Magnetoresistance in 10-15 Ni Nanowires

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The resistance of 10-15 nm Ni nanowires was measured as a function of a changing external magnetic field. The use of carbon nanotube rope templates enables the fabrication of these narrow wires without losing continuity between the electrodes and the wire in the each sample. Some evidence of Domain Wall Magnetoresistance was observed, as expected, however, the magnitude of these resistive effects was not considered large enough to be significant for technological applications. Interestingly, an unexpected decrease in resistance was discovered, which could be due to a gross misalignment of the axis of easy magnetization of the wires.

Over the past few decades, the impending need for smaller storage devices has led to a growing interest in the magnetoresistance of nanostructures. Domain Wall Magnetoresistance (DWMR) has been of particular interest in both Co and Ni. Although plenty of work has been done on DWMR in these metals[1-7], there is disagreement on the magnitude of the DWMR. In 35nm Co wires a 0.1%-0.3% increase in the resistance due to DWMR has been observed[6], however, Ni wires of that size displayed only the effects of Anisotropic Magnetoresistance (AMR)[7]. No work has actually been done with Ni wires that might be small enough to actually have DWMR. Nevertheless, stunning results have been obtained by electrodepositing Ni to create nanocontacts of diameter 10-30nm[7]. The magnetoresistance of the Ni is reported to be of 20%, although it is not clear whether this is due to constrained domain walls or mechanical effects triggered by the magnetization of the sample. Therefore the increase in resistance could be due to magnetorestriction or dipole to dipole interactions between the nanocontacts that open and close the circuit. This result must therefore be verified using other methods of fabrication.

Our samples consist of 10-15 nm Ni wires that lay across a trench between two Nickel leads. The use of carbon nanotube templates and photo-lithography, allows the samples to be narrow enough for the effects of domain walls to be observed. The process of fabrication also provides nanocontacts between the wire and the electrodes that are unambiguously continuous.

The samples are made on a layered wafer of Silicon, Silicon Oxide and Silicon Nitride, with a 70 nm trench cutting through the center of the Silicon Nitride layer. Each blank chip is covered with a layer of photoresist, which is removed with acetone and methanol. An undercut is created in the part of the Silicon Oxide layer that surrounds the trench using Hydrofluoric acid. This prevents the nickel that is later evaporated onto the sample from forming a continuous film through the trench. Carbon nanotube ropes are then deposited on the chip using an optimized sonicated solution of Ethylene Dichloride and tubes. The concentration of the solution allows for the highest probability of there being single ropes across the trench for each lead pair that will be created. These ropes are then used as templates for the creation of nanowires as 10 nm of Ni are evaporated onto the chip using a thermal evaporator at 10^{-7} Torr. During the evaporation process magnets are placed at either end of the chip such that there is a field perpendicular to the trench, which should encourage the easy axis of magnetization of the wires to be along the wire. Photolithography is then used to create a pattern of approximately 20 lead pairs perpendicular to the trench. A layer of photoresist is spun onto the chip, and then a mask aligner is used to expose the parts of the chip where Ni is not wanted to UV light. The pattern is developed and the unwanted Ni is removed using nickel etchant. The final step in the process of fabrication is to remove the remaining photoresist using acetone.

Although some initial experimentation was performed at room temperature, the results in this paper were taken at 4.3 K, using a Helium dunker. The advantages of cooling the samples are threefold. First of all, the superconducting electromagnet in the Dunker enables us to reach the saturation field of the wires. Secondly, the lower temperature reduces the noise due to thermal agitation. Finally, reducing the temperature increases the resistive effects of any domain walls in the samples. In order to make the process of data collection as smooth as possible, a program was designed using Labview. The program controls the external magnetic field that the samples are subjected to by varying an output voltage. The program records the resistance of the sample at discrete intervals throughout a sweep from magnetic saturation field in one direction through to saturation in the opposite direction. The software has two modes that can be used for calculating the resistance. The first is a dc mode in which a constant current is sent across the sample, the second is an ac mode in which a Lock-in amplifier is used to send an alternating current of a constant frequency across the sample. In both cases the voltage across the sample is amplified, filtered, and sent to the program, which calculates the resistance of the wire in the ohmic region. The apparatus allows for the wire to be either perpendicular to the external field or parallel to the field.

Although wire bonds from the chip carrier to the leads were made as close to the trench as possible, the leads inevitably contribute to the resistance of the sample. In order to be able to isolate the behavior of the wires from that of the entire chip, the resistance of the leads was first measured from the saturation field of the wire in one direction to the saturation field of the wire in the other direction (see Fig.1). The resistance was found to remain constant throughout the sweep, except for a peak at the coercive field of the leads, which occurred at magnitudes of less than 100 Oe. The resistance of the leads displays

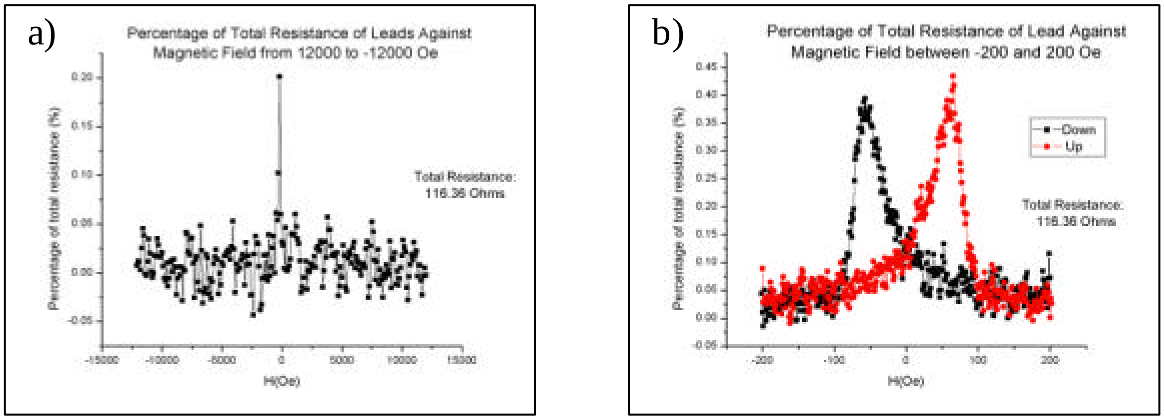

Figure 1 (a) Graph of resistance of leads against external magnetic field for a sweep from saturation field of average wire in positive direction to saturation field in negative direction. (b) Hysteresis of leads between 200 and -200 Oe.

hysteresis when the magnetic field is run up and down. The peaks that are observed in Fig. 1(b) are due to the AMR that occurs when the magnetization in the leads switches direction. Since these measurements where made with the leads perpendicular to external field, when each individual domain is rotating it becomes parallel to the current flowing through the lead, which causes an increase in resistance[8].

The wires that have been measured so far in both the perpendicular and parallel configurations all display a reduction in the resistance around the zero field that encompasses a range of anywhere from 2000 Oe to 10,000 Oe (see Fig. 2). These dips in the graph are not due to the AMR of the leads, which is restricted to absolute magnetic fields below 100 Oe. If the axis of easy magnetization is indeed along the wire, then it could not be due to the AMR of the wire either, since it should cause an increase in the resistance.

The wires that have been tested so far are not perpendicular to the trench. This means that regardless of the configuration of the setup, the current at the saturation field will be at an angle smaller than 90 degrees but larger than 0 degrees. Therefore, in every sweep, the AMR of the sample starts and finishes in an intermediate state in which the resistance due to the AMR can be expected to be neither at its highest or its lowest.

If the AMR is the cause of the dip, then the axis of easy magnetization should be perpendicular to the wire. When the external field is reduced from saturation, there is a point somewhere in the range of 1000 Oe to 5000 Oe at which the constricted nature of the wire causes the domains in the wire to align with the axis of easy magnetization rather than the external field because this position is energetically more favorable. If the axis of easy magnetization is perpendicular to the wire, then the AMR would be expected to drop to its minimum value when all of the domains in the wire are perpendicular to the current flowing through the wire. This could explain a minimum such as the one observes in Fig. 2. To confirm the validity of this explanation, the axis of easy magnetization must be determined using Magnetic Force Microscopy.

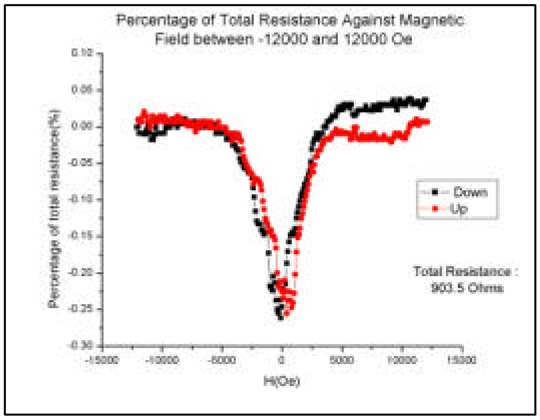

Figure 2 Graph of resistance of sample against external magnetic field, displaying wide dip between 5000 Oe and -5000 Oe in both directions.

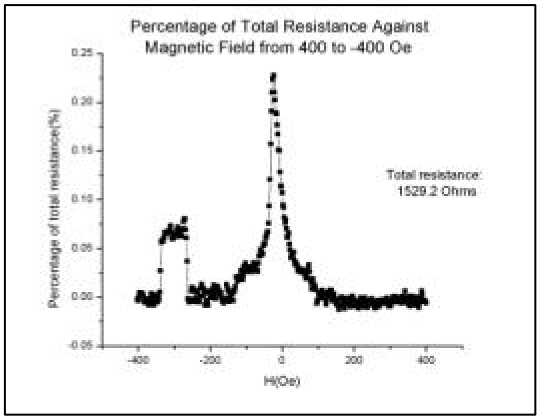

Figure 3 Graph of resistance against external field. The central peak is thought to be due to the AMR of the leads. The plateau on the left could be due to a domain wall.

In one sample signs of domain walls were found. The data recorded was repeatable in that wire, but could not be observed in any other sample. Fig. 3 shows a sweep in which two increases in resistance are seen. The first is a peak around 100 Oe, which is due to the AMR of the leads. The second is a plateau that looks very much like the kind of increase that domain walls cause in wires. Assuming that the increase of the resistance is due only to domain walls throughout the wire, then the effect of these domain walls is only of 0.3%, much smaller than the effects observed by others.

Current work is based on using wires that are as close to being perpendicular to the trench as possible. Using these wires makes the system less complicated because of the symmetry. The configuration of the current and external magnetic field is also being alternated between parallel and perpendicular in order to differentiate between behaviors that are orientation dependent when the wires are perpendicular to the trench.

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[1] J. F. Gregg et al., Phys, Rev. Lett. **77**, 1580 (1996)

[2] M Viret et al., Phys. Rev. B **53**, 8464 (1996)

[3] D. Ravelosona et al., Phys. Rev. B **59,** 4322 (1999)

[4] U. Rudiger et al., Phys. Rev. B, **59**, 11914 (1999)

[5] S. G. Kim et al. IEEE Trans Magn, **35**, 2862 (1999)

[6] U. Ebels, A. Radulescu, Y. Henry, L. Piraux, and K. Ounadjela, Phys. Rev. Lett. **84**, 983 (2000)

[7] N. Garcia, M. Munoz, G. G. Qian, H. Rohrer, I. G. Saveliev, and Y. W. Zhao, Appl. Phys. Lett. **79**, 4550 (2001)

[?] R. C. O' Handley, *Modern Magnetic Materials: Principles and Applications*, John Whiley & Sons, p 573-584 (2000)