Electron Transport Properties in Cobalt/Copper Nanowires

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With the goal of eventually observing current-induced switching in cobalt/copper nanowires, we begin by electrodepositing cobalt into polycarbonate membranes to create simple wires of 200nm diameter. We confirm the validity of these samples using anisotropic magnetoresistance (AMR), thereby demonstrating the success of our sample creation methods. This is followed by preliminary steps toward the creation of simple layered Co/Cu wires for the observation of giant magnetoresistance (GMR). Finally, we describe current-induced switching and some of its potential technological applications.

I. Introduction

Electron transport properties found only in micrometer- to nanometer-scale magnetic structures have recently prompted much research interest, motivated both by the unique physics of these systems and by the promise of future applications to magnetic recording technology [1-4]. Current-induced switching, an effect observable only in nanoscale magnetic materials of a particular geometry, seems particularly promising as a method of drastically improving magnetic random access memory (MRAM). To control current MRAM bits, current pulses are sent through two lines, a read and a write line. In a typical write operation the magnetic field associated with the current pulse will switch the bit's magnetization. However, this method demands both relatively high power and low bit density, as magnetic fields are difficult to limit in extent and may cause false writes as nearby bits are switched along with the target. The hope is that current-induced switching, in which the current itself is used to write the bit, could improve MRAM density, reduce errors, and even simplify the production process by cutting the required lead number in half.

Our goal, then, is to create cobalt/copper nanowires which will display this current-induced switching effect, and may act as a prototype for such improved magnetic memory.

Current-induced switching occurs in structures of a specific geometry, as in Fig. 1. A thicker cobalt (ferromagnetic) layer is separated from a thinner layer by a spacer of copper. If the copper layer is thin enough the two cobalt layers will be aligned or antialigned based on the RKKY interaction (an oscillatory function), but although antialignment would be ideal for our study its achievement is difficult in practice. We instead aim for a copper spacer thick enough to ensure that the layers are decoupled, with their magnetizations randomly aligned in zero fields.

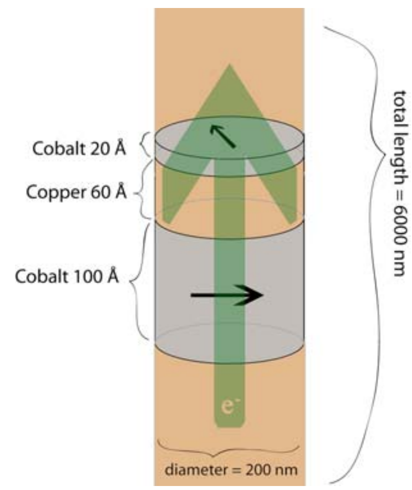


Fig.1: Current-induced switching in a Co/Cu wire. The upper cobalt layer will align with the lower if the current density is high enough.

A current is passed through the wire such that electrons flow from the thick cobalt layer to the thin. As the current passes through the thick layer it gains an overall spin-polarization. Although the electrons would lose this polarization if the following copper spacer were thicker than copper's characteristic spin diffusion length, at a scale such as this they should retain their polarization. Thus, when these electrons strike the upper cobalt layer they will transfer angular momentum, exerting a torque on the thin cobalt layer which - provided we utilize a high enough current density - will cause it to flip its magnetization.

When the two cobalt layers align, the resistance through the wire drops. Fewer conduction electrons are scattered by a ferromagnetic layer whose magnetization matches their polarization, and the associated change observed in the resistance of the wire should provide clear proof of this effect. Furthermore, a system with two clearly defined resistance states naturally lends itself to use as a bit. As change is induced by current alone, such bits could be placed extremely close together without concern over miswrites.

Current-induced switching has already been demonstrated in structures of a fundamentally similar geometry, but in most cases the production method (usually e-beam lithography) was both difficult and slow [1-4]. Our hope is that electrodeposition can be used to demonstrate this effect more easily, and provide a greater number of samples for further investigation into the mechanisms of magnetic reversal.

II. Sample Preparation

The nanowires used for this study were electrodeposited, layer by layer, into the pores of a Nucleopore® polycarbonate membrane. These mass-produced films have a density of 3×10^{8} pores/cm^{2}, and are highly regular. A sample begins with one of these films, coated with sputtered copper on one side to seal the pores. Once the pores are watertight, we use a simple electrodeposition method to fill the pores with the desired layers (see Fig. 2). A voltage difference is applied to an electrolyte containing both copper and cobalt ions in solution, and the ions are attracted down into the membrane pores in an effort to contact the negative electrode. Although the solution contains both ions, copper begins to deposit at a lower absolute voltage than cobalt, allowing us to control the composition of the layers (Note that although copper is always depositing as we deposit cobalt, its concentration in the solution is so low that the impurities caused are negligible – see Ref. 5).

Once the pores are filled, we cap the sample with sputtered copper to ensure good contact with the wires, and slice the membrane into ~0.5 cm^{2} pieces. We then paint perpendicular cross-leads on the sample using silver paint, which acts as a mask in KI-I and HCl etches.

Once the copper has been removed from both sides of the sample except for at the cross-leads

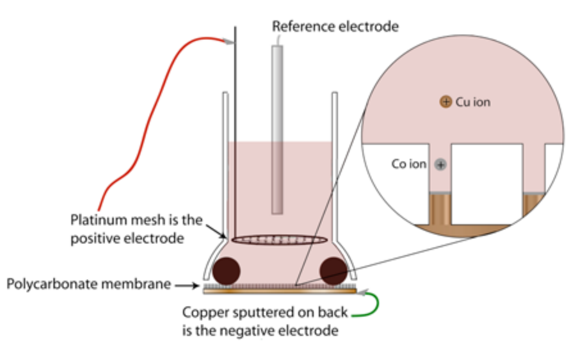


Fig.2: Electrodeposition apparatus. Cobalt or copper ions fill the pores depending on the applied voltage [5].

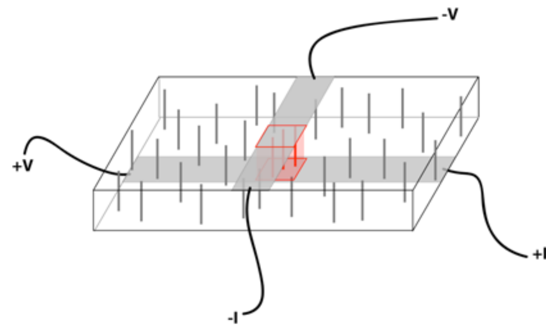


Fig.3: Silver cross-leads on a sample. Only the center wires (red area) conduct through.

(see Fig. 3), only the wires contained in the center cross-section will conduct through. Since too many wires in parallel will not demonstrate any appreciable resistance, we use this method to limit the number of conducting wires and enable the observation of resistive effects. Once the film is etched we attach small platinum wires as leads, allowing for four-point resistance measurements.

III. Results

Instead of attempting to create current-switching samples immediately, we took a piecewise approach to sample fabrication and analysis, beginning with simple cobalt-only nanowires. We aimed to confirm the success of our fabrication process and to check whether current was passing through our wires as expected. If so, we should observe clear anisotropic magnetoresistance (AMR).

AMR is change in the resistance of a sample depending on the relative orientation of the magnetization to the current [6, 7]. In practice, this means that if we apply a strong enough magnetic field parallel to the wire we can observe an increase in resistance; perpendicular to it the opposite will occur. This is due to spin-orbit coupling, causing the 3d electron clouds of the cobalt atoms in the wire to deform (see Fig. 4), and changing the scattering cross-section and the resistance accordingly. AMR is a small effect

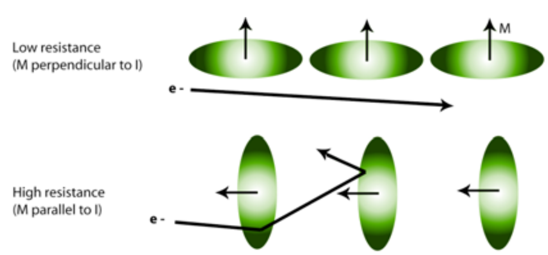


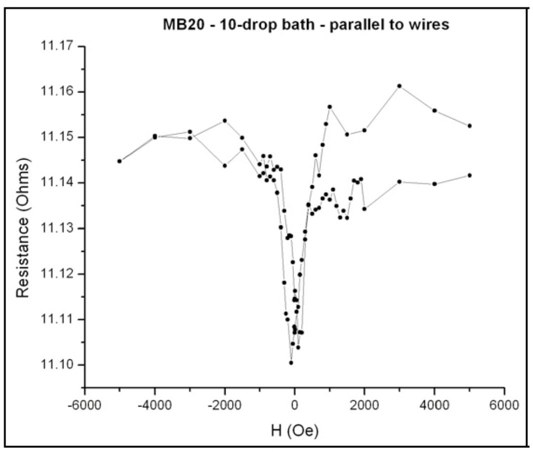
Fig.4: 3d orbitals of cobalt atoms in the wire distort when a magnetic field is applied, changing the scattering cross-section for the conduction electrons and affecting the resistance of the sample [6].

(usually less than 2% change), but is clearly observable in the data seen in Figure 5, which is from a recent cobalt-only sample.

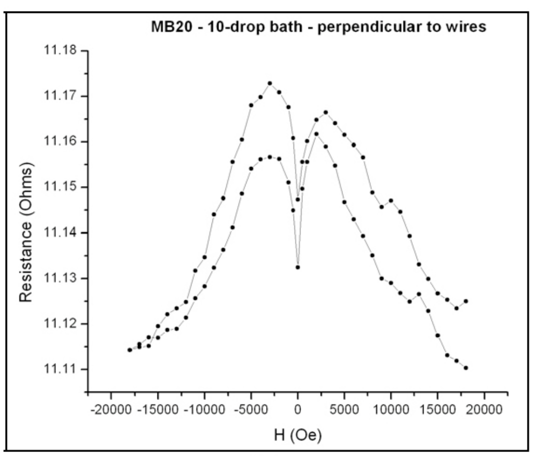
IV. Further Work and Applications

The next step towards current-induced switching, the creation of multilayered wires and the associated observation of giant magnetoresistance (GMR), is currently in progress. We have created wires consisting of 400 Co(50Å)/Cu(70Å) bilayers, and are currently attempting to observe GMR in those samples. GMR is an extension of the resistance change effect described above in relation to current-induced switching. For electrons passing through many ferromagnetic layers, the resistance encountered will directly depend on the relative orientation of the layers; if a magnetic field is applied, we will align all layers and thus expect a resistance drop. This effect is approximately two orders of magnitude greater than AMR in most cases, and should be clear once the proper geometry is achieved.

Finally, we hope to observe current-induced switching in Co/Cu samples created using our electrodeposition method. In addition to being a fast and repeatable way of creating this nanoscale geometry, we hope to use it to observe the reversal mechanisms of the thin cobalt layer. Although most nanoscale ferromagnets switch magnetization through simple coherent reversal, in some cases a more complex vortex state emerges, in which a center perpendicular-to-plane core nucleates and the rest of the moments in the sample circle around it. The core then moves across the disk, finally resulting in magnetization reversal. Current-induced switching samples could offer a simple way of exploring this effect, as well as possibly leading to future improvements in MRAM.



(a)



(b)

Fig.5: Anisotropic magnetoresistance is clearly visible in these plots of the resistance with respect to applied field. In (a) the field is applied parallel to the nanowires, causing the cobalt atoms' 3d electron clouds to distort and leading to an increase in the observed scattering cross-section for the conduction electrons. Resistance correspondingly increases at higher applied fields.
In (b) the field is applied perpendicular to the wires, leading to a drop in resistance. The unexplained drop in resistance at zero field may be due to imperfect alignment of the sample with respect to field. In both cases the effect is small, ~0.5%.

V. Acknowledgements

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[1] E.B. Meyers, D.C. Ralph, J.A. Katine, R.N. Louie, and R.A. Buhrman, *Science* **285**, 867 (1999).
[2] J.A. Katine, F.J. Albert, and R.A. Buhrman, *Applied Physics Letters* **76**, 354 (2000).
[3] F.J. Albert, J.A. Katine, and R.A. Buhrman, *Applied Physics Letters* **77**, 3809 (2000).
[4] J.A. Katine, F.J. Albert, R.A. Buhrman, E.B. Meyers, and D.C. Ralph. *Physical Review Letters* **84**, 3149 (2000).
[5] Kai Liu, "Magnetism and Magneto-Transport in Systems with Different Dimensions." Ph.D. dissertation, Johns Hopkins University, 1998.
[6] Nicola Spaldin, "Magnetic Materials: Fundamentals and Device Applications." Cambridge University Press, 2003.
[7] Stephen Blundell, "Magnetism in Condensed Matter." Oxford University Press, 2001.