Nanoscale ferromagnetic rings fabricated by electron-beam lithography

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We have fabricated nanoscale ferromagnetic rings using electron-beam lithography with a lift-off process for pattern transfer. The resist thickness and electron-beam dose were tailored to produce 10 nm thick rings with outer diameters down to 90 nm. Arrays of rings were produced for magneto-optical Kerr effect measurements which show that down to the smallest diameters, reproducible magnetic switching into the flux-closure vortex state is maintained. © 2003 American Institute of Physics. [DOI: 10.1063/1.1577224]

I. INTRODUCTION

Nanoscale magnetic elements are of current interest because of both the interesting physics at reduced lateral dimensions and the possible industrial applications. For such applications, it is important to have precise control of magnetic switching, which can be achieved when the magnetic elements have a well-defined and reproducible remanent state and the switching processes are simple. The ring geometry has so far displayed these desired characteristics and has a good potential for use in high-density data storage^{1,2} and biodetection.³

Up until now we have thoroughly investigated the magnetic switching in rings with diameters down to 500 nm using primarily magneto-optical Kerr effect (MOKE) measurements and have demonstrated that the rings have particularly simple magnetic states due to their high symmetry. We have shown that in narrow rings, there are two stable magnetic states;^{4–6} the flux-closure vortex state [Figs. 3(a) and 3(c)], and the “onion” state, accessible reversibly from saturation and characterized by the presence of two opposite head-to-head walls [Figs. 3(b) and 3(d)]. Thus two transitions occur in these rings; at intermediate fields, the rings switch from the onion to the vortex state and at high fields they switch from the vortex to the opposite onion state.^{4,7} In addition, we have directly observed the magnetic configurations by photoemission electron microscopy (PEEM) and scanning electron microscopy with polarization analysis (SEMPA),⁸ providing detailed information on the spin structure of the different magnetic states present during a hysteresis cycle.

For device applications such as data storage, the size of the rings has to be scaled down to achieve high densities while maintaining the requisite magnetic characteristics. However, from our micromagnetic simulations,⁹ it can be seen that as the lateral size of the rings is reduced, the vortex state becomes more and more unfavorable due to the increasing curvature of the ring which results in an increased exchange energy. Since it is the stray field-free vortex state that has been suggested for applications in data storage,² it is of

paramount importance to establish whether the vortex state can be attained when the lateral dimensions are reduced. In the present work, we therefore address two key questions regarding scaling down of the lateral dimensions, first how small the rings can be fabricated using electron-beam lithography and second, how the magnetic states and the switching processes are affected as the lateral sizes are reduced.

II. FABRICATION

We employed electron-beam lithography to fabricate magnetic rings. This involves the manufacture of a patterned polymer resist mask followed by transfer of the pattern into the magnetic material. In the first step, a poly (methylmethacrylate) (PMMA) resist, spincoated on a naturally oxidized Si(001) substrate, is patterned using a Leica LION LV1 electron-beam writer. To write the rings, the electron beam follows a circular single pixel path along the ring and the linewidth is determined by the electron-beam dose.¹⁰ The electron-beam energy is set to 2.5 keV to minimize the proximity effect. For pattern transfer, a lift-off process is used. Here, 10 nm polycrystalline permalloy (NiFe) films, with a 2 nm thick gold capping layer to prevent oxidation of the magnetic film, are deposited on the patterned resist on silicon by molecular-beam epitaxy (MBE) evaporation in a ultrahigh vacuum deposition chamber (base pressure 3×10^{-10} mbar). The unwanted resist and magnetic material is then removed in acetone.

To determine the smallest size of ring that we can fabricate, a set of test rings was written with varying diameters ranging from 500 nm down to 30 nm. The minimum linewidth was determined by gradually varying the electron-beam dose and a linewidth of 30 nm was achieved. We used three different resist thicknesses of 25, 35, and 50 nm. The thinner resists provide the smallest feature sizes because as the thickness of the resist increases, the aspect ratio of the structures in the resist increases and the narrowest features in the resist will collapse. However, it is also useful to see what ring diameters are achievable with thicker resists, which will allow fabrication of thicker magnetic elements. For our lithography process, the minimum feature size obtainable is

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FIG. 1. SEM images of the smallest rings achievable for three different PMMA resist thicknesses. The linewidth is 30 nm and the outer diameter is given in the box for each image.

comparable to the resist thickness, so 25, 35, and 50 nm for the three different resist thicknesses, and for lift off, the magnetic material should be no more than two thirds the resist thickness, so 17, 23, and 33 nm. For the current trials, we grew a magnetic film with a 10 nm thickness and a 2 nm Au capping layer to ensure that the lift off worked. The smallest rings achieved for the three PMMA thicknesses of 50 nm, 35 nm, and 25 nm had a linewidth of 30 nm and outer diameters of 140, 120, and 90 nm, respectively (see Fig. 1).

$60\text{ }\mu\text{m} \times 60\text{ }\mu\text{m}$ arrays of the smallest rings achievable were produced in order to determine the reproducibility of the ring fabrication and also to provide large areas of rings so that a sufficiently large signal during MOKE measurements is obtained. The ring arrays were written in the 25 nm thick PMMA resist with linewidth of 30 nm and outer diameters

FIG. 2. Arrays of the smallest rings used for MOKE analysis. The linewidth is 30 nm and the outer diameter is given in the box for each image.

FIG. 3. MOKE measurement showing double switching in a ring with 110 nm outer diameter.

ranging from $1\text{ }\mu\text{m}$ down to 80 nm. The center-to-center spacing of the rings was set to be twice the ring diameter to avoid interaction due to dipolar coupling between the rings. Scanning electron microscope (SEM) images of the smallest arrays are shown in Fig. 2. The smallest rings achievable had an outer diameter of 90 nm. For an outer diameter of 80 nm, the central post of the ring was not present in the resist resulting in an array of magnetic dots and in many areas the magnetic film between the dots did not lift off, leaving a continuous film of permalloy covering more than half of the array. For some of the rings, although the central post of the ring was present in the PMMA resist, the magnetic material in the center of the ring did not lift off. This became more appreciable for the ring array with 90 nm outer diameter, which also contained some magnetic dots and misshaped rings.

III. MAGNETIC MEASUREMENTS

The arrays were measured using MOKE. As the area coverage of the rings with 30 nm linewidth becomes very small as the ring diameter increases, measurements became increasingly difficult, so the maximum ring size measured had a 500 nm diameter. While a thick magnetic layer will favor the vortex state,⁷ we are here limited to a thickness of around 10 nm to ensure a lift off with the 25 nm thick PMMA resist. We therefore chose to deposit permalloy, a soft magnetic material which is more likely to attain the vortex state. For all rings down to the minimum outer diameter of 90 nm, a double switching process is observed and the vortex state is stable over a wide field range as seen in Fig. 3 where, as an example of the magnetic measurements, the hysteresis loop for the 110 nm ring array is shown. The high switching field of the vortex to reverse onion transition can be explained by the fact that the ring width is narrow as also observed in Ref. 7. A detailed study of the size dependence of the switching fields will be published in Ref. 14. For the array of dots with 80 nm outer diameter, single switching at very low fields is present due to the fact that most of the array has not lifted off resulting in the measurement of a continuous film.

IV. CONCLUSION

Nanoscale ferromagnetic rings have been fabricated by electron-beam lithography with lift off and retain the same magnetic switching configurations as found in previously studied larger rings. The smallest rings fabricated have an outer diameter of 90 nm, inner diameter of 30 nm, and thickness of 10 nm. This work has confirmed that sub-200 nm rings can be fabricated down to the diameters suitable for industrial applications and that they exhibit useful magnetic properties. In particular, using a soft magnetic material, the vortex state can be stabilized even in the smallest rings. In order to further reduce the dimensions of the rings, it would be possible to improve the lift-off process by using a thicker PMMA resist with a higher electron-beam energy. Even smaller rings may be achievable using one of the more exotic high-resolution electron-beam resists.^{11–13}

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