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Magnetic nanostructures for non-volatile memories

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ABSTRACT

In this work we present two fabrication approaches for patterning submicron Pacman-like (PL) magnetic nanoelements, the additive and subtractive process. Within the first process, PL structures are revealed using a standard lift-off technique. The second one is based on argon ion milling through titanium mask patterns. In the PL magnet the missing sector itself represents a dipole, which together with the external field, controls the chirality of the nucleated vortex. In order to determine the chirality of the vortex ground state, an array of PL nanomagnets of the diameter 200 nm prepared by the subtractive process, is mapped by the magnetic force microscopy. The experimental results are in good agreement with the results achieved by the micromagnetic simulations.

1. Introduction

Designed magnetic structures with dimensions in the submicrometer scale represent an exciting area of research as they exhibit a specific magnetic ordering, including magnetic vortices. Magnetic vortices have a potential to be used as information carriers in data storage media. One technology being explored by many researchers is bit patterned media (BPM). In BPM, bits are physically isolated, and anisotropy energy of magnetic entities is higher than in conventional recording media that is composed of many tiny grains. Therefore, BPM shows higher thermal stability than standard media. Conceptually, the BPM should solve not only bit-density issue, but also the energy efficiency. The latter requirement reflects new trends in energy use and energy costs of data centers and servers. Up to now, record density has been increased thanks to grain size reduction. To maintain the necessary anisotropy, one has to use materials with high anisotropy constants K_u, resulting in high value of the switching field [1]. For example, today's recording heads for perpendicular magnetic media have to generate writing magnetic field on the level of 2 T [2].

In our previous work we have introduced special mesoscopic structure with broken rotational symmetry that require in one order lower writing field than the one mentioned above [3]. Based on micromagnetic calculations, we have designed "Pacman-like" (PL) nanomagnet and have calculated its magnetic properties. It is shown how to control its ground states by applying in-plane fields only. The intriguing property of this magnetic structure is its ability to store two bits of information simultaneously (in terms of chirality and polarity of the magnetic vortex).

When the dimensions of magnetic element are reduced down to a submicrometer range, small variations in shape and size may change its magnetic properties fundamentally. The most common fabrication methods in that range are lift-off [4–7], pattern transfer by dry etching [8–10], or electro-deposition using a mask material [11–13].

Electron beam lithography (EBL) has been used by many researchers for preparing magnetic patterns [2,14]. The precision of the whole fabrication process is determined not only by the electron beam spot size, but also by primary and secondary electrons scattered in the photoresist (proximity effect), by the etching conditions (which influence vertical and horizontal etching speeds), and by the deposition speed of the magnetic material. Therefore, it is important to optimize the fabrication process to achieve desired properties of the magnetic structures.

In this paper we have performed two different fabrication processes to fabricate PL nanomagnets. In the additive process, the magnetic material was deposited onto the substrate pre-patterned by the EBL process, and then followed by lift-off of the magnetic layer. In the subtractive process, the magnetic material was deposited onto the Si substrate prior to the EBL patterning. Then it was etched through the titanium-mask pattern to form desired structures. Using the processes, an array of 16 PL nanomagnets of different orientations was fabricated. Then, magnetic force microscopy (MFM) was applied to the nanomagnets to study the angular dependence of the vortex ground states. Finally, experimental results (MFM images) were compared with micromagnetic simulations used to calculate vortex dynamics in the nanomagnets.

2. Experiment

As a first step, the Si substrate was covered by a 10-nm-thick titanium layer using e-beam evaporation. The Ti layer improves

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adhesion of subsequent layers and improves image contrast during SEM inspection of fabricated nanomagnets.

PL nanomagnets were patterned using Raith EBL system. We designed $50 \times 50\ \mu m^2$ array of patterns with different diameters ranged from 200 nm to 1000 nm. Patterns were exposed by the dose of 250 $\mu C/cm^2$ at 30 keV. The diameter of the beam was approximately 3–5 nm wide. To achieve low line edge roughness, the exposure pixel spacing should be no larger than the beam diameter. Therefore, the distance between two adjacent pixel exposures (beam step size) was set to 4 nm. The exposure was performed without proximity effect correction algorithm. To reduce magnetic interaction between the neighboring nanomagnets, we selected the PL's center-to-center distance 2.5 times larger than their diameter.

In the first experiment (additive approach), PL nanomagnets were transferred onto the substrate via a lift-off process. To facilitate the lift-off process we used bilayer PMMA resist (90 nm of the 50 K and 100 nm of the 950 K one) to form an appropriate undercut profiles for the Permalloy (Py, $Ni_{81}Fe_{19}$) deposition. After the development in a solution of MIBK and isopropyl alcohol (1:3) for 60 s at room temperature, 40-nm-thick Py layer was evaporated onto the sample and followed by the lift-off process in acetone.

In the second experiment (subtractive approach), the PL nanomagnets were defined by the etching process. The evaporation of Py was performed prior to the pattern transfer. PL array was exposed into the PMMA resist, and then a 30-nm thick layer of titanium was deposited and followed by the lift-off process. A Kaufmann type ion beam etching source was used afterwards to transfer the Ti mask pattern into the magnetic layer.

Magnetic imaging was performed by a scanning probe microscope (SPM) "Ntegra prima", equipped with controlled external magnetic field up to 100 mT. The field is applied in the plane of the sample during magnetic imaging. We have used low momentum MFM probes (MESP-LM, Bruker) with Co/Cr coating for the magnetic field imaging to lower the influence of the MFM tip on the PL nanomagnets – LM probes have reduced magnetic moment as compared to the standard probes. The tips were magnetized before measurements along their symmetry axes. The phase shift of the cantilever oscillations was recorded, and it represents the magnetic field distribution at the lift distance (25–40 nm above the sample).

3. Results and discussion

3.1. Additive approach

Fig. 1(a) shows a design of Pacman-like nanomagnet. It has a coin-like shape with small sector removed from the edge. This missing sector has two important purposes: to facilitate quick relaxation of the magnetic vortex with desired chirality and it enables easy readout of chirality (by measuring the in-plane magnetic field in the gap). Magnetic elements with sharp edges and corners were fabricated by optimizing the exposure time, beam current and evaporating rate of the Py layer. Scanning electron microscope (SEM) images of the PL nanomagnets show that the lift-off process has resulted into clean nanomagnets without fencing (Fig. 1(b)–(d)). Flat and clean PL surface is important for easy magnetic ground-state control, as well as for seamlessly MFM scanning.

3.2. Subtractive approach

Etching through Ti-mask pattern was done by ion milling. We found that Py layer starts to be etched at the energy 350 eV of the Argon ions at the pressure of 10^{-4} mbar. Ion milling is not highly selective etching, so the mask is eroding and this effect initially appears at the small sharp parts of the mask. The PL nanomagnet with diameter below 500 nm has small parts at the opening region only tens nanometers large. If Py layer was etched through the Ti mask of the shape shown in the Fig. 1(a), sharp parts located close to the PL opening were etched away. This effect re-

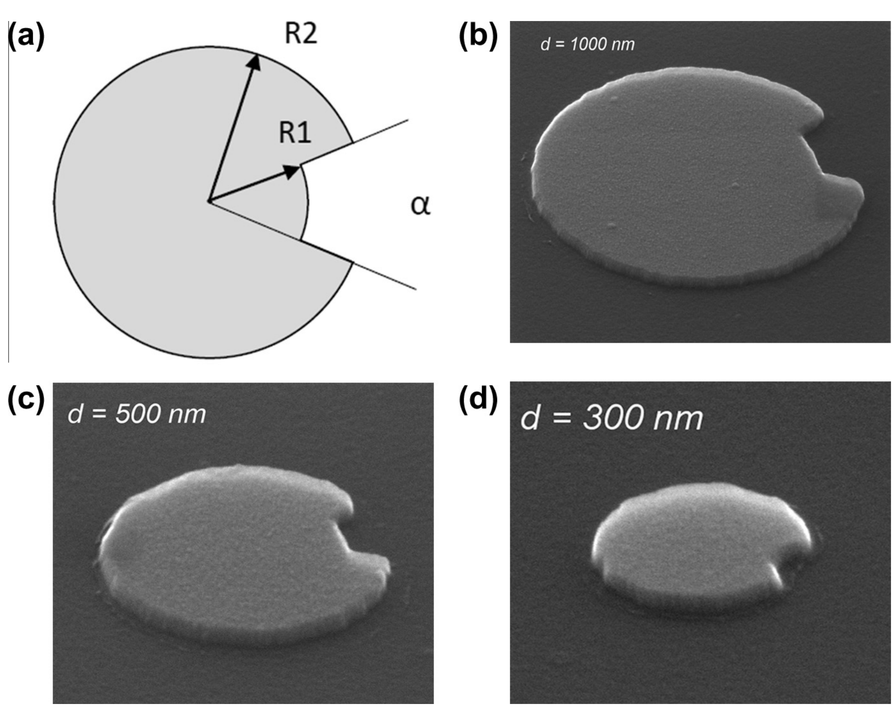

Fig. 1. (a) Pacman-like nanomagnet with the diameter $d = 2R2$, opening angle $\alpha = 45°$, and radii ratio of the opening $R1/R2 = 2/3$. (b–d) SEM images of the fabricated nanostructures with $d = 1000$ nm (b), 500 nm (c), and 300 nm (d), respectively. The sample holder was tilted at the angle of 50° for better inspection of side wall and surface features.