HALL EFFECT

I. INTRODUCTION

Materials can be classified, based on their conductivity, as insulators, semiconductors, conductors and superconductors. Insulators and superconductors form the opposite end in the conductivity spectrum with zero and infinite conductivities respectively. Conductors exhibit finite conductance and in semiconductors, in general, the conductivity can be varied controllably. The concentration of electrons (or holes) in semiconductors (popularly known as the carrier density) is between that of conductors and insulators. Si, Ge, GaAs, lnAs are some examples of semiconductor materials. Modern semiconductors are grown epitaxially using expensive and highly sophisticated Molecular Beam Epitaxy (MBE) techniques.

Semiconductors are an integral part in our daily life and characterization of their properties form the basis in several modern laboratories and industries. Resistivity (or conductivity) measurements provide us with important intrinsic information such as carrier concentration, mobility and scattering rate about any material. Hall measurements, originally discovered more than 100 years ago, are the standard tool for determining the concentration of carriers in semiconductors, conductors and superconductors.

In this experiment you will employ low temperature (*T*) and high magnetic field (*B*) electrical transport measurements to probe the characteristics of semiconductor materials. More specifically, you will measure the temperature dependence of resistivity and the Hall coefficient in doped Si samples. You will learn basic experimental techniques and gain a better understanding of the properties of semiconductors.

(i) Resistance measurements

An applied electric current density $\vec{j}$ flowing through a material will give rise to an electric field with a constant of proportionality represented by the resistivity ρ of the material:

$$\vec{E}=\rho\,\vec{j} \qquad (1)$$

By multiplying both sides of Eq. (1) by the length (l) over which the electric field is applied, and then replacing the current density $\vec{j}$ with the current I, we get an expression for the potential difference across the material:

$$El=\rho jl \qquad (2)$$

$$V=\rho\frac{l}{A}I \qquad (3)$$

where we used $V=El$ and $j=I/A$.

This is just the familiar expression known as Ohm's law ($V=IR$), with the resistance R:

$$R=\rho\frac{l}{A} \qquad (4)$$

where ρ is the resistivity, l the length over which the electric field is applied, and A the cross sectional area through which the current flows. Here we are assuming that j and E are uniform (i.e., do not depend on position in the sample). Since resistance is dependent on the sample geometry, it is useful to transform resistance measurements into more fundamental quantities such as resistivity ρ, which is intrinsic to the material and independent of the measurement geometry.

Consider a sample consisting of a bar of uniform material with thickness t, length l, and width w (see Fig. 1). Current I is flowing along the length of the bar, producing a voltage V across the length of the bar:

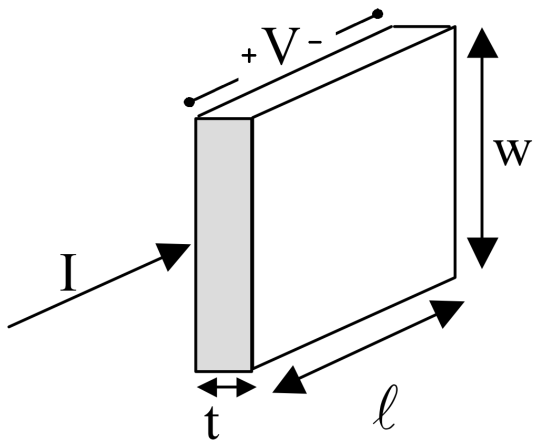

Fig. 1. Longitudinal resistivity measurement configuration

Using Eq. (4), the resistance of this sample is:

$$R=\rho\frac{l}{wt} \qquad (5)$$

A very useful quantity for describing thin-film materials, sheet resistance R_s, can be defined by rearranging Eq. (5):

$$R=\frac{\rho}{t}\frac{l}{w}=R_s\frac{l}{w} \qquad (6)$$

where

$$R_s=\rho/t \qquad (7)$$

R_s is independent of the size of the sample, and only depends on the resistivity ρ and the thickness t of the sample. Notice that for perfectly square samples, $R=R_s$.

The resistivity ρ of a material can be measured for arbitrarily shaped samples (including oval and irregularly shaped samples) using the techniques described in van der Pauw's 1958 paper, if the following conditions are met:

1. The contacts are on the outer perimeter (edges) of the sample.
2. The contacts are sufficiently small.
3. The sample is homogeneous in thickness t.
4. The surface of the sample is singly connected (there are no isolated holes).

To measure ρ using the van der Pauw method, we simply attach four small contacts to the edges of the sample as shown in Fig. 2:

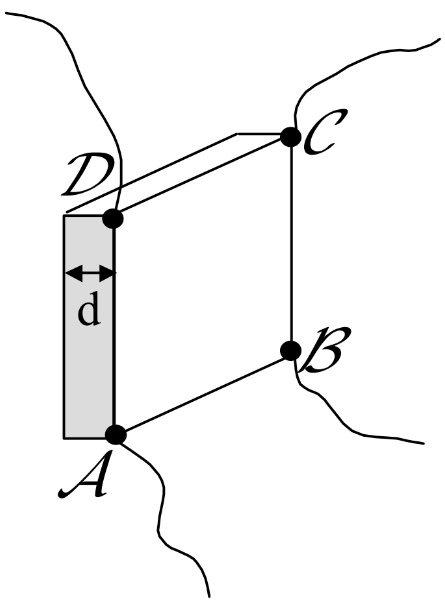

Fig. 2. van der Pauw measurement configuration.

Note that the contacts do not have to be at the corners. They can be anywhere along the edges. If the van der Pauw conditions are met, resistivity ρ can be obtained using the following relation:

$$\rho = \frac{\pi t}{\ln 2} \frac{R_{AB,CD} + R_{BC,DA}}{2} f\left(\frac{R_{AB,CD}}{R_{BC,DA}}\right) \tag{8}$$

where $R_{AB,CD}$ ($R_{BC,DA}$) is the resistance obtained by injecting/collecting a current through contacts A and B (B and C) and measuring the voltage across contacts C and D (D and A). t is the thickness of the sample, and the function f is a slowly varying function that equals unity when the argument is 1. (Fig. 3).

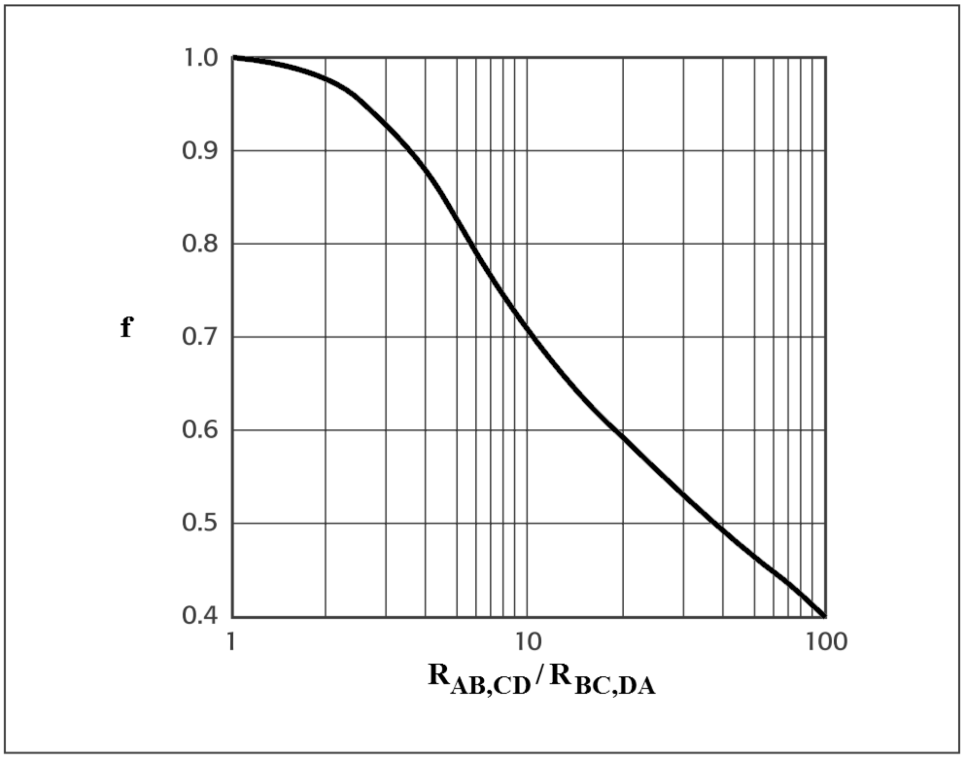

Fig. 3. A plot of the function f() described in Eq. (9).

The value of the function *f()* can be calculated from the relation:

$$\frac{R_{AB,CD}-R_{BC,DA}}{R_{AB,CD}+R_{BC,DA}}=\frac{f}{\ln 2}\cosh^{-1}\left(\frac{e^{(\ln 2/f)}}{2}\right) \qquad (9)$$

A table for the values of $R_{AB,CD}/R_{BC,DA}$ vs. f is provided for you in the appendix. In the van der Pauw geometry, $R_{AB,CD}$ and $R_{BC,DA}$ depend quadratically (or even more strongly) on the dimensions of the sample. As a result, if the distance between contacts A and B in a rectangular sample is twice the distance between B and C, $R_{AB,CD} \geq 4\ R_{BC,DA}$. Note that in case of a perfectly square sample (i.e., $R_{AB,CD}= R_{BC,DA}$), Eq. (8) reduces to:

$$\rho=\frac{\pi t}{\ln 2}R \qquad (10)$$

It is also interesting to explore the conductivity σ of the material, which is simply the reciprocal of the resistivity ρ ($\sigma =1/\rho$). In this case Eq. (1) becomes:

$$\frac{1}{\rho}\vec{E}=\vec{j} \rightarrow \sigma\vec{E}=\vec{j} \qquad (11)$$

In general, σ and ρ are tensors (matrices), which means that E and j are not necessarily parallel to each other. These tensors can be written in terms of x and y components as:

$$\rho=\begin{pmatrix} \rho_{xx} & \rho_{xy} \\ -\rho_{xy} & \rho_{xx} \end{pmatrix} \tag{12}$$

$$\sigma=\begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ -\sigma_{xy} & \sigma_{xx} \end{pmatrix} \tag{13}$$

We can invert the resistivity tensor to obtain conductivity in terms of resistivities. We can further simplify the expression by taking advantage of the fact that typically $\rho_{xy} << \rho_{xx}$:

$$\sigma_{xx}=\frac{\rho_{xx}}{\rho_{xx}^2+\rho_{xy}^2}\approx\frac{1}{\rho_{xx}} \tag{14}$$

$$\sigma_{xy}=\frac{-\rho_{xy}}{\rho_{xx}^2+\rho_{xy}^2}\approx\frac{-\rho_{xy}}{\rho_{xx}^2} \tag{15}$$

Using Eq. (7), we can determine the longitudinal conductivity σ_{xx} in terms of R_s:

$$\sigma_{xx}\approx\frac{1}{\rho_{xx}}=\frac{1}{R_s t} \tag{16}$$

(ii) Hall measurements

If a magnetic field B is applied perpendicular to a film as shown in Fig. 4, then a current flowing through the sample along the x direction will not only produce a voltage drop V_x along the current flow, but will also produce a Hall voltage V_{Hall} along y that is perpendicular to the current. In conductors, this measurement allows one to extract the sign and density of the charge carriers that are responsible for the flow of electrical current. The Hall effect is as fundamental and important in characterizing a material as conventional zero-magnetic field resistance measurements, and can provide information that cannot be accessed with conventional resistance measurements.

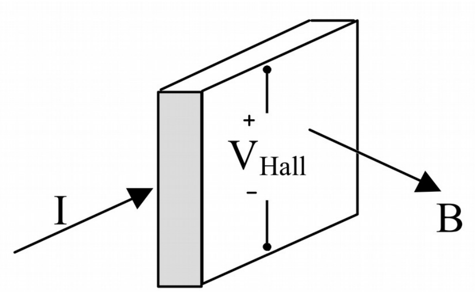

Fig. 4. Hall effect measurement.

The Hall effect is described by Eq. (17), where a current density j_x in the x-direction produces a longitudinal electric field E_x along the current and a transverse electric field E_y perpendicular to the current:

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix}=\begin{pmatrix} \rho_{xx} & \rho_{xy} \\ -\rho_{xy} & \rho_{xx} \end{pmatrix}\begin{pmatrix} j_x \\ 0 \end{pmatrix} \tag{17}$$

In this case, $j_y = 0$ since no current is flowing in the y-direction (there are no sources or sinks to maintain j_y). Note that the off-diagonal components of the resistivity tensor are responsible for the Hall effect, where a current along x is transformed into an electric field along y. Expanding Eq. (17) into its x and y components, we get:

$$E_x = \rho_{xx} j_x \tag{18}$$

$$E_y = -\rho_{xy} j_x \tag{19}$$

Eq. (19) can be transformed into an equivalent Ohm's law form using the same techniques that were applied to Eq. (1), where both sides are multiplied by the length l over which the electric field is acting, and the current density j is replaced by the current I. As result, we can define Hall voltage V_{Hall} as:

$$V_{Hall} = R_{xy} I \tag{20}$$

where R_{xy} is the Hall resistance which translates a current I along x into a voltage V_{Hall} along y. In weak magnetic fields, which is the case in most Hall measurements, R_{xy} is proportional to B and is given by:

$$R_{xy} = \frac{R_H}{t} B \tag{21}$$

where R_H is the Hall constant. For most conductors, R_H is truly a constant that only depends on carrier density as shown below:

$$R_H = \frac{1}{nq} \tag{22}$$

where n is the density of carriers per unit volume and q is the electric charge of the carriers. Notice that if the carrier has negative charge (electrons), R_H becomes negative whereas if the carrier has positive charge (holes), R_H becomes positive.

From Eqs. (20) and (21), we can get an equation that relates R_H to V_{Hall} and B:

$$R_H = \frac{V_{Hall}}{B} \frac{t}{I} \tag{23}$$

Hall constant also offers a way to determine carrier mobility, which is the ratio of carrier drift velocity and the applied electric field:

$$\mu = \frac{v_d}{E} \tag{24}$$

where v_d is the magnitude of the drift velocity of carriers, and E is the magnitude of the applied electric field.

Since:

$$E = \rho j = \rho n q v_d \qquad (25)$$

Eq. 24 becomes:

$$\mu = \frac{1}{\rho n q} = \frac{R_H}{\rho} \qquad (26)$$

Another important quantity in the Hall effect is the Hall angle θ_H, which is simply related to the ratio of the transverse electric field E_y and the longitudinal electric field E_x.

$$\tan\theta_H = \frac{E_y}{E_x} = \frac{V_{Hall}/w}{V_x/l} = \frac{l}{w}\frac{IR_{xy}}{IR} = \frac{l}{w}\frac{R_{xy}}{R} \qquad (27)$$

In Eq. (27), we used the fact that the magnitude of a uniform electric field is simply the voltage per unit distance ($E = V/l$) and used Eqs. (3) and (20) to replace voltages with resistances. Eq. (6) can be used to convert R in the above equation into R_S:

$$\tan\theta_H = \frac{l}{w}\frac{R_{xy}}{R} = \frac{l}{w}\frac{R_{xy}}{R_s(l/w)} = \frac{R_{xy}}{R_s} \qquad (28)$$

The Hall angle can also be expressed in terms of conductivity σ:

$$\begin{pmatrix} \sigma_{xx} & \sigma_{xy} \\ -\sigma_{xy} & \sigma_{xx} \end{pmatrix} \begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} j_x \\ 0 \end{pmatrix} \qquad (29)$$

Solving Eq. (29) for the y-component of j (which is zero in this case), we get:

$$-\sigma_{xy} E_x + \sigma_{xx} E_y = 0 \qquad (30)$$

$$\sigma_{xy} E_x = \sigma_{xx} E_y \rightarrow \frac{E_y}{E_x} = \frac{\sigma_{xy}}{\sigma_{xx}} \qquad (31)$$

Substituting the result from Eq. (31) into Eq. (27), we get:

$$\tan\theta_H = \frac{E_y}{E_x} = \frac{\sigma_{xy}}{\sigma_{xx}} \qquad (32)$$

This shows that $\tan\theta_H$ is simply the ratio of the off-diagonal and diagonal conductivities, σ_{xy} and σ_{xx}. Note that unlike conventional resistance R found in Ohm's law, $V = RI$, where R depends on the sample geometry, R_{xy} is intrinsic to the film. This can be readily seen in Eq. (28). Since $\tan\theta_H$ and R_s are intrinsic properties of the film (independent of film geometry, except for its thickness), R_{xy} must also be intrinsic to the film.

II. EXPERIMENTAL SET-UP

(i) The cryostat

The cryostat is used for performing temperature dependent measurements. It has three independent spaces as shown in Fig. 5. The first is the vacuum space that is evacuated to provide thermal insulation from the room. The second space consists of a reservoir that contains the liquified cryogen, in this case liquid nitrogen. The third and innermost region is the central sample space, which contains the sample probe. Typically, the experimenter first pumps out the central sample space for about 2-3 minutes. Be sure the air in the sample space is well evacuated, otherwise the oxygen content in the air may condense and water may freeze inside the sample space when you fill the cryostat with liquid nitrogen, potentially damaging the sample. To aid in cooling the sample, a small amount of helium gas is introduced into the sample space to serve as heat exchange gas. After the sample space is prepared, the sample space valve is closed and the pump is used to evacuate the outer vacuum space for about 5 minutes. Liquid nitrogen can then be poured into the reservoir through the fill funnel. Your instructor will show you how to evacuate the cryostat. **NEVER add liquid nitrogen until the air in the cryostat is evacuated.**

Data can be taken during cooling and during warming. In either approach, it is important to keep the rate of change of temperature slow and maintain thermal equilibrium inside the specimen can. The temperature of the specimen can be observed on the temperature controller unit. The temperature controller regulates the warming or cooling rate of the sample through a heater coil, and allows the experimenter to set the rate of temperature change. **Make sure the set rate of temperature change is no more than 10 K/min.** Higher rates will prevent a temperature equilibrium inside the sample space and disrupt your measurements. Also, keep in mind that high heater coil currents can generate magnetic fields that may disturb your measurements.

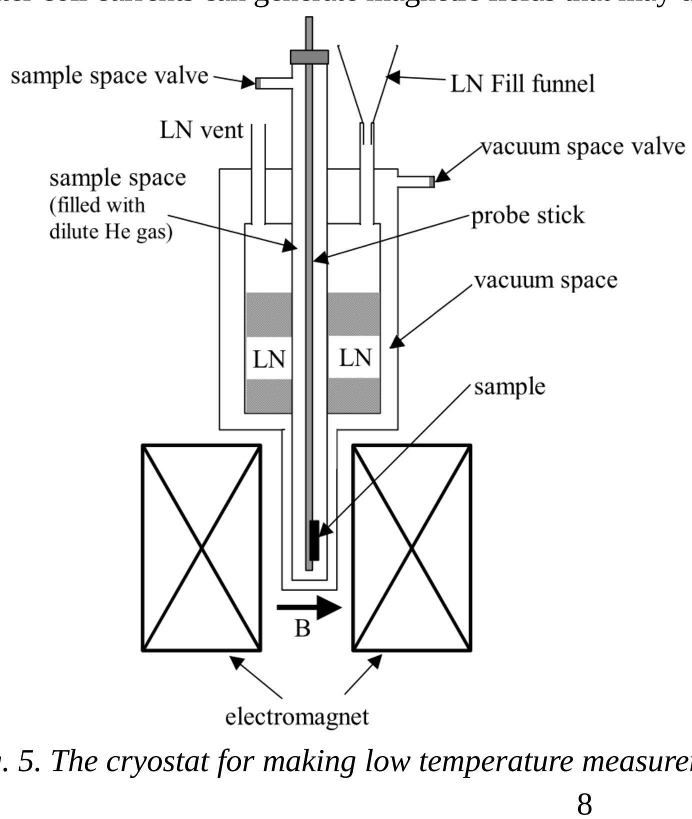

Fig. 5. The cryostat for making low temperature measurements in an external magnetic field.

(ii) Sample probe

The sample probe (see Fig. 6) is used to lower the sample into the cryostat. Handle this probe with care; both the sample and the wires are fragile. The sample is already mounted and wired to the sample probe stick. You should not have to rewire the samples (this is a delicate and time consuming task), but if the measurements appear faulty you will have to check the wiring.

The sample space around the probe is a sealed metal tube that is inside an outer vessel that is filled with liquid nitrogen (LN). The sample makes thermal contact to the LN through a dilute exchange gas. If it becomes difficult to warm the sample up to higher temperatures (i.e., thermal contact between the sample and the surrounding LN is too great), you can pump further on the sample tube to reduce the amount of exchange gas, and thereby reduce the thermal connection between the sample and the cold LN.

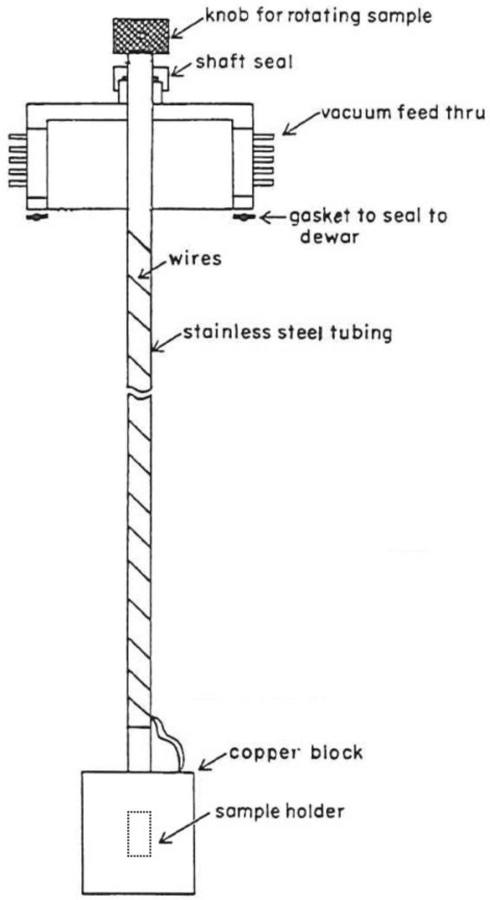

Fig. 6. The sample probe.

The components of the sample probe are:

1. The suspension tube, which slides in the cap to vary the height of the specimen.
2. A copper vessel around the specimen and heater, which helps to keep the temperature uniform and reduces thermal fluctuations.
3. A temperature sensitive diode (DT471) that is used to measure the specimen temperature.
4. A heater which balances the cooling by the cold exchange gas that will surround the can and specimen, and helps control the rate of change of temperature of the specimen.
5. Sample holder which provides a flat mounting surface for the sample and the temperature sensitive diode.

The sample is a doped silicon wafer with a thickness of 300 µm. It is mounted on the front side of the sample holder. A temperature sensitive diode is mounted on the back side of the sample holder. A µA range current is sent from the temperature controller to the diode and the resulting voltage across the diode is measured. The measured voltage is proportional to the temperature of the diode. Note that the diode only works if a positive polarity current is applied.

(iii) Temperature controller

A Lakeshore 330 Autotuning temperature controller is used to control the temperature of the sample in this experiment. Fig. 7 shows the front panel of this instrument. The upper LCD displays the temperature of the sample and the lower one displays the set point. A third vertical LCD displays the heater usage in % with respect to full capacity.

The temperature controller utilizes a PID (Proportional-Integral-Derivative) feedback control loop to approach and maintain the temperature to set values. In a PID feedback control loop, the difference between the set point and the current temperature is continuously calculated. The calculated difference and the values of the P, I and D parameters determine how the controller adjusts the current in the heater coils in order to approach and maintain the temperature to the set point. The P, I, D parameters are set to 50, 25 and 0 respectively for our controller.

The heater can be switched between Off/Low/Medium/High settings using the Heater button. Using the "High" setting is recommended for this experiment. The temperature set point can be changed by pressing the "Set Point" button and entering the new value (in Kelvins). The rate of temperature change can be adjusted by keeping the "Set Point" button pressed, and then entering the new value.

The temperature change rate should not be higher than 10 K/min in order to preserve the temperature equilibrium inside the sample space.

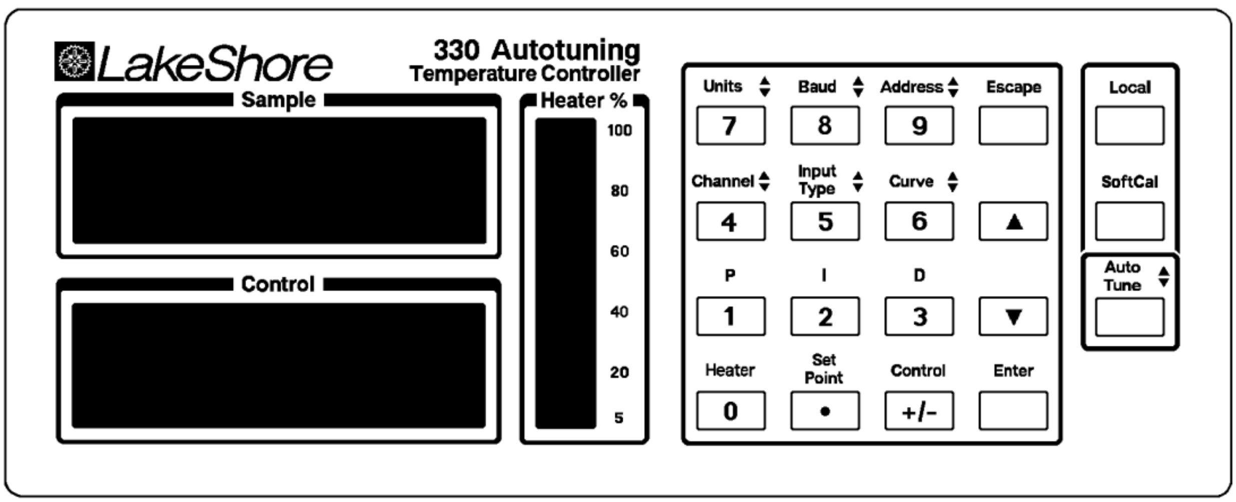

Fig. 7. The front panel of the LakeShore model 330 temperature controller.

(iv) Lock-in amplifier

A Stanford Research Systems Model SR810 Lock-in amplifier is used in making AC measurements in this experiment (Fig. 8). A Lock-in amplifier can extract a signal of a known frequency from an extremely noisy environment. It performs the measurement by multiplying the input signal by the reference signal, and integrating it over a specified time frame. The resulting DC signal only has the signal that is at the same frequency as the reference signal in the noisy environment. The out-of-phase component of the signal that has the same frequency as the reference signal is also attenuated, since sine functions are orthogonal to cosine functions of the same frequency. Therefore, a lock-in amplifier is a phase-sensitive detector. In this experiment, you will generate and measure AC currents and voltages in μA and μV ranges respectively using this instrument.

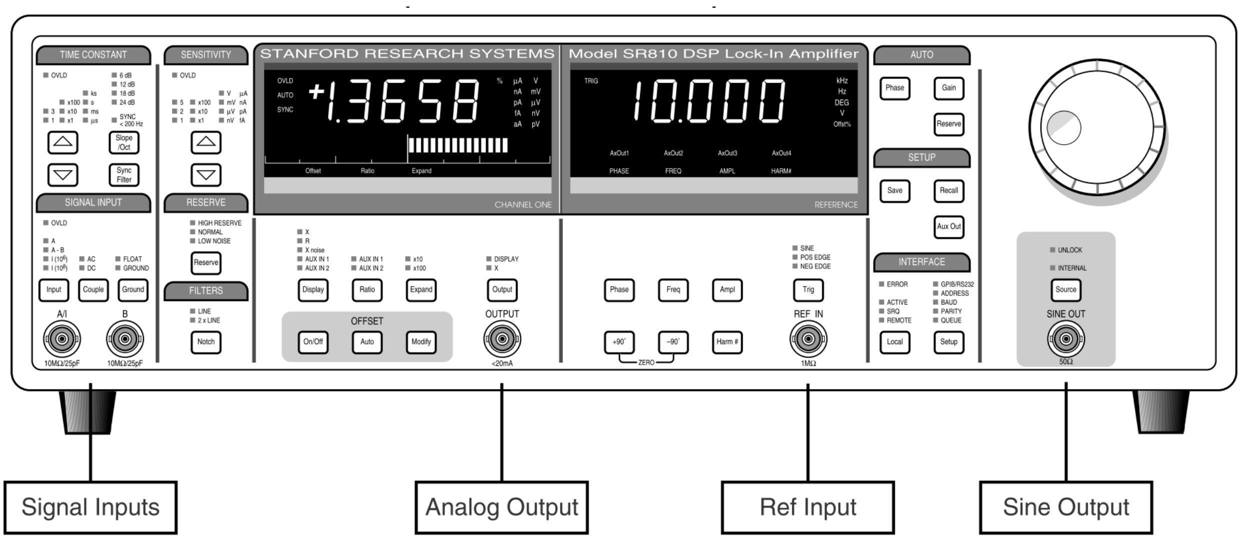

Fig. 8. The front panel of the Stanford Research Systems SR810 Lock-In amplifier.

Your AC current source will be a 1.000 V_{rms} sine wave from the "Sine Out" port of the lock-in amplifier applied over a 1 MΩ resistor. (This will give you 1 μA_{rms} current). You will measure the resulting potential difference on the sample using the "Signal Input" of the lock-in (Signal Input A-B). When making measurements, set the "Signal Input" to A-B, “Couple” to AC, “Ground” to Float, "Time Constant" to 1 s (1×1 s) and 12 dB, and “Display” to R. The "Sensitivity" setting should be set to a value larger than the signal you are trying to measure, otherwise the lock-in amplifier overloads. Sensitivity settings around 10 mV (1×10 mV) usually work well for this experiment. Remember to hit the Phase button under “AUTO” to adjust the phase automatically before reading the measurement off the LCD display.

(v) DC current source

The DC current source you will use is a Keithley 227. You will need to set it up to produce 1 mA DC current. The leftmost knob on the instrument sets current in the tens digit, the next one in the units digit, and the third one in the first decimal digit. To produce 1 mA DC current, set the units digit knob to 1, and the others to 0. Set the rightmost knob to mA with 300 MAX COMP VOLT. Be sure that the output selector is set to ON. Set the meter to A with ×1 to be able to read it.

Fig. 9. Keithley 227 current source

(vi) Vacuum pumping system

A single mechanical pump is used to alternately pump the inner sample space or the outer vacuum space. Valves are provided for pumping and isolating both the sample space and the vacuum space.

If a vacuum is to be maintained in the sample space or the vacuum space, close the sample space valve and the vacuum space valve before shutting off the pump. After the pump has been turned off, vent the input to atmosphere to prevent oil from being drawn into the pumping hose. Allow a minimum of ten seconds before trying to restart the pump.

(vii) The electromagnet

The electromagnet is used to produce the static magnetic field for Hall effect measurements. The magnetic field strength can be set using the current controls on the power supply unit. **Do not exceed 35 A on the power supply unit. Higher currents could lead to overheating and permanently damage the magnet.** On the sample probe, there is a bar for rotating the sample by 180°, which effectively reverses the polarity of the magnetic field for the sample. **Make sure this bar is aligned with the plane of the magnet before starting your experiment.** Table 1 below shows magnetic field strength in Tesla as a function of the electromagnet current (A).

Current (A)	Magnetic field (T)
0	0
5	0.1056
10	0.2125
15	0.3179
20	0.4265
25	0.5258
30	0.6058
35	0.6678

Table 1. Magnetic field strength (T) vs. electromagnet current (A).

III. PROCEDURE

(i) DC 2-contact resistance

Using an ohmmeter, measure the DC 2-contact resistance of the sample for 4 possible longitudinal configurations.

(ii) DC 4-contact resistance

Using a DC current source and a voltmeter, inject 1 mA current through two contacts and measure the resulting voltage on the other two contacts for 8 possible longitudinal configurations (Fig. 10).

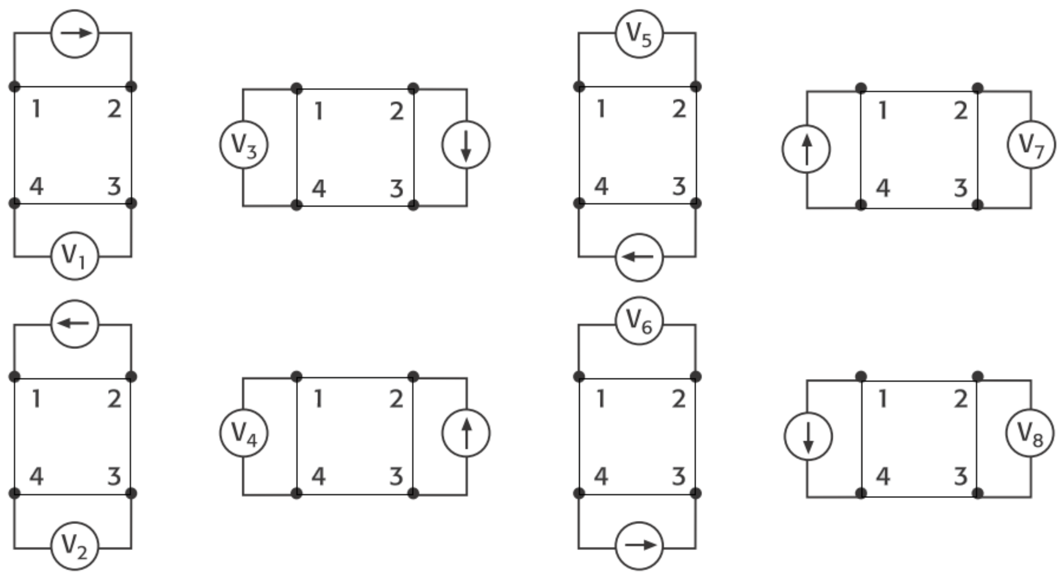

Fig. 10. Longitudinal configurations for DC van der Pauw measurements.

How do these resistances compare with the two probe resistances that you measured in part (i)? **Calculate the resistivity ρ of the sample using the van der Pauw method.**

(iii) DC Hall effect measurement - determining the carrier type

Set up a diagonal 4-probe configuration using a DC current source (see Fig. 11, apply a 1 mA current through one diagonal and measure voltage through the other). **Make sure all the magnetic materials on you are stowed away, no one is behind the magnet where the power cables are, and the cooling water for the magnet is running.** Turn the magnet on. Measure the Hall voltage for both magnetic field directions (use the bar on the sample probe to flip the sample) for magnet currents between 0-35 A in increments of 5 A. Use your data to get a plot of the Hall voltage versus magnetic field strength (-0.67 T to +0.67 T). **Determine if your sample is n-type or p-type silicon from your data.**

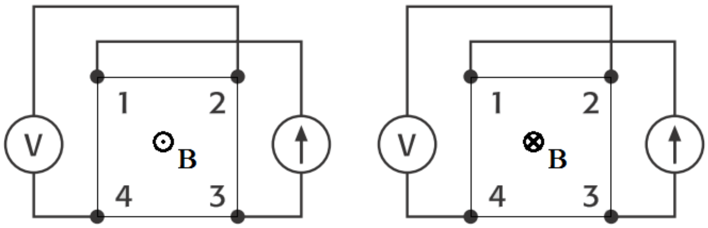

Fig. 11. Diagonal configuration for the DC Hall effect measurement. The sample will need to be flipped by 180º to effectively reverse the magnetic field direction.

(iv) AC 4-contact resistance

Connect the oscillator/reference output of the lock-in amplifier to the 1 MΩ resistor box. Set the output to 1.0 V to get an AC current of 1.0 μA. Set up a longitudinal 4-probe configuration using this current as the source (Fig. 12), and measure the resulting voltage for the 4 possible longitudinal configurations using the A-B input connection on the lock-in amplifier. **Calculate the resistivity ρ of the sample using the van der Pauw method.** Compare your result with that of the DC 4-contact resistance method.

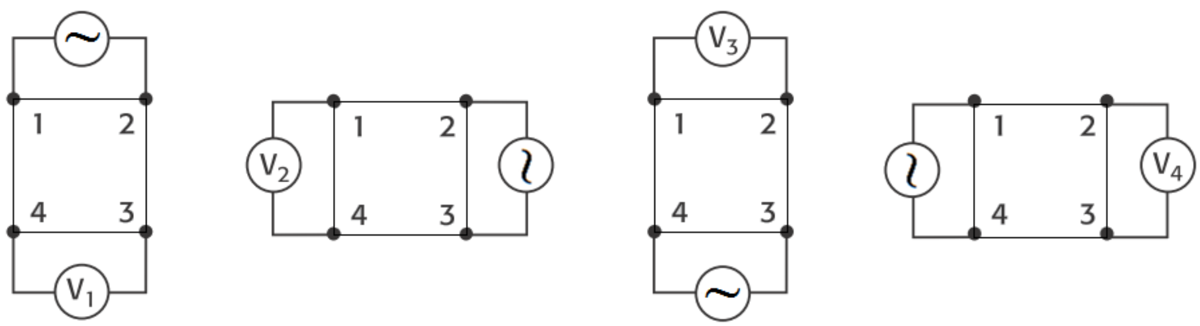

Fig. 12. Longitudinal configurations for AC van der Pauw measurements.

(v) Resistivity versus Temperature

Evacuate both the vacuum space and the sample space of the cryostat to prepare it for liquid nitrogen. Introduce helium exchange gas into the sample space from the lab's helium gas system. After introducing helium exchange gas into the sample space, evacuate it completely once again. Then, introduce the helium remaining in the yellow connection hose into the sample space, without turning on the helium system valve on the wall.

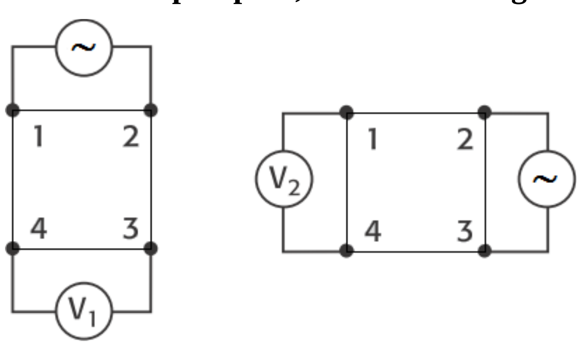

Fig. 13. Longitudinal configurations for AC van der Pauw measurements.

Set the temperature on the temperature controller to 80 K. (You will first need to set the rate to 0 K/min to be able to set the temperature). Once the temperature is set to 80 K, change the rate to 10 K/min. Turn the heater on, and set it to its "High" setting. **Put on a lab coat, protective gloves and goggles.** Using a foam cup and a funnel, fill the cryostat with about 5 liters of liquid nitrogen.

Connect the oscillator/reference output of the lock-in amplifier to the 1 MΩ resistor box. Set the output to 1.0 V to get an AC current of 1.0 μA. Set up a longitudinal 4-probe configuration using this current as the source, and measure the resulting voltage for the 2 longitudinal configurations shown in Fig. 13 using the A-B input connection on the lock-in amplifier. (Notice from your measurements of the previous section that since the sample is approximately symmetric, you get similar results for the other configurations).

Now increase the set temperature by 20 K using the temperature controller, and wait for the temperature to stabilize. Repeat the measurement up to 300 K in 20 K steps. **Once you have all the data, calculate the resistivity ρ for each temperature using the van der Pauw method. Produce a plot of resistivity ρ versus temperature.**

Be aware that the connections on the sample may break due to the effects of rapid temperature change. If you notice a connection is broken, inform your instructor immediately. The sample will have to be warmed up to room temperature to get fixed.

(vi) AC Hall voltage

Set up a diagonal 4-probe configuration using an AC current source. (see Fig. 14; use the oscillator/reference output of the lock-in amplifier as your current source, and measure the voltage using the A-B input connection on the lock-in amplifier).

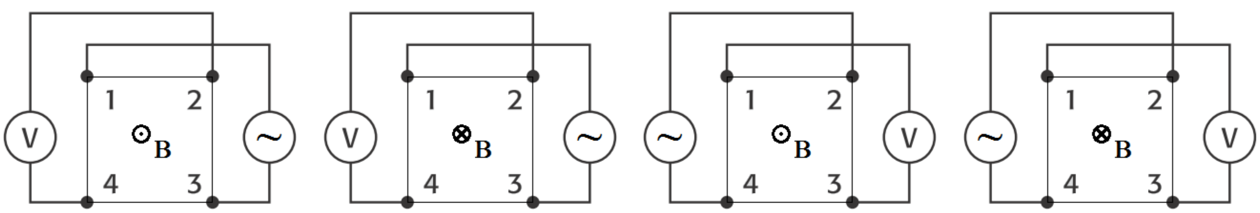

Fig. 14. Diagonal configurations for the AC Hall voltage measurement. The sample will need to be flipped by 180º to effectively reverse the magnetic field direction.

Evacuate both the vacuum space and the sample space of the cryostat to prepare it for liquid nitrogen. Introduce helium exchange gas into the sample space from the lab's helium gas system. After introducing helium exchange gas into the sample space, evacuate it completely once again. Then, introduce the helium remaining in the yellow connection hose into the sample space, without turning on the helium system valve on the wall.

Set the temperature on the temperature controller to 80 K. (You will first need to set the rate to 0 K/min to be able to set the temperature). Once the temperature is set to 80 K, change the rate to 10 K/min. Turn the heater on, and set it to its "High" setting. **Put on a lab coat, protective gloves and goggles.** Using a foam cup and a funnel, fill the cryostat with about 5 liters of liquid nitrogen.

Wait for the temperature to reach and stabilize at 80 K. **Then, make sure all the magnetic materials on you are stowed away, no one is behind the magnet where the power cables are, and the cooling water for the magnet is running.** Turn the magnet on. For magnet currents between 0-35 A in 5 A increments, record the resulting AC voltage for all configurations shown in Fig. 14. Use the bar on the sample probe to flip the sample to get opposite magnetic field directions. Now increase the set temperature by 20 K using the temperature controller, and wait for the temperature to stabilize. Repeat the measurement up to 300 K in 20 K steps.

Use your data to get a plot of the Hall voltage versus magnetic field strength (-0.67 T to +0.67 T) for each temperature setting. Since our sample may not be perfectly symmetric, take the averages of the two different voltage-current configurations with the same magnetic field direction, and use this average as your Hall voltage (average the voltages measured in configurations 1 and 3, 2 and 4 according to Fig. 14). You can show your data for each temperature as a separate linear fit on the same V_{Hall} versus B plot. Use the slopes of these separate lines and Eqs. (23) and (26) to produce plots of carrier density versus temperature and carrier mobility versus temperature.

IV. FOR YOUR REPORT

(i) Your report should be in the general format of a scientific journal article, similar to the articles posted on UB Learns along with this lab manual. However, the individual sections should include a lot more detail, and the discussions should reflect how well you understand the theory and the experiment.

(ii) In the abstract, briefly summarize the procedures and your findings in the experiment. Highlight any important finding. Provide numerical results with errors where applicable.

(iii) In your own words, provide a detailed discussion of the theory behind the experiment.

(iv) Describe your experimental set-up, using clearly labeled figures where necessary. Your description should have sufficient detail to enable experimenters elsewhere to replicate your experiment.

(v) Present your data and discuss your results. Use tables and plots where necessary. For this experiment, remember to include:

- a plot of DC Hall voltage vs. magnetic field strength (-0.67 T to +0.67 T) at room temperature
- a plot of resistivity vs. temperature
- a plot of magnetic field strength vs. current (using the data from the provided table)
- a plot of AC Hall voltage vs. magnetic field strength (-0.67 T to +0.67 T, showing the data for each temperature as a separate linear fit on the same plot)
- a plot of carrier density vs. temperature
- a plot of and carrier mobility vs. temperature

Compare the values you find for the above quantities to those for conductors and insulators. Include sources of error and your error calculations in your discussions.

(vi) In your conclusions, summarize your findings. Discuss their relevance to theoretical expectations.

(vii) Cite all your references properly in the references section.

V. APPENDIX

$R_{AB,CD}/R_{BC,DA}$	f	$R_{AB,CD}/R_{BC,DA}$	f	$R_{AB,CD}/R_{BC,DA}$	f	$R_{AB,CD}/R_{BC,DA}$	f	$R_{AB,CD}/R_{BC,DA}$	f
1.00	1.00	4.60	0.84	8.20	0.73	11.80	0.67	15.40	0.63
1.10	1.00	4.70	0.83	8.30	0.73	11.90	0.67	15.50	0.63
1.20	1.00	4.80	0.83	8.40	0.73	12.00	0.67	15.60	0.63
1.30	0.99	4.90	0.83	8.50	0.73	12.10	0.67	15.70	0.63
1.40	0.99	5.00	0.82	8.60	0.73	12.20	0.67	15.80	0.62
1.50	0.99	5.10	0.82	8.70	0.72	12.30	0.66	15.90	0.62
1.60	0.98	5.20	0.81	8.80	0.72	12.40	0.66	16.00	0.62
1.70	0.98	5.30	0.81	8.90	0.72	12.50	0.66	16.10	0.62
1.80	0.97	5.40	0.81	9.00	0.72	12.60	0.66	16.20	0.62
1.90	0.97	5.50	0.80	9.10	0.72	12.70	0.66	16.30	0.62
2.00	0.96	5.60	0.80	9.20	0.71	12.80	0.66	16.40	0.62
2.10	0.95	5.70	0.80	9.30	0.71	12.90	0.66	16.50	0.62
2.20	0.95	5.80	0.80	9.40	0.71	13.00	0.66	16.60	0.62
2.30	0.94	5.90	0.79	9.50	0.71	13.10	0.65	16.70	0.62
2.40	0.94	6.00	0.79	9.60	0.71	13.20	0.65	16.80	0.61
2.50	0.93	6.10	0.79	9.70	0.70	13.30	0.65	16.90	0.61
2.60	0.93	6.20	0.78	9.80	0.70	13.40	0.65	17.00	0.61
2.70	0.92	6.30	0.78	9.90	0.70	13.50	0.65	17.10	0.61
2.80	0.92	6.40	0.78	10.00	0.70	13.60	0.65	17.20	0.61
2.90	0.91	6.50	0.77	10.10	0.70	13.70	0.65	17.30	0.61
3.00	0.91	6.60	0.77	10.20	0.70	13.80	0.65	17.40	0.61
3.10	0.90	6.70	0.77	10.30	0.69	13.90	0.64	17.50	0.61
3.20	0.90	6.80	0.77	10.40	0.69	14.00	0.64	17.60	0.61
3.30	0.89	6.90	0.76	10.50	0.69	14.10	0.64	17.70	0.61
3.40	0.89	7.00	0.76	10.60	0.69	14.20	0.64	17.80	0.61
3.50	0.88	7.10	0.76	10.70	0.69	14.30	0.64	17.90	0.61
3.60	0.88	7.20	0.76	10.80	0.69	14.40	0.64	18.00	0.60
3.70	0.87	7.30	0.75	10.90	0.68	14.50	0.64	18.10	0.60
3.80	0.87	7.40	0.75	11.00	0.68	14.60	0.64	18.20	0.60
3.90	0.86	7.50	0.75	11.10	0.68	14.70	0.64	18.30	0.60
4.00	0.86	7.60	0.75	11.20	0.68	14.80	0.63	18.40	0.60
4.10	0.86	7.70	0.74	11.30	0.68	14.90	0.63	18.50	0.60
4.20	0.85	7.80	0.74	11.40	0.68	15.00	0.63	18.60	0.60
4.30	0.85	7.90	0.74	11.50	0.68	15.10	0.63	18.70	0.60
4.40	0.84	8.00	0.74	11.60	0.67	15.20	0.63	18.80	0.60
4.50	0.84	8.10	0.74	11.70	0.67	15.30	0.63	18.90	0.60