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An Investigation of Photoconductivity in Indium Antimonide Crystal

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Abstract:

Various Hall Effects have been successfully observed in samples of n-type indium antimonide with values for conductivity, energy gap, Hall mobility and Hall coefficient all agreeing with theory. A particular interest in developing a method for obtaining accurate values of carrier concentrations in semiconductor samples has been fulfilled with an experimental result of (1.6×10^{16} cm^{-3} ±10.7%) giving a percentage difference of (6.7%) to a quoted value of ($1.5\times10^{16}cm^{-3}$) at (77K) using an (80mW C.W. CO_2) laser beam at (10.6µm) to illuminate a similar sample of n-type indium antimonide, an "Optical" Hall effect has been observed. Although some doubt has been raised as to the validity of effect i.e. "thermal" rather than "Optical", values of (45.8×10^{-8} seconds) for recombination times of electron, and ($3.2\times10^{16}cm^{-3}$) for the dynamic carrier concentration were calculated by this method. A similar attempt at illuminating the sample with an R.S. catalogue ultra bright L.E.D proved inconsistent with theory and consequent result have been left inconclusive.

دراسة التوصيلية الضوئية لبلورة الانديوم انتمونايد

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الخلاصة:

تم بنجاح ملاحظة تاثير هول في نماذج من الانديوم النتمونايد مع حساب قيم التوصلية، فجوة الطاقة، حركية هول ومعامل هول وكانت متطابقة مع النتائج النظرية.كذلك تم ايجاد تجريبيا قيمة تركيز الحاملات للأنديوم انتمونايد وكانت بحدود ($1.6\times10^{١٦}cm^{-3}$) مع القيم المحسوبة ($1.5\times10^{١٦}cm^{-3}$) ونسبة الاختلاف حوالي 6.7% وهي متوقعة الى حد ما، وكذلك فأن قيمة زمن التراكب للالكترون بحدود 45.8×10^{-8} إضافة إلى ذلك فأن محاولة تم انجازها لأضاءة نموذج الانديوم انتمونايد بمصباح نوع (الدايود الباعث للضوء) كانت بعض النتائج غير متوافقة مع النظرية.

Introduction

Two of the more important fundamental categories of results in semiconductor physics are photoconductivity and the Hall effect. The former being the basis for calculating dynamic carrier concentration and recombinetion times of electron [1], where the latter can be used to obtain a number of effects, namely conductivity, Hall mobility, carrier concentration and energy gap of a semiconductor material [2,3].

The carrier concentration of semiconductor sample is a particularly important parameter in the design of optical logic elements [4], and consequently any method for obtaining accurate values of it would clearly be beneficial. One of the best methods of doing this is by using the Hall Effect where the carrier concentration is inversely proportional to the voltage created by a semiconductor carrying a current in a magnetic field [5]. In the photoconductivity experiment, light of photon energy greater than that of the energy gap of a semiconductor is shone on the same semiconductor [6]. This will cause excess carriers to be created as electrons move from the valence band into the conduction band through fundamental absorption. This dynamic carrier population is directly proportional to the recombination times of the electrons [7].

If light of sufficient energy could be directed onto a piece of semiconductor in the same direction as the magnetic field in the Hall experiment, then the resultant increase in carrier concentration should be such that a decrease in the Hall voltage will occur, with this changing giving a direct method of calculating recombination times[8]. This combination of effect, the optical Hall Effect, should avoid the necessity of separate experiment to obtain recombination times, carrier concentration etc., and confirm experimentally the already well developed theory of optical excitation of carriers in semiconductors.

Theory

When optical absorption takes place in semiconductor an electron in the valence band absorbs a photon from an optical beam, and transfers to the conduction band. Such as a fundamental absorption takes place only if the photon energy is greater than the energy gap that is $E_g < \hbar\upsilon$.

In Photoconductivity the conductivity of a semiconductor is raised by shining alight beam on the sample. The optical beam causes additional carriers to be excited across the energy gap, which causes a rise in the conductivity. The change in the carrier concentration can be expressed as:

$$\Delta n = \frac{\alpha I(\omega)\tau}{\hbar\omega}$$

Where $I(\omega)$ is the intensity of the beam. α is the absorption coefficient $\hbar\omega$ depends on wavelength of light used, and τ is the recombination time of electrons, in effect the lifetime of a free carrier.

The optical Hall effect, by using the expressions for the Hall voltage and the Photoconductivity of a semiconductor, can therefore be used a means of not only measuring dynamic carrier concentration, but also for the determination of recombination times of electrons. Previously only one or the other could be worked out by the separate effects.

It would be reasonable to assume that if a piece of semiconductor was illuminated in a Hall effects rig, that the additional carriers excited across the gap would cause a rise in conductivity. This conductivity increase would reduce the Hall coefficient and in effect create a lower Hall voltage. From the new value for Hall voltage the change in carrier concentration could be established and hence the optical Hall Effect would give a means of measuring recombination times.

Experimental Equipment

The equipment used for the optical Hall Effect is very similar to that for the basic Hall Effect. With the obvious exception of a light source.

Initial results were performed on an existing D.C. Hall measurement rig, which served not only as a means of observing the Hall Effect. But also gave the opportunity to become familiar with equipment requirements.

Before any results could be taken, a sample had to be prepared and mounted. The type of sample used in all the experiments was n-type Indium antimonide (InSb). The samples were initially polished and cut more roughly rectangular shapes with a thickness of approximately 100µm. They were then placed on a holder and contacts soldered on. Previous methods of doing this appeared unnecessarily complicated and a new design of sample holder was considered.

This basically involved taking a piece of blue Tufliol rod 1 cm. Diameter and cutting a length 4cm long. A 2cm flat strip was milled for the sample to be placed on with four small pins inserted for sample contacts and Hall voltage/current leads to be attached. A ¼ B.S.F. Thread was put at one end to enable the holder to be fitted to a rod which was then' inserted into a cryostat.

Mounting the sample and soldering secure, low resistance contacts proved to be the most demanding part of the project. Samples were eventually mounted by putting a thin film of varnish on the holder and carefully placing the InSb into position. Various attempts were made at putting contacts on the sample. One such case involved discharging a capacitor through tine wires on the sample. In an attempt to achieve very small contacts by welding. This did not prove too successful and eventually it was decided that the best contacts were made using indium solder with a low temperature soldering iron.

With adequate contacts now soldered on. The sample could be placed in the Oxford instruments continuous flow cryostat. Designed for use with liquid nitrogen. The cryostat enabled the Hall Effect to be observed over a temperature range from room temperature down to 77K.

The sample was located in the cryostat between the poles of a Newport instruments electromagnet by a supply which could give a maximum current of 10Amp. When the magnet was cold. Failing to about 8Amp after the magnet heated up. The magnet was calibrated by measuring the field strength for various values of supplied current using a probe with a flux meter. Due to the fact that the sample was hidden in the cryostat it was difficult to establish whether the face of the sample was perpendicular to the magnetic field. However, this was remedied by simply rotating the cryostat central rod until a maximum Hall voltage was observed.

Fig. (1) shows the experimental layout of the remaining components for the Hall Effect. The current down the length of the sample was supplied by a Farnell stabilized power supply in series with a Beckman 10KΩ variable resistor. The voltage across the length of the sample was measured using a D.C. milivoltmeter connected in parallel. The Hall voltage was measured across the sides of the sample with a digital milivoltmeter. The temperature of the sample was measured using a Chromel-Alumel Thermocouple Positioned on the sample holder and wired up directly to a digital meter which gave the temperature directly in °C.

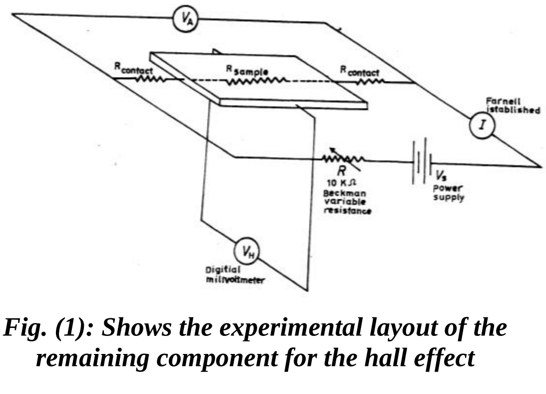

Fig. (1): Shows the experimental layout of the remaining component for the hall effect

Having established the experimental requirements for the Hall Effect. The optical Hall Effect could now be investigated. Fig. (2) shows the arrangement for illuminating the sample. Light of energy $\hbar\omega > E_g$ was shone on the flat face of the sample in the same direction as the magnetic field B. the same Hall effect equipment was used. and V_H etc. read as berate.

It was initially decided to use an R.S. catalogue ultra bright L.E.D. which had a peak wavelength at 635nm (hώ > E,) and an intensity equivalent to 125mcd. The L.E.D. was positioned over the sample in order that tile maximum amount of light would fall in the same direction as the magnetic field. The L.E.D. was powered by a signal generator unit with corresponding Hall voltage being fed directly to a low noise amplifier and then to an oscilloscope where the signal was compared with the original signal generator signal. Unfortunately this method failed on two accounts.

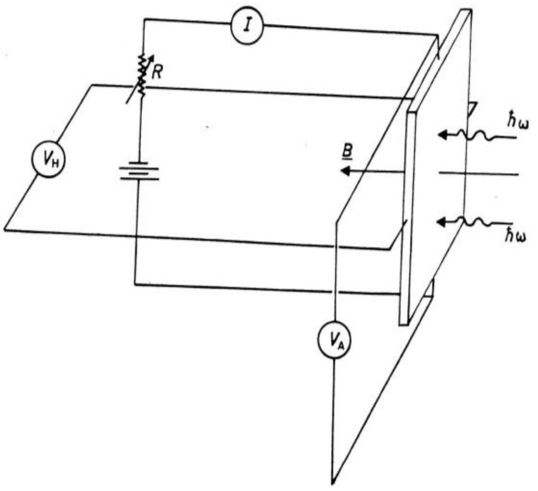

Fig. (2): Shows the arrangement for illuminating the sample

Firstly there was too much noise in the system due to unscreened wiring and secondly. The output of the signal generator was fixed, which although was tine at room temperatures, at low temperatures the resistance of the L.E.D. increased and as a result the intensity tell virtually to zero. Hence. it was decided that D.C. Hall measurements would have to be taken and the signal generator replaced by a Farnell stabilized power supply which enabled the intensity of the L.E.D. to remain constant at low temperatures.

Results were taken by this method and are shown later in the paper. however. they unfortunately proved inconsistent with theory and it was decided to attempt an optical Hall effect at room temperature with a CO_2 continuous wave laser as the source of illumination. Using the same electrical equipment as before but with a different sample-light was focused onto a small spot of diameter of 0.05cm ± 5% in the same direction as the magnetic field. The power incident on the sample was controlled by means of an adjustable aperture and the effect on the Hall voltage was measured as a function of time using a stop watch.

Experimental Results and Discussion

The experimental results initially involved the basic Hall effect with measurements of the Hall coefficient, conductivity etc. as described in the theory and appendix I. Later results involved the optical Hall effect with a CO_2 laser and an ‘Ultra bright' L.E.D. used for illumination purposes.

Hall Effect results:

A sample of dimensions.

t= 0.066 cm = 1.5%
l = 0.670 cm = 0.1 %
w = 0.262 cm = 0.4 %

Was cut and mounted inside the cryostat system. The sample was then adjusted in order that the maximum B field passed through the flat surface. This was achieved by simply rotating the sample until maximum Hall voltage was achieved with respect to the magnetic field. From the equation:

$$V_H = \frac{RHIB}{t}$$

The cryostat was operated over a range from 93K=1.1% to 333K=0.3%

with I=1mA±0.5% and B=4.7KG± 2.2%. The results for Hall coefficient. Conductivity and mobility are given in Figs. (3, 4, 5).

Form Fig. (3) the Hall coefficient is clearly shown to reach a constant value up to 223K±0.4% as the material becomes extrinsic (i.e., the carrier concentration reaches a constant). Calculating the carrier concentration.

$$n = \frac{-r}{R_H e}$$

Where

$$R = \frac{10^8 V_H t}{BI}$$

And

$$r \frac{3\pi}{8}$$

at 93 ^{0}K+ 1.1%
V_H= 0.33mV±1.5%
t= 0.066 cm±1.5%
B=4.7KG±2.2%
I=1mA±0.5%
R_H=477.9cm^{2}C^{-1}±5.7
n=1.6x 10^{16}cm^{-3}±5.7%

This value for the carrier concentration corresponds well with the given value of 1.5×10^{16}cm^{-3} this gives a percentage difference of 6.7%, which is outside the limits tore the measured carrier concentration, however, this can be accommodated in the fact that the possible misalignment of the sample with respect to the maximum magnetic field is 5%. Therefore a more accurate value for n would be 1.6× 10^{16}cm± 10.% which is clearly within error limits.

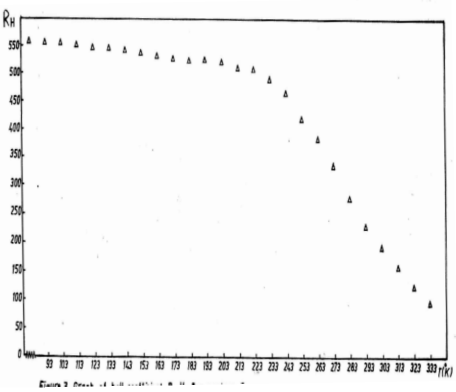

Fig. (3): Graph of hall coefficient R_H vs. temperature T

The graph for conductivity Fig. (4) shows how the lattice scattering dominates below 223K±0.4% as the material becomes extrinsic. Above this value the conductivity starts to increase, due to the material being in the intrinsic region, where an increase in carrier concentration Occurs. At much lower values than observed on the graph the conductivity should tall again due' to the effects of ionized impurity scattering.

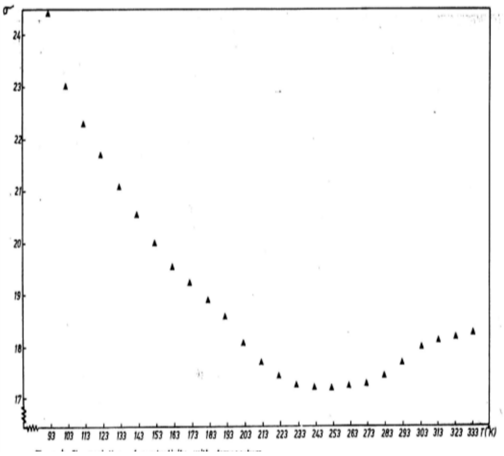

Fig. (4): The variation of conductivity with temperature

Therefore at room temperature the sample resistance is 0.210Ω i.e. 9.8% of the total resistance and the contact resistance is 1.940Ω. The value for mobility quoted tram R. A. Smith (1955) 01'78000cm^{2}V^{-1}S^{-1} at 300K appears very high compared with the value given in Fig. (5), the graph of Hall. Mobility against temperature.

This value 01'3240cm^{2}V^{-1}S^{-1} is small because the Hall mobility has been calculated using the total voltage dropped along the sample and contacts. Instead of the voltage dropped along the sample alone. The measured value is 4.2% of the quoted value. This corresponds well with the sample resistance as a percentage of the total resistance.

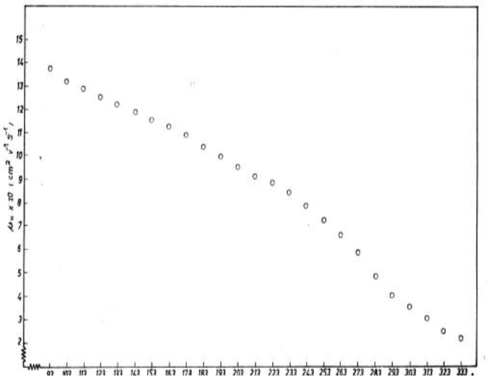

Fig. (5): Graph of hall mobility μ_H vs. temperature T

Fig. (6) shows the curve of In(R_H^{-1}) against T^{-1} Measuring the slope of this curve in the intrinsic region reveals a value for the energy gap of 0.25eV. This value is much higher than the accepted value of 0.18eV (R.A. Smith). This gives a percentage difference of 39%. This large discrepancy in value must be a direct result of the Hall voltage being taken across the voltage contacts as well as the sample. This difference could also be due to the difficulty in observing the exact point where the intrinsic region was located.

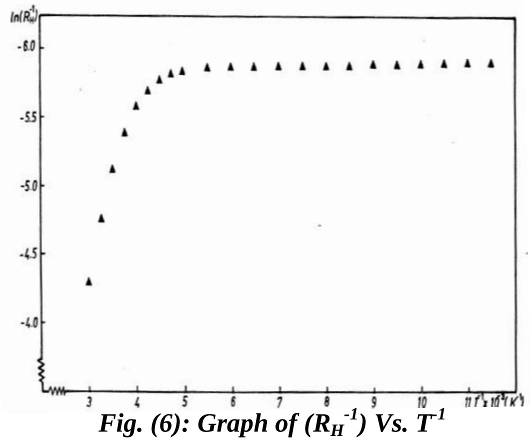

Fig. (6): Graph of (R_H^{-1}) Vs. T^{-1}

Optical Hall Effect Results

Another sample was cut and mounted between the poles of the magnets. The carrier concentration at room temperature (300 OK) was found to be 3.5 10^{16} cm^{-3} $\underline{+}$ 12% using the same method of calculation as before. Having established in unlitconditions. the Hall effect was then optically enhanced by shining continuous wave CO; laser light in the same direction as the magnetic field.

Fig. (7) shows the graph of Hall voltage against time for two values of laser power used to illuminate the sample. Readings were taken at 5 seconds intervals using a stop watch with the behavior of the Hall voltage being recorded in the usual manner. From the curves it can be seen that there was an initial fall in Ha1l voltage when the sample was i1lnminated. This was followed by a slower exponential decay as the sample warmed under the illuminating conditions. When the source was removed. the Hall voltage increased immediately and again there was a slow thermal effect as the sample returned to its original temperature.

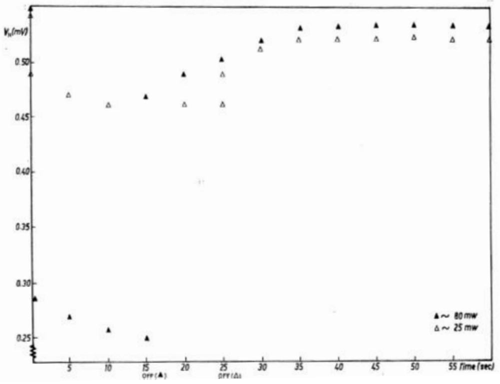

Fig. (7): Graph of Hall voltage Vs. time

It should be noted at this point. Those in order to obtain the value of V_H at T. the curves were extrapolated back by calculating of the region of exponential decay using the other points. Hence the eventual value for V_H at T cannot be justified with any great degree of accuracy. In addition to this. There is also some doubt that even if this value were true for the point at which the Hall voltage initially tell. There is still a problem with whether the change was directly a consequence 91' an optical effect or whether there was an initial localized heating of the sample causing thermal generation of carries.

From the curves it can be seen that there is a thermal effect between 5 seconds and the point of removal of the light source. This rather slow time constant clearly could not effect an immediate optical change in the Hall voltage. This would presumably be in the order of nanoseconds.

However, within the time scale used here. There may be an initial heating of the actual semi-conductor with a short time constant with the former slow heating effect being due to the insulating sample mount and semi conductor combined in thermal equilibrium. The shorter rime constant (thermal effect) would still be much slower than any optical effect and hence with a different experimental arrangement it could be overcome.

Indeed. A different arrangement was used. Which although did not have much success, has been included later for completeness.

Although there is some confusion over the validity of the results obtained for Fig. (7), this does not remove from the tact that by illuminating the semi-conductor sample, there was an immediate decrease in Hall voltage and corresponding increase in carrier concentration. Therefore, assuming the change in n has been created by optical enhancement then this effective dynamic carrier concentration can be expressed as:

$$\Delta n = \frac{\alpha I(\omega)\tau}{\hbar\omega}$$

Where, the recombination times of electrons. Or rather, the effective lifetime of the tree carriers. Can be calculated.

Wavelength of light used=10.6×10^{-4} cm

Absorption coefficient of = 10 cm^{-1}

InSb at room temperature (10.6μm)

$\hbar\omega$ = 1.46×10^{-21} eV

Δn for 80 mW = 3.2×10^{16} cm^{-3}

Δn for 25 mW = 0.4×10^{16} cm^{-3}

$I(\omega)$ for 80 mW = 10.2 Watt cm^{-2}

$I(\omega)$ for 25 mW = 3.2 Watt cm^{-2}

:. recombination time t for 80 m W= 45.8×10^{-8} seconds

:. recombination time t for 25 m W= 18.2×10^{-8} seconds

Therefore from these results it has been shown that the optical Hall effect can be used to determine excess carrier concentrations and recombination times of electrons in semiconductors. The difference in the recombination times for the different intensities of light is possibly due to an initial thermal effect being more pronounced at higher powers of illumination. So the values taken for t at 25 m W are probably more accurate than those at 80 m W. Indeed, there could have been a difference in the temperature of the samples before they were exposed, although. this was kept to a minimum by allowing the Hall voltage to return to the same value Prior to illumination.

With a current of 0.6mA and V_A at 1.6mV for room temperature, the conductivity was calculated to be 26.Icm.IQ.l In a separate resistively measurement (see Appendix III) the conductivity was found to be 25.3 cm.1 Ω which compares well.

Obviously, if this project were to be studied in greater detail then a better arrangement for observing the optical Hall Effect would be required. This could be achieved by using an oscilloscope with a storage facility for the Hall voltage, and a pulsed laser for the optical beam. The oscilloscope would enable the nanosecond optical Hall effect to be observed, whilst the pulsed laser would give a good intensity without Cooking' the sample. In fact, this was attempted at one stage, but it was not without problems. The change in Hall voltage is very small and as a result was lost within the noise of the system having passed through a D.C. amplifier. The method of avoiding temperature effects would be to put the sample in a cryogenic system and cool it until the sample went into the extrinsic region, i.e., constant carrier concentration. Hence, there would be a large temperature range where an increase of around,"20"C could be tolerated and any change in carrier concentration would be due purely to an optical effect.

Fig. (8) shows the resultant Hall voltage/temperature against time. When the L.E.D. was switched on, there was an immediate change in the carrier concentration. But unfortunately it was a decrease where theory would have predicted an increase. The overall trend at the curve is, as expected, a decrease in Hall voltage i.e., increase in carrier concentration, as the L.E.D. gives out heat and the sample warms. The change in n must be due to some inductive pickup when the L.E.D. is switched on, however, it should be added that this effect did not occur at room temperatures. Since there is no reason why the Hall voltage should do this, the results have been left inconclusive.

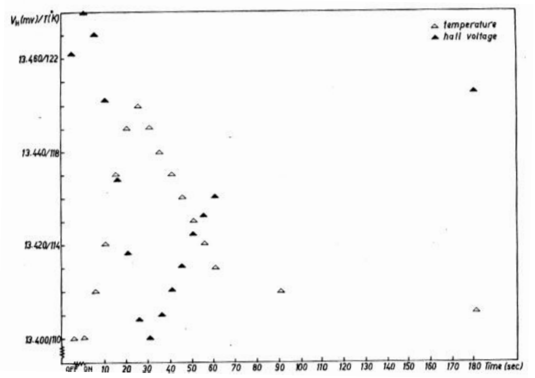

Fig. (8): Graph of Hall voltage and temperature Vs. time

Conclusion

The Hall Effect has been successfully observed with graphs of Hall voltage against magnetic field strength and current being plotted and given results as predicted in the theory. Similarly, conductivity and the Hall coefficient agreed well with theory, with graphs plotted against variations in temperature showing lattice scattering: dominating the conductivity after the material become extrinsic below 223K, the point at which the Hail coefficient become a constant. The Hall mobility was calculated and found to be 4.2% of the quoted value at 300K. However, this corresponds quite well when the contact resistance of 90.2% of the total resistances taken into account. Conversely, the value for the energy gap appeared much higher than the accepted value quoted in Smith. Again the high contact resistance must be involved with additional difficulties arising from deciding exactly where the intrinsic region of the Ln(R^{-1}) against T^{-1} curve was located. The carrier's concentration of the sample used was given as 1.5x10^{16} cm^{-3} at 77°K. the value obtained in the experiment at the same temperature was 1.6 cm^{-3} 10.7°10 given a percentage difference of 6.7% So with the difference laying within the error limits of the experimental value an accurate method of determining carrier concentrations of semi-conductor samples has been achieved.

Of the two methods used to observe an optical Hall Effect. Only one appeared to agree with theory. A change in the Hall voltage has been observed when continuous wave CO_2 laser light at 10.6μm illuminated the sample. The expected decrease in the Hall voltage created values for the dynamic carrier concentration of $3.2x10^{16}$ cm^{-3} with a corresponding recombination time for electrons of 45.8×10^{-8} seconds when light with a power of 80mW was directed onto the sample. Although the results are of the correct order of magnitude. They are of a qualitative nature and no error limits could be meaningfully put on the values. This is primarily because there is some doubt as to the validity of the excess carrier concentration i.e., whether there was a photo generation of carriers or whether the change was due to a thermal effect. However, it should be possible to observe an optical Hall Effect conclusively if the results were taken in the extrinsic region where changes in temperature may be neglected.

Finally, it should be noted that the other method of illuminating the sample with an L.E.D. actually gave the complete opposite effect anticipated in the theory i.e. Hall voltage increased with carrier concentration. This change can only have been accounted for in insufficient screening of electrical components within the cryostat and the results obtained have been left inconclusive.

In conclusion, with accurate Hall measurements being taken and preliminary values of the optical Hall Effect being observed, the two main objectives of the project have been successfully fulfilled.

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