LAB III. CONDUCTIVITY AND THE HALL EFFECT

1. OBJECTIVE

The conductivity, $\sigma$, of a silicon sample at room temperature will be determined using the van der Pauw method. The Hall Effect voltage, $V_H$, and Hall coefficient, $R_H$, for the same sample will be measured using a magnetic field. These measurements will enable the student to determine: the type (n or p) and doping density of the sample as well as the majority carrier’s “Hall mobility.”

2. OVERVIEW

You will use the van der Pauw method to determine the conductivity of your silicon sample in the first section of this lab. You will find the Hall voltage and coefficient in the second section. These measurements will be used to find the semiconductor type (n or p), the doping density, and the majority carrier mobility (Hall mobility) of the silicon sample.

Information essential to your understanding of this lab:
1. An understanding of material types (e.g., n-type, p-type).
2. The relationship between current density and (carrier density/mobility/conductivity).

Materials necessary for this Experiment
1. Standard testing station
2. One mounted Silicon chip
3. Two magnets ~ 0.0125 Weber / m² (1 Weber = 1 V-s) (Use them to sandwich the sample.)

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 x 10^{-19} C</td>
</tr>
<tr>
<td>$\rho$</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 / cm³)</td>
</tr>
<tr>
<td>$N_A$</td>
<td>Acceptor concentration</td>
<td>(number acceptors / cm³)</td>
</tr>
<tr>
<td>$k_B$</td>
<td>Boltzmann's constant</td>
<td>1.38 x 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 / cm²</td>
</tr>
<tr>
<td>$E$</td>
<td>Electric field</td>
<td>V / cm</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>conductivity</td>
<td>(Ω - cm)^{-1}</td>
</tr>
<tr>
<td>$\rho$</td>
<td>resistivity</td>
<td>Ω - cm</td>
</tr>
<tr>
<td>$\mu$</td>
<td>mobilities</td>
<td>cm² / 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 / m²</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_c N_v e^{(-E_i/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>( pn = 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}{\ln 2} \left( \frac{R_{12,34} + R_{23,41}}{2} \right) 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_y = qv_x \times B_z )</td>
</tr>
<tr>
<td>13</td>
<td>Induced Hall Field (( E_y ))</td>
<td>( qE_y = qv_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>
<tr>
<td>16</td>
<td>Induced E-field</td>
<td>( E_y = R_H J_x B_z )</td>
</tr>
<tr>
<td>17</td>
<td>Hall voltage</td>
<td>( V_H = E_y w )</td>
</tr>
<tr>
<td>18</td>
<td>Current density</td>
<td>( J_x = I_x / tw )</td>
</tr>
<tr>
<td>19</td>
<td>Derivation of the carrier density in a p-type material</td>
<td>( p = \frac{1}{q t} \frac{I_x B_z}{V_H} )</td>
</tr>
<tr>
<td>20</td>
<td>Derivation of Hall coefficient</td>
<td>( R_H = \frac{V_H t}{I_x B_z} )</td>
</tr>
<tr>
<td>21</td>
<td>Derivation of the mobility</td>
<td>( \mu_p = \frac{\sigma_p}{qp} = R_H \sigma_p )</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. The answer to this question is a form of Ohm's law, namely:

\[ J = J_e + J_p = \sigma_e E + \sigma_p E \]  

Here, \( J \) is the current density (A/cm\(^2\)) \( E \) is the applied electric field (V/cm) and \( \sigma \) is the conductivity (1/(Ohm-cm)). The \( n \) and \( p \) subscripts refer to electrons and holes. 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.

\[ \sigma_e = q * n^* \mu_e \]  
\[ \sigma_p = q * p^* \mu_p \]  
\[ \sigma = \sigma_e + \sigma_p = q * n^* \mu_e + q * p^* \mu_p \]

Remember \( q = 1.6 \times 10^{-19} \) Coulombs and \( n \) and \( p \) are electron and hole densities (number per cm\(^3\)). The quantities \( \mu_e \) 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 \( v_e = \mu_e E \) and \( v_p = \mu_p E \).

Note that the conductivity of a semiconductor depends upon both the carrier densities and their mobilities. Consequently, a simple measurement of the conductivity alone can only be used to find \( n \) and \( p \) if \( \mu_e \) and \( \mu_p \) are already known. (Note: The values of \( n \) and \( p \) are related by the law of mass action \( (n^*p = n^*_e) \) 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. \( \mu_e \) 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 \( n \sim n^*_e/N_A^* \) for n-type material \( N_D \sim n \) and \( p \sim n^*_p/N_D^* \). Figure 1 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. You will compare these results with measurements of the Hall Effect. The van der Pauw method is commonly used to measure the conductivity of semiconductors, particularly for thin epitaxial layers grown on semi-insulating substrates. You will do this too. 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 \( p \). For example if you had a conductivity of 0.1 mho/cm (resistivity is 10 ohm-cm), \( N_A \) would be approximately \( 1.3 \times 10^{15} \) cm\(^3\). Since the van der Pauw method cannot allow you to determine the type of your semiconductor sample, you’ll have to use the Hall Effect to find that first.
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). 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 ($V_{\text{contact}} = I_{AB}R_{\text{contact}}$) The problem is
that this contact resistance has nothing to do with the semiconductor conductivity! Therefore, we do not want to have $V_{\text{contact}}$ 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 2 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 $R_{\text{contact}}$ and as a result we measure only the voltage due to the resistivity.

**Fig. 2.** 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.

Figure 3 shows a top view and a “3D view” of the semiconductor sample for this lab.

**Fig. 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.

Consider a doped flat semiconductor sample with an arbitrary shape, with contacts 1, 2, 3, and 4 along the periphery as shown in Fig. 4. The resistance is $R_{12,34} = V_{34}/I_{12}$, where the current $I_{12}$ enters the sample through contact 1 and leaves through the contact 2 and $V_{34} = V_3 - V_4$ is the voltage difference between contacts 3 and 4. The van der Pauw method then tells us that the resistivity of the arbitrarily shaped sample is given by:
\[
\rho = \frac{\pi t}{\ln 2} \frac{R_{12,34} + R_{23,41}}{2} f
\]

where \( f \) is a correction factor which is a function of the ratio \( R_r = R_{12,34}/R_{23,41} \). (\( f \) is plotted in Fig. 5.)

\textbf{Fig. 4.} Arbitrarily-shaped sample with four contacts at the periphery.

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.

\textbf{Fig. 5.} \( f \) vs. \( \frac{R_{AB,CD}}{R_{BC,DA}} \) (L. J. van der Pauw, Philips Res. Rprts, 13, 1-9 (1958.).)

### 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). 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. 6. 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

$$J_x = I_x / (w t) = \sigma E_x \sim \sigma_p \ E_x = q \mu_p E_x = q v_x \mu_p$$  \hspace{1cm} (10)

Where $\sigma \sim \sigma_p$ because $p >> n$ in p-type materials. The average hole drift velocity is:

$$v_x = \mu_p E_x$$  \hspace{1cm} (11)

In the absence of a magnetic field, the holes flow in the positive x direction. In a magnetic field, $B_z$, shown in Fig. 6 to be in the +z direction, the holes experience an additional force.

$$F_B = q v_x \times B_z$$  \hspace{1cm} (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 ($B_z$ and $E_y$ induced) must have equal magnitudes and

$$qE_y = q v_x \times B_z \quad \text{or} \quad E_y = \frac{1}{q_p} J_x B_z \quad \text{because} \quad v_x = J_x / q_p$$  \hspace{1cm} (13)

The Hall coefficient is defined as:

$$R_H = \frac{1}{q_p}$$  \hspace{1cm} (15)

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

$$E_y = R_H J_x B_z$$  \hspace{1cm} (16)

The induced voltage between A & C is called the Hall voltage, $V_H$:

$$V_H = E_y w$$  \hspace{1cm} (17)

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

3-7
\[ p = \frac{1}{q} \frac{I_x B_z}{t V_H} \]  

(19)

and

\[ R_H = \frac{V_H I}{I_x B_z} \]  

(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. 6. The Hall mobility may be calculated using equation (6) and the definition of the Hall coefficient, equation (15):

\[ \mu_p = \frac{\sigma_p}{q p} = R_H \sigma_p \]  

(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. 7). 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.

**Ideal Condition**, when sample is symmetric and has low ohmic drop along X direction  

**Practical condition**, when sample is asymmetric

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**Fig. 7.** Measured voltages as a function of the applied currents for ideal (no “ohmic drop”) and non-ideal sample.
4. PREPARATION

Make sure you understand the van der Pauw and Hall theories. Before coming to the lab, solve the following problems. Assume room temperature (300K).

1. Calculate the conductivity of an n-type Si sample with \( N_D = 3 \times 10^{15} \) cm\(^{-3} \) and \( \mu_n = 1350 \) cm\(^2\)/(V-sec.) using the equations found in this manual. Compare your answer with the Irwin curve in Fig. 1. Write a two sentence statement of your findings.

2. An extrinsic p-type Si sample has a measured conductivity of \( \sigma = 0.1 \) (Ohm-cm)\(^{-1} \) and a Hall voltage of 11.16 mV for \( I_s = 10 \) mA and \( B_z = 1,500 \) 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. Hint: The above equations are in CGS units. Convert to MKS units and note the conversion \( B_z = 1,000 \) Gauss =0.1 Weber/m\(^2\) = 0.1 Tesla. (Alternatively \( 10^8 \) Gauss = Wb/cm\(^2\) = V-sec/cm\(^2\)).

3. Refer to the geometry of your sample shown in Fig. 9 a) 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.

5. PROCEDURE

5.1. CONDUCTIVITY MEASUREMENT USING THE VAN DER PAUW METHOD

We are going to use a doped silicon sample which has four contacts (labeled A, B, C and D) at the corners in this Lab. The silicon sample is mounted on a board. **The sample thickness (t) is 600 \( \mu \)m.** You will use a LabView program to measure the voltage and compute the resistivity of the sample. The sample will yield slightly different voltages in the two orthogonal directions due to asymmetries in the sample. The top Keithley SMU is used to measure the voltages and the bottom Keithley SMU is used to supply the current.

You will use **conductivity.vi** to execute the conductivity measurement using the van der Pauw method. 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 for your calculations. Basically, you are forcing the current with the bottom Keithley and measuring the voltage with the top Keithley.

For the first configuration in Figure 8 a), the current is passed from contact A to contact D in discrete bursts at the incremental values set in the program by using 1 mA for the initial current, 10 mA for the final current, and 1 mA for the step current. The voltage is measured from contact B to contact C at these different current levels giving you voltage \( V_{BC} \). If needed, make sure to set the compliance voltage to a suitably high voltage. Next, you will have to configure the program to drive the current between contact A to contact D in the opposite direction by setting the initial current to – 1 mA, the final current to -10 mA, and the step current to – 1 mA. If needed, set the compliance voltage to a suitably negative voltage. This will generate a voltage with the opposite sign to \( V_{BC} \) called \( V_{CB} \). Swap the leads between A to B and D and C and repeat this procedure. For the third phase a positive current is now passed through the B and C contacts and the voltage is measured through the A and D contacts. This should give a positive voltage \( V_{AD} \). Finally, the current is reversed and the voltage again measured between A to D giving a negative voltage \( V_{DA} \).
Ideally the magnitude of the four voltage measurements should be exactly the same; however the asymmetries in the geometry of the device cause some deviation in the measured voltage values.

Fig. 8. Wiring configuration for the Van der Pauw method. **Bottom Keithley acts as a current source and top source as a Voltmeter.**

1. Assemble your circuit as shown in Figure 8 a). Turn on both Keithley SMUs. Open the LabView program called **Conductivity.vi** located in the 3110 folder.
2. Check “yes” for the “Save Data” option. Run the program with the following settings:
   - Initial current: 1 mA.
   - Final current: 10 mA.
   - Step current: 1 mA.
3. This will give you a file with positive current $I_{AD}$ and positive voltage $V_{BC}$.
4. Reverse the current to give you a negative current $I_{DA}$ and negative voltage $V_{CB}$.
5. Convert these values to positive values for convenience.
6. Swap the leads and measure the current and voltages as above.
7. Again convert the negative values to positive values.
8. This will give you:
   - First: $I_{AD} = I_{DA} = I_{BC} = I_{CB}$
   - Second: $V_{BC}$
   - Third: $V_{CB}$
   - Fourth: $V_{AD}$
   - Fifth: $V_{DA}$
9. Save collected measurement data and compute the following in the spreadsheet:
   
   \[ R_{AD,BC} = \frac{V_{BC}}{I_{AD}} \]
   \[ R_{DA,CB} = \frac{V_{CB}}{I_{DA}} \]
   \[ R_{AD,BC} = \frac{1}{2} (R_{AD,BC} + R_{DA,CB}) \]
\[ R_{BC,AD} = \frac{V_{AD}}{I_{BC}} \]
\[ R_{CB,DA} = \frac{V_{DA}}{I_{CB}} \]
\[ R_{BC,AD} = \frac{1}{2} \left( R_{BC,AD} + R_{CB,DA} \right) \]
\[ R_{BC,DA} = \frac{1}{2} \left( R_{BC,DA} + R_{CB,AD} \right) \]

10. Now change the leads so that they are connected as shown in Figure 8 b).
11. Repeat the above procedure.
12. This will give you:
   - First: \( I_{AB} = I_{BA} = I_{DC} = I_{CD} \)
   - Second: \( V_{DC} \)
   - Third: \( V_{CD} \)
   - Fourth: \( V_{AB} \)
   - Fifth: \( V_{BA} \)
13. Compute the following using your spread sheet:
   \[ R_{AB,DC} = \frac{V_{DC}}{I_{AB}} \]
   \[ R_{BA,CD} = \frac{V_{CD}}{I_{BA}} \]
   \[ R_{AB,DC} = \frac{1}{2} \left( R_{AB,DC} + R_{BA,CD} \right) \]
   \[ R_{DC,AB} = \frac{V_{AB}}{I_{DC}} \]
   \[ R_{CD,BA} = \frac{V_{BA}}{I_{CD}} \]
   \[ R_{DC,AB} = \frac{1}{2} \left( R_{DC,AB} + R_{CD,BA} \right) \]
   \[ R_{AB,CD} = \frac{1}{2} \left( R_{AB,CD} + R_{DC,AB} \right) \]

14. Now you can find the bulk conductivity of your Si sample using the equation below and the results from your two previous sets of calculations. Put it in your spread sheet.

\[ \rho = \frac{1}{\sigma} = \frac{\pi \ell}{\ln 2} \left( \frac{R_{BC,DA} + R_{AB,CD}}{2} \right) F \]

Examine Figure 5 to find the value of \( F \), van der Pauw correction factor. Since the semiconductor is approximately symmetric you should expect the two average resistance measurements from your Si sample to be approximately equal to one another yielding “1” for the ratio of \( \frac{R_{AB,CD}}{R_{BC,DA}} \).
5.2 HALL MEASUREMENTS

You will make three sets of measurements on the sample using the configurations shown in Figure 9. The top Keithley SMU is used to measure the voltages and the bottom Keithley SMU is used to supply the current.

Fig. 9. Set-up for Hall effect measurements. **Bottom Keithley acts as a current source and top source as a Voltmeter.**

1. Find the voltage on the material with no magnetic field: Use the program **Hall.vi** and the configuration a) in Figure 9. Obtain a list of voltage values for currents going from 1 to 10 mA with increments of 1 mA. Note the direction of the voltage and the current.
2. Use the same program to get a similar list as the previous step while applying a magnetic field (two magnets are used) in the positive z direction to your sample.
   - Place one magnet on top of the sample with the south pole facing down.
   - Place the other magnet underneath the sample board with the north pole facing up.
3. Use the same program to get a similar list while applying a negative magnetic field to your sample by placing a couple of magnets with the reverse magnetic polarity (top magnet with north pole facing down and bottom magnet with the south pole facing up).
4. Repeat all three steps utilizing configuration b) of Figure 9.

6. LAB REPORT

Type a lab report with a cover sheet containing your name, class (including section number), date the lab was preformed on, and the date the report is due. Use the following outline to draft your lab report.

- **Introduction**: Type a very brief summary of the experiment. Make sure your put your “sample number” in your report. There are two types of samples and their results would be quite different.
- **Van der Pauw conductivity measurements**
o Generate V vs. I plots from the conductivity data. Calculate average value of resistivity of the sample. You should be able to observe that all the plots almost coincide with each other.
o Is there any indication of Joule heating in the sample? Explain what this will do to the resistance.
o What is the room temperature conductivity of your sample? Show your calculation.

- **Hall 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 for both configurations in Figure 9. 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, Hall voltages calculated with the positive magnetic field and with the negative magnetic field should be equal in magnitude but polarity is reversed. If the calculated voltages were not equal in magnitude, briefly explain why it is so.
o Calculate the doping density. Show your calculations. Briefly explain your calculations.
o Calculate the majority carrier mobility. Show your calculations. Briefly explain your calculations.

- **Summary**
o Tabulate the important results of the lab including the conductivity of the sample, carrier mobility of the sample, type of the sample and doping concentration.