

# Effects of bar length on switching field of nanoscale nickel and cobalt bars fabricated using lithography

Linshu Kong<sup>a)</sup> and Stephen Y. Chou

*NanoStructure Laboratory, Department of Electrical Engineering, University of Minnesota, Minneapolis, Minnesota 55455*

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The switching behavior of isolated nanoscale nickel and cobalt bars, which were fabricated using electron-beam lithography, was studied as a function of bar length. The bars have a 35 nm thickness, a 100 nm width, and a length varying from 200 nm to 5  $\mu\text{m}$ . Magnetic force microscopy showed that except for the Ni bars with a length equal to or less than 250 nm, all other as-fabricated bars were single domain. Unlike the bar width dependence, the switching field of the single-domain bars was found to first increase with the bar length, then decrease after reaching a peak. The peak switching field and the corresponding bar length are 640 Oe and 1  $\mu\text{m}$  for Ni and 1250 Oe and 2  $\mu\text{m}$  for Co, respectively. The nonmonotonic length dependence suggests that the magnetization switching may be quasicohesive in the short bars and incoherent in the long bars, and that the exchange coupling is much stronger in Co bars than in Ni bars. Furthermore, the switching field of 1- $\mu\text{m}$ -long Co bars was found to increase monotonically as the bar width decreases, reaching 3000 Oe at a 30 nm width. © 1996 American Institute of Physics. [S0021-8979(96)02121-4]

## I. INTRODUCTION

Magnetic particles are of great interest to magnetic recording.<sup>1-4</sup> With the advancement of nanofabrication technology, it is possible to fabricate magnetic bars which are single domain but have dimensions much larger than those of the single-domain particles studied before. Understanding these lithographically patterned magnetic bars is important in developing ultrahigh-density magnetic recording media, such as quantum magnetic disks that consist of discrete single-domain bits.<sup>5</sup> Previously, the effects of bar width on the switching field of lithographically patterned NiFe and Ni bars have been studied.<sup>6,7</sup> In this article we present the effects of bar length on the switching field of nanoscale Ni and Co bars fabricated using e-beam lithography. We have observed that, unlike the width dependence found previously, the switching field of single domain bars nonmonotonically depends on the bar length.

## II. FABRICATION AND MEASUREMENTS

The isolated Ni and Co bars were fabricated using e-beam lithography and a lift-off technique. In the fabrication, rectangular patterns were exposed in a thin film of polymethyl methacrylate (PMMA) on a silicon substrate with high-resolution e-beam lithography. The exposed PMMA was removed in development, resulting in rectangular trenches in the PMMA. Then Ni or Co was evaporated onto the entire sample. Finally, the sample was immersed in acetone which dissolved the PMMA template and lifted off the metal on the PMMA surface, leaving isolated metal bars on the substrate. The details of the fabrication have been published elsewhere.<sup>7,8</sup> Both Ni and Co bars have a thickness of 35 nm and a width of 100 nm, but the length of Ni bars varies from 250 nm to 5  $\mu\text{m}$  and the Co bars from 200 nm to 5  $\mu\text{m}$ . Figure 1 shows a scanning electron micrograph

(SEM) of a typical 1- $\mu\text{m}$ -long and 100-nm-wide Ni bar.

From x-ray diffraction, the as-deposited Co thin film is found to be polycrystalline and have a hexagonal crystal structure. The initial magnetization states and the switching behavior of the Ni and Co bars were observed using a commercial scanning magnetic force microscope (MFM) with an ultrahigh-resolution tip made in-house. The topological and magnetic images were taken at the same time. In the study of the switching behavior of the single domain bars, the magnetization states of the bars were observed using the MFM first. Then the sample was taken out from the MFM and placed in a magnetic field applied in the direction opposite to the bar's original magnetization. Finally, the sample was put back into the MFM for further examination. This process continued and the applied field was gradually increased until the magnetization of the bar reversed. That field is defined as the switching field of the bar. The accuracy of this measurement is typically 10 Oe. Furthermore, due to fabrication inhomogeneity, there is a slight variation of the switching field

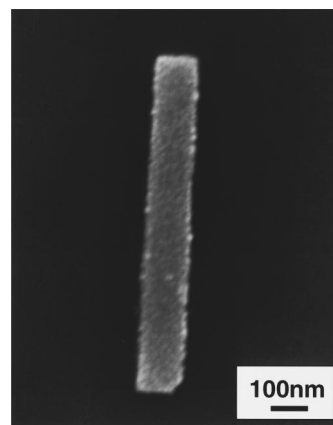


FIG. 1. Scanning electron micrograph of a Ni bar that is 1  $\mu\text{m}$  long, 100 nm wide, and 35 nm thick.

<sup>a)</sup>Electronic mail: lkong@ee.umn.edu

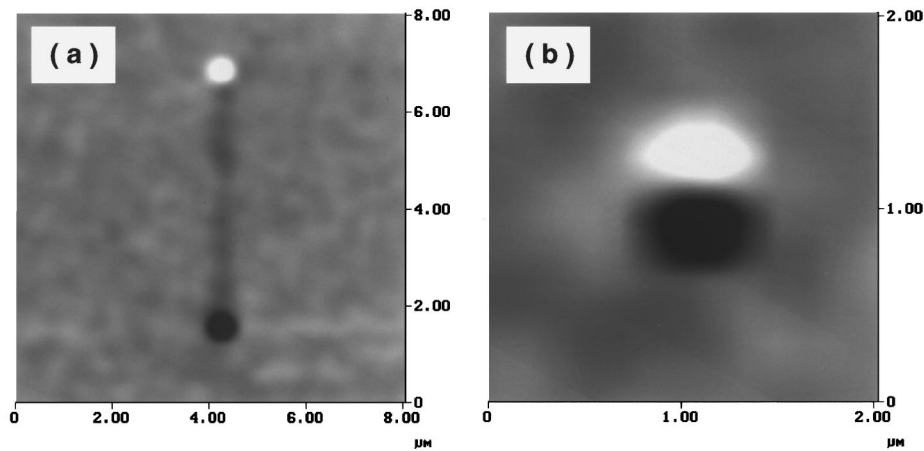


FIG. 2. MFM image of a spontaneous single domain Co bar that is 100 nm wide, 35 nm thick, and (a) 5  $\mu\text{m}$  long and (b) 200 nm long, respectively.

for the bars with the same nominal dimension. Therefore, for a given nominal size, nine bars were measured at the same time, and the switching field given here is the average.

### III. RESULTS AND DISCUSSION

MFM observations show that all the as-fabricated Co bars (with a length from 200 nm to 5  $\mu\text{m}$ ) have spontaneously formed a single domain without any assistance of an external magnetic field. The MFM images of Co bars with lengths of 5  $\mu\text{m}$  and 200 nm are shown in Figs. 2(a) and 2(b). The vibrating sample magnetometer measurements show that the coercivities of as-deposited films are 25 Oe for Ni and 50 Oe for Co. The bar's shape anisotropy is the primary cause of forming single domain in the Co and Ni bars. The easy magnetization direction is along the long axis of the bar and the hard magnetization direction is along the short axis.

For Ni bars, all the bars with a length greater than 250 nm are a spontaneous single domain, but the bar with a 250 nm length is initially multiple domain. Figure 3(a) and 3(b) show the atomic force microscope (AFM) and MFM images of a 250-nm-long Ni bar. The bar width in Fig. 3(a) looks wider than 100 nm because in a tapping mode AFM mea-

surement the image of a structure in the scanning direction (i.e., the horizontal direction) is always larger than the actual size.

For a given bar width, the critical bar length, below which a multidomain emerges, presents a measure of domain-wall energy. As we know, the reason that a magnetic particle changes from the single-domain state to the multidomain state is to minimize the total energy by reducing the magnetostatic energy while adding the domain-wall energy. The higher the domain-wall energy, the shorter the critical bar length, since the decrease in the magnetostatic energy must exceed the wall energy. Hence, the fact that the Co bars in our experiment have a smaller critical length than Ni bars implies the well-known fact that Co has a larger domain-wall energy than Ni because of stronger exchange coupling and higher magnetocrystalline anisotropy in cobalt.

The length dependence of switching field for the single-domain Ni and Co bars with a width of 100 nm and a thickness of 35 nm is shown in Figs. 4(a) and 4(b), respectively. The switching field increases with the bar length first, but decreases after reaching a peak. The peak switching field and corresponding bar length are, respectively, 640 Oe and 1  $\mu\text{m}$  for Ni and 1250 Oe and 2  $\mu\text{m}$  for Co. Furthermore, the switching field of Ni bars decreases with the increase of the

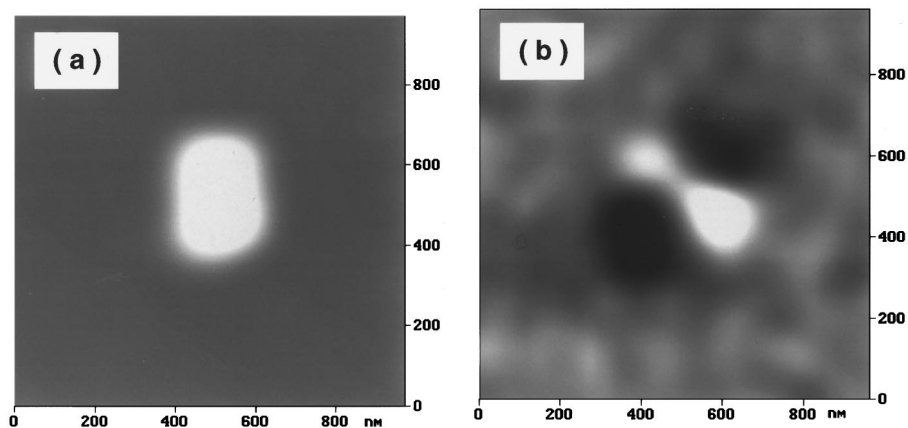


FIG. 3. (a) AFM and (b) MFM image of a multidomain Ni bar that is 250 nm long, 100 nm wide, and 35 nm thick.

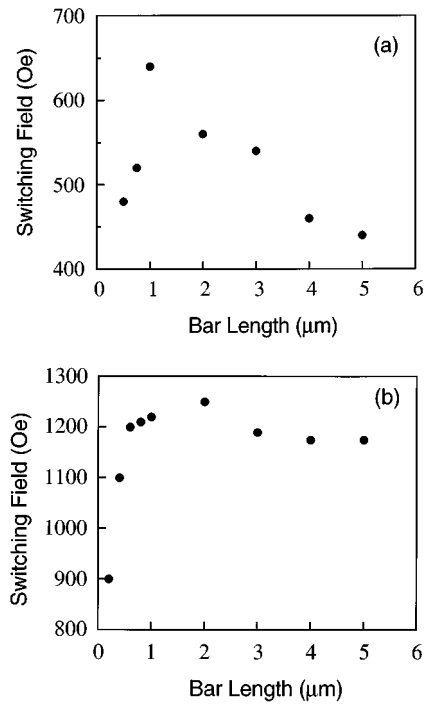


FIG. 4. Length dependence of the switching field for bars with a width of 100 nm and a thickness of 35 nm for (a) Ni and (b) Co.

bar width much faster than that in Co bars. Obviously, the length dependence observed here does not fit the Stoner–Wohlfarth model which assumes a coherent switching and predicts the switching field of a bar to monotonically increase with the increase of the shape anisotropy (therefore, with the bar length).<sup>9</sup>

If the magnetic moments in a bar are switched coherently, the magnetostatic energy during the switching reaches its maximum when the direction of the magnetic moments is aligned in the direction of the short axis of the bar. To maintain a coherent switching, the maximum magnetostatic energy should be less than the exchange energy. This may be the case for the Ni bars with length less than 1 μm and the Co bars with length less than 2 μm.

However, the maximum magnetostatic energy is proportional to the bar length. When the bar length becomes so long that the maximum magnetostatic energy becomes larger than the exchange energy, the coherent switching no longer can be maintained and the vortex state may appear, leading to the incoherent switching. Based on micromagnetics simulations, Schabes has suggested that an incoherent switching occurs in a magnetic particle of a size that is several times larger than the exchange length  $l_{ex} = \sqrt{A/M_S^2}$ , where  $A$  is exchange constant and  $M_S$  is saturation magnetization.<sup>10</sup> The exchange length is about 15.2 nm for Co and 14.6 nm for Ni if we take  $A = 4.7 \times 10^{-6}$  erg/cm and  $M_S = 1430$  emu/cm<sup>3</sup> for Co and  $A = 0.5 \times 10^{-6}$  erg/cm and  $M_S = 483$  emu/cm<sup>3</sup> for Ni. Our experiment seems qualitatively to support his analysis, although the bar length at the peak switching field in our experiments, which may reflect the crossover of coherent and incoherent switching, is much longer than the exchange length.

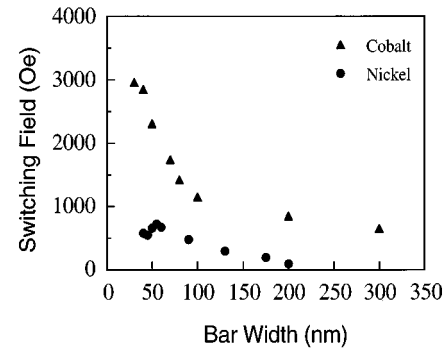


FIG. 5. Width dependence of the switching field for single-domain Co and Ni bars with a length of 1 μm and a thickness of 35 nm.

Finally, the fact that the length of Co bars at the peak switching field is twice as large as that of Ni bars confirms again the well-known fact that the exchange coupling is much stronger in Co than that in Ni. Otherwise, the incoherent switching and hence the peak switching field would have occurred at a much shorter bar length in Co than in Ni, since the magnetization of Co is nearly three times that of Ni.

In addition to the length dependence, the bar width dependence of the switching field for the Co bars which are 35 nm thick and 1 μm long was also investigated and is plotted in Fig. 5, along with the previous measurements of Ni bars as a comparison.<sup>7</sup> The switching field of Co bars increases monotonically with decreasing width and reaches 3000 Oe at a width of 30 nm.

#### IV. SUMMARY

We have studied lithographically patterned nanoscale Co and Ni bars which are 35 nm thick, 100 nm wide and have a length from 200 nm to 5 μm. MFM observations show that all the as-fabricated bars, except for the Ni bars with a length of 250 nm or less, are single domain. A nonmonotonic length dependence of switching field for Ni and Co bars is found. This behavior suggests that the switching may be quasicohherent in the short bars and incoherent in the long bars, and that the exchange constant is much greater in Co than that in Ni. Moreover, it is found that the switching field of 1-μm-long Co bars increases monotonically as the bar width decreases to 30 nm. In the future, the comparison of the experimental data with simulation will lead to better understanding of lithographically patterned magnetic structures.

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<sup>1</sup>A. Aharioni, J. Appl. Phys. **63**, 5879 (1988).

<sup>2</sup>Y. Martin and H. K. Wickramasinghe, Appl. Phys. Lett. **50**, 1455 (1987).

<sup>3</sup>T. Fujiwara, IEEE Trans. Magn. **MAG-26**, 24 (1990).

<sup>4</sup>G. A. Gibson, J. F. Smith, S. Schultz, and D. P. Kern, IEEE Trans. Magn. **MAG-27**, 5187 (1991).

<sup>5</sup>S. Y. Chou, M. Wei, P. R. Krauss, and P. B. Fischer, J. Appl. Phys. **70**,

6673 (1994); J. Vac. Sci. Technol. B **12**, 3695 (1994).

<sup>6</sup>J. F. Smyth, S. Schultz, D. R. Fredkin, D. P. Kern, S. A. Rishon, H. Schmid, M. Cali, and T. R. Koehler, J. Appl. Phys. **69**, 5262 (1991).

<sup>7</sup>M. S. Wei and S. Y. Chou, J. Appl. Phys. **76**, 6679 (1994).

<sup>8</sup>P. B. Fischer and S. Y. Chou, Appl. Phys. Lett. **62**, 2991 (1993).

<sup>9</sup>E. C. Stoner and E. P. Wohlfarth, Philos. Trans. R. Soc. London, Ser. A **240**, 599 (1948).

<sup>10</sup>M. Schabes, J. Magn. Magn. Mater. **95**, 249 (1991).