

Size effects on switching field of isolated and interactive arrays of nanoscale single-domain Ni bars fabricated using electron-beam nanolithography

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Isolated nanoscale Ni bars with a length of $1\ \mu\text{m}$, a width from 15 to 300 nm, and interactive bar arrays with a spacing from 200 to 600 nm were fabricated using electron-beam lithography and were studied using magnetic force microscopy. The study showed that the virgin magnetic state of bars with a width smaller than 150 nm was single domain and otherwise multidomain. It also showed that the switching field of isolated bars initially increases with decreasing bar width, then reaches a maximum switching field of 740 Oe at a width of 55 nm, and afterwards decreases with further bar width reduction. Furthermore, it was found that the switching field of the interactive bars decreases almost linearly with reduction of the spacing between the bars.

I. INTRODUCTION

Understanding the behavior of a single domain magnetic particle and the interaction between the particles is very important, because these particles are the basic constituents of many magnetic recording materials. However, previously most experimental studies of magnetic particles were made in an ensemble of such particles and the properties of a single particle were inferred only through extrapolation. Due to large variation in particle dimensions, randomness of magnetization and unavoidable interaction, detailed information about single particles and their interaction is smeared out.

Due to advance in nanofabrication technology, now it is possible to nanoscale magnetic particle arrays with precise sizes, shapes, and spacing. This opens up new opportunities to understand the fundamentals of micromagnetics and develop new magnetic materials. Recently, the first reported study of nanoscale permalloy bars fabricated using electron beam lithography was carried out by a joint team from the University of California at San Diego and IBM.^{1,2} In that study, isolated bars had a fixed length of $1\ \mu\text{m}$ and a fixed width of 133 nm and interactive bar arrays had a fixed spacing with the strongest coupling along the bars' long axis.

In this article, we present the fabrication and investigation of isolated Ni bars with a width varying from 15 to 300 nm and interactive Ni bar arrays with a spacing varying from 200 to 600 nm with the strongest coupling in the bars' short axis. Furthermore, we report and discuss the effects of bar width and spacing on the switching field of these isolated and interactive bars.

II. FABRICATION OF NANOMAGNETIC BAR ARRAYS

The isolated and interactive nanomagnetic nickel bars were fabricated using electron-beam nanolithography and a lift off process. In the fabrication, a resist, polymethyl methacrylate (PMMA), was first spun onto a silicon substrate. A high resolution electron beam lithography system with a beam diameter of 4 nm was used to expose bar arrays in the PMMA. The exposed PMMA was developed in a cellosolve and methanol solution to form a resist template on the substrate. A nickel film, 35 nm thick, was evaporated onto the entire sample. In the lift off, the sample was submersed in

acetone which dissolved the PMMA template and lifted off the nickel on its surface, but not the nickel on the substrate. After fabrication, bar widths were determined using a scanning electron microscope (SEM) and the bar width presented here is the measured bar width.

For isolated bars, the bar length was fixed at $1\ \mu\text{m}$, but the bar width varied from 15 to 300 nm. The spacing between isolated bars is $10\ \mu\text{m}$. Figure 1 shows a scanning electron micrograph of a Ni bar with a 15 nm width.

For interactive bar arrays, the bar width and length were fixed at 100 nm and $1\ \mu\text{m}$, respectively. The spacing between bars along the long axis is $2\ \mu\text{m}$, but the spacing between the bars along the short axis varies from 200 to 600 nm. Therefore the interaction between bars is primarily along the short axis, and the bar arrays can be regarded as isolated rows of one dimensional interactive arrays. This is very different from that in Ref. 1 where the bars were coupled primarily along the long axis. To illustrate the fabrication resolution

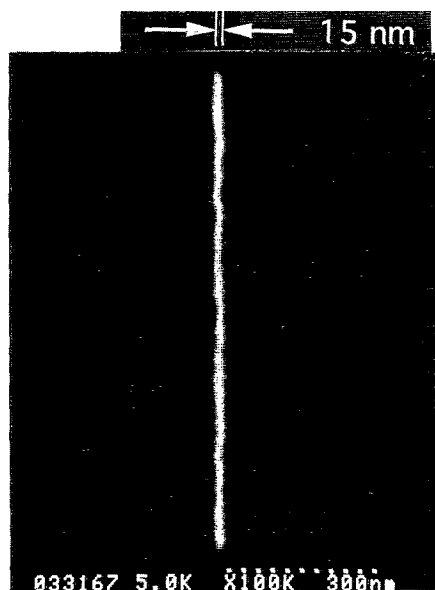


FIG. 1. SEM image of a high aspect ratio isolated Ni bar that is $1\ \mu\text{m}$ long and 15 nm wide.

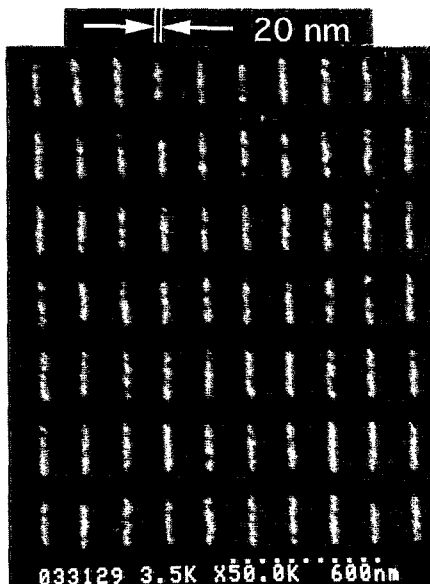


FIG. 2. SEM image of interactive bar arrays. Each bar is 200 nm long, 20 nm wide and 35 nm thick.

and uniformity, Fig. 2 shows a large array of Ni bars which are 200 nm long, 20 nm wide, and 150 nm apart along the short axis and 100 nm apart along the long axis, despite the fact that such dense bar arrays were not able to be resolved in our magnetic force microscopy (MFM) study.

III. MFM MEASUREMENTS

The nanomagnetic bars were studied using a custom built MFM that was modified from a commercial atomic force microscope (AFM). The MFM was operated in amplitude detection mode at ~ 200 mTorr vacuum for a high sensitivity. The MFM tips are the ordinary AFM cantilevers coated with 30 nm of cobalt and have a resonance frequency of 18 kHz. These soft tips give better sensitivity but poorer resolution than that of a harder tip.

In measuring the switching field of the isolated bars, the sample was first saturated in a fixed direction along its easy axis using a 2000 Oe magnetic field and a MFM image was taken to determine its magnetization. Then a test field was applied in the opposite direction and returned to zero. The sample was examined under MFM again to see if its magnetization flipped. If the bar flipped, a smaller test field was applied in next measuring cycle, otherwise a large field was applied. This process continued until the switching field of a nickel bar was located within 10 Oe.

IV. DATA AND ANALYSIS

A. Isolated bars

Before the isolated bars were put into any magnetic field, MFM images of the sample were taken. These images showed that for bars of a width smaller than 150 nm, the virgin magnetic state is single domain with magnetization



FIG. 3. MFM image of a Ni bar which is $1 \mu\text{m}$ long and 100 nm wide. The bright spot stands for the north pole and the dark spot stands for the south pole.

along the direction of its easy (i.e., long) axis; and the bars of wider width are multidomain. A MFM image of a 100 nm wide isolated bar is shown in Fig. 3.

It was found that the magnetization switching field of an isolated bar is a strong function of width, as shown in Fig. 4. The switching field first increases with decreasing bar width, reaches a maximum switching field of 740 Oe at a bar width of 55 nm, then decreases with further reduction of the bar width. The initial increase in the switching field is because the bar is changing from multidomain to single domain. The later decrease is likely due to the fact that thermal energy becomes comparable to magnetization switching energy.⁴

Compared to the study in Ref. 2, where the permalloy bars of a width 133 nm had a switching field greater than 400 Oe, the Ni bar with the same width studied here has a switching field about 100 Oe less. This could be due to two reasons. First, nickel film on Si surface has significant stress, so there

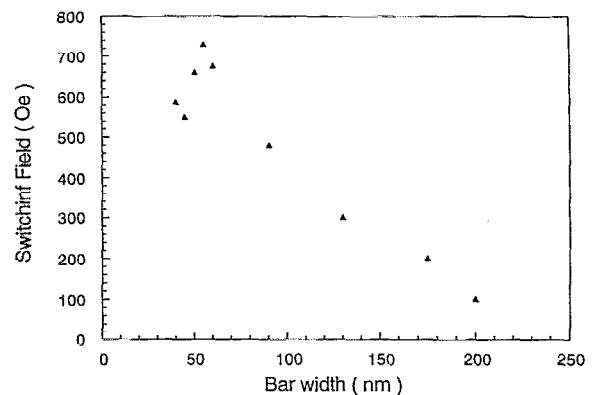


FIG. 4. Switching field of isolated bars vs bar width. The maximum switching field is 740 Oe for 55 nm wide bars. The bars are $1 \mu\text{m}$ long and actual bar width was measured using SEM.

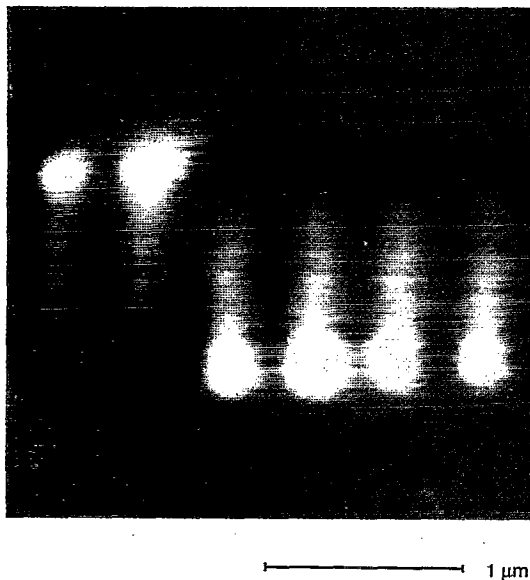


FIG. 5. MFM image of one-dimensional interactive bar arrays with 400 nm spacing.

may be a magnetostriction effect which decreases the net anisotropy. Second, Ni has strong crystalline anisotropy but permalloy does not.

The critical width for superparamagnetism can be estimated from the switching field vs size curve. The switching field of a particle of volume V , can be described by the equation $h_{ci} = 1 - (V_p/V)^{0.5}$, where h_{ci} is reduced coercivity and V_p is the volume below which the particle is superparamagnetic. The equation can be rewritten in terms of the bar width W : $h_{ci} = 1 - (W_p/W)^{0.5}$. By fitting the switching field of the bars with a width smaller than 55 nm, W_p is found to be 18 nm.

B. Interactive nanomagnetic bars

The interactive bar arrays that were studied using MFM have a bar width of 100 nm and a spacing between bars of 0.2, 0.4, and 0.6 μm , respectively, along the short axis. Figure 5 shows a MFM image of these bar arrays. The switching field distribution was measured and is shown in Fig. 6. In this measurement, an average of about 30 bars were counted for each data point and the bars at the end of each row were not counted. Figure 6 shows three facts. First, the smaller the spacing, the smaller the switching field. The switching field for 100 nm wide isolated bar is 300 Oe. But due to interaction, the mean value of switching field (i.e., the field at which 50% of bars can flip) is 205, 232, and 260 Oe for a spacing of 0.2, 0.4, and 0.6 μm , respectively. Second, the switching field decreases with the reduction of spacing at a rate 15 Oe per 100 nm. This behavior is due to the fact that as the spacing decreases, the demagnetization field generated by

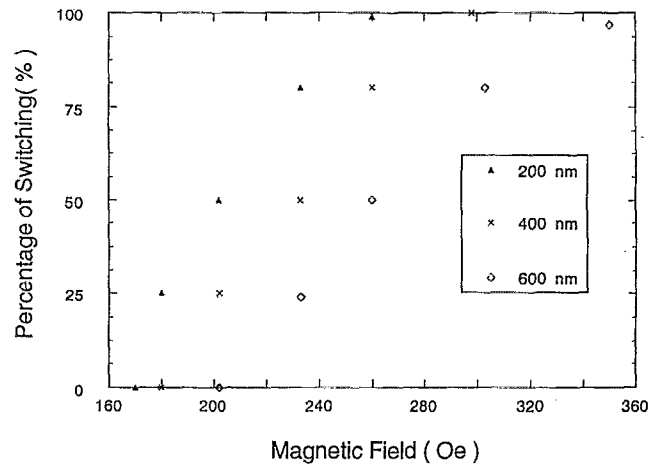


FIG. 6. Percentage of bars that switched vs the applied magnetic field for interactive bars with a spacing along the short axis of 200, 400, and 600 nm.

neighbor bars increases and will help a bar to flip. Third, the broadness of the switching field distribution is about 100 Oe which is due to bar interaction as well as size variations.

V. CONCLUSION

We have fabricated nanoscale isolated magnetic bars with different bar widths as well as interactive bar arrays with different spacing.⁵ The switching field was measured using MFM. The SEM micrographs show that these Ni bars have good uniformity and very high aspect ratio. The MFM studies show that bars with a width smaller than 150 nm were single domain and the switching field depends strongly on the width (therefore the aspect ratio) of the bar. The switching field of the isolated bars first increases with decreasing bar width, then reaches the maximum switching field of 740 Oe with 55 nm wide bars, and afterwards decreases with further reduction of bar width. The switching field of interactive bars decreases almost linearly with the reduction of spacing. The broadness of switching field distribution for interactive bar arrays is 100 Oe.

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