Physics 111B: Hall Effect in Semiconductor

Shreyas Patel
Partner: Deanna Long
University of California Berkeley

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I. INTRODUCTION

Semiconductors play a vital role in modern technology, primarily through there utilization in digital circuitry. They are used to make microscopic transistors, which constitute logic gates and build up to computers.

II. BACKGROUND

A. Electrical Properties of Conductors, Insulators, & Semiconductors

For an isolated atom, electrons occupy set quantized energy levels. These energy levels can hold only a single electron, so an atom with N electrons would have them occupying N distinct energy levels. An atom has an infinite number of energy levels, where the levels further away from the nucleus are more dense.

When an atom is in the ground state, all of the atom's electrons occupy the lowest possible energy levels. For an electron to move to a higher energy level, the level needs to not only be empty but the electron needs sufficient energy that matches the difference in energy between the two levels.

Looking at an isolated atom, all of these possible energy level states are distinct. But when there are multiple atoms within very close proximity of each other, such as within a solid, they begin to influence one another and the distinct energy levels end up becoming delocalized energy bands. These energy bands represent a continuum of possible electron states and are separated by energy gaps which is are regions where there are no possible energy levels where electrons can exist.

Under typical conditions, the electrons in a solid are within the regime of quantum degeneracy. In this regime at zero temperature, the electrons occupy the lowest energy levels up to the Fermi energy, E_F. At a temperature T, such that $E_F = k_B T$ where k_B is the Boltzmann constant, the distribution of electrons is perturbed such that electrons right near E_F are promoted to an energy above it.

The key difference between conductors, insulators, and semiconductors lies in how much energy is necessary to overcome this E_F. For conductors, the Fermi energy lies within an energy band so the electrons can respond and redistribute to even the smallest of electrical perturbations to the system. For insulators, the Fermi energy lies within an energy gap therefore a lot of energy is required

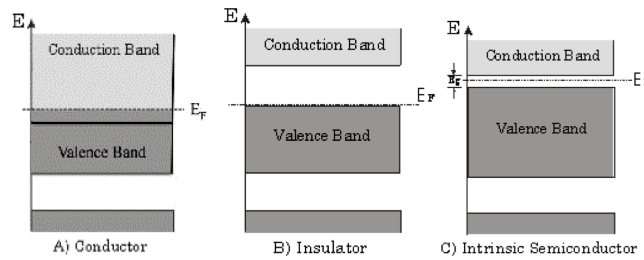


FIG. 1.

for the electrons to be redistributed. So small electric fields and forces that would cause electrical conduction in conductors does nothing to insulators.

Semiconductors lie in a place between conductors and insulators. They are similar to insulators since the Fermi energy boundary lies within a energy band gap, but the key difference is how much energy is necessary to overcome that gap. In semiconductors, that gap is small so it takes less energy then an insulator for electrons to be promoted to a higher energy band, but it still required more energy then conductors by comparison.

The conductivity of a semiconductor is small but strongly temperature dependent. This stems from the energy gap being on the order of mag of $k_B T$ so at a given temperature there may be some electrons that have been promoted to a energy above the Fermi energy. This leaves us with both electrons in the conduction band (energy band above the Fermi energy) and holes in the valence band (energy band below the Fermi energy) allowing conduction to exist in the material.

B. Doping & Semiconductor Types

Semiconductors can have small density of electronic levels introduced within their energy band gaps. This can be done by adding impurity atoms to the semiconductor and is a process called "doping". These impurity atoms either add extra filled electron levels at energies near the conduction band, or unfilled levels near the valence band. This provides either a surplus of electrons or holes to the bands their near respectively. The small energy band gap in the end is what makes semiconductors very susceptible to being doped.

Their are two main type of semiconductors: intrinsic and extrinsic. Intrinsic semiconductors are undoped and the density of electrons to holes is equal. Extrinsic

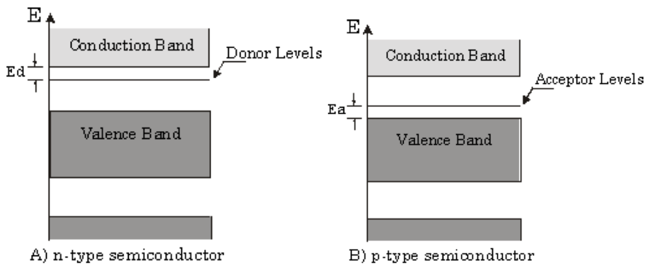


FIG. 2.

semiconductors are dope and therefore have an unequal density of electrons to holes. As a result, extrinsic semiconductors can be further categorized based on which of the densities is greater, giving us either n-type or p-type semiconductors.

N-type semiconductors are produced through the doping process where they have additional filled levels near the conduction band. This results in the majority of their charge carries being negatively charged.

P-type semiconductors are the inverse of this. The majority of their charge carriers are positively charged due to doping adding additional empty levels near the valence band.

C. Conductors vs. Semiconductors

A method of comparing conductors versus semiconductors is to look at their resistivity, ρ. Resistivity is defined as,

$$\rho = \frac{E}{J}[\Omega m] \tag{1}$$

where E is the electric field and J is the current density.

Resistivity is a temperature dependent property where it increases with temperature in conductors while decreases in semiconductors. In semiconductors, this property can also be drastically changed by doping the material.

D. The Hall Effect

The Hall effect is the name of the phenomena that occurs when an electric field is produced in a material perpendicular to the current running through it and the magnetic field it is exposed to due to the Lorentz force being exerted on the charge carriers traveling through the medium.

Looking at this more quantitatively, lets say we have a a magnetic field B being exerted on a semiconductor and is perpendicular to a current I running through it. The free electrons and holes running through the material with a velocity v would then experience the Lorentz force,

$$\overrightarrow{F} = q(\overrightarrow{v} \times \overrightarrow{B})[N] \tag{2}$$

Here, q is the charge of carrier. This force would deflect all charges running through the material to a direction perpendicular to the I and B. For example, if I was towards the x-direction and B towards the z-direction, then all charge carriers in the material would be deflected towards the positive y-direction.

This deflection causes an accumulation of charge on one side. If the predominant charge carrier in the material are electrons, there is a resulting positive charge in the opposite side and an electric field, E_H, pointed in the +y direction. If the predominant charge carriers are holes, then there is a resulting negative charge on the opposite side and E_H would point in the -y direction.

The accumulation of charge will continue to grow and increase the strength of E_H until the force exerted by it on the charges balances out with the Lorentz force so that

$$\overrightarrow{F} = q(\overrightarrow{E} + \overrightarrow{v} \times \overrightarrow{B}) = 0[N] \tag{3}$$

$$\overrightarrow{E_H} = -\overrightarrow{v} \times \overrightarrow{B}[V/m] \tag{4}$$

and the magnitude of the field can be simply seen to be

$$E_H = v_x B_z [V/m] \tag{5}$$

with the potential difference resulting from the electric field being

$$V_H = sE_H[V] \tag{6}$$

V_H is called the Hall voltage is directly related to not only the strength of the electric field, but also the width of the sample, s. The measurements of the Hall voltage can be used to determine whether the material is an n-type or p-type semiconductor, since the sign of the Hall voltage is tied to whether the predominant charge carrier is negative or positive.

For this given sample, the current through it can be related to the density of the charge carriers n and their drift velocity v_x:

$$I = (-env_x)(sd)[A] \tag{7}$$

where sd is the cross-sectional area of the sample and $-e$ is the charge of an electron. This equation can be rewritten to give us the current density, J, as

$$J = -qnv_x[A/m^2] \tag{8}$$

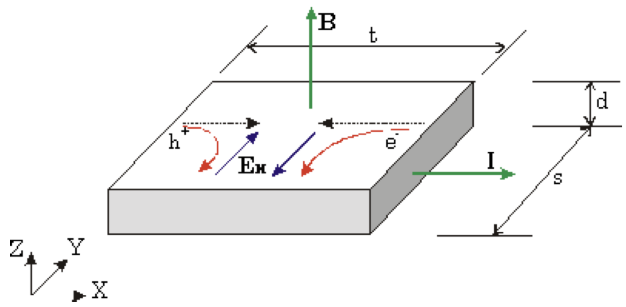


FIG. 3.

Relating this back to the Hall voltage, we see the relation between it and electron density being

$$V_H = -\frac{I_x B_z}{end}[V] \quad (9)$$

and the Hall coefficient R_H as

$$R_H = \frac{E_H}{J_x B_z} = \frac{1}{en}[m^3/C] \quad (10)$$

These equations are used for a negative V_H, or a n-type semiconductor sample. For a p-type, the hole density, p, can be calculated using

$$V_H = -\frac{I_x B_z}{epd}[V] \quad (11)$$

with the Hall coefficient being

$$R_H = -\frac{1}{ep}[m^3/C] \quad (12)$$

The current through the semiconductor can be the result of both electrons and holes, so to isolate the density of each we have to observe the temperature dependence of the Hall voltage instead of just the overall charge-weighted carrier density.

E. The Van Der Pauw Technique

The Van Der Pauw technique is a useful technique to find the Hall voltage and resistivity of a material that utilizes placing four contacts at the peripheral of a sample and using them to drive current and take voltage measurements. For each configuration of current and voltage measurements, you can find the trans-resistance, which is defined as

$$R_{AB,DC} = \frac{V_{DC}}{I_{AB}}[m^3/C] \quad (13)$$

where I_{AB} means the current driven from contact A to B and V_{DC} is the voltage drop between D and C with positive being defined as D having a higher voltage then C.

F. Charge Carrier Mobilities and Drift Velocities

The inverse of thee resistivity gives an equation that can help determine the mobilities of the charge carriers in the material.

$$\frac{1}{\rho} = e \cdot (n \cdot \mu_n + p \cdot \mu_p) \quad (14)$$

μ_n is the electron mobility and μ_p is the hole mobility, and n and p are electron and hole density respectively. From the mobilities we can then find the drift velocity of these carriers.

$$\nu_{de} = \mu_n E \quad (15)$$

$$\nu_{dp} = \mu_p E \quad (16)$$

Here, E is the magnitude of the electric field that drives the current.

III. EXPERIMENTAL PROCEDURES

We took necessary measurements to determine the Hall voltage and resistivity as it varies with temperature during this lab.

A. Temperature Control

The sample originally starts off at room temperature. The measurements will be taken from the temperature range of 95K to 350K, so we initially cool the sample down and let it heat up as we take data. To do this we utilize liquid nitrogen, refilling the reservoir in the device until the sample has reach 95K and begins being heated back up.

The temperature control is done by the computer where once it has reached or gone below the starting temperature it will turn on the heater to begin slowly increasing the temperature until it reaches 350K.

B. Determining Resistivity and Hall Voltage

Using the Van Der Pauw technique, we can use the measurements where the current is being driven between adjacent points to calculate the resistivity. To do this, we use the Van Der Pauw equation

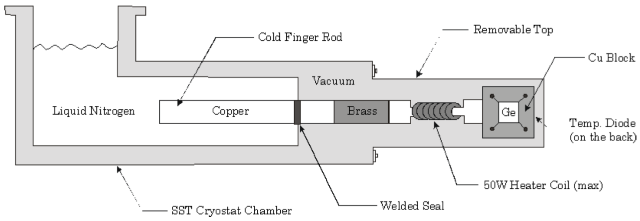


FIG. 4.

$$exp(\frac{-\pi d}{\rho}R_{AB,DC}) + exp(\frac{-\pi d}{\rho}R_{AD,BC}) = 1 \quad (17)$$

Using the fact that all solutions with the same ratio $R_{AB,DC}/R_{AD,BC}$ are related to each other, we can solve for ρ and get

$$\rho = \frac{\pi d}{ln(2)} \cdot \frac{R_{AB,DC} + R_{AD,BC}}{2} \cdot f(\frac{R_{AB,DC}}{R_{AD,BC}}) \quad (18)$$

We approximate the function f to be

$$f(x) = \frac{1}{cosh(ln(x)/2.403)} \quad (19)$$

Measurements where the current is being driven trough the diagonal of the sample are used to calculate the Hall voltage. We first find the average trans-resistance, $(R_{AC,BD} + R_{BD,AC})/2$, and alongside the magnetic field B_z and the dimensions of the sample we can find thee Hall coefficient.

Four total total sets of measurements are taken as seen in I.

IV. RESULTS & ANALYSIS

A. Hall Coefficient and Resistivity

From the graphs, 5, 6, and 7, we see that the relationship between temperature and resistivity is independent of the direction of magnetic field due to the shape being the same for all three fields.

At room temperature, the resistivity of the semiconductor is observed to be $-1.007 \times 10^{-3} cm^3 C^{-1}$ and the resistivity $609.86 \Omega cm$.

The shift from the extrinsic to the intrinsic region is observed to happen at around 290 K. This is also where the Hall coefficient becomes zero.

The semiconductor is p-type, as observed by there being a sign change in the Hall Voltage when it transitioned from the extrinsic to the intrinsic region. Because we observe a sign change, it is independent of what the sign itself is therefore the direction of the magnetic field is not necessary to be known.

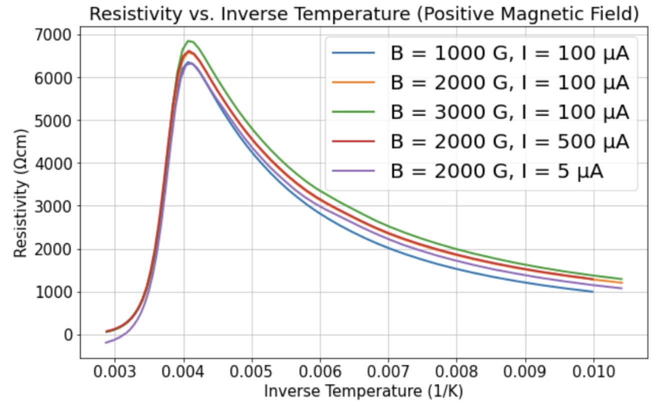


FIG. 5.

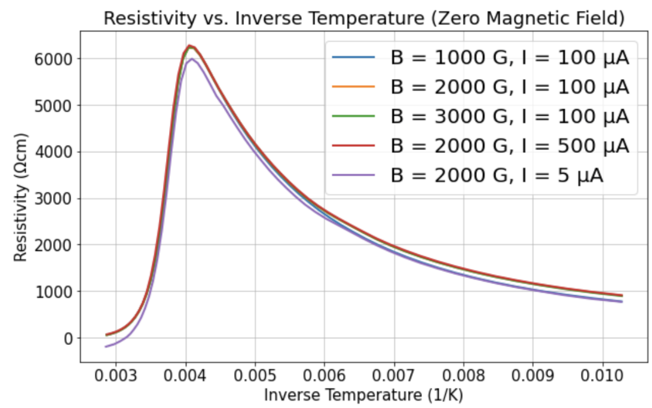


FIG. 6.

From 27 we see that the extrapolated resistivity gives us approximately $7581.43 \Omega cm$ at the inversion temperature while the actual resistivity observed is around $800 \Omega cm$. This would give us a mobility ratio of 1.12.

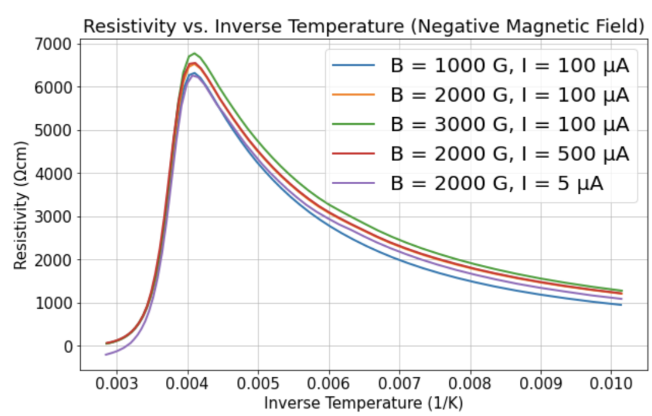
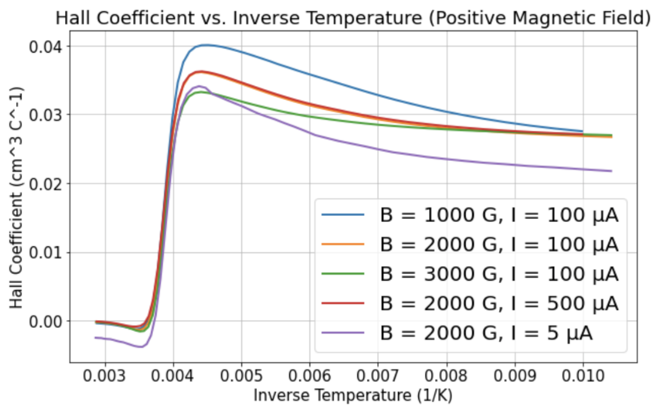


FIG. 7.

TABLE I. Current and voltage measurement sets taken at each temperature interval.

Current	**Voltage**	**Trans-resistance**
I_{AB}	V_{DC}	$R_{AB,DC} = V_{DC}/I_{AB}$
I_{AD}	V_{BC}	$R_{AD,BC} = V_{BC}/I_{AD}$
I_{AC}	V_{BD}	$R_{AC,BD} = V_{BD}/I_{AC}$
I_{BD}	V_{AC}	$R_{BD,AC} = V_{AC}/I_{BD}$



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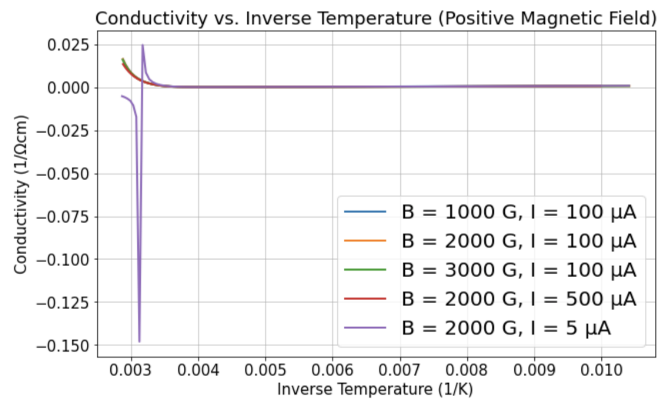

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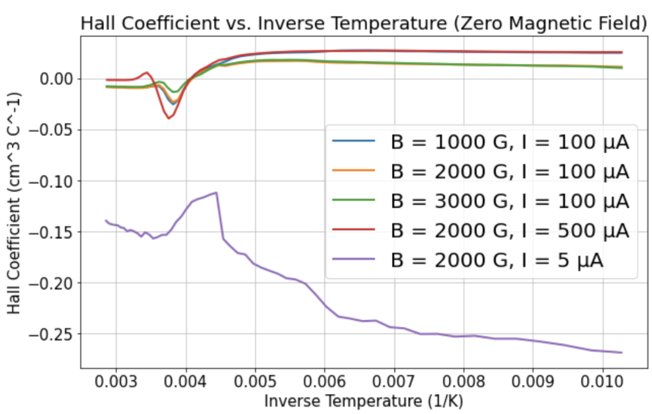

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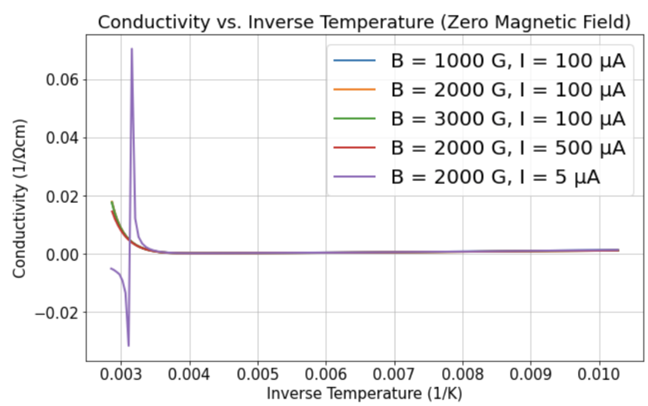

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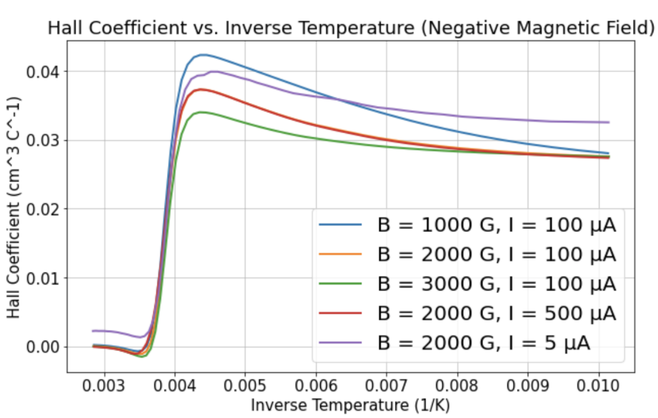

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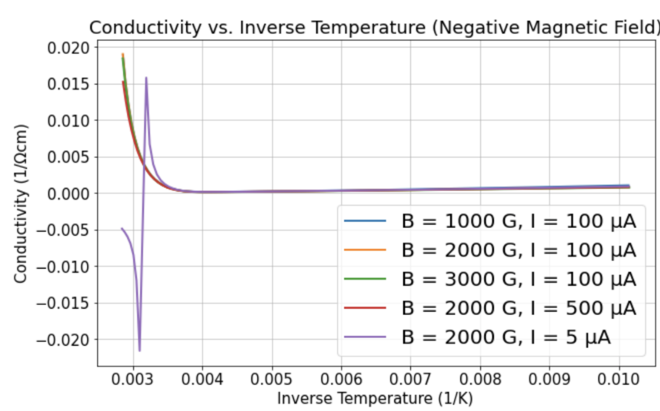

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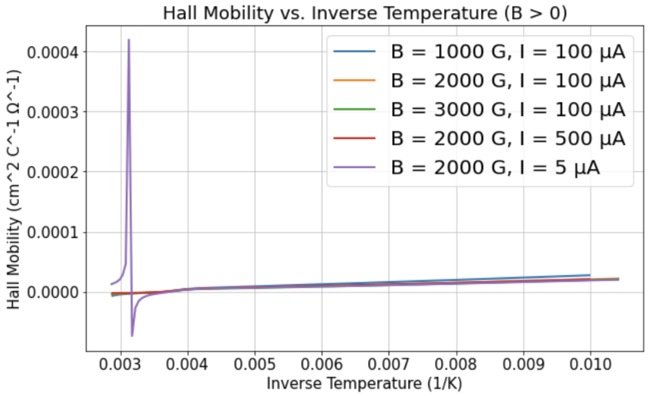

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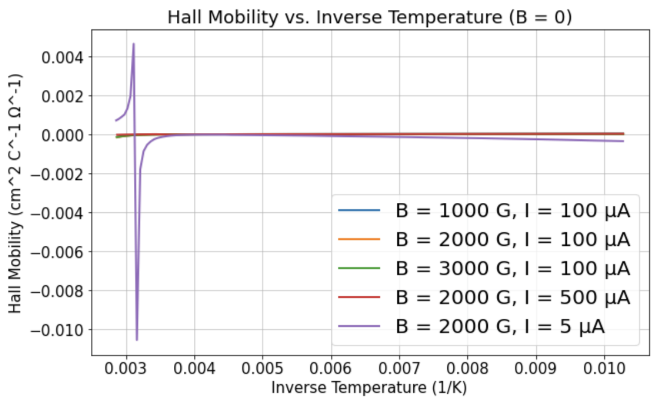

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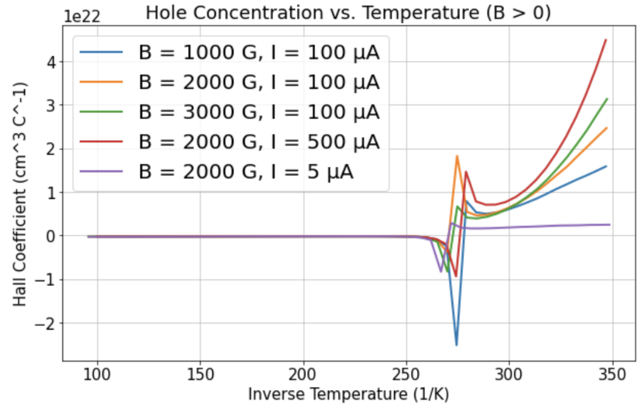


FIG. 17.

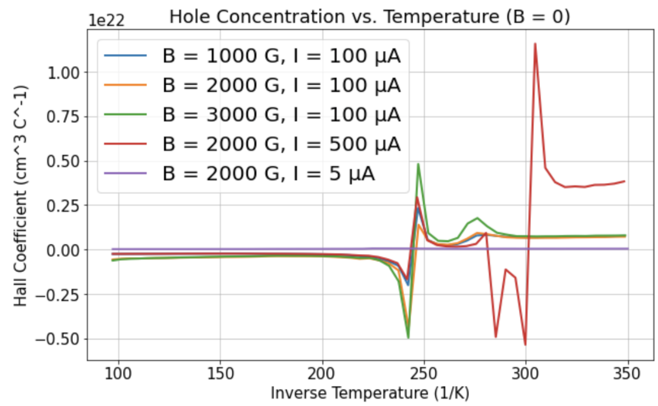
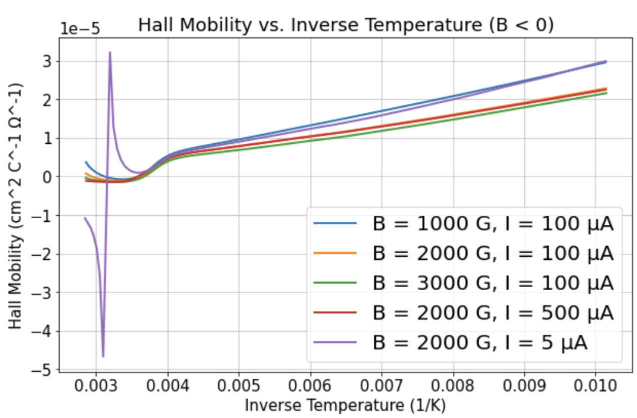


FIG. 18.

V. CONCLUSION

We found that the resistivity of the semiconductor is largely related to its temperature as seen from calculating and comparing the conductivity of the material in relation to temperature.

We were also able to determine the mobility of holes and electrons in the material as will their concentration and what type of semiconductor the sample was.



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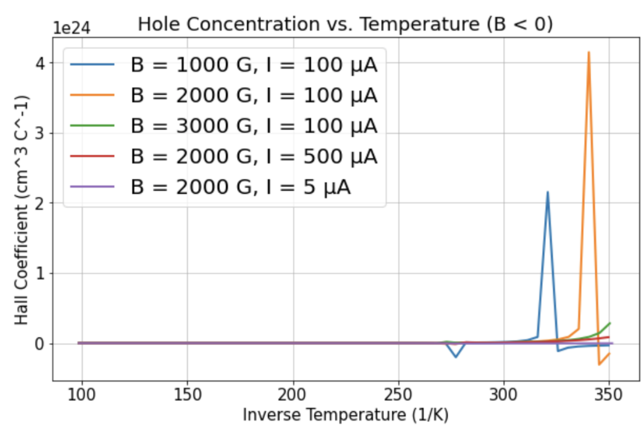

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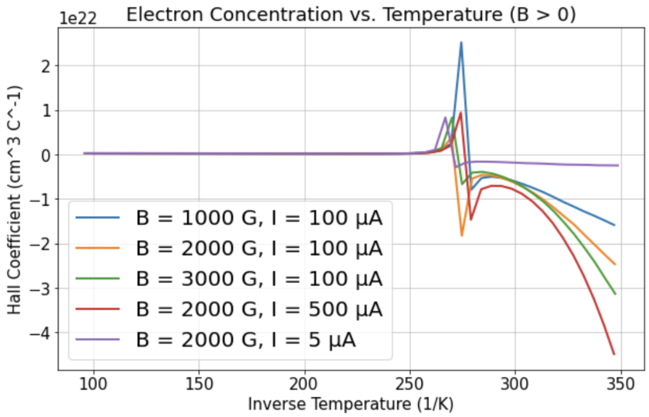

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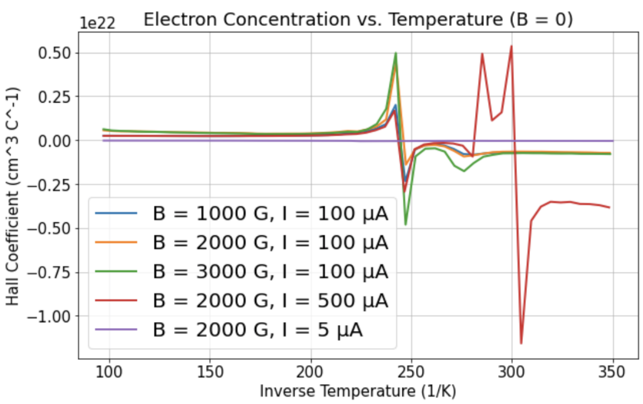

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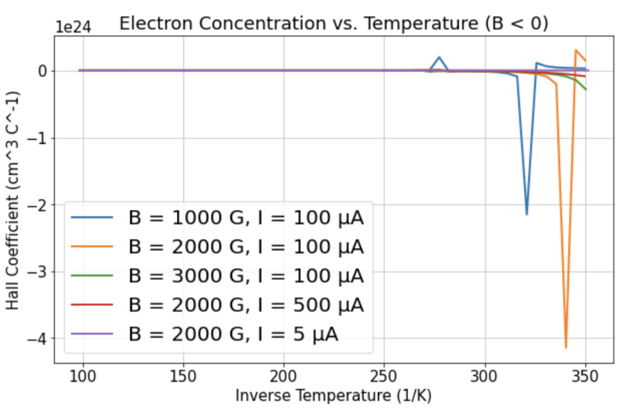

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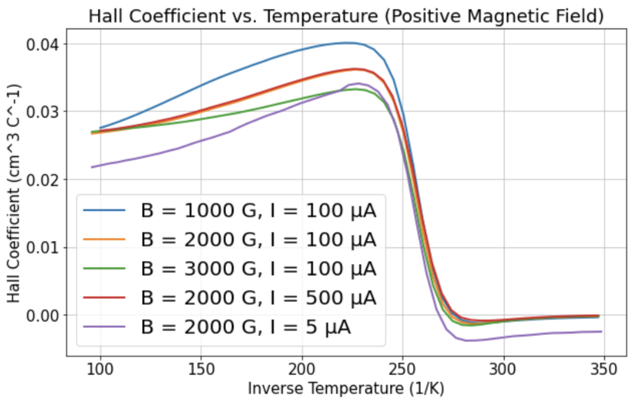

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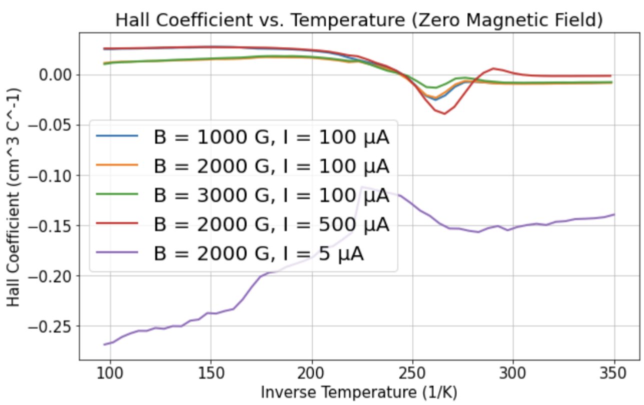

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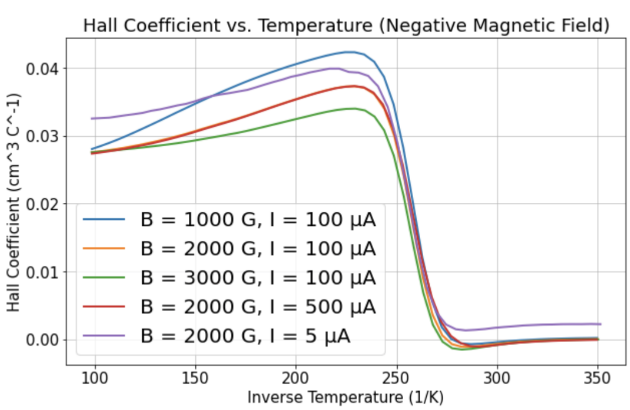

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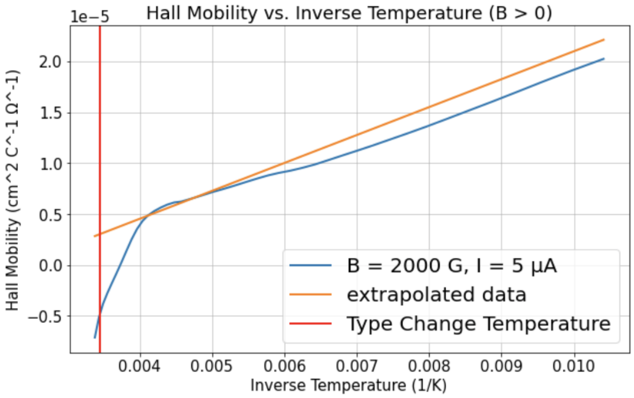
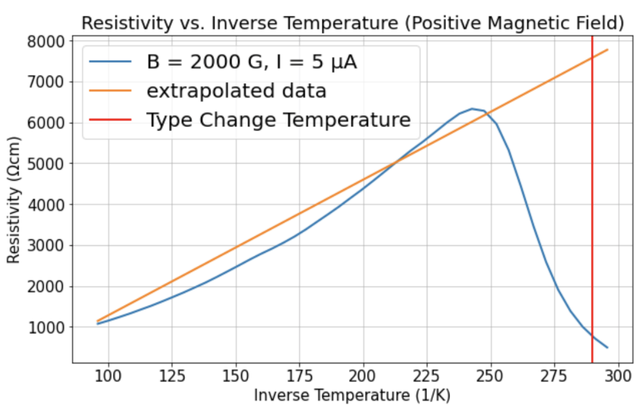


Hall Mobility vs. Inverse Temperature (B > 0)
1e−5
Hall Mobility (cm^2 C^-1 Ω^-1)
Inverse Temperature (1/K)
B = 2000 G, I = 5 μA
extrapolated data
Type Change Temperature

FIG. 26.



Resistivity vs. Inverse Temperature (Positive Magnetic Field)
Resistivity (Ωcm)
Inverse Temperature (1/K)
B = 2000 G, I = 5 μA
extrapolated data
Type Change Temperature

FIG. 27.