LOW-TEMPERATURE, FOUR-WIRE RESISTIVITY MEASUREMENT

In this experiment we will explore two very, useful techniques in the solid-state physics laboratory. The first is the use of very low temperatures, or cryogenics. The second is the use of four-wire techniques when the resistance is either very small or you need high precision.

Library Research

Before you begin this experiment, you need to find out the meaning of and the relationship between several terms. Use the web or the library to find out the meaning of the following four terms:

- Hall Coefficient: $R_H$
- Resistivity: $\rho$
- Mobility: $\mu$
- Carrier Concentration: $n$

How do carrier concentration and mobility effect the Hall Coefficient? The Resistivity?

Four-wire resistance measurement

To start with, let's measure the resistance of a wire that you might use in the laboratory. Bear in mind that up till now you have probably assumed zero resistance for all cables. Let's find out exactly how much resistance it does have. Take a short piece of "banana" cable, that is, a wire can that has a single "banana" plug on each end. Find a multimeter which can be used as a "four-wire" ohmmeter. (It will have at least four input plugs.) The Agilent 34401A at the bottom of the rack with the “GPIB 13” label is a good choice. Turn on the power switch at the right-hand side of the instrument rack. Connect the wire to the two "Input" plugs (NOT the "Sense" plugs) on the right hand side. Make a standard two-wire resistance measurement.

Record the resistance in your notes, and record whether the value is zero or not. If the meter records zero ohms on the most sensitive scale, then be sure to write out this zero value to the appropriate number of places and using appropriate units. This does not mean that the resistance is exactly zero, but it instead gives you an upper bound for the resistance, according to this meter.

What would happen if you measured the resistance of this wire using ohmmeter leads? Remove your sample wire, insert a pair of meter leads into the ohmmeter and remeasure the [two-wire] resistance of the wire. Write this value in your notebook along with an explanation of what you've just measured, and a diagram. In fact, be sure to draw a diagram every single difference measurement configuration you do this afternoon.

Is there a difference between the two measurements so far? Why or why not?

If the meters introduced an extra resistance into the value displayed on the meter, this is because the meter itself has no idea how much resistance is included in the meter leads attached to its plugs. Usually, if you are measuring a large enough resistance, this hardly matters. But for some scientists and engineers, it does. And certainly, for this particular sample -- the wire -- it does. What the ohmmeter measures is the ratio between the voltage across its two input plugs and the current flowing between those same two plugs through the exterior circuit. If there is any voltage drop at all across the leads, that will alter your measurement or the resistance of your specimen. Fortunately, there is an easy way to fix this. That is to separate the voltage-measuring part of the circuit from the current-carrying part of the circuit. We can do this with a four-wire technique.

Rather than connecting separate circuits to your specimen, one which has a separate current source and current meter and another with a voltmeter to measure potential difference, this can all be done with a type of meter known as a four-wire resistance meter. This kind of meter has four plugs two of which provide the current to your specimen, and two of which measure the voltage drop across that specimen. This removes the error produced by the voltage drop across the meter leads.

Take four more banana wires. Connect these to the four input plugs on your meter. Connect the two "Input plugs" that belong to the current circuit of the meter to the two ends of your specimen. Connect the two "Sense"
plugs (the voltage part of this circuit) to the two ends of your specimen. In other words, one current plug and one voltage plug will be connected to the right end of your specimen wire, and one current plug and one voltage plug will be connected to the left end. Measure the resistance, using the most sensitive scale of the meter. Record this value, sketch the apparatus. Now sketch a schematic electrical diagram for this experiment.

Congratulations, you have just measured the resistance using a 4 wire, D.C. measurement approach. Are your results consistent with the two-wire measurement results? Explain.

van der Pauw Measurement

Read L. J. van der Pauw’s article (T: drive). Skim over the math if you wish, but focus on the gist of the article. You will be working with a specimen like the kind described by van der Pauw, a specimen of uniform thickness with no internal holes. If you attach four infinitesimal electrical contacts to its edge, you can calculate the resistivity of the material, if you know the thickness. You do this by sending current between two of the electrical contacts of the specimen and measuring the voltage across the other two. Now, because the placement of the contacts is somewhat arbitrary, you need to make a second, independent resistance measurement to measure the resistivity. For both of these measurements,

The LabVIEW program that will do all this will measure four resistances, R1, R2, R3, and R4, which are related to the resistivity, and two, R5 and R6 related to the Hall coefficient, another property of the material of the specimen. By symmetry, R1 should equal R3 and R2=R4. R5 and R6 will be almost equal, but their difference will represent the quantity you are trying to measure.

The software will measure all of these values for a given specimen temperature, and then record the data to a file. These data can be retrieved later to study how resistance and/or Hall coefficient vary with temperature.

Cryogenics

Physical experiments are all about reducing the number of variables and then determining how each effects the system you are studying. One physical quantity that can alter the electrical resistance of an object is temperature, which is a measure of the energy available in the material. It can alter the resistance of an object in at least three ways:
a) It can change the physical dimensions of the object. (This is an effect we can usually ignore.)
b) It can change the number of charge carriers in the material. (This is true for semiconductors, but not for metals.)
c) It can change the “mobility” of the charge carriers, by increasing scattering between the charge carriers and the much heavier ions they leave behind.
Because of (c), the resistivity of metals increases with increasing temperature, while because of (b), the resistivity of semiconductors generally decreases with increasing temperature.

Low-temperature electrical experiments are very common in physics, particularly in solid-state physics. Why? Electrical measurements are a very useful, and a relatively easy and cheap way to tell what’s happening in the material on the sub-atomic level. It’s a “cheap atomic microscope”. If we then use cryogenic techniques, we can see how what happens on a subatomic level varies with energy, one of the most fundamental physical quantities there is.

PROCEDURE:

Your instructor will decide what specimen or specimens you will use in this experiment. Make sure the wires to the specimen are electrically connected to the plugs C, P, R, and D at the top of the instrumentation rack. Be sure that the cryostat thermal shield is screwed on, and that the plane of the specimen is perpendicular to the magnetic field.

Once it is mounted in the cryostat, you will want to do the following.

1. Turn on the power switch to the instrument rack. It is on the right hand side of the rack as you face it.
2. Make sure the following instruments are turned on: Agilent 34401A (“GPIB 14”) digital multimeter
Keithley 705 Scanner ("GPIB 17") -- actually the device that will do the “van der Pauw switching”
Lake Shore 120 Current supply (small, hidden blue box) -- Turn on the power toggle and flip the direction toggle either up or down.
Lake Shore 332 Temperature Controller ("GPIB 15")
Keithley 181 Nanovoltmeter (no “GPIB” label) -- Press the 2mV button to switch the sensitivity scale.
3. Turn on the computer and log in.
4. Double click the “van der Pauw.vi” icon.
5. Eventually you will see the front panel of a “virtual instrument” which will take care of the measurement during this experiment, while you take care of the temperature. Click the white, right-pointing arrow at the top left of the screen. This starts the virtual instrument. It will perform the switching operation and measure van der Pauw resistances. Find the “Delay” control near the top right of the screen. Increase this to at least 0.7 seconds. (But no more than 1s) After the instrument has gone through one cycle of measurements -- all six possibilities of van der Pauw measurements -- it will prompt you for an output file to save your measurements. Choose a place on your P: drive. After you give it a file name, it will hopefully continue to take data till you tell it to stop. If not, then click the white arrow and try again. When you are ready to stop, click the “Stop” button near the bottom of the screen, and wait for it to complete the current cycle. If it does not stop, click “Stop” again. The second click is usually enough to get it to obey.

You are now ready to alter the temperature and see how the resistivity (and Hall constant) responds.

1. Make sure that the vacuum jacket of the cryostat has been evacuated. Use a mechanical pump and let it pump at least two minutes or more. It should be noisy at the start of pumping on air, and then quiet down. If it doesn’t quiet down, you are not producing a good enough vacuum.
2. Put a funnel in the top of the cryostat. Have your instructor show you how to get a thermos full of liquid nitrogen from the dewar, and pour it down the funnel. If liquid comes squirting out the side vent of the cryostat, you need to wait before adding more. Follow all of the safety rules your instructor gives you. Liquid nitrogen is a dangerous substance and must be treated with proper respect.
3. Eventually, at something below 100K, the temperature will level out. If the “thermometer” were in direct contact with the liquid nitrogen, this would occur at about 77K. Once this happens, liquid will actually collect inside the cryostat. You can check this by sticking a thin hollow tube down the top of the cryostat. Bits of liquid will spit out the top. “Top off” the liquid level, and your instructor will show you how to lower the temperature even further by pumping on the liquid. This may get you to about 60K.
4. When you pump on the liquid, some of it will boil off, and then the pumping no longer works. (This cooling effect is like the effect that sweat has on your body on a dry hot day.) Then the temperature will rise again. Turn off the pump. Let the temperature rise again. If it levels off again under 100K, tilt the cryostat and pour off any excess liquid nitrogen. This will speed up the warming up process. The instructor will set up an external heater to allow you to speed the process even more.
5. Allow the computer to continue to collect data as the cryostat warms up. You can do other work while it does its work.
6. When the cryostat reaches room temperature (or above, but do not exceed 320K), be sure to turn off the heater and the computer. You can now access your data. Use Excel to open the file and save it as an Excel spreadsheet.