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Magnetization reversal and magnetic anisotropy of Fe, Ni and Co nanowires in nanoporous alumina membranes

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ABSTRACT

The magnetization reversal and magnetic anisotropy of Fe, Ni and Co nanowires is studied at low temperatures. All nanowires show a strong shape anisotropy with the easy axis being parallel to the long axis of the wires. Co nanowires additionally show a temperature dependent magnetocrystalline anisotropy along the hexagonal c-axis, which is directed nearly perpendicular to the long axis of the wires, as is confirmed by X-Ray diffraction measurements [1] and reported by Strijkers et al. who performed NMR measurements on samples prepared in a similar way [2]. Therefore, at low temperatures and for large wire diameters a competition between magnetocrystalline and shape anisotropies can be observed. Co wires with a small diameter, however, do not show a significant magnetocrystalline anisotropy. Fcc-Co, which is only known as a high-temperature Co modification and which does not have a large magnetocrystalline anisotropy constant, becomes the predominant Co modification here [1,3]. Investigations on the size dependence of the switching field for Fe and Ni nanowires provide information about the magnetization reversal process, which takes place via a nucleation of small magnetic domains probably at the end of the wires, and subsequent propagation of the domain wall along the wire.

INTRODUCTION

Nanostructured materials are of considerable interest because of many new possible applications in different fields such as information technology, biotechnology, medicine or environmental engineering. Scientifically they are interesting because the physical properties of a material can change significantly if its lateral dimensions are reduced down to the nanometer scale. These changes can occur if the size of at least one dimension is reduced down to a regime comparable, for example to that of the DeBroglie wavelengths of electrons, the excitation wavelengths of phonons or magnons, or the domain wall width D_W as regards ferromagnetic materials. A cylindrical particle with a diameter smaller or comparable to D_W and a length that is much larger than D_W can be considered to be one-dimensional.

One-dimensional nanostructures can be built by performing chemical or electrochemical reactions in the pores of a suitable host or matrix material. As matrix material polycarbonate membranes [4], zeolites [5] or alumina membranes [6] may be used.

We chose nanoporous alumina membranes as the template material because they are easily accessible by anodic oxidation of high purity aluminum in polyprotic acids, they are chemically and physically stable and their properties (pore diameter, thickness) can be easily varied. Metals can be plated into the pores using a simple AC plating procedure.

The nanowires thus achieved can be considered as being one-dimensional if their diameter is in the order of 10-50 nm. Since the pore diameter, and therefore the wire diameter, can be varied between 5 and 250 nm by the above mentioned method the nanowires produced here fulfill this condition.

The magnetization of one-dimensional Fe, Ni and Co wires is investigated here. Fe and Ni show a strong shape anisotropy for all wire diameters and all temperatures investigated. The easy axis lies parallel to the long axis of the wire. For Co, however, there is a strong competition between the shape anisotropy and a magnetocrystalline anisotropy. This magnetocrystalline anisotropy, which is well-known for hcp-Co with an easy axis perpendicular to the long axis of the wire, can be found in pores with a rather large pore diameter at low temperatures. At increasing temperatures the magnetocrystalline anisotropy becomes less important and the shape anisotropy predominates. In smaller pores hcp-Co is substituted bit by bit by fcc-Co which does not show a significant magnetocrystalline anisotropy. Therefore, Co wires with a small diameter do not show a competition between shape and magnetocrystalline anisotropy anymore.

Magnetization reversal in one-dimensional ferromagnets has been widely investigated. For wires having a diameter D smaller than $\sqrt{\pi}\, D_W$ rotation in unison was predicted to be the responsible magnetization reversal process, whereas wires having a larger diameter than $\sqrt{\pi}\, D_W$ should reverse via a curling mode [7,8]. In both cases all spins are reversed simultaneously. Other reversal mechanisms including the formation of domain walls are also discussed [9,10]. Investigations on the temperature dependence of the coercive field for Fe and Ni wires that help to identify the responsible magnetization reversal process for different wires diameters are presented here.

EXPERIMENTAL DETAILS

Nanoporous alumina membranes are prepared by anodizing aluminum foils (99.8 %) in polyprotic acids like sulfuric acid, phosphoric acid or oxalic acid at 0°C and a constant anodizing voltage. The pore diameter achieved depends nearly linearly on the anodizing voltage applied (approx. 1.2 nm/V). In order to clean and make a smooth surface the aluminum foils are treated with chromic acid and electropolished in a mixture of concentrated phosphoric and sulfuric acid (11:7 (v/v)) prior to the anodizing. The pore diameters achieved here range between 6 and 50 nm.

Metal plating is performed using an AC plating procedure. The aluminum that is not consumed during the anodizing and that is still underneath the membrane serves as an electrode during the metal plating. Graphite may be used as a counter electrode. The plating voltage used for all metals is 16 V (50 Hz).

Magnetic measurements were performed using a SQUID magnetometer at temperatures between 3 and 300 K and in fields between –5 and +5 T.

DISCUSSION

Figure 1 shows a TEM picture of a cross-sectioned alumina membrane filled with Ni. It is clearly visible that the Ni wires propagate parallel to each other.

Figure 1. TEM picture of a 20 V alumina membrane filled with Ni (cross section)

The magnetization curves of Fe and Ni wires with an average diameter of 12 nm are shown in figure 2. An almost square shape of the curves can be observed when the magnetic field is applied parallel to the long axes of the wires whereas hardly any hysteresis can be seen when the magnetic field is directed perpendicular to the long axes. This indicates a strong shape anisotropy for both Fe and Ni wires, i.e. there are two stable orientations for the magnetic moments namely, pointing parallel and antiparallel to the long axis of the wire. These orientations are separated by an energy barrier. The shape anisotropy can be observed independent of the wire diameter.

For finite cylinders the coercive field B_{c0} at T = 0 K is predicted to be independent of the wire diameter D if the magnetic moments are reversed via rotation in unison

$$B_{c0} = \frac{\mu_0}{2} M_{sb} \qquad (1)$$

where M_{sb} is the saturation magnetization of the bulk. If the magnetization is reversed via a curling mode, however, the coercive field B_{c0} depends on D [7,8]

$$B_{c0} = 0.54 \mu_0 M_{sb} \left(\frac{\sqrt{\pi} D_W}{D}\right)^2 \qquad (2).$$

Figure 3 shows the measured coercive fields as a function of $D/(\pi^{1/2} D_W)$ with $\pi^{1/2} D_W$ = 11 nm and 39 nm for Fe and Ni respectively [3]. For large wire diameters the measured values follow the predicted curve for the curling process. For small wire diameter the value for $2B_{c0}/\mu_0 M_{sb}$ remains nearly constant as predicted for the rotation in unison but is a factor of 3 too low. For small wire diameters the magnetization reversal mechanism needs to be modified. Investigations on the temperature dependence of the coercive field, the magnetic relaxation and the magnetic viscosity, not presented here, [3] gave evidence for a mechanism including the nucleation of a magnetic domain and a following propagation of the domain wall along the wire. The domain is likely to be formed near structural defects or at the ends of the wire.

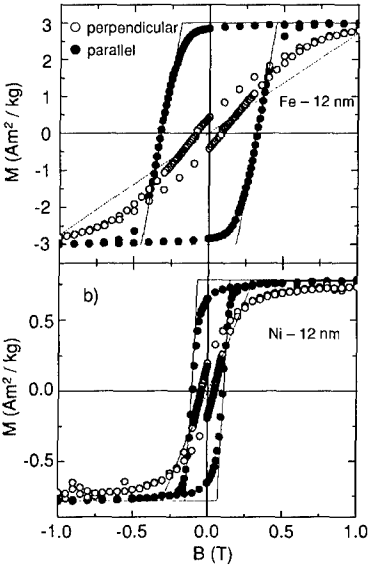

Figure 2. Magnetization curves of 12 nm Fe and Ni wires indicating a strong shape anisotropy

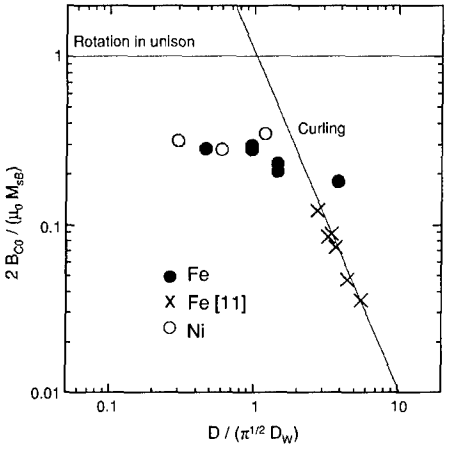

Figure 3. Size dependence of the coercivity for Fe and Ni nanowires (data from Ref [11] are included for wire diameters larger than those used in this work)

Apart from the shape anisotropy Co nanowires show a temperature and size dependent magnetocrystalline anisotropy along the hexagonal c-axis, which is directed nearly perpendicular to the long axis of the nanowire [1,2]. Therefore, at low temperatures wires with a large pore diameter show a hysteresis in the magnetization curve for both the magnetic field applied parallel and perpendicular to the long axes of the wires (cf. Fig. 4). At room temperature, however, the magnetocrystalline anisotropy constant becomes significantly smaller than at 5 K. This causes the loss of the hysteresis in the magnetization curve when the magnetic field is applied perpendicular to the long axes of the wires. Furthermore, the magnetocrystalline anisotropy becomes less important if the wire diameter is decreased. This can be attributed to the fact that in all the wires a mixture of fcc-Co and hcp-Co can be found. The amount of fcc-Co increases if the pore diameter decreases [1,2]. Fcc-Co, however, does not show a significant magnetocrystalline anisotropy. This in turn leads to a prevailing shape anisotropy in Co wires with a small diameter even at low temperatures. It is not yet understood what causes the amount of fcc-Co, which in the bulk is only known as a high temperature Co modification, to increase in small pores. However, intensive EXAFS and WAXS studies on this subject are in progress .

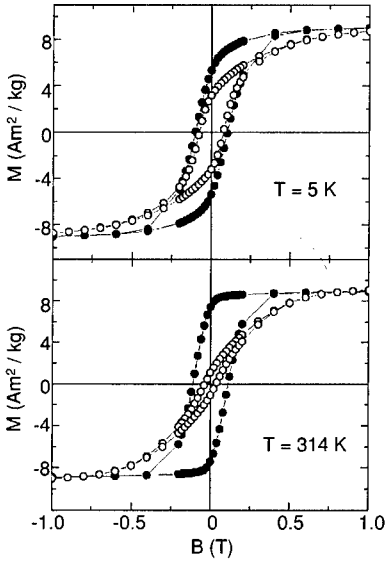

Figure 4. Magnetization curves for Co nanowires (D = 50 nm) at two different temperatures

CONCLUSIONS

Extensive studies on the magnetization reversal process in one-dimensional Fe and Co wires have been performed showing that for small wire diameters, i.e. diameters in the range of the domain wall widths, the magnetization reversal process takes place including the formation of small domains at imperfections or at the ends of the wires followed by the propagation of the

domain walls along the wire. In Fe and Ni wires the shape anisotropy predominates, whereas Co wires show a competition between this shape anisotropy and a magnetocrystalline anisotropy. The magnetocrystalline anisotropy (with the easy axis nearly perpendicular to the long axis of the wire) is temperature and size dependent. In small Co wires and at elevated temperatures the shape anisotropy predominates, whereas in large pores and at low temperatures the shape and magnetocrystalline anisotropy constants nearly equal each other. A decreasing amount of hcp-Co in favor of fcc-Co in small pores is determined by EXAFS and WAXS spectroscopies. This causes a reduction of the magnetocrystalline anisotropy strength in small pores.

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