Switching characteristics and magnetization vortices of thin-film cobalt in nanometer-scale patterned arrays

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The switching characteristics and magnetization vortices of 15 nm thick cobalt structures patterned to different widths of 100, 200, and 600 nm were investigated. The effects of linewidth and aspect ratio (length/width) were systematically studied using an alternating gradient magnetometer (AGM), an atomic force microscope/magnetic force microscope (MFM) and superconducting quantum interference device. The AGM and MFM show that trapped magnetization vortices appear in structures with low aspect ratios (length/width)=1.5, 2, but not in structures with high aspect ratio (length/width)=3,4. It is found that the magnetization vortices of these patterned elements are strongly dependent on the width of the element with narrower linewidth more clearly showing the presence of magnetization vortices.
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Magnetic films patterned into nanometer scale can serve as a means of storing information.[1] Magnetic random access memory, such a device under development, is based on the magnetoresistance (MR) of these patterned elements. To compete and succeed as a new memory technology, high-density cells are required. Performance of these MR elements will depend critically on the switching characteristics from one state to another. Understanding the switching behavior of bits as a function of bit size is essential to push the density limits of the technology. The switching characteristics depend sensitively on the geometry of the bit (element length, width, and film thickness) and the material properties (exchange constant, crystalline anisotropy, etc.).[2–6] In this letter, we report on a systematic study of magnetic switching characteristics for patterned magnetic film arrays at nanometer scale with different geometries; different widths 100, 200, and 600 nm at different aspect ratios 1.5, 2, 3, and 4.

A 15 nm thick cobalt film was deposited using magnetron sputtering on 150 nm thick silicon oxide layer atop a silicon substrate. Controlled arrays of nanoscale bits were fabricated utilizing electron beam lithography and followed by ion milling. Each array consists of 10^8 bits. The spacing between bits was varied with bit width and ranged from 0.5 to 5 μm. The easy axis of the material lies along the length of the bit. We have investigated different arrays with different aspect ratios 1.5, 2, 3, and 4 and different bit widths 100, 200, and 600 nm. The arrays of the patterned bits were studied using a Quantum Design superconducting quantum interfaces device magnetometer and an alternating gradient magnetometer (AGM). A Digital Instrument Dimension 3000-atomic/magnetic force microscope (MFM) is used to provide direct remanent state information of each individual bit.

Figure 1 shows the switching field characteristics of different aspect ratios length/width $(L/W)=1.5$, 2, and 3 for a width=100 nm. The switching behavior of the bits is shown to be strongly dependent on the aspect ratio. An aspect ration of 1.5 has a low remanence and a distorted hysteresis curve. The magnetic response at aspect ratio 1.5, and a smaller degree at aspect ratio 2, is due to the formation of magnetization vortices. Structures with higher aspect ratio, $L/W=3$, do not display this behavior, as can be seen by the singular transition in their hysteresis curve. This gradual transition from vortex intermediate state to singular transition with increasing aspect ratio is due to fewer bits going through an intermediate vortex state with increasing aspect ratio. This behavior will be seen in the section summarizing the MFM results.

The magnetization was studied as a function of aspect ratio using micromagnetic simulation based on LLG equations. It was found that the magnetization at aspect ratio $L/W=1$ has no easy axis to rotate and the magnetic flux closes on itself leaving low moment and remanence (vortex state), while increasing the aspect ratio provides a well-defined anisotropy axis,[7] which hinders flux closure through

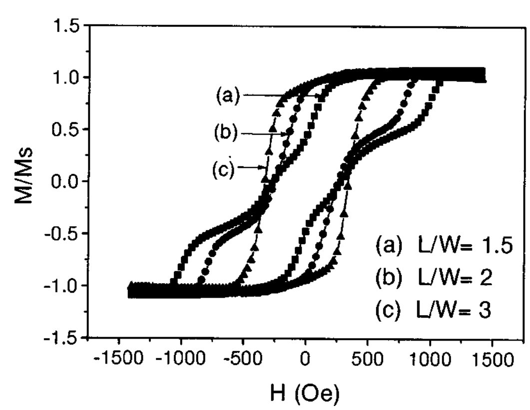

FIG. 1. The magnetic hysteresis loops as a function of applied magnetic field for an element with 100 nm width at different aspect ratios.

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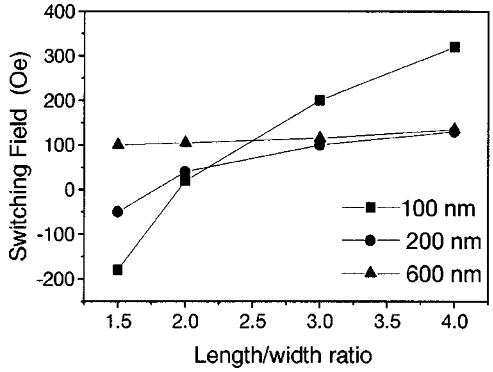

FIG. 2. The switching field vs length/width ratio for elements with different widths.

vortex formation. However, bit width also plays a role in the formation of vortex states. At the widths of 100 and 200 nm, vortices are observed at aspect ratios of 1.5 and 2, but not of 3 and 4. However, bits of width 600 nm display a weak tendency for vortex formation at aspect ratio=1.5, which completely disappear at higher aspect ratios. This means that there is a strong relation between the vortices and aspect ratio and element width.

Figure 2 displays the switching field as a function of the aspect ratio for different widths=100, 200, and 600 nm. The relatively flat behavior of the 600 nm bits, with respect to the aspect ratio, reflects the stability of these bits to vortex formation. In contrast, bits of width 100 nm, and to a smaller degree of 200 nm width, have a higher propensity for vortex formation. This explains the curved behavior in Fig. 2

In the Stoner–Wohlfarth single domain model,[8] switching characteristics of a single domain element are simply determined by their geometric factors and magnetization M. For rectangular thin film elements with the switching field in the easy axis direction, Hc can be approximated by that of a flat ellipsoid and expressed as

$$Hc = t/w\, f(e),$$

and

$$e = (1 - W^2/L^2)^{1/2}, \tag{1}$$

where L, W, and t are the element length, width, and thickness, respectively, and $L \gg W \gg t$; $f(e)$ contains complete elliptic integrals, which are functions of (e) only. For a fixed aspect ratio L/W the single domain Hc should be inversely proportional to the element width W. When compared with our results, this single domain model is not followed, for low aspect ratio bits. This again explains that these bits have a multidomain remanent vortex state.

MFM allows a visual picture of these bits at $H_$applied=0(Oe). Figures 3–5 show the MFM images for different aspect ratios=1.5, 2, 3 for width=200 nm. In these figures we compare the AGM results (the magnetization behavior) with the MFM images. Figure 3 shows the aspect ratio=1.5, where a few bits are found in the single domain state in which the North and South poles appear as white and dark dots, while the rest of the bits are found in a low moment vortex state. This explains the trapping in the magnetization curve as shown in Fig. 3(b). The early switching behavior of these low aspect ratio bits is due to the vast majority of bits entering a vortex state. Figure 4 shows an aspect ratio of 2, a lower percentage of bits is found in a vortex state, and the rest in the single domain state. This explains the higher remanence and sharper hysteresis curve.[9–11] Figure 5 presents an aspect ratio of 3, which has

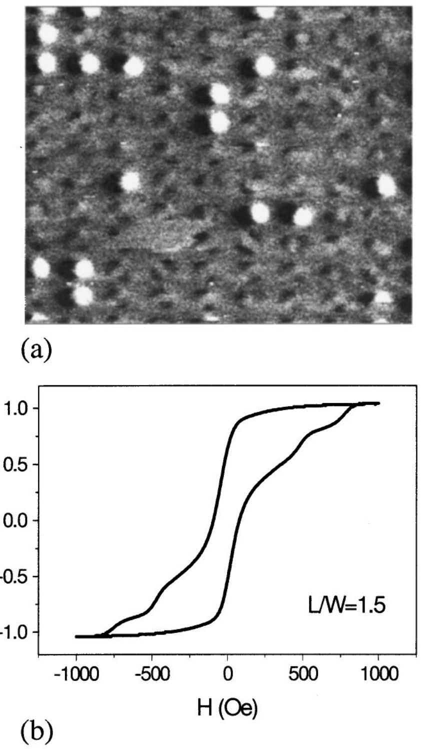

FIG. 3. (a) The MFM image for an element with 200 nm×300 nm dimension ($L/W=1.5$). (b) The magnetic hysteresis loop vs applied magnetic field.

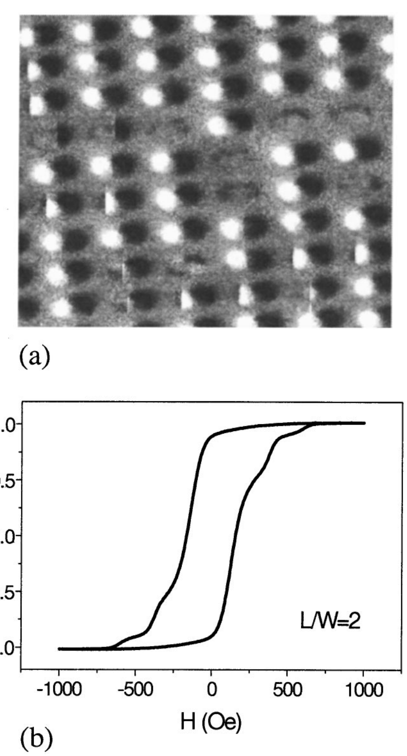

FIG. 4. (a) The MFM image for element with 200 nm×400 nm dimension ($L/W=2$). (b) The magnetic hysteresis loop vs applied magnetic field.

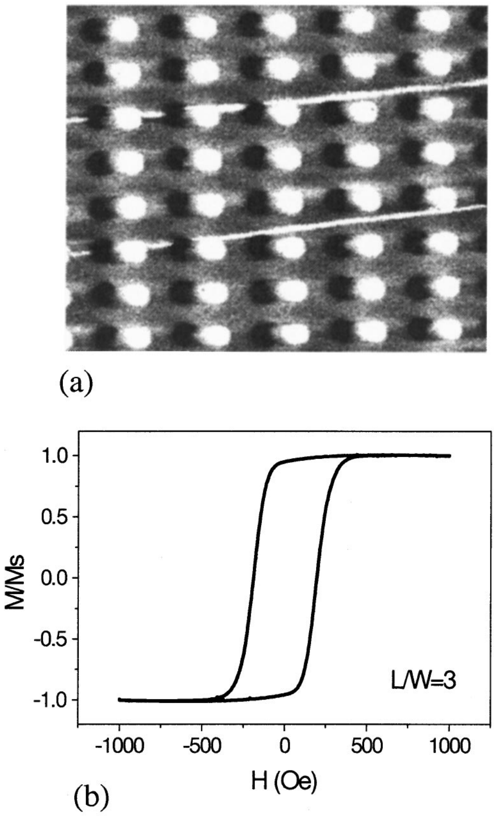

FIG. 5. (a) The MFM image for element with 200 nm×600 nm dimension ($L/W=3$). (b) The magnetic hysteresis loop vs applied magnetic field.

no bits in a vortex state at H_applied=0(Oe) and all the bits are found in the single domain state. Note also that the South Pole of all bits in on one direction, which means the magnetic moment of all bits is the same direction. All bits of this size are aligned along their easy axis. These results are compatible with the AGM results and explain the relation between the magnetization behavior and the aspect ratio.

We have described the switching characteristics of nanometer scale patterned arrays as a function of the aspect ratio. We have observed magnetic vortices in these bits in which the magnetic flux closes on itself. The tendency for vortex formation is found to increase with decreasing aspect ratio and bit width. Ways around this vortex formation will have to be studied to push this memory technology to higher densities.

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[1] R. M. H. New, R. F. W. Pease, R. L. White, R. M. Osgood, and K. Babcock, J. Appl. Phys. **79**, 5851 (1996).
[2] S. Tehrani, E. Chen, M. Durlam, T. Zhu, and H. Goronkin, Tech. Dig. Int. Electron Devices Meet. **96**, 193 (1996).
[3] J. F. Smyth, S. Schutlz, D. R. Fredkin, T. Hoehler, I. R. McFaydlin, D. P. Kern, and S. A. Rishton, J. Appl. Phys. **63**, 4237 (1988).
[4] M. Lederman, G. A. Gibson, and S. Schutz, J. Appl. Phys. **73**, 6961 (1993).
[5] K. J. Kirk, J. N. Chapman, and C. D. W. Wilkinson, Appl. Phys. Lett. **71**, 539 (1997).
[6] Y. F. Zheng and J. G. Zhu, IEEE Trans. Magn. **32**, 4237 (1996).
[7] Y. Otani, S. Gu Kim, T. Kohda, and K. Fukamichi, IEEE Trans. Magn. **34**, 1090 (1998).
[8] E. C. Stoner and E. P. Wohlfarth, Philos. Trans. R. Soc. London, Ser. A **240**, 559 (1984).
[9] Y. Zheng and J. Zhu, J. Appl. Phys. **81**, 5471 (1997).
[10] J. Shi, S. Tehrani, T. Zhu, Y. F. Zheng, and J. G. Zhu, Appl. Phys. Lett. **74**, 2525 (1999).
[11] W. Y. Lee, S. Gardelis, B. C. Choi, Y. B. Xu, C. G. Smith, C. H. W. Barnes, D. A. Ritchie, E. H. Linfield, and J. A. C Bland, J. Appl. Phys. **85**, 6682 (1999).