LAB III. CONDUCTIVITY & THE HALL EFFECT

1. OBJECTIVE

In this lab, we will empirically calculate the resistivity (using the Van der Pauw Method), along with the doping density and type (using the Hall effect) of a small square piece of doped silicon. From these quantities the conductivity and the mobility will be determined. These quantities form a part of the description of a doped piece of single-crystalline silicon, and they are essential quantities to know when designing devices based these specialized materials.

2. OVERVIEW

In this lab, we have built a four-probe board that holds a square piece of doped silicon wafer. The wafer has metal contacts placed near its four corners, each wired up to a lead (see Figure 3.) Two SMUs will be used via LabVIEW. One is used as a current source, to drive current through the wafer. Another is used as a voltmeter to measure voltage between two contacts of the wafer.

In the first part of the lab, this setup is used to perform the van der Pauw Method of measuring the resistivity, $\rho$, of the sample. In the second part, a similar setup - along with two bar magnets - are used to create the Hall effect and determine the Hall voltage and Hall coefficient. These measurements will be used to find the doping density, dopant type, and the majority carrier mobility (Hall mobility) of the silicon sample.

Information essential to your understanding of this lab:

1. An understanding of conductivity using the concepts of current density and electric field (i.e. a version of Ohm’s Law.)
2. How the Van Der Pauw Method works.
3. How the Hall Effect works.
4. How one can calculate characteristic parameters of a sample of silicon using these methods.

Materials necessary for this Experiment:

1. Standard testing station
2. Two Banana Plug leads
3. One four-probe board with doped Si wafer
4. Two bar magnets
3. BACKGROUND INFORMATION

3.1 CHART OF SYMBOLS

Table 1. Symbols used in this lab.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Symbol Name</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h^+$</td>
<td>Hole</td>
<td>Positive charge particle</td>
</tr>
<tr>
<td>$e^-$</td>
<td>electron</td>
<td>Negative charge particle</td>
</tr>
<tr>
<td>$q$</td>
<td>magnitude of electronic charge</td>
<td>$1.6 \times 10^{-19}$ C</td>
</tr>
<tr>
<td>$p$</td>
<td>hole concentration</td>
<td>(number $h^+$ / cm$^3$)</td>
</tr>
<tr>
<td>$n$</td>
<td>electron concentration</td>
<td>(number $e^-$ / cm$^3$)</td>
</tr>
<tr>
<td>$n_i$</td>
<td>intrinsic carrier concentration</td>
<td></td>
</tr>
<tr>
<td>$N_D$</td>
<td>Donor concentration</td>
<td>(number donors / cm$^3$)</td>
</tr>
<tr>
<td>$N_A$</td>
<td>Acceptor concentration</td>
<td>(number acceptors / cm$^3$)</td>
</tr>
<tr>
<td>$k_B$</td>
<td>Boltzmann’s constant</td>
<td>$1.38 \times 10^{-23}$ joules / K</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature</td>
<td>K</td>
</tr>
<tr>
<td>$E_g$</td>
<td>Energy gap of semiconductor</td>
<td>eV</td>
</tr>
<tr>
<td>$J$</td>
<td>Current density</td>
<td>A / cm$^2$</td>
</tr>
<tr>
<td>$E$</td>
<td>Electric field</td>
<td>V / cm</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>conductivity</td>
<td>($\Omega$ - cm)$^{-1}$</td>
</tr>
<tr>
<td>$\rho$</td>
<td>resistivity</td>
<td>$\Omega$ - cm</td>
</tr>
<tr>
<td>$\mu$</td>
<td>mobilities</td>
<td>cm$^2$ / V-sec</td>
</tr>
<tr>
<td>$v_d$</td>
<td>drift velocity</td>
<td>cm / sec</td>
</tr>
<tr>
<td>$B$</td>
<td>magnetic field</td>
<td>Weber / m$^2$</td>
</tr>
<tr>
<td>$N_v$</td>
<td>valence band effective density of states</td>
<td>cm$^{-3}$</td>
</tr>
<tr>
<td>$N_c$</td>
<td>conduction band effective density of states</td>
<td>cm$^{-3}$</td>
</tr>
</tbody>
</table>
### 3.2 CHART OF EQUATIONS

**Table 2. Equations used in this lab.**

<table>
<thead>
<tr>
<th>Equation</th>
<th>Name</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Intrinsic carrier equation</td>
<td>( n_i^2 = N_e N_i e^{(-E_e / 2kT)} )</td>
</tr>
<tr>
<td>2</td>
<td>Charge Neutrality</td>
<td>( p + N_D = n + N_A )</td>
</tr>
<tr>
<td>3</td>
<td>Law of Mass Action</td>
<td>( p_n = n_i^2(T) )</td>
</tr>
<tr>
<td>4</td>
<td>Current density</td>
<td>( J = J_n + J_p = \sigma_n E + \sigma_p E )</td>
</tr>
<tr>
<td>5</td>
<td>Conductivity due to n</td>
<td>( \sigma_n = q \mu_n n )</td>
</tr>
<tr>
<td>6</td>
<td>Conductivity due to p</td>
<td>( \sigma_p = q \mu_p p )</td>
</tr>
<tr>
<td>7</td>
<td>Conductivity of a material</td>
<td>( \sigma = \frac{1}{\rho} = q \mu_n n + q \mu_p p )</td>
</tr>
<tr>
<td>8</td>
<td>Resistivity formula for the van der Pauw</td>
<td>( \rho = \frac{\pi \left( R_{12,34} + R_{23,41} \right)}{\ln 2} F )</td>
</tr>
<tr>
<td>9</td>
<td>Resistivity formula in terms of sheet resistance</td>
<td>( \rho = \frac{1}{\sigma} = R_s t )</td>
</tr>
<tr>
<td>10</td>
<td>Current density</td>
<td>( J_x = \sigma_p E_x )</td>
</tr>
<tr>
<td>11</td>
<td>Drift velocity</td>
<td>( v_x = \mu_p E_x )</td>
</tr>
<tr>
<td>12</td>
<td>Lorentz force (y-direction)</td>
<td>( F_B = q v_x \times B_z )</td>
</tr>
<tr>
<td>13</td>
<td>Induced Hall Field (( E_y ))</td>
<td>( qE_y = q v_x \times B_z )</td>
</tr>
<tr>
<td>14</td>
<td>E-field equation for the semiconductor sample</td>
<td>( E_y = \frac{1}{qp} J_x B_z )</td>
</tr>
<tr>
<td>15</td>
<td>Hall coefficient</td>
<td>( R_H = \frac{1}{qp} )</td>
</tr>
</tbody>
</table>
### 3.3 Conductivity of a Semiconductor

One of the most basic questions asked in semiconductor devices is “what current will flow for a given applied voltage?”, or equivalently “what is the current density for a given electric field?” for a uniform bar of semiconductor (See Figure 1.) The answer to this question is a form of Ohm’s law (see Section 3.4 in Streetman and Banerjee):

\[
J = J_n + J_p = \sigma_n E + \sigma_p E
\]  

(4)

Here, \( J \) is the current density \((\text{A/cm}^2)\), or net charge going through the cross-sectional area of the bar, per unit time. \( E \) is the applied electric field \((\text{V/cm})\), or voltage across the length of the bar. Sigma, \( \sigma \), the proportionality factor between \( J \) and \( E \), is typically measured in units of \((\Omega \cdot \text{cm})^{-1}\). One can read \( \sigma \) as \( J/E \) or “how much current passes through a material for a given a voltage across it.” We can see the term \( \sigma \) is a measure of how well a material conducts electric charge. It means that for a given \( E \), a material with a higher \( \sigma \) conducts more current. Naturally, \( \sigma \) is called “conductivity”, and is an \textit{intrinsic} property of a material.
The $n$ and $p$ subscripts refer to contribution to the current density from electrons and holes, respectively. This equation tells us that the total current density $J$ is equal to the sum of the electron and hole current densities. Those are given by the electron conductivity $*E$ plus the hole conductivity $*E$. Note that the conductivity increases as the numbers of electrons and holes increases, due to:

\[
\sigma_n = q*n* \mu_n \\
\sigma_p = q*p* \mu_p \\
\sigma = \sigma_n + \sigma_p = q*n* \mu_n + q*p* \mu_p
\]  

Remember $q = 1.6 \times 10^{-19}$ Coulombs and $n$ and $p$ are electron and hole densities (number per cm$^3$.) The quantities $\mu_n$ and $\mu_p$ are called the “electron and hole mobilities” respectively (cm$^2$/V-sec). Mobilities describe the average velocity (m/s) per unit electric field that electrons or holes experience as they propagate through the lattice of the semiconductor. In fact, we write that the electron and hole average velocities are defined as $v_n = \mu_n*E$ and $v_p = \mu_p*E$.

Note that the conductivity of a semiconductor depends upon both the carrier densities and their mobilities. Consequently, it seems that a measurement of the conductivity can only be used to find $n$ and $p$ if $\mu_n$ and $\mu_p$ are already known. (Note: The values of $n$ and $p$ are related by the law of mass action ($n*p = n_i^2$) and so we only need to know either $n$ or $p$ to know them both.) It would be nice if the mobilities were simple constants, but they are not. $\mu_n$ and $\mu_p$ are functions of temperature as well as the doping concentrations ($N_A$ and $N_D$) and therefore functions of $n$ and $p$! Fortunately, we know these functions from many prior calibration measurements done by scientists worldwide. So a simple measurement of conductivity still can be used to give us an estimate of $n$ and $p$ provided we at least know the semiconductor type (n-type or p-type). We use the Irwin curves to make the connection between the semiconductor conductivity and its’ doping density ($N_A$ or $N_D$). Note that for p-type material $N_A \sim p$ and $n \sim n_i^2/N_A$; for n-type material $N_D \sim n$ and $p \sim n_i^2/N_D$. Figure 2 shows the Irwin curves. It is a plot of...
the silicon conductivity as a function of either $N_A$ or $N_D$ assuming that the other is equal to zero. You should familiarize yourself with it.

There are many measurement methods to find the conductivity of a sample. One of the most common methods is called the “four-point probe method." We will be doing a variant of the four-point probe method called the **van der Pauw method** in this lab. It is a measurement method for arbitrarily-shaped samples. The van der Pauw method is commonly used to measure the conductivity of semiconductors, particularly for thin epitaxial layers grown on semi-insulating substrates. Using this method, you will measure the conductivity of your sample. Once you find the resistivity of the sample, you can use the Irwin curves to estimate the values of $n$ or $p$. Note: the van der Pauw method does not allow you to determine the type of your semiconductor sample, you’ll have to use the Hall Effect to determine type, then find the doping density. For example, if you calculated a conductivity of 0.1 mho/cm (from resistivity is 10 ohm-cm) using van der Pauw method, and found out the sample was p-type from Hall Effect results, then from the Irwin curves you can say $N_A$ would be approximately $1.3 \times 10^{15}$ cm$^{-3}$. You will compare the values of doping density and conductivity from the van der Pauw methods with the values derived from the Hall Effect measurements.
Figure 2. Irwin curve for singly doped silicon at 300K.
3.4. THE VAN DER PAUW METHOD

L. J. van der Pauw proved that the resistivity of an arbitrarily shaped sample could be estimated from measurements of its resistance provided the sample satisfied the following conditions: 1) contacts are at the boundary; 2) contacts are small; 3) the sample is uniformly doped and uniformly thick; 4) there are no holes in the sample. He derived a correction factor, $f$, to use in that estimation.

In the van der Pauw method, and in all 4-point probe methods, a current is forced between two contacts (call them contacts A & B) while the voltage is measured between two different contacts (C & D); See Figure 3. It is often the case that UG students wonder why the voltage is NOT measured between contacts A & B. The thought is: “Wouldn’t you get the resistance by simply dividing $V_{AB}$ by $I_{AB}$?” The answer is: You would get a resistance, but it would be the WRONG resistance. The resistance that is correct is $V_{CD}/I_{AB}$. $V_{AB}/I_{AB}$ gives too large a resistance because it always includes something called the “contact resistance” too. The contact resistance is a resistance that sits exactly at the contact between the metal probe (the contact) and the semiconductor. This resistance has a voltage drop across it whenever there is current flowing through it ($V_{contact}=I_{AB}*R_{contact}$.) The problem is that this contact resistance has nothing to do with the semiconductor conductivity! Therefore, we do not want to have $V_{contact}$ be part of our measured voltage. We want only the voltage caused by the conductivity of our sample to be divided by $I_{AB}$. Figure 4 shows a schematic diagram of this problem. By measuring $V_{CD}$ on contacts with zero current flowing through them, we get no voltage drop across $R_{contact}$ and as a result we measure only the voltage due to the resistivity.
Figure 3. a) a top view of the sample used in the lab; b) a 3-D view of the doped silicon material to be tested in the lab.

Figure 4. Contact resistances and the resistivity of the silicon sample. The current flowing between contacts A&B causes a voltage drop due to the contact resistances there, but the fact that no current flows through contacts C&D allows them to measure just the voltage due to the resistivity.
Consider a doped flat semiconductor sample with an arbitrary shape, with contacts A, B, C, and D along the periphery as shown in Fig. 5. The resistance is \( R_{AB,CD} = \frac{V_{CD}}{I_{AB}} \), where the current \( I_{AB} \) enters the sample through contact A and leaves through the contact B and \( V_{CD} = V_C - V_D \) is the voltage difference between contacts C and D. The van der Pauw method then tells us that the resistivity of the arbitrarily shaped sample is given by:

\[
\rho = \frac{\pi}{\ln 2} \frac{R_{AB,CD} + R_{BC,DA}}{2} f
\]

where \( f \) is a correction factor which is a function of the ratio \( R_r = \frac{R_{AB,CD}}{R_{BC,DA}} \). (\( f \) is plotted in Fig. 6.)

For a symmetrical sample we would get \( R_r = 1 \) and the correction factor \( f = 1 \). In order to measure the resistivity of the sample more accurately, typical measurement consists of a series of measurement using different current values and different current injection direction.

Figure 5. Arbitrarily-shaped sample with four contacts at the periphery.
3.5. HALL EFFECT MEASUREMENTS

The Hall Effect yields a direct measure of the majority carrier density. In the Hall measurement, a uniform magnetic field, $B_z$, is applied normal to the direction of a current flow ($I_x$). The magnetic field induces a force on the moving charged particles pushing them in a direction perpendicular ("normal") to both the particle flow and $B_z$. This induces a voltage at the facets where the charges collect called the "Hall voltage" as well as information about the carrier density.

In order to explain how the Hall Effect arises, we shall assume a p-type semiconductor having the geometry shown in Fig. 7. A voltage $V_x$ is applied to the ohmic contacts on the front and back (B & D) which causes holes to flow in the positive $x$ direction under the field $E_x = V_x/l$. The current is given by

$$J_x = I_x / (w t) = \sigma E_x \sim \sigma_p E_x = q\mu_p E_x = q\nu_x$$

Figure 6. $f$ vs.  (L. J. van der Pauw, Philips Res. Rprts, 13, 1-9 (1958).)
Where \( \sigma \sim \sigma_p \) because \( p >> n \) in p-type materials. The average hole drift velocity is:

\[
\vec{v}_x = \mu_p \vec{E}_x
\]  

(11)

Figure 7. The fields and voltage polarities in p-type silicon for the Hall effect measurement.

In the absence of a magnetic field, the holes flow in the positive x direction. In a magnetic field, \( B_z \), shown in Fig. 7 to be in the +z direction, the holes experience an additional force.

\[
\vec{F}_{MAGNETIC} = q\vec{v}_x \times \vec{B}_z
\]  

(12)

that pushes the holes in the negative y direction. The holes thus collect at the left side of the structure, on surface A and leave behind negatively charged acceptors at the right contact C. These charges induce an electric field directed in the +y direction that creates an electric field induced force opposite to the magnetic force. No current can flow in the y direction, because nothing is connected to contacts A and C. No current flow, means that the semiconductor must have no net force in that direction. Therefore, the two opposite forces (induced by \( B_z \) and \( E_y \)) must have equal magnitudes and

\[
q\vec{E}_y = q\vec{v}_x \times \vec{B}_z
\]  

or

(13)
\[ E_y = \frac{1}{q_p} J_x B_z \quad \text{because} \quad v_x = J_y/q_p \quad (14) \]

The Hall coefficient is defined as:

\[ R_H = \frac{1}{q_p} \quad (15) \]

So equation (14) may be re-written as:

\[ E_y = R_H J_x B_z \quad (16) \]

The induced voltage between A & C is called the Hall voltage, \( V_H \):

\[ V_H = E_y w \quad (17) \]

By using equations (15), (16) and (17) we can solve for the carrier density \( p \):

\[ p = \frac{1}{q_p t} \frac{I_x B_z}{V_H} \quad (19) \]

and

\[ R_H = \frac{V_H t}{I_x B_z} \quad (20) \]

Thus, \( p \) can be found from a measurement of the Hall voltage, \( V_H \), at a current \( I_x \) in a magnetic field \( B_z \), as shown in Fig. 7. The Hall mobility may be calculated using equation (6) and the definition of the Hall coefficient, equation (15):

\[ \mu_p = \frac{\sigma_p}{q_p} = \frac{R_H}{\sigma_p} \quad (21) \]

Next we examine the effects obtained when an n-type sample is measured. For the applied current \( I_x \) shown in Fig. 6, the electrons will move in the -x direction. The force due to \( B_z \) will push the electrons in the -y direction to contact A leaving positively charged acceptors on the right side (contact C).
In this case the electric field will point in the \(-y\) direction, and the \(+y\) contact C will be positive relative to the \(-y\) terminal A. Thus the polarity of the Hall voltage for p and n materials is opposite. From Eq. (19), the sign of the Hall coefficient is also negative for n-type material in this geometry.

By understanding these concepts you should be able to identify any uniformly doped semiconductor’s carrier density and type based on the sign of the Hall voltage. You will need this knowledge to successfully complete the Lab.

If the sample was ideal, Hall voltage should be linearly increased with the applied current (Fig. 8). The Hall voltage should be linearly increased with the applied magnetic field as well. Moreover, if the sample was ideal (i.e., there is no asymmetry in the sample), there should be no “ohmic drop” and the measured voltage is “true” Hall voltages. However, if the sample was non-ideal, depending on the asymmetry of the sample, the measured voltages may be shifted due to “ohmic drop”. In this case, the measured voltage is NOT “true” Hall voltages. You must calculate the differences between the voltages measured with and without the magnetic fields to calculate “true” Hall voltages.

Figure 8. Measured voltages as a function of the applied currents for ideal (no “ohmic drop”) and non-ideal sample.
4. PREPARATION

Please read section 3.4 in Streetman and Baneerjee and make sure you understand the van der Pauw and Hall Effect methods discussed in Section 3 of this manual.

Before coming to the lab, solve the following problems. Show work clearly and legibly.

1. Assume room temperature (300K)
   a. Calculate the conductivity of an n-type Si sample with \( N_D = 3 \times 10^{15} \text{ cm}^{-3} \) and \( \mu_n = 1350 \text{ cm}^2/(\text{V-sec.}) \) using the equations found in this manual (Table 2.) Compare your answer with the conductivity value derived from the Irwin curves in Fig. 2. Write a two-three sentence statement of your findings.
   b. An extrinsic p-type Si sample has a measured conductivity of \( \sigma = 0.1 \text{ (Ohm-cm)}^{-1} \) and a Hall voltage of 11.16 mV for \( I_x = 10 \text{ mA} \) and \( B_z = 1,500 \text{ Gauss} \). The sample thickness is 0.06 cm and the width is 1 cm. Find the doping density, \( N_A \), and the hole Hall mobility, \( \mu_p \), by using both the conductivity and the Hall measurements. Note: The magnetic field is in CGS units; convert it to MKS units and note that the conversion is 1,000 Gauss = 10\(^{-5}\) Weber/cm\(^2\) = 0.1 Weber/m\(^2\) = 0.1 Tesla.

2. Refer to the geometry of your sample shown in Fig. 11 and assume that it is doped n-type with an applied magnetic field pointing out of the page. If current was flowing from terminal A to C and you connected the negative lead of the Keithley (voltmeter) to contact B and the positive lead to contact D what would the voltage polarity on the voltmeter be? Assume that there is no asymmetry in the sample. Explain your answer succinctly and coherently.
5. PROCEDURE

For this lab, a square doped silicon wafer was mounted and packaged onto a DIP14 Socket (dual in-line pin socket with 14 pins). If you look closely, this wafer has four rectangular contacts (labeled A, B, C and D in Figure 9) at the corners. These contacts are wire bonded to an adjacent pad, which in turn is soldered to the three closest pins on the DIP14 socket. If you flip the board, you will see these pins are soldered to wires that lead to the four connectors. The connector position corresponds to contact position on the wafer (See Fig. 9.) The wafer thickness \( t \) is 600 \( \mu m \).

![Contact to Connector configuration.](image)

5.1 CONDUCTIVITY MEASUREMENT USING THE VAN DER PAUW METHOD

You will use the LabVIEW program `conductivity.vi` in the VIs>3110 folder on your Desktop to make the van der Pauw measurements. The LabVIEW program uses two Keithley SMUs. We will choose the top Keithley SMU as the voltmeter and the bottom Keithley SMU as the current source. If executed correctly the program will yield three columns of information with ten entries in each column. Column 1 gives the Source Current, Column 2 gives the Source Voltage, and Column 3 gives the Measured Voltage. You will use the Source Current and the Measured Voltage columns for your calculations.
Steps:

1. Get 4-probe board. Record the board number and whether the number is circumscribed by a square or circle.

2. Turn on the two Keithley SMUs.

3. Open Conductivity.vi:
   - Check “yes” for the “Save Data” option.
   - Assign Top SMU as voltmeter; Bottom SMU as Current Source.
   - For Current Source set:
     - Initial current: 1 mA,
     - Final current: 10 mA,
     - Step current: 1 mA.

4. Get two pairs banana plug leads. Plug the leads to SMUs in the appropriate ports.

5. Connect the banana plug leads to the 4-probe board as in Figure 10 and run Conductivity.vi for each configuration below. Save the dataset with an appropriate filename:
   1. $I_{AD}, V_{BC}$ (show this setup to and run vi for TA; get signature)
   2. $I_{DA}, V_{CB}$
   3. $I_{BC}, V_{AD}$
   4. $I_{CB}, V_{DA}$
   5. $I_{AB}, V_{DC}$
   6. $I_{BA}, V_{CD}$
   7. $I_{DC}, V_{AB}$
   8. $I_{CD}, V_{BA}$

6. For each item in Step 5, use a spreadsheet to calculate the resistance (i.e. $R_{AD,BC} = \frac{dV_{BC}}{dI_{AD}}$) using the SLOPE() formula. If you prefer, you may generate plots and use the ADD TRENDLINE feature.
7. In the spreadsheet calculate the following. Clearly label each calculation:

1. \[ R_{AD,BC} = \frac{1}{2} (R_{AD,BC} + R_{DA,CD}) \]

2. \[ R_{BC,AD} = \frac{1}{2} (R_{BC,AD} + R_{CD,DA}) \]

3. \[ R_{BC,DA} = \frac{1}{2} (R_{AD,BC} + R_{BC,AD}) \]

4. \[ R_{AB,DC} = \frac{1}{2} (R_{AB,DC} + R_{BA,CD}) \]

5. \[ R_{DC,AB} = \frac{1}{2} (R_{DC,AB} + R_{CD,BA}) \]

6. \[ R_{AB,CD} = \frac{1}{2} (R_{AB,DC} + R_{DC,AB}) \]

7. \[ \frac{R_{AB,CD}}{R_{BC,DA}} \]

8. \[ \rho = \frac{1}{\sigma} = \frac{\pi}{\ln(2)} \left( \frac{\frac{R_{BC,DA} + R_{AB,CD}}{2}}{f} \right) \] (use Fig. 6 to estimate f)

9. \[ \sigma \]

8. Save Excel results.

**Figure 10. Wiring configuration van der Pauw method.**
5.2 HALL EFFECT

You will use the LabVIEW program Hall.vi in the VIs>3110 folder on your Desktop to make the Hall Effect Pauw measurements. The LabVIEW program uses two Keithley SMUs. We will choose the top Keithley SMU as the voltmeter and the bottom Keithley SMU as the current source. If executed correctly the program will yield three columns of information with ten entries in each column. Column 1 gives the Source Current, Column 2 gives the Source Voltage, and Column 3 gives the Measured Voltage. You will use the Source Current and the Measured Voltage columns for your calculations.

Steps:

1. Setup the SMUs cables to the 4-probe board like so:

![Diagram of Hall Effect Configuration 1](image)

*Figure 11. Hall Effect Configuration 1.*

2. Open Hall.vi. Set current source parameters to 1 to 10 mA with increments of 1 mA.

3. Run Hall.vi with no magnets near the Si sample. Save and title the dataset.

4. Get data for +z (North up) set up:
   - 1. Identify direction of magnets in housing
   - 2. Place the Si sample in the magnet housing with North up
   - 3. Run Hall.vi; save and title dataset.

5. Get data for -z (South up) set up:
   - 1. Now, place the Si sample in the magnet housing with South up
   - 2. Run Hall.vi; save and title dataset.

6. Setup the SMUs cables to the 4-probe board like so:
7. Repeat Steps 4, 5, and 6 from above.
8. Generate Plots (see Section 6); get TA’s signature.

6. LAB REPORT

Type a lab report with a cover sheet containing your name, class (including section number), date the lab was performed on, and the date the report is due, lab partner name, and title. Use the following outline as guide when writing your lab report.

- **Abstract:** Give a brief, coherent summary of what the lab is about, i.e. the methods used and why. Mention what results you determined / calculated / compared. Make sure you refer to your “sample number.”

Try to limit your abstract to not more than 5 sentences – the goal is to quickly let a peer of equal competence know what your report is about and what significant calculations it contains.

- **Van der Pauw conductivity measurements:**
  - Plot all V vs. I data from the conductivity dataset in one plot. Properly title and label your axes with units. Do the plots almost coincide with each other?
  - Create a table presenting the calculated values from section 5.1 step 6 and 7; remember units. Caption the table.
  - Show the explicit calculation of resistivity of the sample – i.e. type out the equation of the formula, show values used, final result, etc.
  - What is the room temperature conductivity of your sample? Show your calculations.
  - What is the doping density as determined from your resistivity value and the Irwin curves? Briefly explain how you determined it. Could you determine it without the Hall Effect procedure?

- **Hall Effect measurements:**
o Generate $V_y$ vs. $I_x$ plots that show your measured voltage when the magnetic field was in the positive z direction, negative z direction and your baseline on the same graph. You should have two graphs with 3 plots each – one graph for configurations 1 and one for configuration 2. Make sure the plots are clearly distinguishable and labeled.

o What is the ohmic drop voltages in configuration 1 and configuration 2? How did you determine ohmic drop voltages? Show work, values used, etc. Clearly report the values.

o Calculate the true Hall Voltage for both configurations. Remember that the measured voltages are not true Hall voltage ($V_H$). In order to calculate the true Hall voltage ($V_H$), you have to find the difference between voltages measured with and without the magnetic field. Ideally, the Hall voltages calculated with the positive magnetic field and with the negative magnetic field should be equal in magnitude but polarity is reversed. But, in reality, there is a discrepancy due to errors involved in the measurement. Show work, values used, etc. Clearly report the values.

o What is the dopant-type of your sample? How did you determine the dopant type?

o Calculate the doping density. Show explicit calculation using formula, values used, etc. Assume that the magnetic flex density at the surface of silicon sample is 30 gauss.

o Estimate resistivity using Irwin curves. How does it compare with the resistivity derived from the van der Pauw method? Use percent-error formula to quantify the comparison. Are the values close to each other?

o Calculate the majority carrier mobility. Show explicit calculation using formula, values used, etc.

• **Conclusion:**

  Create one table containing these important results:

  1. The van der Pauw method: conductivity, resistivity, and estimated doping density of the sample.

  2. The Hall Effect method: Hall Voltage, doping type, doping density, estimated resistivity, and carrier mobility of the sample.

• **Attach:** Signed instructor verification form.