METROLOGY AND MEASUREMENT SYSTEMS
VOL. XV, NUMBER 2 (2008)

GHOLAMREZA NABIYOUNI

University of Arak
Department of Physics, Iran
e-mail: g-nabiyouni@araku.ac.ir

GIANT MAGNETORESISCANCE IN SPINTRONIC CO/PT NANOWIRE STRUCTURES

We used electrodeposition for growing of pure metallic, alloy and multilayer nanowires. Electrodeposition of cobalt/platinum nanowires was achieved in the cylindrical pores of a commercially available nuclear tracked polycarbonate membrane. In order to make an ohmic contact, prior to electrodeposition one side (the back one) of the membranes was coated with gold, using a simple evaporation technique. An assembly of nanowires with an average diameter of 80 nm and a length of 6 microns was achieved. Our multilayer nanowires were grown from an electrolyte containing Co^{2+} and Pt^{2+} ions.

The samples were then characterized using scanning and transmission electron microscopy. The selected area diffraction patterns of the wires showed that the growth is polycrystalline, though the measured grain size was relatively large [1]. Magnetic properties of the nanowires were studied using vibrating sample magnetometry (VSM). Resistivity of the Co/Pt multilayer nanowires then was measured as a function of applied magnetic field in both parallel and perpendicular to the nanowire growth directions. The samples clearly exhibit a giant magnetoresistance (GMR) effect which can be explained in terms of spin-dependent scattering phenomena. The results are of particular interest since they promise potential devices for nano-magnetic sensors, especially devices based on spintronic materials [2, 3, 4].

1. INTRODUCTION

Electrodeposition is a simple technique for the fabrication of quantum dots, nanowires and thin films. It can be carried out at ambient temperature and pressure, and therefore requires much less complex apparatus than vacuum-based techniques such as molecular beam epitaxy, sputtering, chemical vapour deposition, or evaporation. Electrodeposition usually takes place in a single or double cell containing a solution (electrolyte) and two or three electrodes. The electrode is a conducting material, usually a metal or a semiconductor, in which charge is carried by electron movement and it may be a solid or a liquid. The electrolyte is a conducting medium, usually a liquid or a fused salt solution, in which charge is carried by the movement of ions. Figure 1 shows the schematic diagram of a three-electrode electrodeposition cell connected to

a computer-controlled potentiostat. A schematic diagram for a gold-coated membrane (ready for electrodeposition) is illustrated in Fig. 2.

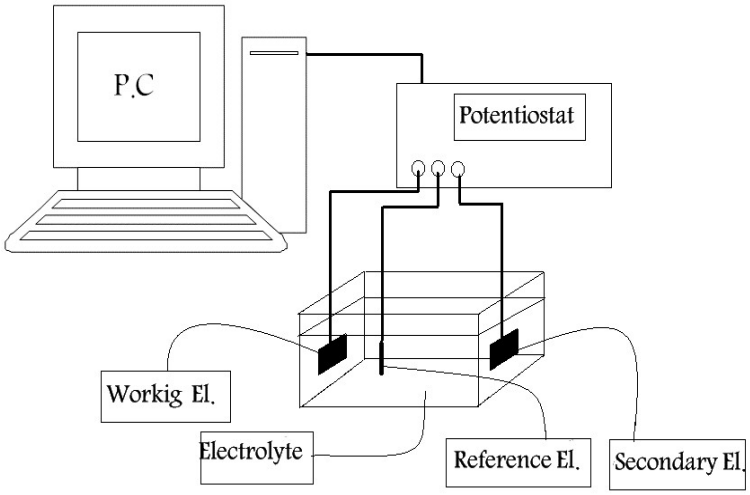

Fig. 1. Experimental set-up for electrodeposition of multilayer nanowires.

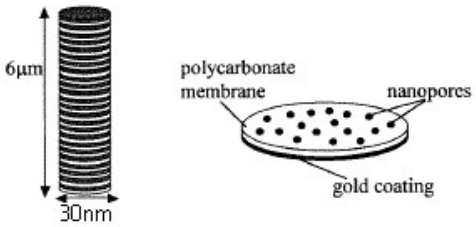

Fig. 2. Schematic diagram of a gold-coated (on the back side) polycarbonate membrane.

Among the different deposition techniques, electrodeposition has also the advantage of being a selective method: when a conducting substrate is covered by a patterned resist layer, deposition occurs only where the substrate is exposed. This is particularly important for high-aspect ratio features, because deposition on the resist, which is unavoidable e.g. in the case of metal evaporation, could easily block them. We took advantage of the selectivity of electrodeposition to prepare Co/Pt multilayers in nanoporous track-etched polycarbonate membranes, producing multilayered nanowires with diameters of a few tens of nm and lengths of several μm. Since the layering was

perpendicular to the long-axis of the wires, it was possible to measure the current-perpendicular-to-plane giant magnetoresistance (CPP-GMR).

2. EXPERIMENTS

A single electrolyte containing Co and Pt ions was used for this study. The electrolyte contained 0.5 mol Ni sulphate ($CoSo_4$), 0.01 mol hydrogen hexachloro platinic (IV) hexahydrate; ($H_2(PtCl_6)$, $6H_2O$), and 0.49 mol boric acid (H_3BO_3) per litre of purified water, and was adjusted to pH = 2 using sulfuric acid. Since Pt is the more noble metal, it was present at low concentration in the electrolyte, and Co at high concentration. Applying an appropriate external negative potential to the polycarbonate membrane leads to fill the membrane hole by Co and Pt atoms and make Co/Pt alloys or nanowires. At the less negative potential, e.g. -0.15V, only Pt which is more noble will deposit, while applying the more negative potential, e.g. -1.75V, leads to deposit the less noble metal (Co) [5]. Switching the potential between -0.15 and -1.75V makes it possible to grow magnetic multilayer nanowires. All potentials are quoted relative to a saturated calomel reference electrode [6]. The substrates used to fabricate the nanowires were nanoporous polycarbonate membranes. In order to use the polycarbonate membrane as a WE, one side of the membrane had to have an electrical contact. This was achieved by coating a good conductor such as gold on the shiny side of the membrane. Deposition was carried out at room temperature in a three-electrode cell, using a potentiostat controlled by a computer. A large number of Co/Pt multilayered nanowires were then deposited within the pores of the masked membranes under different deposition conditions.

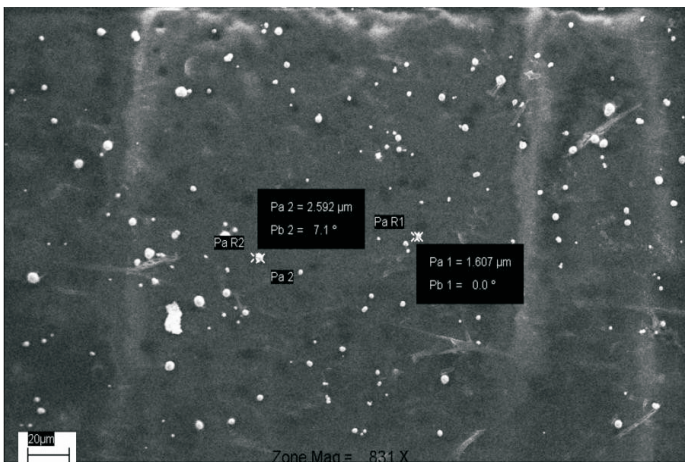

Fig. 3. SEM image of a polycarbonate membrane filled with nanowire.

The samples were then characterized using scanning electron microscopy. The nominal thickness of the wires is fixed to 8μm rather than actual membrane hole depths (6μm), so after filling the membrane holes the Co/Pt multilayers continue to grow and make some islands on the top side of polycarbonate membranes. Figure 3 shows the SEM image of a polycarbonate membrane filled with Co/Pt nanowires. The estimated grown wire density is less than the membrane pore density given by the supplier company. One possible reason for this discrepancy could be due to the fact that some membrane holes were being reblocked after exposing to α particles.

In order to take TEM images, the filled nanoporous polycarbonate membrane was then dissolved in a chloroform solution while the Co/Pt nanowires deposited at the bottom of chloroform container. A drop taken from this solution is placed on a carbon-coated TEM mesh grid, then it is ready for image taking. The selected area diffraction patterns of the wires showed that the growth is polycrystalline, though the measured grain size was relatively large. Figure 4 gives a TEM image of a Co/Pt nanowire. The measured nanowire lengths are rather smaller than the membrane thickness, suggesting that the nanowires probably have been broken during the TEM sample preparation. The nanowire diameters are also bigger than what the polycarbonate membrane supplier company gives for membrane hole diameters.

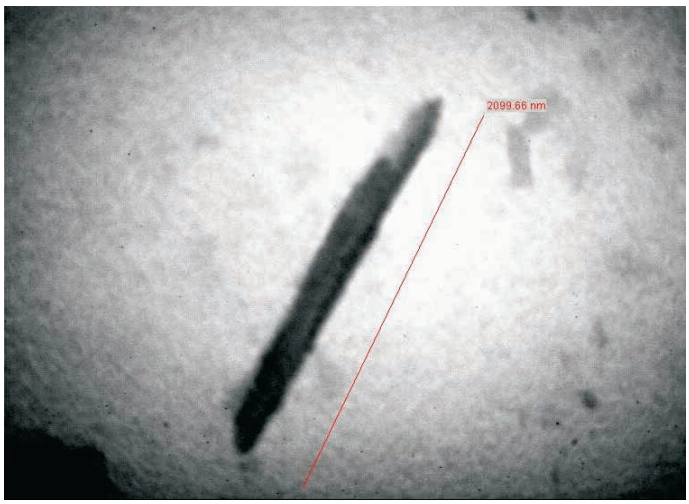

Fig. 4. TEM image of an electrodeposited nanowire.

Magnetic properties of the nanowires were studied using vibrating sample magnetomerty (VSM). Figure 5 shows a hysteresis loop of a pure Co nanowire and Fig. 6 gives a hysteresis loop for a Co/Pt nanowire. In both cases the magnetic field is applied perpendicularly to the nanowire lengths.

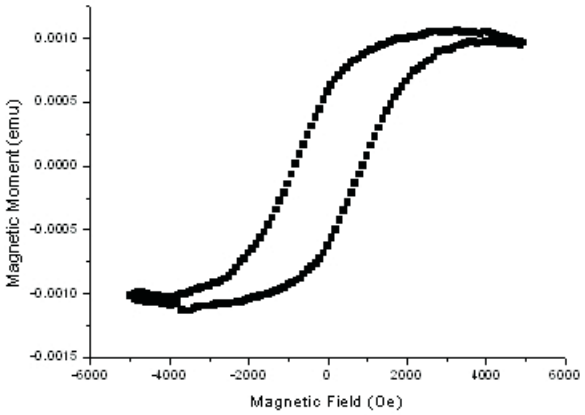

Fig. 5. A hysteresis loop of a Co nanowire.

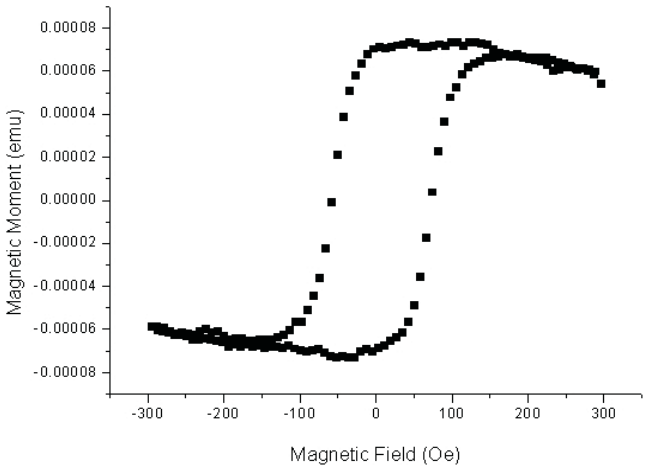

Fig. 6. A hysteresis loop of a Co/Pt nanowire.

In order to investigate the variation of nanowire resistivity as a function of the applied magnetic field and to study the magnetoresistance effect, the Co/Pt nanowire resistivities were measured as follows: A constant DC current (1mA) passes through the nanowire (in their length direction) and the potential difference between two sides of the membrane was measured. The ratio of voltage to current gives a quantity which is directly proportional to the nanowire resistivity. The Co/Pt-filled membranes then were located in a magnetic field supplied by a DC electromagnet. The applied magnetic field (which is varied between ±2000 Oe) is parallel to membrane surface and perpendicular to the nanowire lengths. The giant magnetoresistance (GMR) is defined as [7]:

$$GMR\% = \frac{R(H) - R(H_{\max})}{R(H_{\max})} \times 100,$$

where R is what we call the nanowire resistance (V/I), and H is the applied magnetic field intensity.

In this work we have grown a series of Co/Pt multilayer nanowires. The Co thickness in each bilayer has been kept constant at 5nm, while the Pt thickness was varied between 1 and 5nm. We have obtained a maximum GMR value of 6% for a multilayer nanowire consisting of several thousands of Co(5nm)/Pt(2nm) bilayers. The result is presented in Fig. 7.

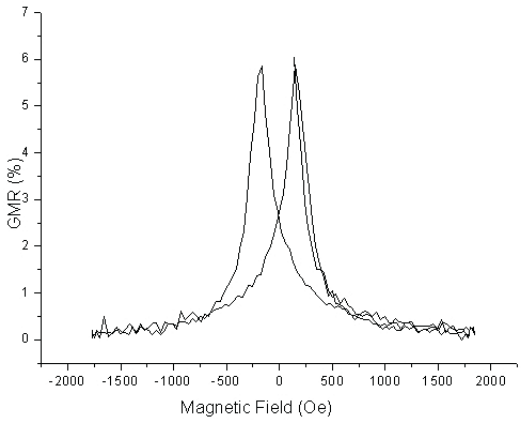

Fig. 7. Percentage change in the giant magnetoresistance as a function of magnetic field for a Co/Pt nanowire.

3. DISCUSSION AND CONCLUSION

It is well known that the resistivity of metals is caused by scattering of conduction electrons. The amount of scattering and hence the resistivity is related to whether the scattered electrons are spin-moment-up (majority spin) or spin-moment-down (minority spin) i.e. whether their spin moments are parallel or antiparallel to the magnetization. Electric current is carried by both spin-moment-up and spin-moment-down electrons which may be considered as moving in two different channels with associated resistivity of $\rho_\uparrow$ and $\rho_\downarrow$ respectively. The total current is therefore the sum of the currents carried by spin-moment-up and spin-moment-down electrons. In non-magnetic metals, the two currents and hence the resistivities of the two channels are equal, but in ferromagnetic metals and magnetic multilayers they are different.

$$\rho = \frac{\rho_\uparrow \rho_\downarrow}{\rho_\uparrow + \rho_\downarrow}.$$

It is generally accepted that GMR arises from spin-dependent scattering with electrons of one spin moment scattered more strongly than those of the other. The fact that for the ferromagnetic transition metals the spin-moment-down electrons (minority spins) are usually scattered more strongly than the spin-moment-up electrons (majority spins), can be understood in term of the density of states at the Fermi level [8]. In non-magnetic metals and in the absence of an external magnetic field, the densities of states for spin-moment-up and spin-moment-down electrons are equal. Application of a magnetic field splits the spin moment up and spin moment down bands. In ferromagnetic metals, however, the spin-moment-up and spin-moment-down bands are split due to the local magnetization, and the result is an asymmetry between the scattering of majority-and minority-spin conduction electrons. The spin-moment-down electrons have more unoccupied d states available to be scattered into, than the spin moment up electrons, and hence they are scattered more strongly than the spin-moment-up electrons [9].

The resistivity of a magnetic multilayer for each conduction channel (spin moment up or spin moment down) depends on the relative alignment of the magnetizations of neighbouring layers. If the magnetizations of successive magnetic layers are antiparallel, each spin moment direction is alternately strongly scattered when the spin moment direction and the magnetization are antiparallel, and weakly scattered when the spin moment direction and the magnetization are parallel. The effective resistivity of two successive ferromagnetic layers in an antiparallel configuration can be written as:

$$\frac{1}{\rho} = \frac{1}{\rho_\uparrow + \rho_\downarrow} + \frac{1}{\rho_\downarrow + \rho_\uparrow},$$

so $\rho \sim \rho_\downarrow/2$ (assuming $\rho_\uparrow \ll \rho_\downarrow$) which is still large. If the magnetizations of successive layers in the multilayer specimen are parallel (due to application of a magnetic field), spin-moment-up electrons are hardly scattered whereas spin-moment-down electrons

are very strongly scattered. Thus the effective resistivity of successive layers in parallel alignment may be written as

$$\frac{1}{\rho} = \frac{1}{\rho_\uparrow + \rho_\uparrow} + \frac{1}{\rho_\downarrow + \rho_\downarrow},$$

so $\rho \sim 2\rho_\uparrow$ which is quite small.

Thus in magnetic multilayers, if the magnetizations of the magnetic layers are initially antiparallel to each other, the application of an external magnetic field can rearrange them to be parallel to the field and decrease the resistivity of the sample.

This is the origin of GMR, as first proposed by Baibich *et al*. [10]. The discussion is only correct if the thicknesses of the individual layers are much smaller than the mean free path of the conduction electrons. The electron mean free path for metallic (e.g. Co or Pt) thin films has been found to be about 50nm [11]. Since the Co and Pt thicknesses in our multilayer nanowire samples are only a few nanometers, it is quite possible to expect that (to some extent) antiferromagnetic coupling between two magnetic moments of the successive ferromagnetic layers has been formed, so that the application of an adequate magnetic field can realign the magnetic moments to parallel configuration and reduce the nanowire electric resistivity. However our previous work indicates that the antiferromagnetic coupling between two magnetic layers in the electrodeposited layer is only partial [11]. This might be a possible reason for the fact that GMR in electrodeposited multilayers is not so high. To the best knowledge of the author, the maximum GMR values that were ever recorded for electrodeposited multilayers are 25% and 55% for Co-Ni-Cu/Cu multilayer thin films grown on a (100)--textured polycrystalline Cu substrate [12], and Co-Cu/Cu multilayer nanowires grown into nanoporous alumina [13], respectively.

ACKNOWLEDGEMENTS

This work has been supported financially by the University of Arak, Iran, under the grant application number of 11.7227. The author would like to thank Professor Walther Schwarzacher from H. H. Wills Physics laboratory, University of Bristol, UK, since the magnetic measurements of this work have been done in his research lab.

REFERENCES

1. Kazeminezhad I., Nabiyouni G.: “Synthesis of Electrodeposited Ni-rich/Cu Multilayered Nanowires”, *Proc. of International Conference on Micro and Nano Technologies ICMNT’06*, Tizi-Ouzou, Algeria, 2006, pp. 208–209.
2. Johnson M.: “Spin injection in metals and semiconductors”, *Semicon. Sci. Technol*., no. 17, 2002, pp. 298–309.
3. Roukes M. L.: “Electronics in a spin”, *Nature*, vol. 411, 2001, pp. 747–748.
4. Awschalom D. D., Kawakami R. K.: “Teaching Magnets New Tricks”, *Nature*, vol. 408, 2000, pp. 923.

5. Brett C. M. A., Brett A. M. O.: *Electrochemistry. Principles, Methods and Applications*, Oxford University Press, NY, 2000.
6. Schwarzacher W., Lashmore D. S.: "Giant magnetoresistance in electrodeposited films", *IEEE Trans. Magn.*, vol. 32, no. 4, 1996, pp. 3133–3153.
7. Alper M., Attenborough K., Hart R., Lane S. J., Lashmore D. S., Younes C., Schwarzacher W. S.: "Giant magnetoresistance in electrodeposited superlattices", *Appl. Phys. Lett.*, vol. 63, no. 15, 1993, pp. 2144–2146.
8. Mizutani U.: *Introduction to The Electron Theory of Metals*, Cambridge University Press, 2002.
9. Buschow K. H. J., De Boer F. R.: *Physics of Magnetism and Magnetic Materials*, Kluwer Academic Publishers, 2003.
10. Baibich M. N., Broto J. M., Fert A., Nguyen Van Dau F., Petroff F., Etienne P., Creuzet G., Friedrich A., Chazelas J.: "Giant magnetoresistance of (001)Fe/(001)Cr magnetic superlattices", *Phys. Rev. Lett.*, vol. 61, no. 21, 1988, pp. 2472–2475.
11. Bozec D., Howson M. A., Hickey B. J., Shatz S., Wiser N., Tsymbal E. Y., Pettifor D. G.: "Mean free path effects on the current perpendicular to the plane magnetoresistance of magnetic multilayers", *Phys. Rev. Lett*. vol. 85, no. 6, 2000, pp. 1314–1317.
12. Nabiyouni G., Schwarzacher W.: "Dependence of GMR on crystal orientation in electrodeposited Co-Ni-Cu/Cu superlattices", *J. Magn. Magn. Mater.*, vol. 156, no. 1–3, 1996, pp. 355–356.
13. Evans P. R., Yi G., Schwarzacher W.: "Current perpendicular to plane giant magnetoresistance of multilayered nanowires electrodeposited in anodic aluminum oxide membranes", *Appl. Phys. Lett.*, vol. 76, no. 4, 2000, pp. 481–483.