Magnetic behavior of an array of cobalt nanowires

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Cobalt nanowires have been electrodeposited into the pores of Anodisc™ alumina membranes after placing on one side a layer of sputtered copper, which acts as electrode and substrate during the electrodeposition. Nanowires are 60 μm long, 170–220 nm in diameter depending on the size of the pores of the alumina membrane. This array of nanowires exhibits uniaxial magnetic anisotropy related to the particular shape of each individual nanowire. On the contrary to the expected behavior in a uniaxial magnetic system, the coercivity of the array exhibits a maximum when the applied field is in a perpendicular direction with respect to the easy axis. This magnetic behavior is analyzed considering dipolar interactions among nanowires, and the magnetization of the array is obtained as a function of the magnetic characteristics of each nanowire using an iterative method. © *1999 American Institute of Physics.* [S0021-8979(99)63208-X]

INTRODUCTION

The production by different methods of magnetic wires with diameter in the nanometric scale has recently attracted much attention. Their main interest lies in the fundamental scopes as the micromagnetic reversal process and quantum effects,[1–3] as well as in applied aspects in various issues of giant magnetoresistance and magnetic recording.[4–7] In particular, the deposition of metals inside the nanometric pores of a membrane is the most inexpensive technique to produce nanosized patterned structures.[1–8] The pore diameter and the separation wall thickness define the density of the nanowires as well as their diameter. This geometrical condition, along with the growing parameters, will determine the material structure and its magnetic properties. In this work, we perform an experimental study of the magnetic properties of an array of cobalt nanowires and a simple model to explain its magnetic behavior is proposed.

EXPERIMENTAL TECHNIQUES

Cobalt nanowires were electrodeposited into the pores of Anodisc™ alumina membranes 60 μm in thickness and whose pore diameter was nominally 200 nm. The membranes were cut to have a rectangular 10 mm² shape. Previous to the deposition, a 5000 Å layer of Cu was sputtered on one side of the membranes in order to act as substrate and cathode during the electrodeposition. A three-electrode electrochemical cell was used, controlled with a PC and an Amel Instruments potentiostat. The deposition was carried out in potentiostatic mode with the electrolyte given by Whitney *et al.*[8] applying −1.6 V with respect to the Hg/Hg$_2$SO$_4$ reference electrode.

Structural characterization was performed by means of x-ray diffraction using a Philips X'PERT diffractometer with

Cu $K\alpha$ radiation. The filling of the pores as well as the morphology of the array of nanowires after dissolving the alumina was monitored by scanning electron microscopy (SEM) in a ZEISS DSM 960 microscope.

Room-temperature magnetic characterization of the array was performed using an LDJ vibrating sample magnetometer (VSM).

RESULTS AND DISCUSSION

During the electrodeposition, complete filling of the pores was monitored measuring the supplied current.[8] As a result of this process, the nanowires were 60 μm long. Although the pore diameter of the membrane was nominally 200 nm, SEM images revealed that the pore diameter was not constant but it varied in the 170–220 nm range. In order to visualize the nanowires, the alumina matrix was dissolved using a 5 M NaOH solution for 20 min. Figure 1 shows a
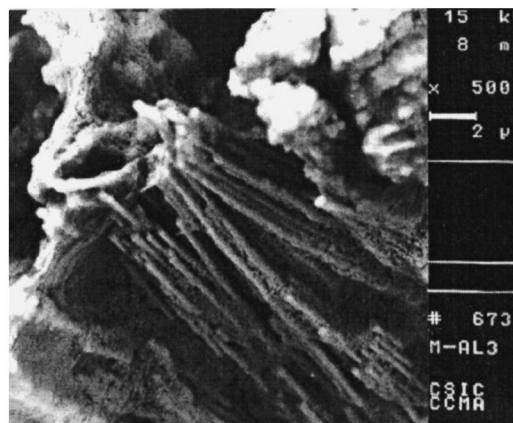

FIG. 1. SEM image of electrochemically grown Co nanowires after dissolving the alumina membrane support.

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SEM image corresponding to Co nanowires after dissolving the alumina. They consist of metallic wires 170–220 nm in diameter.

The typical x-ray diffraction pattern of the samples is shown in Fig. 2. The peaks can be regarded to be alumina, copper, cobalt, and boron oxide. It is important to notice that Co is mainly crystallized in the fcc structure instead of the hexagonal one, which is imposed by the sputtered Cu layer.[9]

Figure 3 shows two hysteresis loops of the array of nanowires with the membrane support: when the applied field is parallel to the nanowires (perpendicular to the surface of the membrane) and when the applied field is perpendicular with respect to the nanowires (so, in the plane of the membrane), respectively. These hysteresis loops reveal that the array exhibits uniaxial magnetic anisotropy with the easy axis parallel to the nanowires whose origin is associated with their shape. The angular dependence of the out-of-plane coercivity and the remanent-saturation magnetization ratio is illustrated in Fig. 4, being θ, the angle between the surface of the membrane and the applied magnetic field. It can be observed that maximum remanent magnetization is obtained for an applied field which is parallel to the nanowires ($\theta = 90°$), while the coercivity of the array is maximum when the field is applied in a perpendicular direction with respect to the nanowires ($\theta = 0°$). In order to elucidate the existence of a preferential direction within the surface plane, the angular dependence of the in-plane coercivity and the remanent-saturation magnetization ratio was studied, being ϕ, the angle between the longest edge of the sample surface and the in-plane applied field. As shown in Fig. 5, all the in-plane directions (directions contained in a plane perpendicular to the nanowires) are equivalent.

In summary, the array exhibits an easy axis which is parallel to the nanowires, but with the anomaly that the coercive field is minimum in that direction. Furthermore, the remanent magnetization is always lower than 7% of the saturation magnetization, which also indicates very strong interaction among the nanowires.[1]

The decrease of the coercivity along the easy axis can be analyzed with a simple model which considers magnetic dipolar interactions among nanowires. As previously reported,
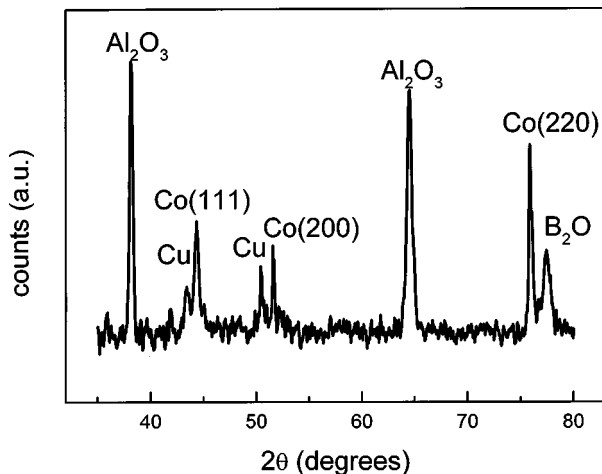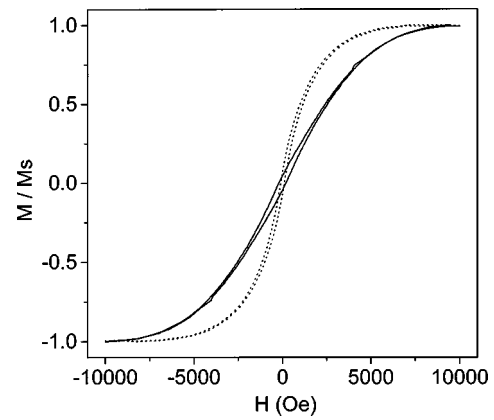

FIG. 3. Hysteresis loops of the supported array of Co nanowires. Dotted line: with the applied field parallel to the nanowires. Solid line: with the applied field in a perpendicular direction with respect to the nanowires.

this kind of interaction explains the properties of the hysteresis loop of a set of ferromagnetic amorphous wires.[10] In our case, to estimate this interaction, we assume that each nanowire is characterized by a square hysteresis loop that is expressed by the generic function $M = M(H)$. The magnetic field generated by each nanowire affects the magnetic state of its neighboring nanowires. If $H_a(t)$ is the applied magnetic field at the time t, the magnetization M_i of the nanowire i is given by

$$M_i = M_i \left[H_a(t) - \sum_{j=1}^{j=N} K_{ij} M_j \right], \qquad (1)$$

N being the total number of nanowires and K_{ij} depending on the distance between the nanowires i and j.

In the array of nanowires whose properties are described in this work we found some particularities: (i) Only an estimation of the density of the nanowires can be obtained, but not the exact number. (ii) The magnetization process of each single nanowire can only be assumed, but it is not properly measured.

Taking into account these difficulties, some approximations have been assumed: (a) Each nanowire is character-
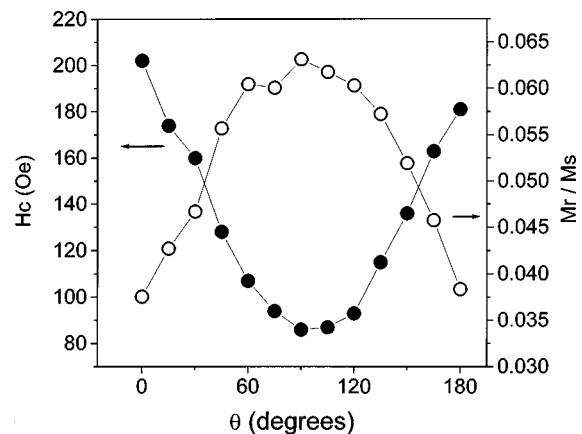

FIG. 2. X-ray diffraction pattern of the supported array of Co nanowires.

FIG. 4. Angular dependence of the out-of-plane coercivity and the remanent-saturation magnetization ratio, being θ, the angle between the surface of the membrane and the applied magnetic field.
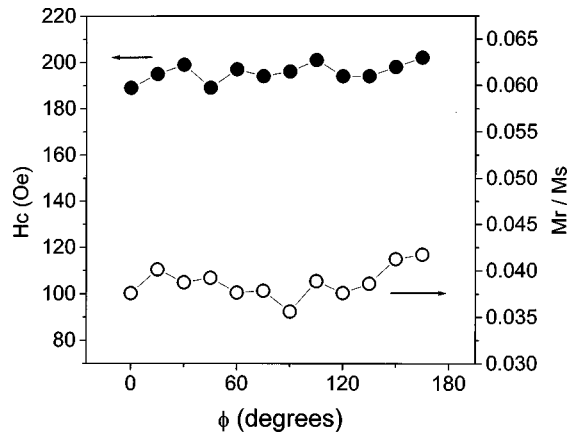
FIG. 5. Angular dependence of the in-plane coercivity and the remanent-saturation magnetization ratio, being ϕ, the angle between the longest edge of the surface of the membrane and the in-plane applied field.

FIG. 6. Solid line: modeled hysteresis loop of 100 interacting nanowires with the following distribution of magnetization and coercive field: $M^* = M_0$, $\Delta M = M_0/7$, $H_c = H_0$, and $\Delta H_c = H_0/5$. Dotted line: modeled hysteresis loop of the same 100 nanowires but without interaction.

ized by a coercive field H_i and a magnetization M_i, which is always parallel to the nanowire axis.   (b) The K_{ij} constants are the same for all the nanowires and do not depend on the distance between them ($K_{ij} = K$).

The system of Eq. (1) is solved by means of an iterative algorithm. Finally, the magnitude $M = (M_1 + M_2 + \cdots + M_N)/N$ is obtained, which represents the magnetization of the array of N nanowires.

As the number of interacting nanowires in our samples is extremely high (order of 10^8), many wires have similar values of magnetization and coercive field, so a distribution of values can be assumed as follows: $M^* - \Delta M < M < M^* + \Delta M$, and so $H_c^* - \Delta H_c < H_c < H_c^* + \Delta H_c$. Figure 6 shows the hysteresis loop (solid line) obtained with this model corresponding to 100 nanowires for the following distribution of magnetization and coercive field: $M^* = M_0$, $\Delta M = M_0/7$, $H_c = H_0$, and $\Delta H_c = H_0/5$. The hysteresis loop obtained is narrower than the one which corresponds to the same array of nanowires without interaction among them (dotted line). It is worth emphasizing that the decrease of the value of the coercive field is proportional to the value of K: higher interaction leads to lower coercivity.

This simple model explains the experimental reduction of H_c obtained in our array of nanowires. When the magnetic field is applied in the direction of the easy axis of the nanowires, the dipolar interaction is enhanced and the field emanating from each wire favors the reversal of magnetization.

CONCLUSIONS

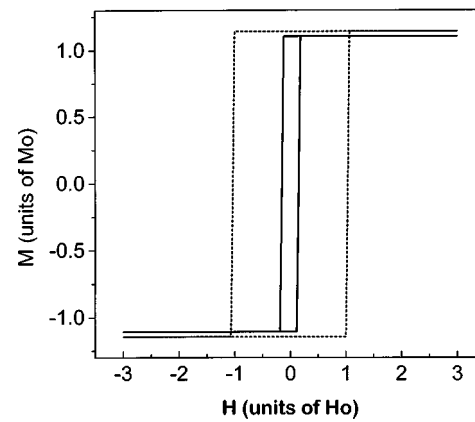We have fabricated and characterized an array of electrodeposited cobalt nanowires. The magnetic properties of the array have been explained considering shape anisotropy and magnetic dipolar interactions among nanowires. The easy-shape anisotropy direction in each nanowire is parallel to the nanowire axis. However, when the nanowires are set in the form of an array, the dipolar interactions among the nanowires change drastically the magnetic behavior, producing a decrease of the coercive field in the easy axis of the nanowires when the interaction is strong enough.

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