In-plane anisotropy of coercive field in permalloy square ring arrays

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Magnetic ring arrays are promising candidates for application in magnetic random access memory devices. The magnetic reversal processes and anisotropy of the coercivity in arrays of square-shaped nanorings with different spacings were investigated by vector magneto-optical Kerr effect magnetometry, magnetic force microscopy, and micromagnetic simulations. Two-step magnetization reversal demonstrates fourfold symmetry in the film plane resulting from the shape anisotropy in rings. Our numerical simulations show good agreement with the experiment. © 2006 American Institute of Physics. [DOI: 10.1063/1.2171949]

INTRODUCTION

Magnetic nanostructures demonstrate a wealth of magnetic properties, which are extremely sensitive to shapes and the order of nanoelements strongly interacting via exchange and dipolar coupling. From a technological point of view, such materials are important for applications in magnetic recording and, in particular, for rapidly developing magnetic random access memory (MRAM) devices. Magnetic nanorings are among the most promising candidates for the future MRAM applications. Their main advantage stems from the presence of a hole in the center of the ring, which eliminates the highly energetic vortex core existing in a dot element. Recently, magnetic properties of arrays with square-shaped nanorings have been reported in several publications. However, these studies have concentrated on magnetic reversal for magnetic fields along the main symmetry directions and specific arrays with well-separated ring elements. In this work we explore the in-plane anisotropy of coercive field in permalloy square nanoring arrays with different spacings to understand the impact of shape-induced magnetic anisotropy and interelement dipolar interactions.

SAMPLE PREPARATION AND MAGNETIC MEASUREMENTS

In this work we study three arrays of permalloy nanorings with different interelement spacing distances of 45, 70, and 200 nm. Below we refer to these samples as P45, P70, and P200, respectively. Figure 1 shows a scanning electron microscopy (SEM) image for the first array. In all arrays the dimensions of square rings are 950 nm for the lateral size, 200 nm for the side width, and 25 nm for the thickness. In the preparation a standard 3 in. (100) silicon wafer was spin coated with bilayer resists polymethyl methacrylate (PMMA) and P(MMA-MAA) copolymers and baked. The wafer was then placed into a Raith e-beam writer and desired patterns consisting of ring elements were written. Using e-beam evaporation in a high-vacuum chamber with a typical evaporation rate of 0.1–0.2 Å/s a 25 nm permalloy film was deposited onto the holes in the resist. After a lift-off in ac-

FIG. 1. SEM image of the P45 array of square-shaped 950 nm nanorings with 45 nm separation.

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etone the arrays of magnetic permalloy rings were obtained. Using longitudinal magnetooptical Kerr effect (MOKE) with both longitudinal and transverse magnetic fields we have measured the hysteresis loops for parallel and transverse components of magnetization. Measurements of $M$ vs $H$ curves were performed at room temperature for magnetic fields in the film plane with various angles between the field direction and the edge of the rings. The magnetic force microscope (MFM) images were obtained with a Digital Instruments 3000 scanning probe microscope using lift mode with a fly height of 100 nm and a standard low-moment ferromagnetic tip. Magnetic simulations have been done using OOMMF software suite. 8

RESULTS AND DISCUSSION

Our measurements demonstrate that magnetization reversal is normally realized by a two-step process and is affected strongly by the direction of the applied magnetic field.
magnetostatic energy $E_{ms}$ we can reproduce our experimental behavior in the framework of a simple model based on Stoner-Wohlfarth approach.\(^9\) Describing the energy variations as $\Delta N M_r^2 \sin^2 \varphi/2$ and $\Delta N M_r^2 \cos^2 \varphi/2$ for the parallel and transverse sides of the ring, respectively, and taking $\Delta H_r = \Delta E_{ms}/M_r$ we obtain the best fit for $\Delta N = 0.08$, which is well comparable with the difference in the demagnetizing factors for ring sides of $\Delta N = 0.11$.

With the magnetic field parallel to the diagonal direction ($\varphi = 45^\circ$) we would expect a single transition from the symmetry consideration, which also agrees with the numerical simulations. Presence of two transitions may originate from small misalignment in the sample plane or some mosaic spread in the effective directions of squares resulting from the accuracy of lithography. The possible impact of interelement dipolar interaction is planned to be explored by numerical simulations.

Experimental results for the first switching field $H_{s1}$ demonstrate the relatively small effect of spacing between the rings. As the spacing decreases, the coercivity slowly decreases. This can be explained by the increased coupling between the square rings, which decreases demagnetizing effects and make the behavior more similar to an unpatterned film. Indeed the demagnetizing field of noncompensated poles on the surface of a ring tend to be compensated by the opposite poles of neighboring element decreasing the shape anisotropy and resulting into decreased coercivity for closer-spaced elements.

CONCLUSIONS

In conclusion we have studied the in-plane anisotropy of the magnetic properties in two-dimensional arrays of square nanorings. The pronounced two-step magnetization processes have been analyzed using vector MOKE. The shape of the rings affects the magnetization process significantly leading to a fourfold anisotropy of the switching fields. The experimental results demonstrate a rather weak impact of interelement interactions with decreasing coercivity for smaller interelement spacing.

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\(^{8}\)M. J. Donahue and D. G. Porter, OOMMF Version 1.0; http://math.nist.gov/oommf