InSb was found to contain an impurity concentration of $N_D = (5.1 \pm 0.5)m^{-3}$, similar to values published values for pure samples of InSb. The band gap was calculated $E_g = (0.257 \pm 0.002)eV$, differing to reported literature values for intrinsic InSb ($0.17eV$ at room temperature) by more than two standard deviations. The band gap error of 1% may be attributed to the random errors associated with the sample current and Hall voltage.

[1] Vavilov, V. S. Semiconductors in the modern world. *Physics-Uspekhi*, **38**(5):555–558, 1995.

[2] Liu, T. S. and Peretti, E. A. Lattice parameter of InSb. *Journal of Metals*, **191**:791, 1951.

[3] Hellwege, K. H. and Madelung, O. *Landolt-Börnstein: Numerical Data and Functional Relationships in Science and Technology - New Series*, volume **17**. Springer, 1982.

[4] Hall, E. H. On a New Action of the Magnet on Electric Currents. *American Journal of Mathematics*, **2**(3):287–292, 1879.

[5] Tanner, Brian K. *Introduction to the Physics of Electrons in Solids*. Cambridge University Press, 1995.

[6] Kittel, C. *Introduction to Solid State Physics*. John Wiley & Sons, sixth edition, 1986.

[7] Feynman, R. P. *The Feynman Lectures on Physics*, volume 3. Addison-Wesley, 1965.

[8] Hook, J. R. and Hall, H. E. *Solid State Physics*. John Wiley & Sons, 1991.

[9] Austin, I. G. and McClymont, D. R. The interpretation of hall effect, conductivity and infra-red measurements in indium antimonide. *Physica*, **20**(7):1077–1083, 1954.

[10] Littler, C. L. and Seiler, D. G. Temperature dependence of the energy gap of InSb using nonlinear optical techniques. *Applied Physics Letters*, **46**(10):986–988, 1985.