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Nanomagnetics

Manipulating magnetic properties by tuneable magnetic dipoles in ferromagnetic thin film

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Abstract— In the present work we demonstrate how a unique nanomodulation within a continuous ferromagnetic film can induce magnetic dipoles at sub-micron-scale on pre-defined locations and plays a key role to tune the global magnetic properties of the film due to dipole-dipole interactions. Arrays of tuneable magnetic dipoles are generated at in-plane and out-of-plane directions, which can be rotated in plane within the three dimensional modulated structure of a continuous film. In-plane magnetic dipole rotation in the field directions opens up a methodology to control overall magnetic properties of a ferromagnetic thin film. Formation of magnetic dipoles and their tuneability have been studied in detail by MFM imaging and high resolution magnetic measurements. This has been further studied by micromagnetic simulation (OOMMF) and verified experimentally in nanomodulated $Ni_{45}Fe_{55}$ alloy film. A nano pattern bigger than single magnetic domain size tries to form vortex at remanence state as it is the lowest possible energy state. However this unique three dimensional nano structure prevents vortex formation due to competition between in-plane and out-of-plane dipole-dipole interaction. It is also observed that at zero remanence the magnetization goes through a transformation from a metastable to a stable state where the dipole-dipole interaction depends on their geometrical arrangements. Thus magnetic properties of the continuous film can be varied by the pattern geometry. A detail analytical study of dipolar energy for the system agrees well with experimental and simulated results.

Index Terms—Nanomagnetics, Soft Magnetic Materials, magnetic anisotropy, magnetic film, nanoimprint lithography

I. INTRODUCTION

Recent developments of different nanofabrication techniques have increased the interest in exploiting the properties of mesoscopic magnetic nano structures of metal-alloy ferromagnetic materials due to their promising technological applications in spintronics devices. [Daughton 1997, Allwood 2002, Imre 2006, Cowburn 2000] Interestingly, due to the geometrically induced magneto static interactions [Cowburn 2000, Shibata 2003] these pattern structures opens up rich research and application opportunities, which involves study and control of unusual magnetic behavior based on magnetization reversal. [Shibata 2003, Thirion 2003] In recent years a number of two dimensional magnetic micro structures with specific geometrical order have been investigated where the magnetic properties are determined by the dipole-dipole interactions between magnetic domains controlled by geometry of the micro structures. Based on structural geometry magnetic spin ice [Wang 2006], magnetic monopoles [Jason 2011], moving monopoles [Castelnovo 2008], magnonics for microwave circuits [Shimon 2013, Haldar 2016] or reconfigurable microwave materials [Shinjo 2000, Cowburn 1999] have been invented lately in the micro-nano-structured magnetic media which have potential technological applications at reduced dimension. With the downsizing of the magnetic structure the relevant technology in one hand is facing difficulties to create sufficient magnetic anisotropy energy to be able to remain robust at thermal perturbation and on the other hand to achieve low magnetostatic energy between individual micro structures to retain the scope of independent magnetic tuneability. In this work, we show the possibility to manipulate overall magnetic energy by a unique three dimensional dipole configuration in a nano modulated continuous thin ferromagnetic film. The interaction between magnetic dipoles of patterned nano magnets with a particular symmetry forces magnetic spins to remain with certain remanence magnetization state instead of vortex formation in a multidomain magnetic nano structure, where the in plane and out of plane dipole formation allow to tune magnetic dipoles by an external field.

II. EXPERIMENT, SIMULATION AND ANALYSIS

To investigate the effect of magnetic dipolar interaction in a nanomodulated continuous media, we have fabricated an ordered square array of nano pattern through a combination of cost effective, industry compatible nanoimprint lithography and electroplating technique (Fig.1a). [Li 2010, Li 2011] The three dimensional structure of the patterned ferromagnetic $Ni_{45}Fe_{55}$ thin film has been delineated by AFM imaging (Fig. 1 b & c). Figure 1(d) is a typical scanning electron microscope (SEM) image of a cross section of different layers. The separation (w) between two consecutive peaks is 800 nm in <10> and <01> directions and the thickness (t) of the film is 250 nm. The amplitude of the wave structure is 100 nm. Magnetic force microscopy (MFM) was carried out on the sample film by a commercial atomic force microscope in MFM mode (VFM2-HV-

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Asylum Research High Voltage Variable Field Module-Version 2) and MESP-RC probes (Bruker AFM Probes International), where the VFM2-HV was used to apply static magnetic fields up to ± 0.1 Tesla

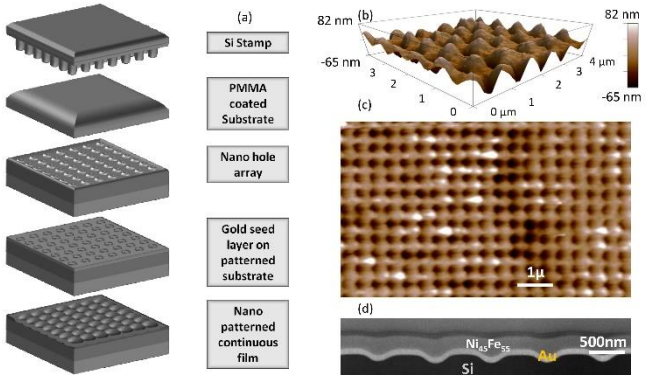


Fig. 1. (a) Fabrication process steps of nanoimprint lithography and nanomodulated film deposition, (b) 3D AFM image of nanomodulated $Ni_{45}Fe_{55}$ thin film, (c) AFM topography image shows square array pattern and (d) SEM cross section image shows wave like modulated film.

(~1G resolution), parallel to the sample plane. The magnetization of each of the nanometre size magnetic dipoles (Fig. 2. a & b) and their interactions have been mapped with a ferromagnetic tip having low remanence. The low remanence tips were used to ensure that the tip magnetization does not influence the film's magnetization configuration within its own detection limit.

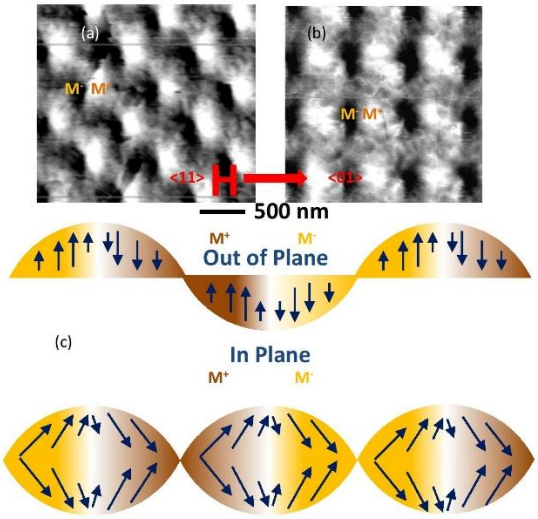


Fig. 2. (a & b) MFM phase images of dipoles at remanence state. An external field of 1000 Oe was applied in <10> and <11> directions before imaging. The images were taken at a 50-nm distance from sample surface. The applied external field was able to rotate the dipoles. (c) Schematic magnetic spin configuration for in plane and out of plane dipoles in nano modulated film shows how both in-plane and out-of-plane dipoles are formed in 3D modulated structure.

Three dimensional modulation of the ferromagnetic nanostructure forces the macrospin configuration of magnetization to follow a wave like propagation which collectively generates in plane and out of plane dipoles (Fig. 2.c) though there is no internal boundaries between the patterns. [Maity 2012] No diploes were found at high field (1000 Oe) measurements (Fig. 3.a). Magnetic hysteresis loops were measured by SQUID magnetometer (MPMS XL5, Quantum Design) under a maximum field H_m of 1000 Oe [Fig.3.b-d]. A well-designed protocol was followed to demagnetize the sample before starting each measurement. [Maity 2013] The variation of magnetic anisotropy was investigated by micromagnetic simulation (Fig.4a) and measuring coercivity (HC) and remanence (Mr) under external field at different directions (Fig.4b) in a quasi-static hysteresis loop tracer from SHB instruments (Model MESA 200).

III. DISCUSSION

The static dipolar energy depends upon the dipole interaction. The static energy of a magnetic micro structure generally consists of magnetic anisotropy energy, demagnetization energy, exchange energy and Zeeman energy. In a square array of magnetic nano structure, the magnetic ordering is determined by minimization of collective magnetostatic energy, whereas the magnetic anisotropy energy depends on the dipolar interaction if it is strong enough to retain the magnetization after removal of the applied field. For a square array pattern of 400-nm diameter and 100-nm modulation the energy density of vortex $0.49\times10^4 J/m^3$ is lower than energy of single domain state $1.33\times10^4 J/m^3$. [Li 2010, Maity 2012] Hence there will be a natural tendency to adopt vortex state in this modulated film to minimize the energy. Here the competition between two different dipoles (in-plane and out-of-plane) and possible spin pinning between two consecutive dipoles through continuous ferromagnetic media keeps the magnetization stable in the direction of applied field and resists vortex formation. We varied the angle of applied field direction with respect to the pattern array. The dipoles rotate with the rotation of applied filed which is shown by MFM images in Figure 2 (a & b) which remains aligned even after the field is removed. This

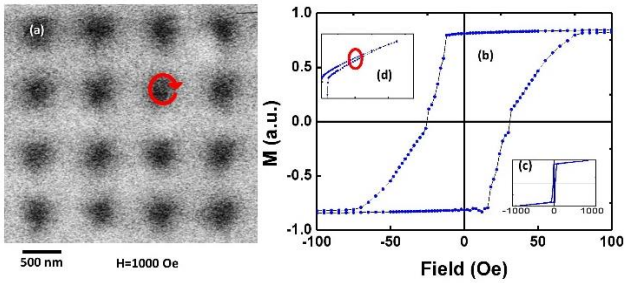


Fig. 3. (a) Unsaturated metastable state at high field (1000 Oe) were observed (b & c) Step like hysteresis was observed due to the existence of metastable dipoles. Unsaturated magnetization state at high field range is shown in (d).

demonstrates the stability and tuneability of such artificially created dipole clusters. We applied a field of 1000 Oe, which is large enough to saturate $Ni_{45}Fe_{55}$ film and mapped the magnetization of the pattern structure very carefully in MFM-VFM2-HV. Interestingly an unsaturated magnetic domain core has been observed at the centre of each nanopatterns at high field due to the gyration motion of out of plane magnetic spins at the core (Fig. 3.a). The wave pattern creates a strong out of plane dipoles which becomes difficult to align at a particular in plane direction even by applying a high external field. This has been observed in the measured MH curve. The competition between two different dipoles generates a collective metastable magnetic configuration, which has been clearly verified by the observation of a step like MH curve (Figure 3.b & c) measured in SQUID magnetometer (MPMS-XL5). The blown up curve shows a

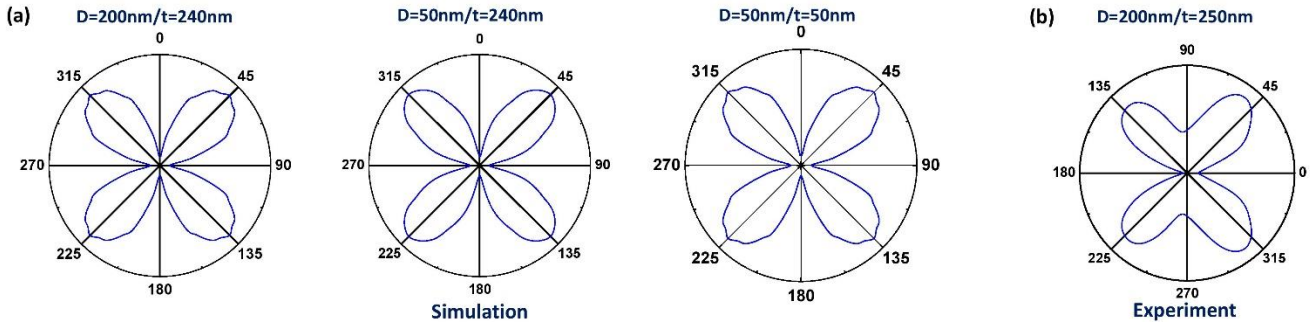


Fig. 4. Simulated (a) and experimental (b) results of angle dependence of remanent magnetization (M_r) in nanomodulated film are plotted where remanent magnetization is proportional to magnetostatic energy.

prominent step like hysteresis loop (Fig. 3. b). The hysteresis loop saturates at very high field (Figure 3.c). A slight difference between the paths of ascending and descending branches at saturation was observed (Fig. 3.d) which vanishes at high field.

The magnetostatic energy due to the dipolar configuration can be described by modeling the nanopatterned structure as follows. For modeling we assumed that each pattern has a magnetic dipole, circularly shaped, which can be rotated across the centre of the dipole moment and spins of the neighboring patterns are not exchange coupled. The system energy includes magnetostatic energy, Zeeman energy and exchange energy.

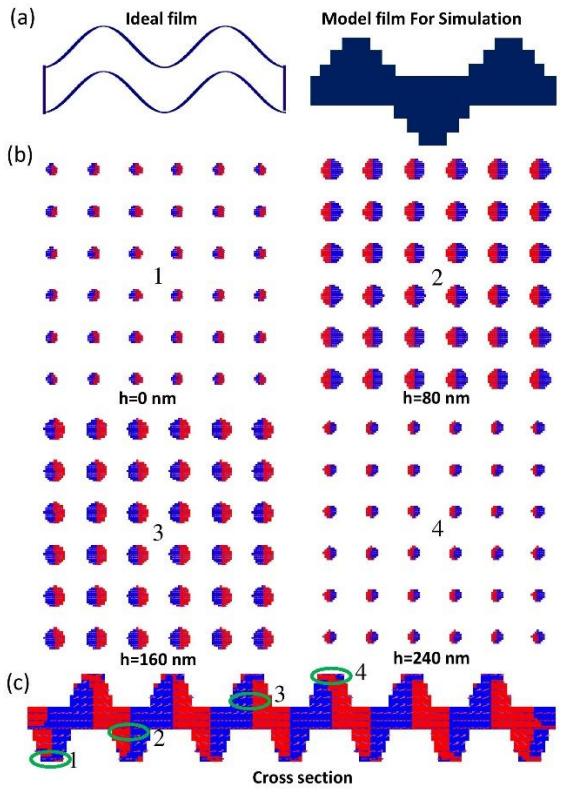


Fig. 5. (a) Schematic diagram of nanomodulated thin film for OOMMF simulation is shown. (b & C) OOMMF simulated image shows existence of magnetic dipoles in all cross-sectional layers of the film. h denotes height from bottom surface.

The total dipolar energy in the infinite array can be expressed as

$$E_{Total}|_{-\infty}^{+\infty} = -\int_{surface} \nabla . M_s \, \widehat{m_i}(R_i) \frac{\widetilde{R_{ij}}}{|R_{ij}|^3} dV + \int_{volume} \nabla . M_s \, \widehat{m_i}(R_i) \frac{\widetilde{R_{ij}}}{|R_{ij}|^3} dS$$

Where M_S is saturation magnetization and m_i is magnetization for each dipole.

For the modulated surface the magnetostatic energy can be written as:

$$E_M|_{volume} = -\frac{1}{2}\int \overrightarrow{M_i} . \overrightarrow{H_i} dV = \frac{1}{2}\int (\sigma_i . \emptyset|_{top\ surface} - \sigma_i . \emptyset|_{bottom\ surface})$$

Due to the symmetry of the surface $E_{M|volume}$ is zero.

Dipolar interaction in a patterned array can be written as [Paolo 2002, Guslienko 2001]

$$E_{dipole} = \frac{1}{2} g^2 \mu_B^2 \sum_{R_i} \sum_{R_j} \left[\frac{M_i . M_j}{R_{ij}^3} - 3 \frac{\left(\widetilde{M_i} . \widetilde{R_{ij}}\right)\left(\widetilde{M_j} . \widetilde{R_{ij}}\right)}{R_{ij}^5} \right]$$

The dipoles in a 3D-patterned structure interacts with each other depending upon symmetry in the presence of external magnetic field. For such infinite patterned structure the dipolar energy can be calculated as:

$$E_{dipole} = -g^2 \mu_B^2 \int_n \left[\frac{m^2}{\left(r \sin \frac{90^\circ}{n}\right)^3} \right]$$

Where g is the gyromagnetic ratio, μ_B is the Bohr magneton, m is moment of single dipole, r is the distance between centers of two consecutive dipoles or pattern and n is integer. Thus due to the interaction between in-plane and out-of-plane dipoles a finite amount of dipolar energy exists at remanence state which allows the dipoles to align along the direction of externally applied field forming a "dipole-chain". It was observed that the magnetostatic energy in nanomodulated film varies as a function of applied field direction. Hence, the pattern of a square array clearly shows fourfold symmetry of anisotropy which comes from dipolar interaction in three-dimensional (3D) nanomodulation, delineating the dependence of

anisotropy symmetry on the symmetry of modulation. [Maity 2012]

IV. CONCLUSION

In conclusion, we have demonstrated that in a unique three dimensional nanomodulated continuous ferromagnetic film the magnetostatic energy can be tuned by magnetic interaction among the artificially created magnetic dipoles in a patterned array with in-plane external magnetic field. Strong in plane and out of plane dipoles are generated by in-plane magnetic field due to 3D nanomodulation. The competition between in-plane and out-of-plane magnetic dipoles resists vortex formation in nanostructured thin ferromagnetic film. The magnetic dipoles can be rotated by external field in preferred directions, which leads to controllable magnetic anisotropy in such 3D nanomodulated ferromagnetic thin film. The dipoles remain aligned in the direction of applied field even after the field is removed which can be a key factor in the case of applications of such patterned media in nanomagnet based non-volatile ultra-high density patterned magnetic memory and logic operation. [Stamps 2014, Niemier 2011] Additionally such 3D nanomodulated array in a continuous film could open up advanced microwave circuits applications, where microwave properties can be tuned by reconfigurable magnetic properties of metastable tuneable dipoles and spatial arrangements of the magnetization. [Haldar 2016, Guslienko 2014] The micromagnetic simulation shows a qualitative agreement with the experimental results. Qualitative analysis of magnetostatic energy for this nanomodulated film shows the existence of tuneable magnetic dipoles with finite energy at magnetically frustrated state. The 3D nanomodulation described in this letter can also be demonstrated for even thinner and smaller pattern dimension prepared by other techniques such as sputtering or any other physical vapour deposition (PVD) in combination with sophisticated lithography techniques such as e-beam lithography, block co-polymer, etc. for miniaturized spintronic or magnonic devices.

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