Hall effect measurements of the carrier density and mobility of a 3D electron gas in a GaAs/AlGaAs heterostructure

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We measured the Hall resistance of GaAs to be -1455 ± 53.8 at 300K and 2331 ± 139 at 77K. We measured the sheet resistance of our GaAs / AlGaAs heterostructure to be $R_\square = 2070\Omega \pm 164\Omega$ at 300K...

I. OVERVIEW

The various layers of our sample are show in figure I. The first layer (from the bottom) is a one micron layer of epitaxially grown GaAs. Next there is an undoped layer of GaAlAs which serves as a spacer between the undoped GaAs below and the silicon doped GaAlAs layer above. The silicon dopant significantly lowers the conduction band energy. As can be seen in the energy diagram in figure I, the conduction band passes below the Fermi level (a phenomina known as inversion) in a small region between layers, where a 2 dimensional electron gas (2D EG) can form. The spacer between the undoped GaAs and the doped GaAlAs prevents the scattering of carriers from dopant atoms; a technique called "modulation doping". Topping off the heterostructure is a 10nm GaAs "cap" layer which protects and isolates the layers below.

The relevant physics of the Hall effect are reviewed in the appendix. The Hall resistance is defined through the following relation in two dimensions:

$$V_H = I R_H B \tag{1}$$

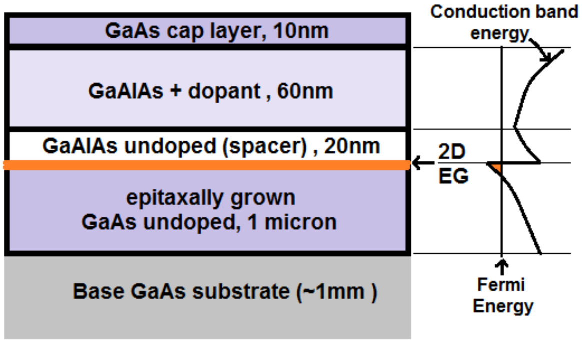

FIG. 1. Expitaxally grown layers of our sample (not to scale).

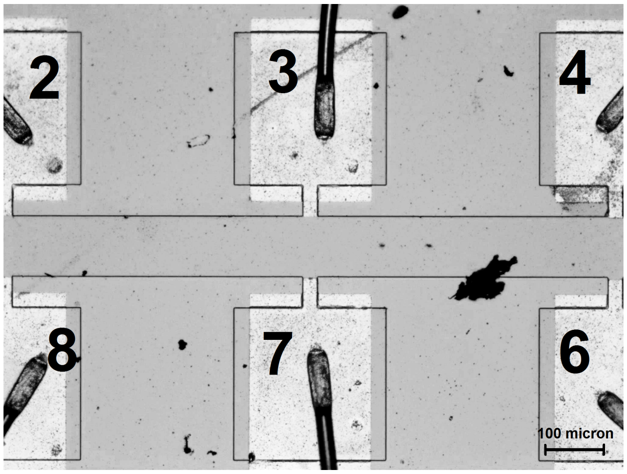

FIG. 2. Microscope image of the sample. The metal contacts appear lighter and have thin gold wires attached to them.

If we assume only one type of carrier, the mobility can be calculated using the equation

$$\mu_H = \frac{R_H}{R_\square} \tag{2}$$

We use the subscript H to denote that this is the Hall mobility. In many cases the Hall mobility, as calculated here, is not equal to the true mobility of the electrons. The Hall coefficient often has to be divided by a quantity called the "Hall factor", which we assumed to be one (a good assumption for degenerate intrinsic semiconductors and if B is small enough that second order effects are negligible). The Hall factor can be significantly different than one if there the material is highly non-degenerate (ie. at high temperature) and/or if there are major sources of scattering, such as ionized impurities.[2] For bulk (3D) GaAs, the Hall factor is around 1.05 at 77K and around 1.15 at 300K.[3]

The relaxation time, denoted τ the average time between collisions for a given electron. It can be calculated using the equation:

$$\tau = \frac{m^* \mu}{e} \tag{3}$$

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II. PRELIMINARY MEASUREMENTS

By noting the direction of current flow, the orientation of the sample with the respect to the magnetic field, and the sign of the Hall voltage, we determined (using the right hand rule) that the dominant carriers in GaAs are negative (electrons). We determined the sheet resistance the parameter $\gamma = l/w$ ($= 5.11 \pm .027$ for adjacent contacts) by measuring l and w using the number of pixels in the picture shown in figure I. During the course of our measurements we measured the voltage between the pairs 6-7, 6-8, and 7-8 at 300K and 77K at fixed current and zero magnetic field. These measurements gave three different values for the sheet resistance at each temeperature, which were averaged to give $R_\square = 2070 \pm 164.7\Omega$ at 300K and $R_\square = 136.26 \pm 7.87\Omega$ at 77K.

III. MEASUREMENT OF R_H , n, μ_p AND μ_n

The semiconductor we are studying is an intrinsic semiconductor (does not contain a dopant) which is known to have both electrons and holes. The Hall coefficient is (see appendix):

$$R_H = \frac{1}{ne}\frac{\mu_p - \mu_n}{\mu_p + \mu_n} \tag{4}$$

The formula for the magnetoresistance is:

$$\rho = \rho(0)(1 + \mu_e\mu_p B^2) \tag{5}$$

In our experiment we are able to measure R_H, $\rho(0)$ and the coefficient $A = \rho(0)\mu_n\mu_p$. In equation 4, n is the total carrier concentration : $n = n_p + n_n$. For an instrinsic semiconductor such as GaAs we know that $n_p = n_e = n/2$, but it is not necessarily the case that $\mu_p = \mu_n$, which would imply zero Hall voltage. Equation 4 and equation 5) give us two equation for three unknowns (n, μ_n, μ_p). To reduce the number of unknowns one can use the defining formula, $\mu = \frac{v_d}{E}$ to get $1/(en)$ in terms of μ_n and μ_p:

$$\begin{aligned} j &= nev = n(e\mu_p + e\mu_n) \\ &= neE(\mu_p + \mu_n) \end{aligned} \tag{6}$$

(Here most authors would put a negative sign would go in front of the term $e\mu_p$, but we chose to let it be absorbed into μ_p).

$$\frac{1}{ne} = \rho(0)(\mu_p + \mu_n) \tag{7}$$

Plugging this into equation 4 leaves us with two equations for two unknowns:

$$\begin{aligned} A &= \rho(0)\mu_n\mu_p \\ R_h &= \rho(0)(\mu_p - \mu_n) \end{aligned} \tag{8}$$

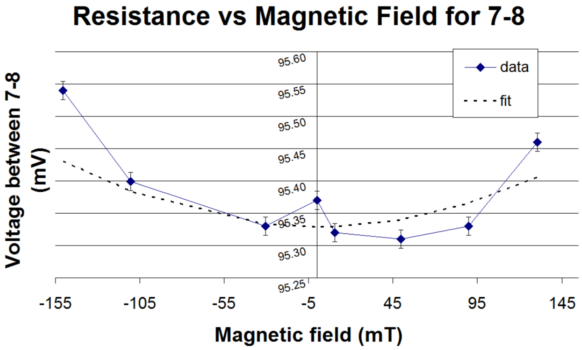

FIG. 3. Best magnetoresistance data we took at 300K.

Solving these equations yields

$$\begin{aligned} \mu_p &= \frac{R_H \pm \sqrt{R_H^2 + 2A\rho(0)}}{2\rho(0)} \\ \mu_n &= \frac{A}{2\rho(0)\mu_p} \end{aligned} \tag{9}$$

In our experiment we did not directly measure ρ vs B, what we measured was the voltage along the length l vs B. Using Ohm's law $E = j\rho$, the relation for the 2D current density $j = I/w$, and the relation $V = El$, we get the equation:

$$V = \frac{I\rho l}{w} = I\rho\gamma \tag{10}$$

Thus, the coefficient we measured from our fit, which can be denoted by C, is related to A by $C = IA\gamma \rightarrow A = C/(\gamma I)$. The magnetoresistance data we used is shown in figure III for 300K and in figure **??** for 77K. At 300K the fit had a $\chi^2 = 6.86$ corresponding to a p-value of $p = .33$, and at 77K the fit had a $\chi^2 =$ corresponding to a p-value of $p =$. At 77K two fits were used, shown in figures III and III, which had χ^2 values of 8.14 ($p = .228$) and 0.887 ($p = .98$) respectively. The results for A were averaged between the two fits. The poor χ^2's show that these fits were not good, for reasons we will speculate on in the section on errors. The fits also allowed for the calculation of $R_\square$ by looking at the y-intercept of the graph. $R_\square$ was found to be $2068 \pm 0.22\Omega$ at 300K (the error was calculated by looking at the change necessary to change χ^2 by 1). Despite the (apparently) small error, I choose to use the value of 2070Ω and associated error described before, because the overall the magnetoresistance data was of poor quality and the fits were not good, neither in visual apperence or p-value.

Our fits for R_H are shown in figure III. When taking our data we ran into an issue of a hysteresis effect, resulting different y-intercepts as $B = 0$ is approached from different directions. To help compensate for this, we took our data by alternating B between each point taken, which averages over the hysteresis effect and also prevents the buildup of a large "ferroelectric" voltage /

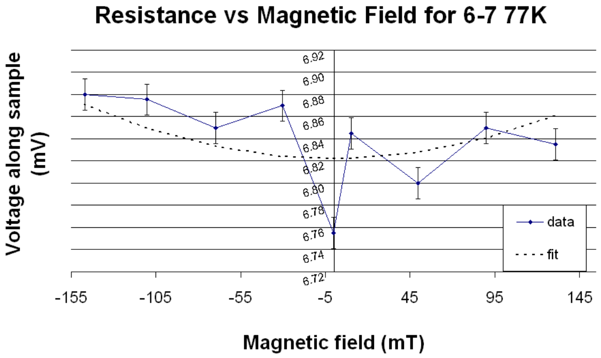

FIG. 4. Data from 6-7 at 77K

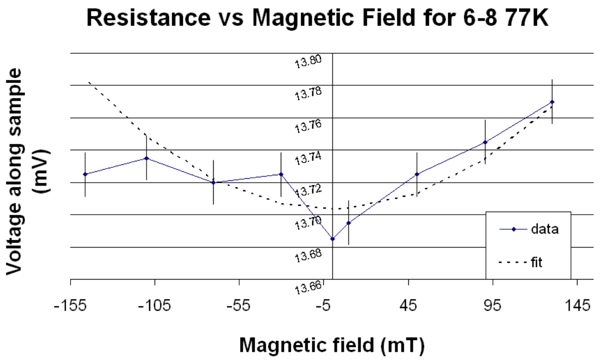

FIG. 5. Data from 6-8 at 77K

large hysteresis. However we could not completely remove the hysteresis, so the points near $B = 0$ were not included in the fits. In all cases, two fits were done, one for postive and one for negative values of B. These fits were done using the method of linear regression (least squares) to get the slope and y-intercept. Linear regression was used because it is an analytic technique, and does require a searching of parameter space like χ^2. Searching parameter space often leads to solutions which are only local minima and is more time consuming because usually many initial values need to be tried to get ensure an accurate fit. It is also much easier to calculate the error in the parameters from a linear regression, as exact equations are available.[1] For each fit the R^2 value (described in the appendix) is reported on the graph, showing that all the fits were very good.

At 300K we found $R_H = -1455 \pm 53.8$ m^3/C. If we naivly assume one type of carrier and plug into the formula $R_H = 1/(ne)$ this yields a carrier concentration of $4.296 \times 10^9 \pm 1.588 \times 10^{8})$cm^{-3} wchich is about 1000 times greater than the carrier concentration of bulk GaAs, but close to the carrier concentration of bulk silicon ($1.45x10^{10}$cm^{-35}).

The results for carrier concentration and mobility and other microscopic parameters are summarized in the following table:

	300K	77K	Units
$R_\square$	2070 ±164.7	136.3±7.8	Ω
R_H	-1455±53.8	-2331±139	m^3/C
μ_n	.7027	34.22	m$^2/(Vs)$
μ_p	.0639	0.0129	m$^2/(Vs)$
n	3.94×10^9	2.680×10^9	cm^{-3}
τ_n	.267	13.0	ps
τ_p	.123	.025	ps
V_{fe}	$1.923\ \times10^5$	2.43×10^5	m/s
ϵ_f	.013	.00919	eV
l_e	72.81	2925	nm
λ_{Db}	39.991	48.477	nm

Our value for μ_n at 300L is within error of the accepted value .85 m^2/(Vs). The accepted value for μ_p at 300K is .04 m^2/(Vs). Again one sees that the carrier concentration is a factor of 1000 larger than in bulk (3D) GaAs, suggesting a possible error in converting units, however the larger carrier concentration makes sense considering that there is an inversion layer in our sample.

The relaxation constant τ was calculated using the formula:

$$\tau = \frac{m^* \mu}{e} \tag{11}$$

where we used effective masses derived from band theory for bulk GaAs of $m_e^* = .067 m_e$ and $m_p^* = .34 m_e$.[4]

The cyclotron orbit can be estimated using the formula:

$$r_c = \frac{\gamma m^* v_f}{eB} \tag{12}$$

Assuming a field of 150mT (the highest we used), and using the calculated Fermi velocities this yields

$$\begin{aligned} r_c &= 690.7 \text{ nm} \quad \text{at 300K} \\ r_c &= 567.9 \text{ nm} \quad \text{at 77K} \end{aligned} \tag{13}$$

Thus we see that an electron would not be able to complete a cyclotron orbit at 300K or at 77K ($c = \pi r_c^2 = 1,009,986 nm$) with a 150mT field.

We can also compare l to the lattice constant for GaAs at 300K, which is is $.565 nm$.[5]

A. Discussion of change with temperature

At room temperature, intrinsic semiconductors are usually non-degenerate. This means that $\epsilon_c - \epsilon_f > 3kT$. If a semiconductor becomes degenerate, then many electrons will be in the conduction band and it will begin to behave more like a conductor. When a material is non-degenerate, it is good to use the following formula for v_{avg}:[2]

$$\begin{aligned} v_{avg} &= \left(\frac{8kT}{\pi m_e^*}\right)^{1/2} \\ &= 4.12 = 5 \times 10^5 \text{m/s} \quad \text{at 300K} \end{aligned} \tag{14}$$

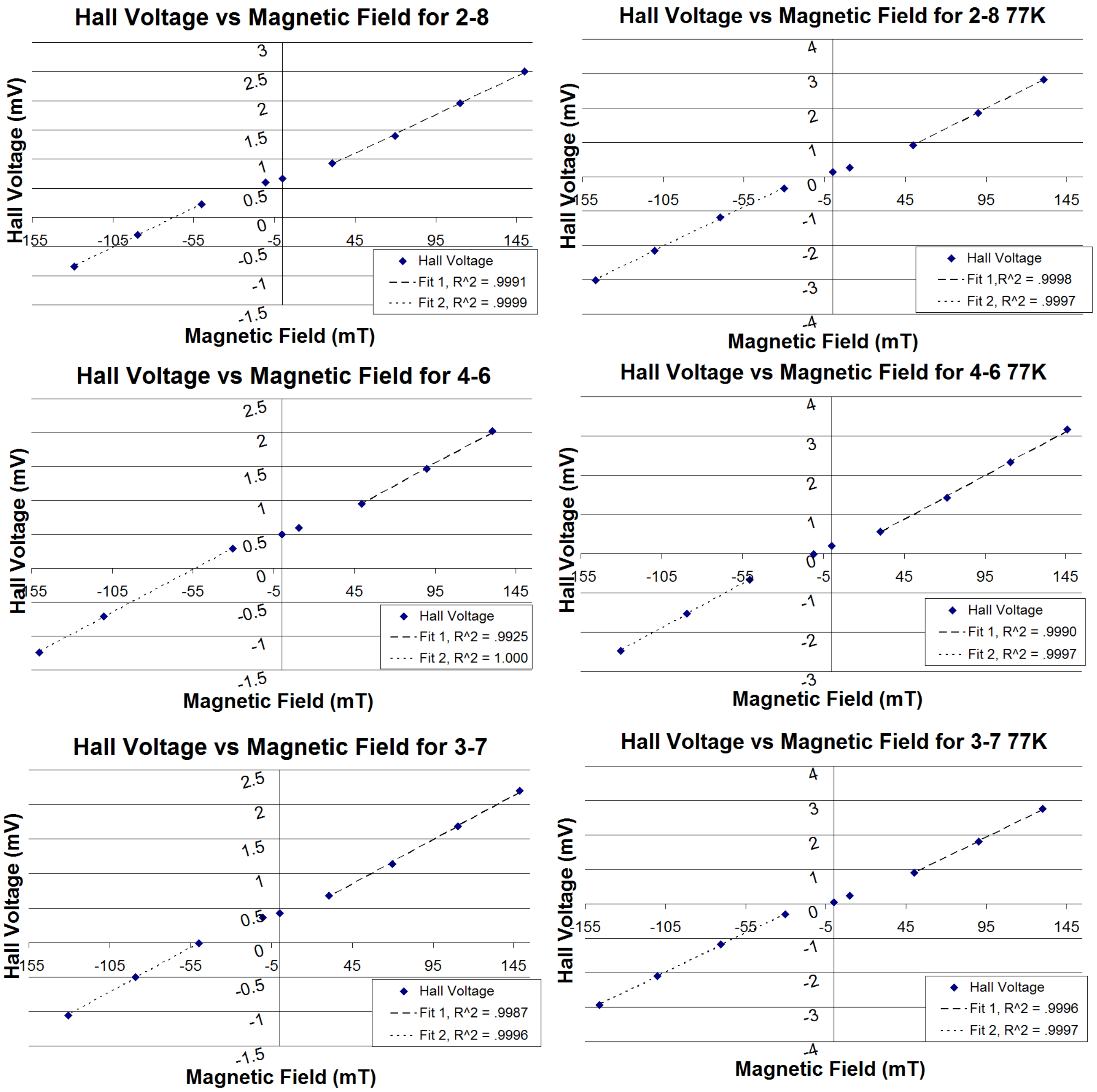

FIG. 6. All of the data & fits we used to determine R_H at 300K and 77K.

Our sample was probably degenerate in the inversion layer, but otherwise non-degerate.

The carrier density as a function of temperature is well described by the equation

$$n = Ne^{-(\epsilon_f - \epsilon_c)/(kT)} \tag{15}$$

The temperature dependece of the mobility depends on many factors. If the sample is pure, then lattice scattering by longitudinal acoustic (LA) phonons will dominate. This leads to a temperature dependence of $\mu \propto T^{-3/2}$.[2] (More discussion should go here)

B. Constant B, varying I measurement of R_H

We also measured R_H by fixing the magnetic field at 187mT (the highest we could achieve) and then varying the current between $1 - 10\mu$A. The results are shown

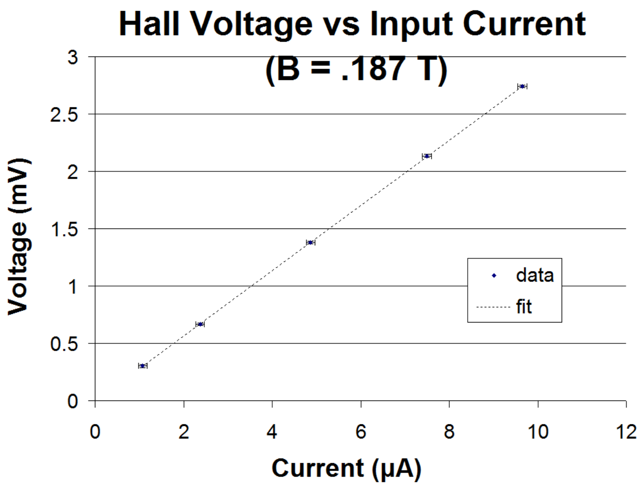

FIG. 7. Data taken with $B = 187\text{mT}$

in figure III B. We found $R_H = 1532.2pm6.869$ m^3/C, which is not consistant with our previous value. The reason for the inconsistancy is not known, but suggests a systematic error either in the experiment or the calculation.

IV. SOURCES OF ERROR

A. Geometrical errors

There are several sources of error with regards to the geometry. The length to width ratio was measured on a computer using a microscope photo of the sample to minimize measurement error, but still a small amount of error was incured. Another possible source of error is from geometric offset of the fingers used to measure the Hall voltage. Geometrical offset results in an additional voltage scales with the current and is present even with non-zero magnetic field. It is apparent as the non-zero y-intercepts in fig III, and can be easily be avoided by always dealing with the slope.

B. Thermal effects

Thermal emf is due to "pyroelectricity" – the creation of a voltage gradient due to a temperature gradient. Thermal emf can be compensated for by reversing the current – the voltage across the sample reverses direction, but the thermal emf does not. By making two measurements taken with the current going in opposite directions and then subtracting them, one can cancel out the thermal emf : $[(V + V_{emf}) - (-V + V_{emf})]/2 = V$. An additional possible source of error was due to the fact that the temperature of our sample was constantly changing as Joule heat begins to dissipate when the current is turned on. In semiconductors, the resistivity decreases with temperature. We found that it took a very long time (≈ 5 mins) for the sample temperature to equilibriate (as seen by the decreasing voltages). Then, when the current was removed, the sample would cool down very quickly. Even in "equilibrium" the voltage would continue to fluctuate on the order of .01mV. For this reason, we choose to make our measurements very quickly and only allow current to flow for very short times. We tried to do this as consistantly as possible, but estimated that our precision was limited to $\approx$ .01mV.

C. Sample positioning

The positioning of the sample was important as the sample should be perpendicular to the magnetic field. We aligned the sample as best we could but estimated that the sample still had an inclination of about $2\,°$. We can correct for this by multiplying our measured value of magnetic field by $\cos(2\,°) = 0.9994$. The error in estimating the angle is negligible compared to the instrumental error in B (.1 mT).

D. Internal resistance of the voltmeter

Most voltmeters (whith the exception of balancing potentiometers), such as the Agilent 34401A multimeters we utilized, have a small amount of current flowing through them. Starting with a total input current I, we write $I = I_v + I_x$ where I_v is the current flowing through the voltmeter and I_x is the current flowing through the sample. We know $I_v R_v = I_x R_x$ and that $I_v = \frac{I_x R_x}{R_v} \approx \frac{I R_x}{R_v} = \frac{V}{R_v}$. The voltmeter works by measuring I_v and then infering V. This scheme works well, but can be jepordized if the contact resistances are large, because they will effect the current flow through the voltmeter. In that case, $I_v(R_v + 2R_{\text{cont}}) = I_x R_x$ so we get $I_v \approx \frac{I R_x}{R_v + 2R_{\text{cont}}}$. One easy way to correct for this would be to figure out R_{cont}. However contact resistances are hard to characterize. Making low-resistance contacts onto semiconductors is a challenging engineering problem. Contacts are often non-ohmic, which further complicates their characterization, because then their resistance depends on current in a non-linear way.

ACKNOWLEDGMENTS

Thanks to Prof. Laszlo Mihaly for his guidance in carrying out the experiment.

Appendix A: Background physics

1. Drude model

The Drude model is a simple model of conductivity which assumes that carriers travel for an average time τ before being scattered. Since scattering is assumed to be equally likely in every direction, on average an electron's velocity is reset to zero after scattering. We take the average velocity (known as the "drift velocity") in an electric field to be $v_d = (1/2)a\tau = (eE\tau)/(2m^*)$. However, it turns out that we made a mistake here, which is actually very similiar to a mistake that Drude made in his orginal paper. The relaxation time, τ is defined to be the average time between collisions, *for a given electron, chosen randomly.* It turns out that, quite counter intuitively for those who have not done the calculation, this is different then the average time between collisions averaged over a collection of N electrons, a quantity called the "ensemble average". It turns out that the ensemble average is equal to 2τ. To see this, we start by noting that the probability of a collision in a small interval of time is $P_c(dt) = dt/\tau$. The probability of no collisions in a time interval t, denoted as $P_{nc}(t)$ can be calculated by breaking up t into N small time intervals $t = N\delta t$:

$$P_{nc}(t) = (1 - P_c(\delta t))^N = \left(1 - \frac{t}{N\tau}\right)^N = e^{-\frac{t}{\tau}} \tag{A1}$$

where we have implictely taken the limit as $\delta t \to 0, N \to \infty$. The function P_{nc} is known as a "cummulative probability function". A probability density function, giving the probability of a collision at any time t (after a collision at t=0) can be found by taking the derivative of this function.

$$PD_c = \frac{d}{dt}(1 - e^{-\frac{t}{\tau}}) = \frac{1}{\tau}e^{-\frac{t}{\tau}} \tag{A2}$$

The interpretation of this function is as follows: if we pick N electrons at random, there is a probability $PD_c(t)dt$ of finding an electron who's last collision was between t and $t + dt$ ago. The average time until the last collision is given by:

$$\langle t \rangle = \int_0^\infty t\frac{1}{\tau}e^{-\frac{t}{\tau}}dt = \tau \tag{A3}$$

An identical calculation tells us that the average time until the next collision, for a randomly chosen electron, is also τ. Thus, the average time between collisions, T for a randomly chosen electron, is 2τ. This can be confirmed by looking at the probability distribution for T. This is confusing because, if we focus on a particular electron, we can calculate the probability there is no collision between $[0, t]$ and then a collision at $t + dt$ as $e^{-\frac{t}{\tau}} \times dt/\tau$. The average over all possible times tells us, that for a given electron, the average time between collisions is τ. This average (which can be called "time average") is different than the ensemble average by a factor of 2.

It turns out that this factor of 2 is going to cancel out the factor of 1/2 in the equation for v_d. Thus, if one neglects the factor of 1/2 and the factor of 2, one still obtains the correct result, albeit through incorrect means. Indeed, this is excatly what one sees in many popular textbooks, with the above details ommited.

The current density is defined as $j = nev_d$, so we obtain

$$j = \frac{e^2 n\tau E}{m*} \equiv \frac{E}{\rho} \tag{A4}$$

Where ρ is the resistivity: $\rho = m^*/(e^2 n\tau)$, which is related to the resistance by the equation $\rho = (Rw\delta)/L$, or in the case of a 2D material, $\rho = (Rw)/L \equiv R\gamma$. The mobility is defined as:

$$\mu \equiv \frac{v_d}{E} = \frac{e\tau}{m^*} \tag{A5}$$

2. Hall effect

When both an electric and magnetic field are present, the carriers in the material will experience a force $\mathbf{F} = e(\mathbf{E}+\mathbf{v}\times\mathbf{B})$. We assume both fields are constant in space and time, and that the magnetic field is perpendicular to the current. The correct expression for the Hall voltage can be derived through a simple physical argument. We note that the magnetic force will cause charge to build up along the edge of the sample, until compensated by the resulting electric field. In other words, in equilibrium:

$$eE_y = ev_d B \tag{A6}$$

Thus,

$$V_H = E_y w = v_d B w \tag{A7}$$

Now we multiple both sides by $ne\delta$ and use $j = nev_d$ to obtain the correct expression.

$$V_H = \frac{jBw\delta}{ne\delta} \tag{A8}$$

We now use the relation $I = jw\delta$ and note that the "Hall resistance" is defined to be $R_H \equiv 1/ne$, so we obtain the conventional formula:

$$V_H = \frac{IR_H B}{\delta} \tag{A9}$$

In two dimentions, the above derivations for the resistivity and mobility are all the same, except that n is measured in charges / m^2 and current density is measured in A/m. We prefer to express things in terms of what is called the "resistance per square" or "sheet resistance" (where one assumes a square sample, ie. $l = w$):

$$R_\square \equiv \frac{m^*}{e^2 n\tau} \tag{A10}$$

To avoid confusion, it would probably be better to call $R_\square$ the "sheet resistivity" since this is the same as the conventional equation for ($3D$) resistivity, but the term "sheet resistance" is the one in use. Ohm's law in 2D is

$$j = \frac{E}{R_\Box} = \frac{I}{w} \tag{A11}$$

If we then assume that E is along the length l we can convert this to the more conventional form by multiplying both sides by l,

$$\begin{aligned} \frac{lI}{w} &= \frac{V}{R_\Box} \\ V &= IR_\Box \frac{l}{w} = IR \end{aligned} \tag{A12}$$

Thus it is clear that $R_\Box$ can be calculated by dividing the measured value of R by $l/w \equiv \gamma$:

$$R_\Box = R/\gamma \tag{A13}$$

The derivation of the Hall voltage is only slightly different, resulting the same expression as eqn. A9 but with no δ:

$$V_H = IR_H B \tag{A14}$$

To find the mobility, (assuming one type of carrier) in summary we have the following two easily derivable relations:

$$\begin{aligned} \mu &= R_H/\rho \qquad (3D) \\ \mu &= R_H/R_\Box \qquad (2D) \end{aligned} \tag{A15}$$

One should distinguish between 2D mobility and 3D mobility, but here we did not, assuming the type would be clear from context.

3. Magnetoresistance formulae

So far we have been considering the Hall effect in metals, where all of the carriers are electrons. In semiconductors, there can also be holes. In impurity free ("intrinsic") semiconductors, the number of electrons will equal the number of holes. In the special case when the electrons and holes have equal concentrations and equal mobilties, then the electrons will travel in one direction, and the holes will travel in the other. They will both move in the same direction under the application of a magnetic field, and therefore there will be no Hall voltage. However, there can still be magnetoresistance. The correct equations can be derived by repeating the derivation with two types of carriers and setting $j_y = 0$ instead of $v_y = 0$. The derivation involves a large degree of manipulation however to correctly factor out ρ.

$$\begin{aligned} \rho &= \rho(0)(1 + \mu_e \mu_p B^2) \\ R_H &= \frac{\mu_p - \mu_n}{ne(\mu_p + \mu_n)} \end{aligned} \tag{A16}$$

Appendix B: Derivation of the Fermi energy & Fermi velocity for a 2D electron gas

The derivation of the Fermi energy for a 2D electron gas of density n goes as follows: We need to solve the Schödinger equation in 2D, in a square sample of area $A = L^2$. After finding the energy levels, we find will find the density of states, a quantity which will be the same as L goes to infinity. The Schödinger equation is a wave equation:

$$-\frac{\hbar^2}{2m}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)\psi = \epsilon\psi \tag{B1}$$

The solutions in free space are plane waves:

$$\psi_{\vec{k}} = \frac{1}{\sqrt{V}} e^{i\vec{k}\cdot\vec{r}} \tag{B2}$$

We apply periodic boundary conditions ($\psi_{\vec{k}}(\vec{r}) = \psi_{\vec{k}}(\vec{r} \pm L\hat{x} \pm L\hat{y})$ since they permit more physically realistic running waves instead of the standing waves we would get if we set $\psi = 0$ along the edges of our square (incidently either choice will lead to the same result, however). Thus only certain values for k_x and k_y are allowed:

$$k_x = \frac{2\pi n_x}{L}, \qquad k_y = \frac{2\pi n_y}{L} \tag{B3}$$

The area per point in k-space is clearly seen to be $\left(\frac{2\pi}{L}\right)^2$. As we extend L to infinity, the number of points in k-space per unit area becomes the inverse of this quantity

$$\frac{A^2}{4\pi^2} \tag{B4}$$

Now one begines to imagine filling up these levels with two electrons in each level. The area of the "Fermi sphere" is defined to be πk_f^2. Now we imagine having N electrons in our box. The number of electrons in the Fermi sphere is $N = \frac{k_f^2 L^2}{2\pi}$. Now the number density can be related to the Fermi wave-vector:

$$\begin{aligned} n_e &= \frac{N}{L^2} = \frac{k_f^2}{2\pi} \\ k_f &= \sqrt{2\pi n_e} \end{aligned} \tag{B5}$$

The Fermi velocity is defined as $v_f \equiv \hbar k_f/m^*$:

$$v_f = \frac{\hbar\sqrt{2\pi n_e}}{m^*} \tag{B6}$$

The Fermi energy is simply $(\hbar^2 k_f^2)/2m^*$:

$$\epsilon_f = \frac{\hbar^2 \pi n_e}{m^*} \tag{B7}$$

Appendix C: Linear regression formulae and R^2

The R^2 value is the square of the Pearson product moment correlation coefficient, which is defined as

$$R = \frac{n\sum XY - (\sum X)(\sum Y)}{\sqrt{[n\sum X^2 - (\sum X)^2]\,[n\sum Y^2 - (\sum Y)^2]}} \tag{C1}$$

R varies between -1 and 1 with 1 signifying perfect correlation, -1 perfect anti-correlation and 0 no correlation. R^2 is refered to as the "coefficient of determination" in some literature and varies between 0 and 1.

REFERENCES

[1] University of Delaware Dept. of Chemical Engineering Annette D. Shine. Fitting experimental data to straight lines, March 2012.

[2] J.S. Blakemore. *Solid State Physics.* W.B. Saunders Company, Toronto, Ontaria, 1974.

[3] Ioffe Institute New Semiconductor Materials Database. Electrical properties of gaas, May 2012.

[4] www.SiliconFarEast.com. Effective mass in semiconductors, May 2012.

[5] Bart J. Van Zeghbroeck. Properties of si, ge, and gaas at 300k, May 2012.