Magnetic anisotropy in prismatic nickel nanowires

L. Sun and P. C. Searson
Department of Materials Science and Engineering, Johns Hopkins University, Baltimore, Maryland 21218

C. L. Chien
Department of Physics and Astronomy, Johns Hopkins University, Baltimore, Maryland 21218

(Received 18 June 2001; accepted for publication 13 October 2001)

Nickel nanowire arrays with a diamond-shaped cross section and the same orientation have been fabricated in nanoporous single mica crystal membranes by electrodeposition. All wires are 5 μm long with an effective diameter of 120 nm. The sample can be considered as a collection of laterally and vertically aligned identical micromagnetic prisms. We report on the magnetic anisotropy due to the quasi-one-dimensional wire shape and diamond cross section. © 2001 American Institute of Physics. [DOI: 10.1063/1.1428113]

Electrodeposition of metals into porous templates has been used as a method to fabricate a wide range of quasi-one-dimensional nanostructures. The intrinsic properties of nanowire arrays are directly related to properties of the nanoporous template such as the pore shape, the relative pore orientation in the assembly, the pore size distribution, and the surface roughness of the pores.

Ferromagnetic nanowires exhibit strong shape anisotropy due to the high aspect ratio where the nanowire axis is the easy axis for magnetization. The difference in the saturation field with the applied magnetic field perpendicular or parallel to the wire axis corresponds to 2πM_s, where M_s is the saturation magnetization, as expected for an infinitely long cylinder. Furthermore, large enhancements in coercivity and squareness have been reported with decreasing wire diameter.

Nanowires formed in polycarbonate or alumina membranes are circular in cross section and hence there is no shape anisotropy perpendicular to the wire axis. However, nuclear track etching in crystalline inorganic materials can be used to produce nanoporous templates with asymmetric cross sections. Etched particle tracks in [001] single crystal muscovite mica are diamond shaped in cross section with angles of 60° and 120°. Due to the crystal structure of the mica, the diamond-shaped pores are aligned with respect to each other allowing the investigation of anisotropic magnetic properties perpendicular to the wire axis.

Figure 1 shows a plan view scanning electron micrograph image of etched particle tracks in a single crystal mica membrane. The particles are collimated so that the damage tracks are within 2° to the membrane normal. The length of the diagonals of the diamond-shaped pores are 115 and 200 nm, respectively. For convenience we define an effective diameter of 120 nm and a pore density of 2×10^8 cm\(^{-2}\), we obtain a porosity of 2.26% and an average pore–pore distance of 700 nm.

Nickel nanowire arrays were prepared by electrochemical deposition of nickel from a solution of 20 g L\(^{-1}\) NiCl\(_2\)-6H\(_2\)O, 515 g L\(^{-1}\) Ni(H\(_2\)NSO\(_3\))\(_2\)-4H\(_2\)O, and 20 g L\(^{-1}\) H\(_3\)BO\(_3\) at −1.0 V (Ag/AgCl). From buoyancy measurements we determined the density of Ni thin films deposited from sulfamate solution at −1.0 V to be 98% that of pure Ni. The saturation magnetization of the electrodeposited thin films was 98.6% that of pure Ni, indicating a low impurity concentration. Electrical contacts were made by sputter deposition of 300 nm gold onto one side of the nanoporous mica templates. For 5 μm long nanowires the effective aspect ratio (defined by the ratio of the wire length and effective diameter) is 41.7. Since the pores in the mica are aligned, the nanowire array can be considered a collection of identical laterally and vertically aligned micromagnetic prisms.

Magnetic measurements were performed on a vibrating sample magnetometer (VSM) from 80 K to room temperature. The saturation magnetization was obtained from linear extrapolation of the high field magnetization data (6500–10 000 Oe) to zero field. The saturation field was defined as the field where the magnetization reached M_s. The data were corrected for the background signal obtained from a blank mica film from the same sample (unirradiated area). Due to the relatively large wire spacing, magnetic interactions between wires can be neglected. Furthermore, the crystalline anisotropy of Ni can also be neglected as a result of the polycrystalline structure of the as-grown wires and the relatively small crystalline anisotropy. Consequently, aniso...

FIG. 1. Scanning electron microscope image of 120 nm pores in single crystal mica.
tropic magnetic properties are dominated by the wire shape.

Figure 2 shows the magnetization hysteresis loops for the nanowire array when the applied field is parallel to wire axis \( c \) and perpendicular to the wire axis along the diamond diagonals \( a \) and \( b \). Due to the large wire aspect ratio, the magnetic easy axis is parallel to the nanowire. The measured squareness (SQ, defined by the ratio of remanent magnetization and saturation magnetization \( M_r/M_s \)) along the wire axis is 0.89. Perpendicular to the wire are the magnetic hard axes, however, there is clear in-plane magnetic anisotropy due to the diamond-shaped cross section. Rotating the field from along the short diagonal \( a \) to along the long diagonal \( b \) results in a decrease in the saturation field from 4650 to 3380 Oe, as shown in Fig. 3. At the same time, the coercivity decreases from 220 to 80 Oe and the squareness decreases from 0.066 to 0.056. Measurement of hysteresis loops as a function of temperature revealed that the coercivity increased linearly with decreasing temperature although the squareness was essentially independent of temperature.

This in-plane magnetization anisotropy can be qualitatively discussed based on the ellipsoid approximation. For an ellipsoid with three different axes \( a, b, \) and \( c \), the demagnetization factors along three axes are defined as \( N_a, N_b, \) and \( N_c \), respectively. Using the notation shown in the inset of Fig. 2, the magnetization energy can be written as

\[
E_F = 2\pi M_s^2 (N_c \cos^2 \theta + N_a \sin^2 \theta \cos^2 \phi + N_b \sin^2 \theta \sin^2 \phi),
\]

where \( \theta \) is the angle between the applied field and \( c \), and \( \phi \) is the angle between the in-plane projection of the applied field and \( a \).

When the magnetization aligns in the \( ab \) plane (\( \theta = 90^\circ \)), Eq. (1) reduces to

\[
E_F = 2\pi M_s^2 (N_c \cos^2 \phi + N_b \sin^2 \phi) = K_a \cos^2 \phi + K_b \sin^2 \phi,
\]

where \( K_a \) and \( K_b \) are the uniaxial anisotropy constants along the \( a \) and \( b \) directions. From this expression we can write the saturation field as

\[
H_s = 4\pi M_s (N_c \cos^2 \phi + N_b \sin^2 \phi) = \frac{2K_a}{M_s} \cos^2 \phi + \frac{2K_b}{M_s} \sin^2 \phi.
\]

FIG. 2. Magnetization hysteresis loops for 120 nm Ni nanowires with the applied field (a) parallel to the wire axis, (b) perpendicular to the wire axis along the short diagonal of the diamond, and (c) along the long diagonal of the diamond.

FIG. 3. The angular dependence of (a) the saturation field and (b) the coercivity with the applied magnetic field parallel to the wire axis. The solid line in the plot of the saturation field corresponds to a fit according to Eq. (3).

\[
E_F = 2\pi M_s^2 (N_c \cos^2 \phi + N_b \sin^2 \phi) = K_a \cos^2 \phi + K_b \sin^2 \phi,
\]

where \( K_a \) and \( K_b \) are the uniaxial anisotropy constants along the \( a \) and \( b \) directions. From this expression we can write the saturation field as

\[
H_s = 4\pi M_s (N_c \cos^2 \phi + N_b \sin^2 \phi) = \frac{2K_a}{M_s} \cos^2 \phi + \frac{2K_b}{M_s} \sin^2 \phi.
\]

Figure 3 shows excellent agreement between the measured angular dependence of the saturation field and Eq. (3). From the fit, we obtain \( K_a = 1.13 \times 10^6 \text{erg cm}^{-3} \) and \( K_b = 8.2 \times 10^5 \text{erg cm}^{-3} \). The corresponding demagnetizing factors are \( N_a = 0.764 \) and \( N_b = 0.556 \). These values can be compared to the calculated demagnetizing factors for a tri-axial ellipsoid with \( c/a = 43.8 \) and \( c/b = 25.3 \) of \( N_a = 0.633 \) and \( N_b = 0.365 \). These values are in reasonable agreement given the difference in cross section between a diamond and an ellipse. Thus the in-plane shape anisotropy caused by the diamond-shaped cross section can be described by a simple model based on two mutually perpendicular anisotropic axes.

Hysteresis loops were measured with the external field rotated in the \( ac \) plane or the \( bc \) plane from parallel to the wire axis (\( \theta = 0^\circ \)) to along the \( a \) or \( b \) axis of the diamond (\( \theta = 90^\circ \)). The squareness of the hysteresis loops decreases with increasing \( \theta \). Since the magnetization at zero external field is aligned along the easy axis and the magnetization is measured along the field direction, we expect the SQ to be dependent on \( \theta \) according to

\[
SQ = \sin \theta |
\]

\[
\theta.
\]
For the case of curling, the magnetic field corresponding to the onset of magnetization reversal for an elongated ellipsoid is approximately equal to the coercivity so that Fig. 4(b) can be used to determine the angular dependence of the nucleation field for the nanowires. According to the curling model, the angular dependence of the normalized nucleation field for an ellipsoid in the limit of an infinitely large aspect ratio is given by:

\[ H_n / H_n(\theta = 0) = 1 / \cos \theta. \]  

(5)

Figure 4(b) shows that the coercivity increases with increasing angle as expected for the curling mechanism. Other groups have used magnetoresistance and micro-SQUID (superconducting quantum interference device) measurements to determine the nucleation field in cylindrical nickel nanowires 75–80 nm in diameter and have shown a similar increase in nucleation field with increasing angle consistent with the curling model.

At higher angles when the external field rotates away from the wire axis there is a critical angle, dependent on diameter and aspect ratio, above which magnetization reversal occurs by coherent rotation. For coherent rotation, the coercivity decreases with increasing \( \theta \). From Fig. 4(b) it is seen that the transition to coherent rotation occurs at about 78° when the field is aligned in the \( bc \) plane. When the field is aligned in the \( bc \) plane the transition is shifted to about 85° due to the increase in the length of the diagonal (decrease in aspect ratio).

In summary, Ni nanowire arrays with a diamond-shaped cross section and the same orientation have been fabricated to study the magnetic shape anisotropy perpendicular and parallel to the wire axis. The magnetic anisotropy due to the diamond-shaped cross section can be well described by two mutually perpendicular uniaxial anisotropic axes along the diagonals based on a simple ellipsoid approximation. As the applied field rotates from the wire axis (\( \theta = 0° \)) to perpendicular to the wire axis (\( \theta = 90° \)), the squareness of the hysteresis loop follows a \( \cos \theta \) dependence caused by the uniaxial anisotropy along the wire axis. The magnetization reversal is dominated by curling for values of \( \theta \) up to about 80°.

The authors acknowledge helpful discussions with Gary Prinz. This work was supported by the JHU MRSEC (NSF Grant No. DMR00-80031).

\[ \text{FIG. 4. Dependence of (a) squareness and (b) coercivity on the angle of the applied magnetic field with respect to (C) the wire axis and the short diagonal of the diamond (ac plane) and (\( \Delta \)) the wire axis and the long diagonal of the diamond (bc plane). The dashed line corresponds to } H_n = H_n(\theta = 0°)/\cos \theta. \]