Application of mesoscopic magnetic rings for logic devices

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Abstract — **We present a combined experimental and theoretical study of the ground and metastable states in micron-size ferromagnetic rings as a function of the ring geometry. Our goal is to evaluate the applicability of magnetic ring structures with their bi-directional ground states for applications in magnetic quantum-dot cellular automata (MQCA) structures [1]-[2].**

Index Terms — **magnetic devices, magnetic QCA, nano-magnetism, ring geometry, simulation.**

I. Introduction

Magnetic memory and logic devices based on magnetic nano-structures represent a fast growing field in which combined theoretical and experimental study of micromagnetism implements innovative designs. Well-established applications include magnetic random access memories (MRAM), hard disk drive (HDD) media and head sensors, and other spintronic applications. In addition to these (mostly memory applications), magnetically-coupled logic devices have been proposed which process information in an entirely magnetic way [1]-[3]. These novel structures consist of either dipole-dipole coupled single-domain nanomagnets or narrow ferromagnetic wires in which the propagation of domain walls could be controlled by local magnetic fields. Here, we propose a related design for magnetic logic devices based on building blocks of exchange-coupled (touching) rings.

Very recently, micron and submicron-size ferromagnetic rings have attracted considerable attention. Narrow ring structures were found to exhibit two types of stable magnetic states: polarized (so-called "onion") states, where field lines split around the center in opposite directions with head-to-head and tail-to-tail domain walls at opposite sides, and totally flux-closed (so-called "vortex") states, where field lines encircle the center with either clockwise or counter-clockwise rotation. Zhu et al [4] proposed to use the chiralities of the vortex states (the rotation direction of magnetization) in circular rings as the carriers of information for data storage.

In this work, we investigate isolated and touching rings with various widths for application in all-magnetic logic devices.

II. Experiment and Simulation

20 nm thick permalloy rings with 1 μm outer diameter and various line widths ranging from 200 to 400 nm were fabricated by combination of electron beam lithography, e-beam evaporation, and lift-off techniques. The fabrication of wide rings (small inner diameter) presents a challenge and requires an optimization of the e-beam resist parameters [5] due to the narrow post in the middle. For this reason, we employed single-layer resist with thicknesses between 70 to 200 nm.

The magnetic structures were characterized by magnetic force microscopy (MFM), which gives images of sample magnetization with contrast proportional to the second derivative of the z-component of the local magnetic field above the sample. The maximum stray fields at the domain boundaries appear as dark and bright spots in the MFM images.

For the simulations, we used the object oriented micromagnetic framework (OOMMF) [6] code developed by the National Institute of Standards and Technology. The 2D simulations were performed for 20 nm thick geometries of polycrystalline permalloy (K_u=0).

III. Results and Discussion

Figure 1 shows the calculated remanent states of in-plane magnetized ring with 800 nm outer diameter and three different widths (150 nm, 250 nm, and 350 nm).

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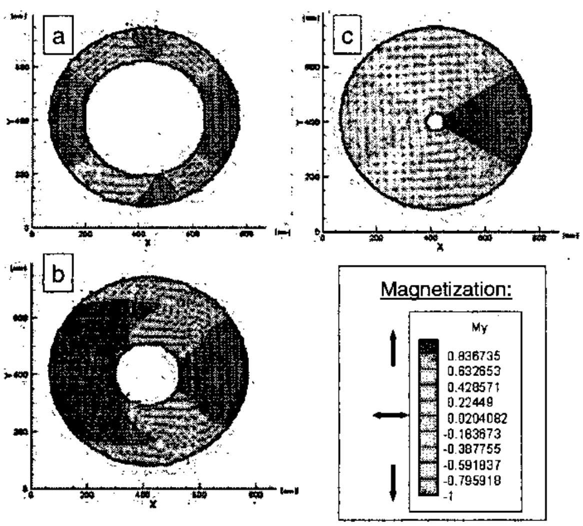

Fig. 1. OOMMF simulation of the remanent states of rings with 800 nm outer diameter and different widths (150 nm, 250 nm, and 350 nm) after relaxation from an initial completely magnetized in-plane state: (a) onion state with transverse domain walls in the narrow ring, (b) vortex-type domain walls for the intermediate case, and (c) vortex state for the wide ring.

For the case of the narrowest ring in Fig. 1 (a), the remanent state is the onion state. In wide rings (with large inner and outer circle diameter ratio), the domain walls are expected to undergo a transition from initially transverse domain walls (head-to-head domains) to vortex-type domain walls. This type of behavior was predicted by McMichael and Donahue [7] for magnetic strips with varying widths. The vortex-type domain walls can provide stable magnetic states at remanence, as shown in Fig. 1 (b). However, if the vortex cores are not constrained by local shape anisotropy, they can move along the ring and annihilate, and, as a result, wide rings relax to vortex remanent state as the external field is removed (Fig. 1 (c)). The switching process of wide rings is demonstrated in detail in Fig. 2.

The vortex state, as an intermediate magnetic configuration in the reversal process from onion state to the onion state of opposite polarity, was studied earlier by Li et al [8] and Klaui et al [9]. They found that the nucleation of the high-energy cores is dependent on the thickness and the value of magneto-crystalline anisotropy of the material, i.e. the local vortex formation is more favorable when the rings are thicker and have less magneto-crystalline anisotropy. We used these results when we chose permalloy (a soft magnetic material) for the study.

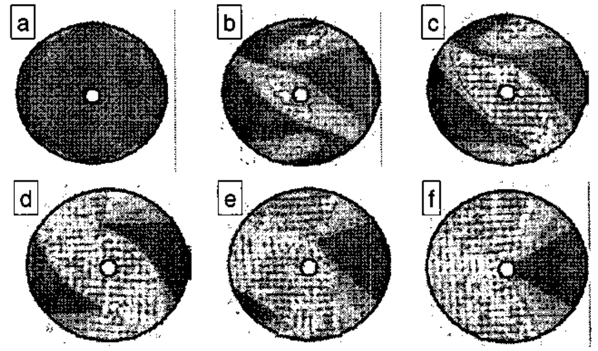

Fig. 2. Steps in the relaxation process of a wide ring from an initial completely polarized state (a) trough the nucleation of vortex-type domain walls and their annihilation to the vortex state at remanence (f). In (e), we observe the upper, counter-clockwise domain wall to become dominant n defining the chirality of the remanent vortex state. The other, clockwise domain wall is expelled from the ring.

In addition to the above case of individual rings, we also studied chains of coupled rings. Our simulations of a line of touching rings showed that the neighbors have a great influence on the domain formation and on the switching process in a given ring. This is due to the sensitivity of the high-energy cores (vortex-type domain walls) to local anisotropies such as the shape anisotropy.

Fig. 3 shows chains of wide rings in the remanent state after an external magnetic field was applied horizontally. As a preliminary result, we can confirm that the captured magnetic configuration is qualitatively the same for each ring in the upper chain, which denotes well-defined domain structure in a metastable state. In contrast, we observe coupled switching in the pairs of rings (opposite contrast).

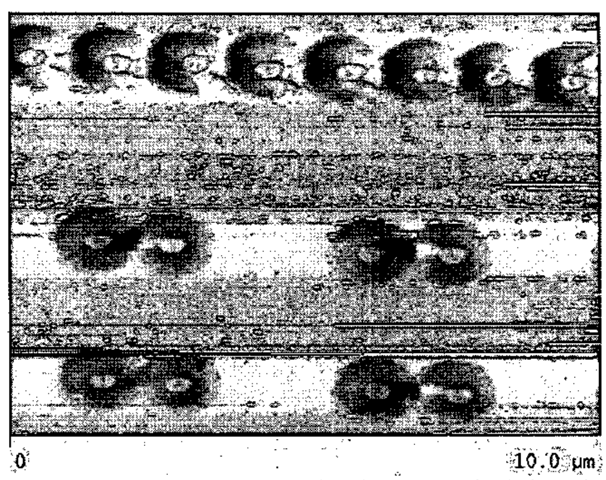

Fig. 3. MFM image of 500 nm wide rings magnetized along the chain

It was found earlier that the magnetization process of chains of touching rings displays a clear anisotropy [10], [11]. For fields perpendicular to the chain direction the switching occurs pair-wise [10]. For fields applied parallel to the chains, the switching of the edge ring element triggers the switching process, and extended sections of the chains were found to switch simultaneously. In these sections, neighboring rings display vortices of alternating chirality [11] similar to the interlocking gears in gear trains (shown in Fig. 4 (b)). A chain of 2, 4 or 6 touching rings switching into alternating vortex states can be seen as an inverter chain and represents the basic for digital computation. Wide rings with two remanent vortex states (clockwise and counter-clockwise) appear to be promising candidates for MQCA [2]. However, suitable clocking schemes have to be developed.

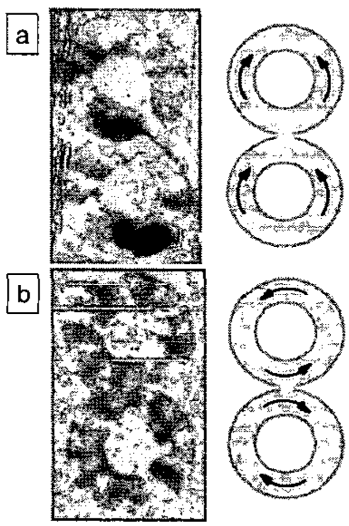

Fig. 4. MFM image and schematic representation of magnetization of two touching rings in: (a) onion states and (b) vortex states. The rings display vortices of alternating chirality similar to the interlocking gears in gear trains.

Fig. 4 shows pairs of 250 nm wide touching rings (a) in onion and (b) in vortex state. In the onion state, two head-to head domain walls in the ring correspond to the dark and bright areas. The fine alternating pattern of dark and bright stripes in MFM images of the rings in the vortex states were observed earlier by Lorentz microscopy in larger Co rings [8], and were attributed to "magnetic ripples" [11].

IV. Summary

In summary, we investigated ground and metastable states of mesoscopic ferromagnetic rings as a function of widths. We found that for the wide rings the remanent states are the vortex states. We found that the switching behavior of short and long chains of touching rings depends strongly on ring-ring interactions and on ring geometry. We propose to use the "wide" rings as the building blocks of magnetically-coupled logic devices as a possible realization of magnetic quantum-dot cellular automata (MQCA) [1]-[2].

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