Giant Magnetoresistance

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I. Introduction

Giant magnetoresistance (GMR) was discovered in 1986 in magnetic multilayers. These structures had thin metallic layers that alternated magnetic and nonmagnetic materials, such as Fe (magnetic) and Cr (nonmagnetic) or Co (magnetic) and Cu (nonmagnetic). Magnetoresistance refers to the change in resistance as a magnetic field is applied, typically expressed as a percentage. Previous to the discovery of GMR, the largest known magnetoresistance values were a fraction of one percent. With the magnetic multilayer structures, resistance could decrease by more than 50% in a magnetic field. Even spin valves, which consist of only two magnetic layers separated by one nonmagnetic conductive layer, could achieve magnetoresistance values of greater than 10%. Due to the unprecedented large magnetoresistance values, this phenomenon was called “giant magnetoresistance.”

Within less than a decade, a very short time from discovery to market, GMR devices were incorporated into products as magnetic field sensors. Spin valves had a major impact on hard disk drives, since the large increase in the sensitivity allowed the magnetic bits on the hard drive to be much smaller, resulting in more compact high capacity drives. Spin valves are also being researched for potential application as bits in magnetic random access memory (MRAM).

GMR originates from the fact that electrons have a magnetic moment called spin. Electrons in a magnetic material experience a different resistance depending on whether their spin is aligned parallel (up) or anti-parallel (down) to the magnetization of the material. This is a consequence of the different density of states for up- and down-spin electrons, and requires solid state physics for an explanation. Typically, up-spin electrons experience less scattering and therefore a lower resistance than down-spin electrons.

A spin valve, which has two narrowly separated magnetic layers, will have a different resistance depending on whether the magnetizations of the two magnetic layers are parallel or anti-parallel to each other. When the layers are aligned parallel, the up-spin electrons can easily conduct through the entire material, resulting in a low resistance state. When the layers are anti-parallel, both up-spin and down-spin electrons scatter heavily at different parts of the spin valve, resulting in a state with an overall higher resistance. A simple model is shown below in Figure 1:

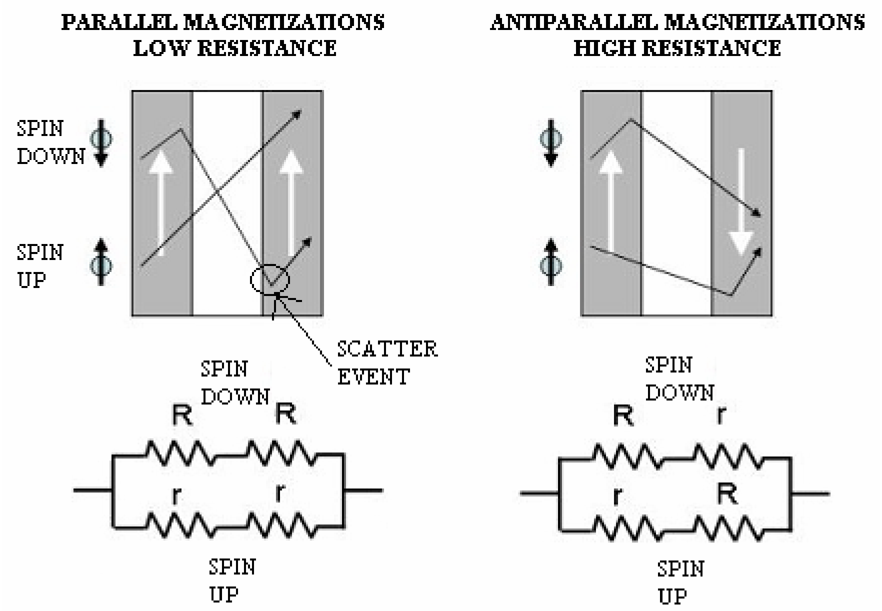


Fig.1 Schematic of a Spin Valve with parallel and anti-parallel magnetization.

An equivalent resistor network model is shown below the diagrams of the spin valves. A spin parallel to the magnetization of a layer experiences a relatively low resistance of ‘r’ and a spin anti-parallel to the layer experiences a relatively high resistance of ‘R’.

The exact structure of the spin valve we will study in lab is shown in Figure 2. These samples make use of an anti-ferromagnetic pinning layer that makes it very difficult to flip the direction of the adjacent ferromagnetic layer, i.e. the ‘pinned’ layer. The other ferromagnetic layer is the ‘free’ layer, which requires a much lower field to change the direction of its magnetization. This arrangement makes it simple to achieve parallel and anti-parallel alignment of the two layers by flipping only the ‘free’ layer.

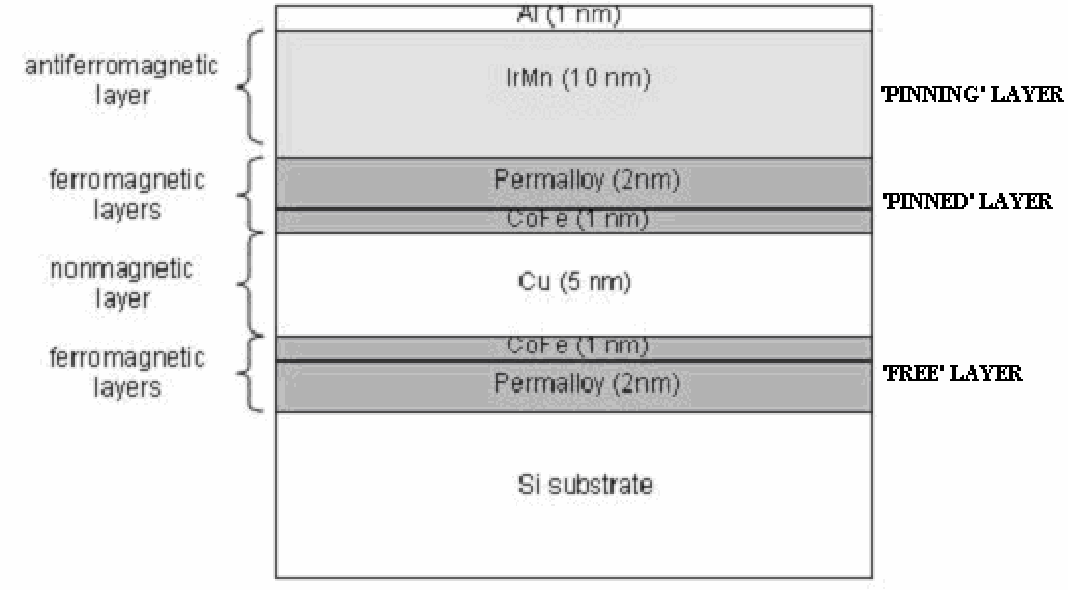


Fig.2 Schematic of a Spin Valve

It is important to mention that like any other magnetic system, a spin valve presents a hysteretic behavior. Hysteresis represents the *history* dependence of the behavior of physical systems. In a spin valve, when you cycle an applied magnetic field its magnetization goes through a hysteretic loop. As it can be observed in Figure 3, the magnetization curve as the field is ramped up is not the same as when the field is ramped down, this is because it takes certain amount of energy to restore a magnetized system to its original state.

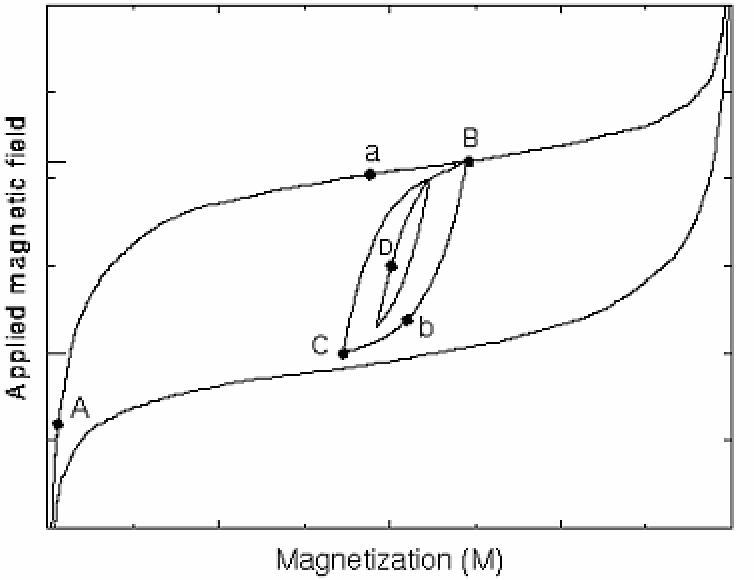
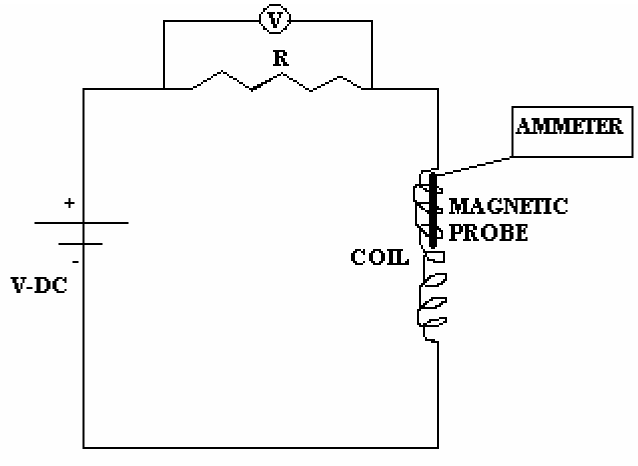


Fig. 3 Magnetization Loop with Hysteresis

II. Procedure

A. Connect the circuit



1. Connect the power source to the proto-board.
2. Connect the yellow multimeter across the ceramic resistor, measure and record its resistance R, and keep it connected.
3. Connect the coil to the proto-board.

B. Calibrate the electromagnet

1. Insert magnetic field probe so tip is in center of coil (electromagnet).
2. Record magnetic field in the center of the coil as a function of current through the coil (hint, what is the current through the resistor?) at over a wide range of current and magnetic field values. Note that the probe measures a field at no applied voltage highly dependent on its orientation (can you think of why?), make sure it remains in the same direction for the whole calibration.
3. The dial on the magnetic field probe has units of amperes. The probe is calibrated so that 1 A corresponds to 1 gauss. Record your magnetic field data in gauss.
4. Plot the magnetic field as a function of current through the coil. Using Excel find a linear fit to your data and record the equation so that you can determine the magnetic field in your coil for a given current through it.
5. Print one plot for each lab partner.

C. Test run

1. Remove the magnetic field probe and insert the sample (spin valve) in the center of the coil.
2. Connect the spin valve leads to the orange multimeter and measure the resistance of the sample at no applied voltage.

3. Increase the voltage of the power supply to the coil to its maximum setting. Note the resistance of your sample. Note the maximum current the power supply can generate through the coil.
4. Decrease the voltage of the power supply until you reach the minimum setting. Note the resistance of your sample.
5. Switch the leads on your power supply so that the current will run the opposite direction through the coil (this reverses the direction of the magnetic field).
6. Increase the voltage of the power supply to the coil to its maximum setting. Note the resistance of your sample.
7. Decrease the voltage of the power supply until you reach the minimum setting. Note the resistance of your sample.
8. Discuss the resistance data with your lab partner. At what point did the magnetic layers have their magnetizations in parallel alignment? Anti-parallel alignment?

D. Measure magnetoresistance

1. Switch the leads on your power supply back to what they were at the start of your test run.
2. Based on the maximum current the power supply can generate through the coil, decide how much you will change the current between each data point.
3. Repeat the same sequence that you did for the test run (start from zero applied field, increase field, decrease field, switch leads, increase field, decrease field) while recording the resistance of your sample as a function of current through the coil at regular intervals.
4. Enter your data into a spreadsheet. Convert current through the coil to magnetic field in the coil. Plot resistance of your sample as a function of magnetic field separating the data for the ramp-up and ramp-down. Connect the data points with a line to better observe the hysteresis loop.
5. Print one copy of the data and one plot for each lab partner.

III. Analysis

1. Attach the calibration plot for your electromagnet to your lab report. What is the equation to convert current to Gauss?
2. Attach the magnetoresistance plot for your sample to your lab report. Put arrows on your plot to indicate the direction of the field change for each segment. Label segments of your data where the magnetic layers have parallel alignment and where they have antiparallel alignment.
3. Why does the GMR curve differ for increasing applied magnetic field and decreasing applied magnetic field?
4. Calculate the giant magnetoresistance ratio for your sample by dividing the maximum change in resistance by the average resistance. How does it compare to a typical spin valve GMR of 5% for read heads?
5. Spin valves are used in read heads to sense the direction of magnetization of individual bits on hard disk drives. What is the minimum magnetic field a bit must exert on your spin valve to completely flip the free magnetic layer? What is the ratio of this switching field to the Earth's magnetic field?
6. Spin valves are also being developed for use as memory elements in magnetic random access memory (MRAM). The parallel and antiparallel states compose a two-state system that can encode "0" or "1." Describe how you would both read (i.e. detect the state) and write (i.e. change the state) to a spin valve memory element.
7. If your sample was missing the IrMn layer, would you still expect to see the GMR effect? Explain why or why not.