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Ferromagnetic resonance study of nanoscale ferromagnetic ring lattices

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Square lattices of permalloy rings with different inner diameters (D_i) were fabricated by electron beam lithography and investigated by ferromagnetic resonance (FMR). Results reveal that FMR spectra are sensitive to the ring dimensions. A large shift of the uniform mode from 1200 to 1800 Oe, and a dramatic decrease in its intensity are observed as D_i increases from 0 to 300 nm. Other resonance peaks at fields slightly below the uniform mode greatly increase in intensity and shift to lower field with increasing D_i. An isolated resonance below 200 Oe is also observed. Possible reasons for these variations are discussed. © *2004 American Institute of Physics.*

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I. INTRODUCTION

Nanoscale magnetic elements are of interest because of their potential industrial applications in high-density computer memory, and the interesting physics they exhibit as a consequence of their reduced dimensions. The key issue for device applications is to achieve controlled magnetization switching that is both fast and reproducible. The magnetic switching mechanisms of various geometries, such as wires, rectangles, needles, cylinders, and disks,[1–4] have been studied, but it is found that their magnetic properties are hard to control because they are very sensitive to shape fluctuations and edge roughness introduced during fabrication. Experiments and theoretical calculations[5,6] indicate that ring geometry has much better switching behavior and its zero stray field in the vortex configuration also favors high-density storage. Ring-shaped elements have two stable magnetic states: a complete flux closure or ‘‘vortex state’’ and a polarized ‘‘onion’’ state characterized by the presence of two opposite head-to-head and tail-to-tail domain walls.[7,8] Yoo *et al.*[8] found that in Co nanorings, the stable magnetic configurations depend on the thickness and width of the rings. In soft magnetic nanorings, the vortex state remains stable over a wide field range for rings with diameters extending down to 90 nm (with the ring width kept at 30 nm).[9]

Ferromagnetic resonance (FMR) has been widely used to measure the magnetic properties of bulk magnetic crystals and thin films.[10–12] Spin wave resonance was directly observed via FMR in permalloy films 45 years ago,[13] and more recently it has been shown that FMR is sensitive to the patterned structure of magnetic nanodots.[14] The magneto-optical Kerr effect also has been extensively used in the measurement of nanoring magnets;[6–9] however FMR has not been used previously to characterize nanoring magnets. In this article, we present a systematic FMR study of permalloy nanoring lattices of variable ring width, but constant outer diameter

II. EXPERIMENT

A set of square permalloy ring lattices having constant thickness $t=25$ nm were fabricated using electron beam lithography and lift-off techniques. First, a thin layer of ZEP positive resist was spun onto Si (100) substrates, and then patterned with a Raith 50 electron beam writer system operated at 30 kV. After development, a permalloy film was deposited using electron-beam evaporation in a vacuum of about 10^{-7} Torr, followed by ultrasonic-assisted liftoff in acetone. The four ring lattices were all of the same lateral dimensions of 1.5 mm by 1.5 mm, outer diameter D_0 of 700 nm, spacing $d=1$ μm; but each lattice had a different inner diameter (D_i) 0, 40, 80, and 300 nm, respectively. They are denoted as samples A, B, C, and D, respectively, in the following discussion. Unpatterned permalloy films 25 nm thick were also prepared at the same condition for comparison. An as-deposited permalloy reference film was found to be magnetically soft with coercive and uniaxial anisotropy fields of a few Gauss. The ring lattices were first examined using a Philips XL30 scanning electron microscope (SEM) for structural analysis (see Fig. 1). A Bruker ESP 300E electron paramagnetic resonance spectrometer was used in FMR measurement at room temperature with a microwave frequency of 9.75 GHz, microwave power of 9.50 mW, field modulation amplitude of 10 G, and modulation frequency of 100 Hz. Samples were initially aligned in a plane perpendicular to the magnetic ac field with one edge parallel to the dc field. The samples were then rotated with respect to the dc field direction while keeping the field within the ring lattice plane.

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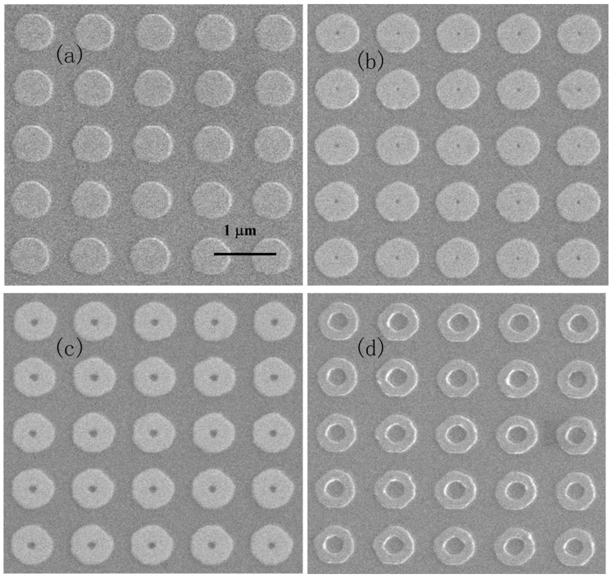

FIG. 1. SEM images of the square permalloy nanoring lattices of 25 nm thickness, 1 μm spacing, 700 nm outer diameter, and 0 (a), 40 (b), 80 (c), and 300 nm (d) inner diameters, respectively.

III. RESULTS AND DISCUSSION

SEM images of the four nanoring lattices are shown in Fig. 1. The uniform contrast of the top surfaces of the rings indicates a very smooth permalloy film. Figure 2 shows derivative FMR spectra of the four samples as a function of angle with respect to the dc magnetic field. For reference, a reference spectrum of the plane permalloy film is also shown [Fig. 2(e)]. The resonance peak of the reference film at ~1150 Oe corresponds to the uniform FMR mode. In sample A $D_i = 0$ [Fig. 2(a)], a large resonance peak is observed at ~1200 Oe, which corresponds to its uniform resonance mode. Two small resonance peaks at ~110 and 1410 Oe are also clearly seen. The very weak peak at ~430 Oe (indicated by an arrow) and the 1410 Oe peak were reported by Jung *et al.*[14] for periodic dot arrays, where the first mode was found to be essentially an exchange-coupled spin-wave mode, and the second resonance was with a "hybrid coupling" of exchange and dipolar interactions. However, the low field resonance peak at ~110 Oe, which most probably comes from a high frequency resonance of individual dots, has not been observed before. For sample B, [$D_i = 40$ nm; Fig. 2(b)], a large uniform resonance peak is observed at ~1330 Oe and two small peaks are observed at approximately 180 and 1610 Oe (i.e., both below and above the uniform mode), and other strong resonance peaks appear near 1100 Oe. Sample C, which has a larger $D_i = 80$ nm [Fig. 2(c)], exhibits a large uniform mode shift to ~1340 Oe, and very strong resonance peaks are seen at near 830 Oe. A small low-field resonance peak is found at almost the same position as in sample B, but the resonance peak above the uniform mode moves to higher field. Sample D is the ring lattice with the largest hole [$D_i = 300$ nm; Fig. 2(d)], and exhibits a low field resonance at ~275 Oe, which is also the strongest peak; the large uniform mode is dramatically reduced, and most interestingly, a series of resonance peaks appear in a broad range extending from ~710 to 2110 Oe.

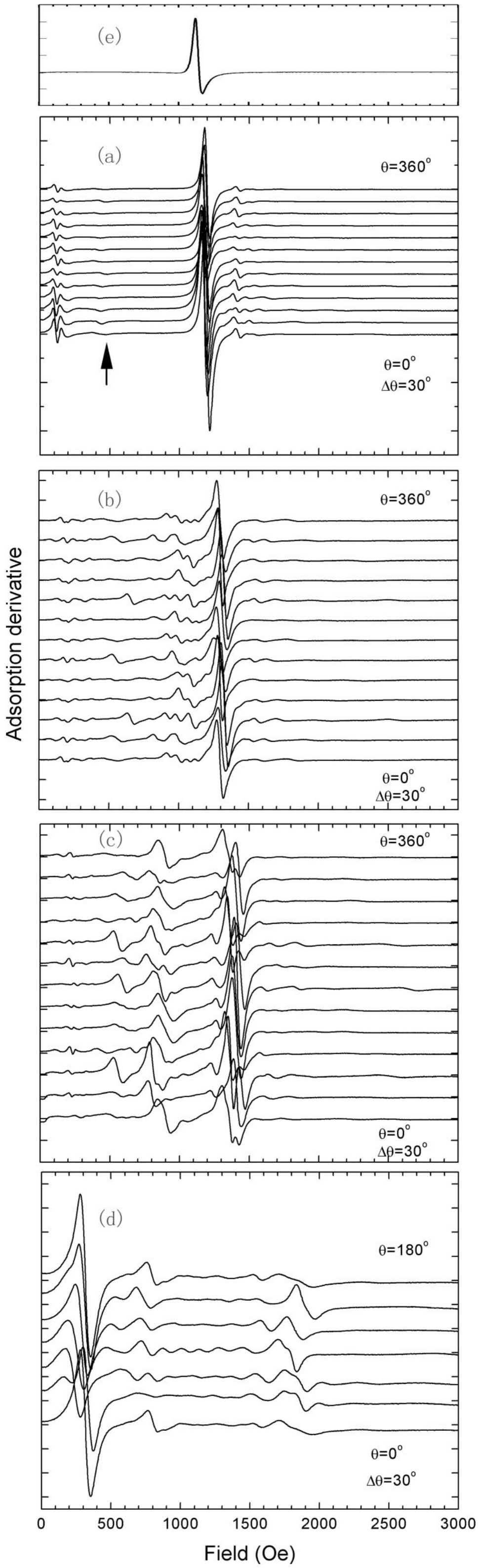

FIG. 2. Room temperature derivative FMR spectra of the nanoring lattices of 25 nm thickness, 1 μm spacing, 700 nm outer diameter, and 0 (a), 40 (b), 80 (c), and 300 nm (d) inner diameters, respectively. θ is the angle between the in-plane applied dc magnetic field and the square ring lattice symmetry axis. (e) Equivalent reference spectrum of a 25 nm thick plane permalloy film.

Comparing the spectra of all samples investigated in Fig. 2, one of the more striking results is that the uniform mode shifts from ~1150 Oe to higher magnetic field ~1800 Oe with increasing inner diameter (i.e., decreasing ring width), and the relative peak intensity decreases dramatically. The uniform mode is characterized by all the spins maintaining a perfect uniform amplitude and phase during precession. However, bulk spins are always different from the boundary or surface spins, which are often pinned by boundary or surface anisotropy imperfections. In patterned films, the edge surface area is increased and the relative number of bulk spins is decreased. As one proceeds from the top to the bottom of Fig. 2, more spins are placed near a surface or edge, and therefore, higher magnetic field is required to stabilize the uniform mode, and the relative intensity of the uniform mode decreases. Another striking trend in Figs. 2(a)–2(d) is that the resonance peaks close to but below the uniform mode greatly increase in intensity and shift to lower field with increasing inner diameter D_i. Considering that the only difference among the samples is the inner diameter, which could affect the spin exchange energy, with the inner diameter increases the ring curvature along the inner edge decreases and the spins are relatively better aligned, which in turn enhances the corresponding peak intensity and decreases the resonance field.

From the point of view of angular symmetry, samples of smaller D_i show better symmetry than samples of bigger D_i since for narrower rings, edge roughness or imperfections provide more signals relatively, which reduce the symmetry of the ring lattices. The lattice of $D_i=0$ exhibits an almost perfect fourfold symmetry as it should due to its square lattice structure [Fig. 2(a)]. The ring lattice with smallest $D_i=40$ nm [Fig. 2(b)] exhibits a perfect twofold symmetry and a reasonably good fourfold symmetry. Both samples with larger inner diameters $D_i=80$ and 300 nm, respectively, exhibit a near-perfect, twofold symmetry and a moderately good fourfold symmetry. This is probably a direct consequence of increased defects density (e.g., edge imperfections or thickness modulations) introduced during sample fabrication. As shown in the SEM images (Fig. 1), the dot and ring structures are not perfect and flattened edges are apparent. With increasing inner diameter, the imperfections of the structures are more visible. For sample D, the ring lattice with the largest hole, nominally flattened edges are observed along both inner and outer edges. In this sense, deviations from perfect fourfold symmetry do reflect the edge imperfections of the entire dot or ring lattices.

IV. CONCLUSIONS

Systematic FMR measurements have been performed on a set of permalloy ring lattices of similar dimensions but with different inner diameters. Prominent spectra variations are found to accompany changes of the ring inner diameter. The results clearly indicate that FMR spectra are extremely sensitive to the detailed structure of the nanomagnets, which indicates FMR can be applied as a sensitive probe of the fabrication quality of nanomagnet arrays. Moreover, FMR is a convenient method that provides magnetic information on the entire sample. Systematic micromagnetic simulations are necessary to fully understand the FMR spectra, and such efforts are currently underway in our laboratory.

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[1] J. Yu, U. Rüdiger, L. Thomas, S. S. P. Parkin, and A. D. J. Kent, J. Appl. Phys. **85**, 5501 (1999).
[2] K. J. Kirk, J. N. Chamman, S. McVitie, P. R. Aitchison, and C. D. W. Wilkinson, Appl. Phys. Lett. **75**, 3683 (1999).
[3] M. Schneider, H. Hoffmann, S. Otto, Th. Haug, and J. Zweck, J. Appl. Phys. **92**, 1466 (2002).
[4] R. P. Cowburn, D. K. Koltsov, A. O. Adeyeye, and M. E. Welland, Phys. Rev. Lett. **83**, 1042 (1999).
[5] S. P. Li, D. Peyrade, M. Natali, A. Lebib, and Y. Chen, Phys. Rev. Lett. **86**, 1102 (2001).
[6] J. G. Zhu, Y. Zheng, and G. A. Prinz, J. Appl. Phys. **87**, 6668 (2000).
[7] J. Rothman, M. Kläui, L. Lopez-Diaz, C. A. F. Vaz, A. Bleloch, J. A. C. Bland, Z. Cui, and R. Speaks, Phys. Rev. Lett. **86**, 1098 (2001).
[8] Y. G. Yoo, M. Kläui, C. A. F. Vaz, L. J. Heyderman, and J. A. C. Bland, Appl. Phys. Lett. **82**, 2470 (2003).
[9] L. J. Heyderman, C. David, M. Kläui, C. A. F. Vaz, and J. A. C. Bland, J. Appl. Phys. **93**, 10011 (2003).
[10] W. S. Ament and G. T. Rado, Phys. Rev. **97**, 1558 (1955).
[11] L. R. Walker, Phys. Rev. **105**, 390 (1957).
[12] C. Kittel, Phys. Rev. **110**, 836 (1958).
[13] M. H. Seavey, Jr. and P. E. Tannenwald, Phys. Rev. Lett. **1**, 168 (1958).
[14] S. Jung, B. Watkin, L. DeLong, J. B. Ketterson, and V. Chandrasekhar, Phys. Rev. B **66**, 132401 (2002).