Electrical Resistivity and Hall Effect (Part I)

Overview

In the first part of this experiment you will 1) attach leads to a Co/Cu multilayer thin film, 2) measure its electrical resistivity, and 3) measure the giant magnetoresistance effect in an external magnetic field. The rest of this document will guide you through the background and experiments to perform.

In the second part of the experiment you will study a semiconductor germanium crystal where the leads have already been attached. You will 1) measure the temperature-dependence of resistivity, 2) determine the energy gap E_g, and 3) study the Hall effect. Refer to the experimental guide "Electrical Resistivity and Hall Effect in Germanium" for this part.

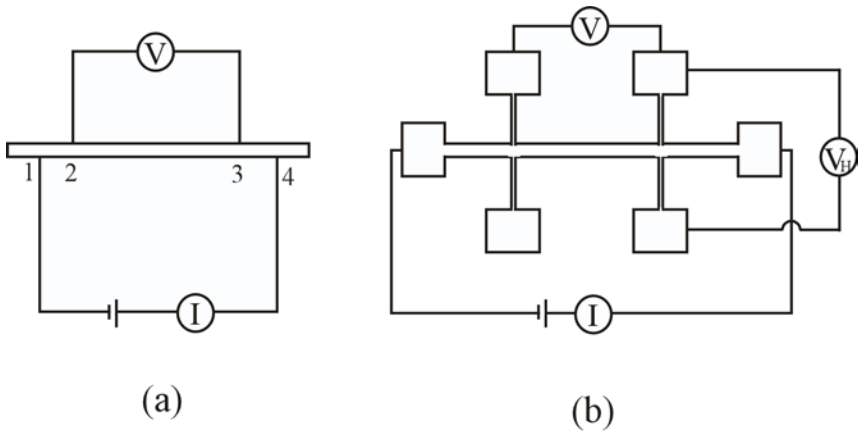
1. Four probe measurement

Electrical resistivity is widely used in physics to study electrical transport phenomena. In a simple measurement of the electrical resistance of a test sample, one may attach two wires to the sample and measure with a multimeter. This inadvertently also measures the resistance of the contact point of the wires to the sample. When the contact resistance is far smaller than the resistance of the sample, it can be ignored. However, when one is measuring a very small sample resistance, the contact resistance can dominate and completely obscure changes in the resistance of the sample itself.

The effects of contact resistance can be eliminated with the use of a four point probe. A schematic of a four point probe is shown in Fig. 1 below, where four wires (or probes) have been attached to the test sample. A constant current is made to flow the length of the sample through probes 1 and 4. The voltage drop between probes 2 and 3 can be measured by a digital voltmeter. The resistance of the sample between probes 2 and 3 is the ratio of the voltage registering on the digital voltmeter to the value of the output current of the power supply. The high impedance of the digital voltmeter minimizes the current flow through the portion of the circuit comprising the voltmeter. Thus, since there is no potential drop across the contact resistance associated with probes 2 and 3, only the resistance associated with the test sample between probes 2 and 3 is measured.

A reasonable aspect ratio of the bar (>2) is desirable to avoid the non-uniformity of the current distribution. (For measuring samples with more general shapes, the van der Pauw method may be used,[1] which will not be explored in this experiment.) The applied current or voltage should be kept low to avoid Joule heating. Electrical contacts are realized by the attachment of fine wires, e.g., Cu, Ag, or Au, to the sample by soldering. Sometimes contact pads are used, where are made of a different material, e.g., Au, Al. One should be concerned with the possible contact potential between the pad and the test material. A common bar-shaped sample with patterned contact pads is shown in Fig. 1b, where the Hall voltage V_H can also be measured.

If the solder is incompatible with the test material, or the heat from the soldering is unacceptable, one may attach the leads using certain adhesives, e.g., silver paint or silver epoxy. They should have good electrical conductivity in the desired working temperature range. However, the curing process of the glue is usually time-consuming and the mechanical strength of the contact is far less than soldering.



(a)

(b)

Fig. 1. Schematic of the four-probe resistivity measurement of (a) a bar-shaped sample, and (b) a patterned sample with contact pads that also allow measurement of the Hall resistance.

2. Giant Magnetoresistance effect

Magnetoresistance (MR) refers to the change in electrical resistance of a material in a magnetic field. The MR size is typically represented by the percentage change of the resistance. All metals have an intrinsic ordinary magnetoresistance (OMR) due to the curving of the conduction electron trajectory in a magnetic field by the Lorentz force. The OMR in metals is usually negligibly small. In homogeneous ferromagnetic (FM) materials, a different type of MR is present, called anisotropic magnetoresistance (AMR). The AMR refers to the dependence of the resistance on the relative orientation of the sensing current direction and the magnetization direction. It is due to the anisotropy of the spin-orbit scattering,[2] a mechanism *intrinsic* to the specific FM materials. This effect has been used in magnetoresistive field sensors, where the effect size is still small, generally no more than a few percent.

Over the last two decades, the phenomenon of **giant magnetoresistance** (GMR) has attracted a great deal of attention for both fundamental interest and technological applications. It was first discovered in 1988 in Fe/Cr,[3] and subsequently in other multilayers in which the interlayer exchange coupling results in an antiferromagnetic (AF) alignment of the adjacent magnetic layers.[4] The GMR in these magnetic heterostructures has very large magnitude, up to tens of percent,[5] which historically justified the term “giant”. The discovery opened the door to Spintronics and led to the 2007 Nobel Prize in Physics for Peter Grünberg and Albert Fert. As noted by the Nobel committee, the use of GMR can be regarded “as one of the first major applications of nanotechnology”. The most notable applications of spintronics to date include the use of GMR in readheads for magnetic hard disk drives and magnetic random access memory (MRAM). The former has transformed the entire magnetic recording industry, from computers to consumer electronics, such as TiVos and camcorders. The latter offers fast, scalable, nonvolatile and energy efficient memory that requires zero data-retention power and very low standby power.

The primary origin of the GMR is *spin-dependent scattering* of the conduction electrons, i.e., spin-up and spin-down electrons having different scattering cross sections. This mechanism is *not intrinsic* to the host metal, but depends on the specific scattering impurities, and additionally also on the lattice potential variations at the interfaces. When the spin-dependent scattering rate is changed by the external field, the GMR effect results. Fig. 2 illustrates the realization of GMR in different systems. The essential features are the high resistivity state at low magnetic field due to the spin disorder, and the low resistivity state at high field due to the spin ordering. In multilayers, the ferromagnet (FM) layers are separated by spacers. Spin disorder results from the antiparallel spin alignment in the adjacent FM layers. It can be established, to various extents, by AF exchange coupling, by utilizing two FM layers with different coercivity, or by AF/FM exchange bias, etc. In granular solids, the spin disorder is the randomness of the spins in the absence of a magnetic field.

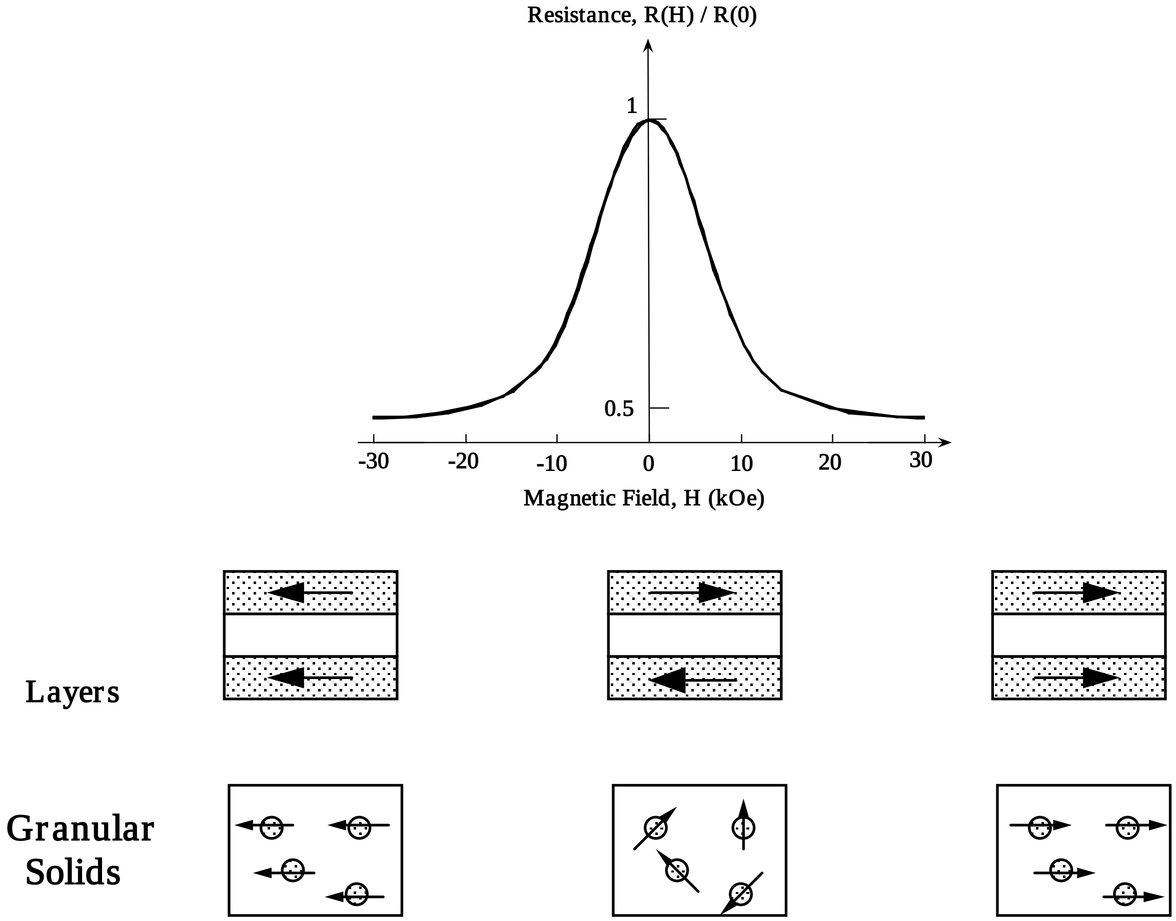


Fig. 2. Schematic of the realization of GMR in layers and granular solids. The spin disorder at low field gives rise to a high resistivity state, whereas the spin ordering at high field gives rise to a low resistivity state.

The working of the mechanism of the GMR is illustrated in Fig. 3 for the multilayer geometry, qualitatively by the "**two-current**" model. [6] The assumptions are no spin-mixing, and that the electron mean free path within the layer is much larger than the layer thickness. Conduction is realized by two channels of electrons with spin-up $(\uparrow)$ and spin-down $(\downarrow)$. The respective resistivities are $\rho_\uparrow$ and $\rho_\downarrow$. When the magnetizations of all layers are parallel (P), spin-up electrons (those with $\mathbf{s}_z=+1/2$ in Fig. 3) form a low resistivity channel throughout the sample, shunting the current, and the total resistivity

$$\rho_P = \frac{\rho_\uparrow \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow} \tag{1}$$

is low. When the magnetizations are antiparallel (AP), both channels experience alternatingly high and low resistivity in successive FM layers. The resistivity in each channel is $(\rho_\uparrow + \rho_\downarrow)/2$ and the total resistivity

$$\rho_{AP} = \frac{\rho_\uparrow + \rho_\downarrow}{4} \tag{2}$$

is high. The GMR can be expressed as

$$GMR = \frac{\rho_P - \rho_{AP}}{\rho_P} = -\frac{\left(\rho_\downarrow - \rho_\uparrow\right)^2}{4\rho_\uparrow \rho_\downarrow} = -\frac{(\alpha - 1)^2}{4\alpha}\ , \tag{3}$$

where $\alpha = \rho_\downarrow / \rho_\uparrow$.

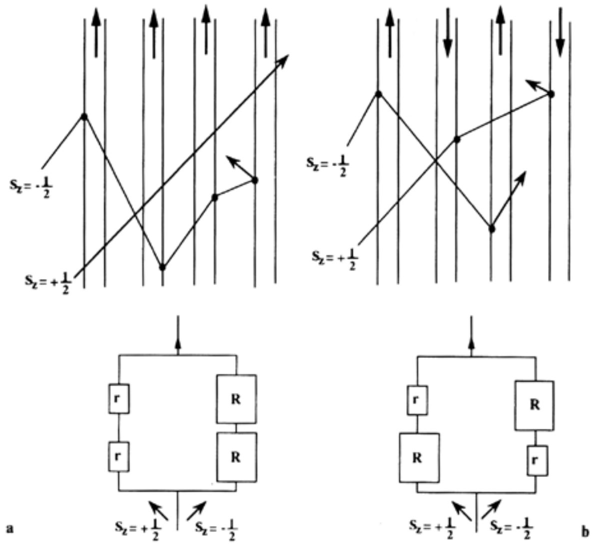


Fig. 3. Schematic of conduction in a magnetic multilayer for parallel magnetizations (high field) in (a) and for antiparallel magnetizations (low field) in (b). The upper figures represent electron trajectories in a multilayer for both spin direction ($s_Z = \pm 1/2$). The lower figures represent the equivalent resistor arrays. (Taken from Ref.6.)

The measurement of MR usually depends on the relative orientation of the sensing current, the applied magnetic field **H**, and the sample. For a thin film sample, the MR can be measured in the longitudinal, transverse, and perpendicular geometries, as shown in Fig. 4, where the applied magnetic field is respectively parallel to the current (Fig. 4a), in the film plane but perpendicular to the current (Fig. 4b), and perpendicular to the film plane (Fig. 4c).

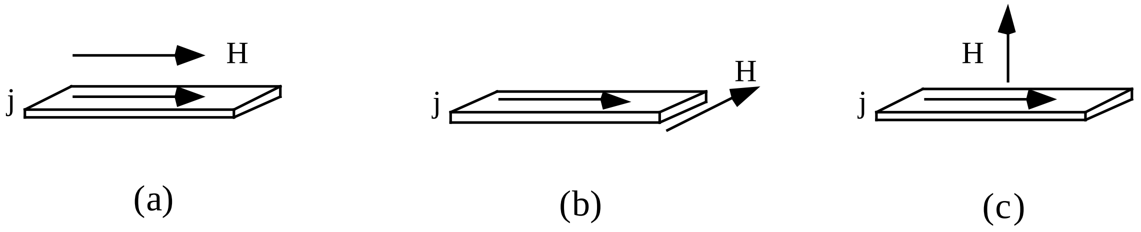


Fig. 4. Measuring geometries for the (a) longitudinal, (b) transverse, and (c) perpendicular magnetoresistance.

3. Experiments

3.1 Attaching leads to Co/Cu multilayer film

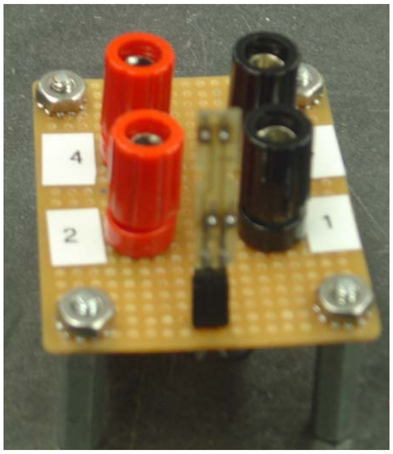
(1) To start your experiment you will attach fine Pt or Cu wires onto a film of Co/Cu grown on Si (100) substrates. The film has the following structure: 8 repeats of [Co(10Å)/Cu(20Å)] multilayer (total thickness 240 Å) and a capping layer of 40 Å Fe film. For practice purposes, Cu films are also provided, which should be used first until you are comfortable with the technique.

(2) Handle the sample with a pair of tweezers. Do NOT touch the sample surface with your bare hands.

(3) Use the In provided, cut a small piece into thin slices and adhere one piece onto the film using a wooden tip. Lay the Pt wire with tweezers on top of the In, and cover up with another In slice.

(4) Turn on the soldering iron to ~ 180-200 ºC, just above the In melting point of 156 ºC. After the iron is hot, quickly touch the In pads and solder the wire onto your film. Minimize heating the rest of the sample.

(5) Solder the wires onto the probe station provided. Make sure the Pt or Cu lead wires do not touch one another. Keep track of the current and voltage connectors (the numbering might be different from that in Fig. 1!).



3.2. Resistivity measurement

(1) Use a multimeter directly measure the resistance of the test sample in a 2-probe geometry.

(2) Connect a HP6205B dc power supply through a 10kΩ resistor to the current leads. Keep the applied voltage below 10V.

(3) Attach a HP3478A multimeter to the two voltage leads (Fig. 1a); pay attention to polarity.

(4) Measure the resistivity of the Co/Cu film using as small a current as possible to minimize heating, while obtaining a reliable voltage reading.

(5) Compare with the 2-probe value as well as the bulk Co and Cu resistivity (ρ_{Co}=6.2 μΩ·cm, ρ_{Cu}=1.7 μΩ ·cm).

3.3. GMR measurement

(1) Calibrate the Gauss probe and position it right next to the sample.
(2) Position the horse-shoe magnet over the sample such that the magnetic field is in the plane of the film (either the longitudinal or the transverse geometry shown in Fig. 4 is satisfied), find the location where the field on the sample is at a maximum $H_{max.}$
(3) Measure the resistance R as a function of magnetic field, starting at + H_{max} and slowly pulling the magnet away to reduce the field at the sample location to zero.
(4) Reverse the polarity of the magnet and move it back in to bring the field to -H_{max}; measure R along the way as a function of the magnetic field H.
(5) Continue this process until the magnetic field is cycled through + H_{max} to -H_{max} to +H_{max} and plot the magnetoresistance (similar to Fig. 2) using MR={[R(H)-R(0)]/R(0)}×100%, where R(H) and R(0) are the resistance in a field H and at zero field, respectively.
(6) Do you have a single peak in your MR plot, like Fig. 2? Why?

Optional experiments:

(7) Change the magnet configuration to align the field perpendicular to the film plane and repeat the MR measurement. Do you see a difference and why? Note that the GMR effect is *intrinsically* isotropic, i.e. independent of the measurement geometry.
(8) Use the electromagnet for the Zeeman experiment to allow a more controlled variation of magnetic field and repeat the MR measurement.

References

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