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Deterministic multi-step rotation of magnetic single-domain state in Nickel nanodisks using multiferroic magnetoelastic coupling

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ABSTRACT

We demonstrate deterministic multi-step rotation of a magnetic single-domain (SD) state in Nickel nanodisks using the multiferroic magnetoelastic effect. Ferromagnetic Nickel nanodisks are fabricated on a piezoelectric Lead Zirconate Titanate (PZT) substrate, surrounded by patterned electrodes. With the application of a voltage between opposing electrode pairs, we generate anisotropic in-plane strains that reshape the magnetic energy landscape of the Nickel disks, reorienting magnetization toward a new easy axis. By applying a series of voltages sequentially to adjacent electrode pairs, circulating in-plane anisotropic strains are applied to the Nickel disks, deterministically rotating a SD state in the Nickel disks by increments of 45°. The rotation of the SD state is numerically predicted by a fully-coupled micromagnetic/elastodynamic finite element analysis (FEA) model, and the predictions are experimentally verified with magnetic force microscopy (MFM). This experimental result will provide a new pathway to develop energy efficient magnetic manipulation techniques at the nanoscale.

1. Introduction

Ferromagnetic materials, traditionally used in memory applications [1,2], are being incorporated into a wider range of emerging applications, which include nanotweezers [3,4], microfluidics [5,6], and biomedical applications [7,8]. These newer applications exploit the favorable scalability of the permanent magnetic diploe due to its relatively large energy density [9], in addition to its compatibility in fluidic environments. Previously, two major approaches have been studied to adapt magnetism at the nanoscale/microscale: scaling current-based magnetic coils [10], and employing external magnetic fields [6,11]. However, Joule heating causes significant limitations in current-based magnetic devices, as devices are miniaturized below the microscale due to reduced efficiency and challenges of heat dissipation. Use of external magnetic field control requires external magnetic sources such as permanent magnets or electromagnetic coils, which do not provide control at the individual element-level control and limit overall system scalability. Therefore, control of magnetism is one of the major challenges when scaling magnetic systems below the microscale.

Recently, a new indirect approach to control magnetism has been suggested: strain-mediated multiferroic heterostructures [12–16]. Strain-mediated multiferroic composites consist of piezoelectric and magnetoelastic materials that are coupled via strain transfer at their interfaces. Instead of using an electric current or an external magnetic field to manipulate magnetization in the material, multiferroic composites use a piezoelectrically generated strain to control magnetization in nano/microstructures [17–25]. However, since most of the previous studies adapted single crystal piezoelectric materials that generate strain along specific crystal directions [25,26], the control of magnetism was confined by the crystal directions, with a lack of isotropic controllability. More recently, researchers suggested a way to generate isotropic strains with surface patterned electrodes on polycrystalline piezoelectric materials [27–30]. However, experimental work is unavailable to verify this type of magnetization control on elements below the micron scale.

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In this work, we fabricate multiferroic heterostructures of Ni nanodisks on a Lead Zirconate Titanate (PZT) polycrystalline substrate to control rotation of magnetic single-domain (SD) states in Ni nanodisks. An array of surface electrodes is patterned on top of the PZT substrate to generate anisotropic in-plane strains in steps of 45°. The PZT-induced strains and corresponding magnetoelastic behavior in the SD states are predicted by a finite element analysis (FEA) that combines Landau-Lifshitz-Gilbert micromagnetics and elastodynamics. Lastly, we experimentally verify the rotation of the SD states in Ni nanodisks with magnetic force microscopy (MFM).

2. Theory

SD states in thin film ferromagnetic disks are achievable when the devices are scaled to sub-micron length scales (Fig. 1). The critical size to form a SD state depends on the exchange length, saturation magnetization, and shape anisotropy of the material. For a 15 nm thick Ni disk, a SD state starts to form in disks with diameter less than 400 nm [32]. The SD state in thin film disks possesses several useful properties for magnetic applications. First, due to its homogeneous configuration of magnetization, the magnetic single-domain emits a stray magnetic field at opposing sides of the disk, creating a dipole field for interaction with the external environment (Fig. 1). Second, the ferromagnetic structures have non-volatile, spontaneous magnetization, which can serve as a constant magnetic source. In addition, due to its symmetric circular shape, the disk structure does not possess shape anisotropy in the azimuthal angle or any preferential easy axis in-plane. Therefore, we can achieve isotopic rotation of SD states in the disks.

The magnetic energies that influence the SD state in the Ni nanodisks are the magnetocrystalline energy, exchange energy, demagnetization energy, and magnetoelastic energy. In this study, Ni disks are deposited by electron-beam evaporation and form polycrystalline structures, which means the macroscopic magnetocrystalline anisotropy energy is negligible compared to the other energy terms [33]. Therefore, creation of a magnetic SD state in Ni disks can be determined by an energy minimization process and balance between the exchange energy and demagnetization energy. After applying a saturating magnetic field, the initial homogeneous magnetization in disk structures produces a large internal demagnetization field that tends to create multi-domains or a vortex state to reduce the large demagnetization energy, which comes with increase of the exchange energy. Below a certain size scale, the exchange energy dominates the demagnetization energy, reducing the favorability to form multi-domain states.

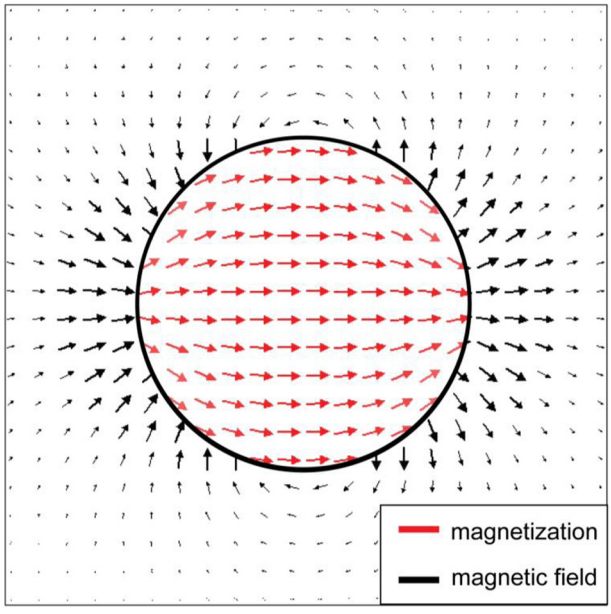

Fig. 1. Magnetic single-domain state in a Ni disk with thickness of 15 nm and diameter of 400 nm. The magnetic state is obtained using the Object Oriented MicroMagnetic Framework [31] (OOMMF) simulation tool. Nickel has saturation magnetization, Ms = 485 emu/cc, exchange constant, A = 9.0 $\times 10^{-12}$ J/m, and saturation magnetostriction, $\lambda_s = -34$ ppm. The Ni disk emits a maximum stray magnetic field of |Hmax| = 2.8 kOe.

By applying strain to the SD states, we can reshape the energy landscape through control of the magnetoelastic energy. For polycrystalline thin film disks, we assume the in-plane isotropic magnetoelastic energy, which is given as

$$\begin{aligned} E_{m.e.} &= -\frac{3}{2}\lambda_s E\left(s_x \cos^2\theta + s_y \sin^2\theta\right) \\ &= -\frac{3}{2}\lambda_s E\left[(s_x - s_y)\cos^2\theta + s_y\right] \end{aligned} \quad (1)$$

where λ_s is saturation magnetostriction, E is Young's modulus, θ is the angle between magnetization and strain, and s_x and s_y are strain in x, and y, respectively (Fig. 2a). If the applied strain provides sufficiently large energy to overcome the local energy barrier that is imposed by the current exchange energy and demagnetization energy, the magnetization realigns toward the new easy axis formed by the strain. To more effectively drive the SD states, we calculate the optimal control angle to apply a strain with respect to a magnetic single-domain. This is found by the magnetoelastic effective field,

$$\begin{aligned} \vec{H}_{m.e.} &= -\frac{1}{\mu_0}\nabla E_{m.e.} = \frac{1}{\mu_0}\frac{1}{r}\frac{\partial}{\partial\theta}(-\nabla E_{m.e.})\cdot\hat{\theta} \\ &= -\frac{3}{2}\frac{1}{\mu_0}\frac{1}{r}\lambda_s E(s_x - s_y)\sin 2\theta\cdot\hat{\theta} \end{aligned} \quad (2)$$

This effective field is the local field that the disk experiences due to the applied strain. The magnetic effective field is a function of $(s_x - s_y)$ and $\sin 2\theta$. The maximum magnitudes of the field are at ±45°, or ±135°. In addition, the effective field can be increased by a larger strain difference, $(s_x - s_y)$. Therefore, applying different polarity of orthogonal strains ($s_x \cdot s_y < 0$) at +45° or −45° toward a magnetic single-domain maximizes the initial effective field to overcome the local energy barrier and reorient the magnetization toward the new easy axis. For example, the magnetoelastic energy and magnetoelastic effective field for $(s_x - s_y) < 0$ and $\lambda_s < 0$ are shown in Fig. 2b. In this case, the minimum $E_{m.e.}$, or easy axis, is created along the x axis, and the maximum effective field is generated when magnetization with θ = ±45, ±135°.

Additional rotation of the SD state beyond the initial 45° step requires the generation of strains in multiple angles. This is suggested by recent studies [27–30], which analytically simulated the generation of orthogonal localized strains on a 500 nm thick PZT film with six surface patterned electrodes [28]. When applying a 10 MV/m electric field between the electrode pair and bottom of the PZT film, ~1000 ppm of in-plane anisotropic strain is generated at the center of the top surface of the electrodes, enabling manipulation of the magnetic state in a single ring structure [28].

3. Results and discussions

In this study, we use 300 μm thick polycrystalline PZT substrates (PZT 610HD from TRS Technologies) and pattern eight surface electrodes on the substrate (Fig. 3a). The polycrystalline PZT substrates show negligible macroscopic crystalline anisotropy, so they are suitable to generate in-plane isotropic strains with the