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Magnetic anisotropy in a permalloy microgrid fabricated by near-field optical lithography

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We report the fabrication and magnetic properties of permalloy microgrids prepared by near-field optical lithography and characterized using high-sensitivity magneto-optical Kerr effect techniques. A fourfold magnetic anisotropy induced by the grid architecture is identified. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1379048]

An understanding of the magnetic anisotropy in patterned ferromagnetic structures is important for the design and optimization of high-density data storage and integrated magnetoelectronic devices.[1] The anisotropy strongly depends on the pattern geometry in the submicrometer regime. For example, a configurational anisotropy can be found due to the small deviation of the magnetization from the uniform state in square dots[2] and a strong uniaxial anisotropy can be obtained in submicrometer magnetic wires.[3,4] Magnetization anisotropy behaviors are expected in more complex geometries. Two-dimensional (2D) microgrids are significantly different from the extensively studied zero[5,6] (dots) and one[3,4,7] (wires) dimensional patterned structures, since the microgrid geometry introduces a fourfold anisotropy. In addition, the 2D grids can be used to design materials with properties that depend on the magnetic dispersion. In this work, we have studied the fabrication and the magnetization reversal of submicrometer grids prepared by high-resolution near-field optical patterning and high-sensitivity magneto-optical Kerr effect (MOKE) measurements. A fourfold magnetic anisotropy is found in the microgrid structure and that can be described by a double uniaxial system in a perpendicular geometry.

The near-field optical lithography (NFOL) enables simple submicrometer resolution patterning with a flexible polymeric mask under conformable microcontact conditions. Figure 1 shows the fabrication principle and process. A prepolymer of polydimethlysiloxane (PDMS) cast and cured against an x-ray lithography patterned master forms an elastomeric mask that is transparent to visible and near-ultraviolet light (UV).[8] High resolution features can be obtained by exposing the photoresist with an UV light through the PDMS mask. With a transparent PDMS mask having topographic features with a π-phase shift thickness, for example, resist features as small as 100 nm can be obtained because of the light propagation edge effect. Typically, a circular disk on the PDMS results in a ring feature in the resist with the same diameter [Fig. 1(a)]. When the disk size is small enough, the ring contrast will be reduced and a single small dot develops. For the grid fabrication a PDMS mask with a pattern as shown in Fig. 1(b) can be chosen. Here we have utilized a mask with a pattern of circular dots with a small separation. The polycrystalline permalloy ($Ni_{80}Fe_{20}$) film with a 3 nm Au capping layer was deposited by e-beam evaporation on a Si(001) substrate. A thin layer poly(methylmethacrylate) (PMMA) resist was first coated on the sample surface and prebaked at 70 °C for 30 min. Then a 10-nm-thick germanium layer was deposited by sputtering, followed by spin coating of the top layer photoresist (AZ 5214 E). After baking at 120 °C for 1 min the PDMS mask was placed in contact with the sample. Because the mask is elastomeric, a conformal mask–sample contact is guaranteed. Exposures were done with 405 nm light, followed by a development in AZ 726 MIF solution. The PMMA patterns on the sample surface are then defined by sequential reactive ion etching with SF_6 and O_2 plasma, respectively. The patterns are subsequently transferred to the magnetic film by ion milling. Direct wet etching can also be used to transfer patterns into permalloy without above PMMA and Ge deposition processes. The etching solution is HNO_3:HCl:H_2O $=1:3:20$.

Figure 2(a) shows the scanning electron micrograph (SEM) of a PMMA resist dot array and 20-nm-thick permalloy dot array obtained by ion milling with the PMMA dot array as the etching mask (inset). To increase the contrast of the image the Si substrate was slightly etched by a SF_6+CHF_3 plasma. A microstructure of 10-nm-thick permalloy grid defined by NFOL and subsequent wet etching is shown in Fig. 2(b). Typical MOKE hysteresis loops measured on patterned films are shown in Fig. 3. For 400-nm-diameter and 20-nm-thick dots the hysteresis loop [loop(a)] indicates the existence of a vortex state.[6] However, the hysteresis loops for the 10-nm-thick dots with the same diameter show a high remanence [loop(b)] which is characteristic of single-domain behavior and magnetization reversal occurs by coherent spin rotation.[6]

A MOKE loop measured in the diagonal direction of the grid is shown in Fig. 3(c). The angular dependence of the

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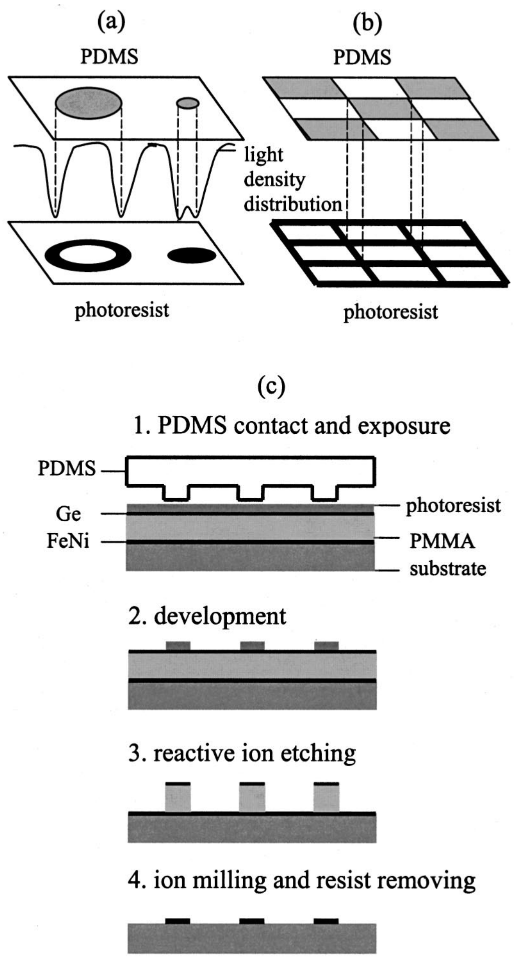

FIG. 1. Schematic illustration of principles of dots (a), grid (b) fabrication, and pattern transfer process(c).

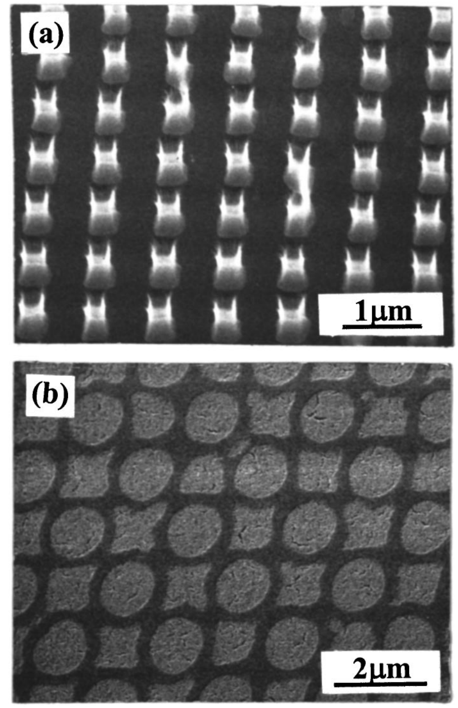

FIG. 2. (a) SEM images of PMMA resist pattern and 20-nm-thick permalloy dot array obtained by ion milling (inset). (b) A microstructure of 10-nm-thick permalloy grid defined by NFOL and subsequent wet etching.

remanence measured from MOKE loops is presented in Fig. 4(a), where θ is the angle between a given arm of the grid and the applied field direction. Although the MOKE loops measured along different directions have similar shape, a fourfold symmetry of the remanence still can be defined and it oscillates between a minimum (~0.5, along the grid edges) and a maximum (~0.7, along the diagonal direction of the grid). A small coercive field oscillation with fourfold symmetry is also observed.

In the following, we present a description of the remanence behavior which takes into account the anisotropy induced by the grid. The approach is based on treating the two arms of the microgrid as uniaxial strips with their axes at 90°. When a magnetic field H is applied in the grid plane at an angle ϕ with respect to one (vertical) arm of the grid, the magnetization in the two arms is oriented at angles φ_1, φ_2 with respect to the grid arms [Fig. 4(b)]. The magnetic anisotropy energy in the grid can be described as

$$E_a = C(\sin^2 \varphi_1 + \sin^2 \varphi_2), \tag{1}$$

where C is a constant. Here we use this equation to obtain the remanence values along the arm and the diagonal direction of the grid. The total energy in the system, defined by the magnetic anisotropy energy and the Zeeman energy is

$$E = C(\sin^2 \vartheta_1 + \cos^2 \vartheta_2) - \tfrac{1}{2}\mu_0 H M_s \cos \vartheta_1 - \tfrac{1}{2}\mu_0 H M_s \cos \vartheta_2, \tag{2}$$

where $\vartheta_1 = \phi - \varphi_1, \vartheta_2 = 90° - \phi - \varphi_2$. In the static case: $\partial E/\partial \vartheta_1 = \partial E/\partial \vartheta_2 = 0$, and for the remanent state $H=0$. From Eq. (2) we have

$$2C(1-\cos^2 \vartheta_1)^{1/2} \cos \vartheta_1 = 0,$$
$$2C(1-\cos^2 \vartheta_2)^{1/2} \cos \vartheta_2 = 0. \tag{3}$$

There are two solutions for Eq. (3): ($\cos \vartheta_1 = 1, \cos \vartheta_2 = 0$) and ($\cos \vartheta_1 = 0, \cos \vartheta_2 = 1$). The remanent magnetization M_r is given by

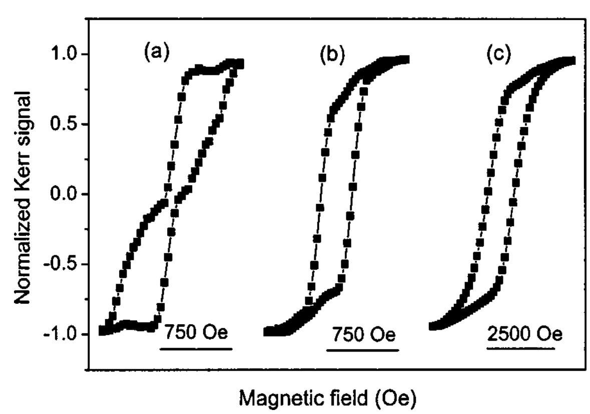

FIG. 3. Typical MOKE loops measured on patterned permalloy films. Loops (a) and (b) were taken on 400-nm-diameter dots with a thickness of 20 and 10 nm, respectively. Loop (c) was obtained in the diagonal direction of the grid.

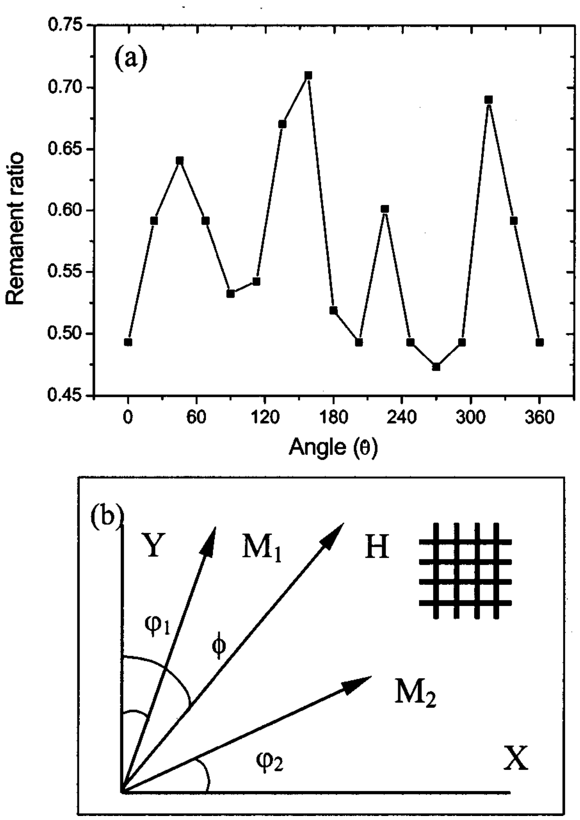

FIG. 4. Angular dependence of the measured remanent ratio on permalloy grid (a) and magnetization vectors of grid in an external field (b).

$$M_r = \frac{M_s}{2}(\cos \vartheta_1 + \cos \vartheta_2) = \frac{1}{2} M_s . \tag{4}$$

This agrees well with the experimental result for $\phi = 0$. Now we consider a magnetic field applied in the diagonal direction, i.e., $\phi = 45°$. A similar derivation process yields

$$2C(2\cos^2 \vartheta - 1) = 0 \quad \text{and} \quad \cos \vartheta = \frac{M_r}{M_s} = \frac{\sqrt{2}}{2}. \tag{5}$$

Again, this agrees with the experimental observation. Finally, we note that the above expression to apply requires the existence of a well-defined shape anisotropy in the wires, i.e., requires that the length is much larger than the width of the wire segments. In addition, the crystalline anisotropy in the magnetic film must be small.

In summary, we have fabricated a permalloy grid and dot arrays with submicrometer resolution over large areas by near-field optical lithography. Compared with conventional nanofabrication techniques, near-field optical lithography is low cost, easy to use, and promising for obtaining deep submicrometer resolution. MOKE measurements have been performed on the fabricated structures which confirm a vortex and single domain state of the dots according to the film thickness. A fourfold anisotropy induced by the grid architecture is found which can be described by a double uniaxial system.

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