

Study of Magnetization State Transition in Closely Spaced Nanomagnet 2D array for computation

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The work investigated the dipole-dipole interaction for finite 2D arrays of ferromagnetic circular nanomagnet. Starting with two basic arrangements of coupled nanomagnets namely, longitudinal and transverse, different diameter and thickness are studied. The phase plot results exhibit that for longitudinal arrangements the single domain state is pervasive over a large range of thickness values as compared to the transverse arrangement or isolated nanomagnet cases. The study is further extended to finite arrays (3 x 3 and 5 x 5) of circular nanomagnets. The magnetic force microscopy (MFM) results show that arrays of nanomagnets favors anti-ferromagnetic ordering at remanence. We have correlated our experimental results with micromagnetic simulations. Based on our study, we can conclude that nanomagnets with 100 nm diameter, 15 nm thickness and 20 nm spacing has single domain state in an array configuration with one-step switching, which results in fast operation, a property ideal for computing.

Keywords: nanomagnet, field coupled computing, nanomagnet arrays

I. INTRODUCTION

The magnetic properties of periodic arrays of nanomagnet with deep submicron dimensions have an enormous technological impact, e.g. in the new generation of ultra-high density magnetic information storage devices, magnetic sensors. Besides, system of nanometric size possess an increasing importance in computing^{1,2}. For high density devices to be competitive the nanomagnets have to be patterned in close proximity and therefore studies that focus on the effect of dipolar interaction between nanomagnets are of great current interest.

In order to pattern nanostructures, optimization of the geometry and size of small magnetic elements is important. So far, investigation have been carried for elements with different geometrical details, such as in-plane aspect ratio, shape (rectangular, elliptical, triangular, square ring, circular, circular rings, pentagonal, etc). In recent years, there has been a substantial work reported on the magnetic state of single nanomagnet (single domain or vortex). Cowburn et al.³ presented the phase plot, showing the transition between single domain state to vortex state as a function of thickness and diameter for single nanomagnet.

Previous work that reported on properties of array (1D or 2D) of nanomagnets has been focused on the high density storage or media applications, where the structures are sufficiently spaced to consider magnetostatic coupling between element negligible. In order to achieve minimum interaction between the elements, array of nanomagnet have been studied with large thickness (40 – 80 *nm*) and diameter (200 – 1500 *nm*) that creates the vortex configuration of each nanomagnet. However, there has been no work reported so far on closely spaced nanomagnet array, which is required for computation. The key requirements to implement nanomagnet array for computation application are:

- Fast and reproducible operation, which is related to the magnetization reversal or switching process of individual nanomagnet in the system. The single domain state with coherent (one step) reversal process is ideal for the computation, since it is associated with sharp and shorter switching as shown in FIG. 1. As opposed to the vortex state, where reversal takes places in more than one step including formation of nucleation. It is evident from the FIG. 1, the one step reversal constitutes the fast operation.
- Dipole-dipole interaction, which is the main cause of information flow from one nano-

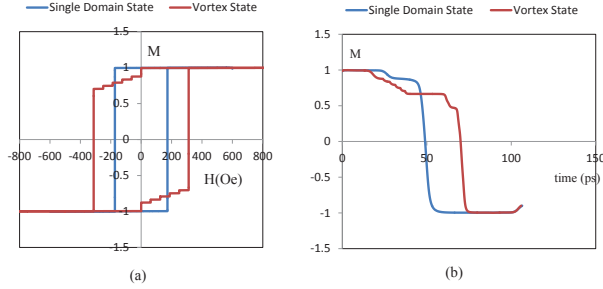


FIG. 1. (a) Simulated hysteresis of 100 *nm* diameter with thickness 10 *nm* (having single domain state) and 15 *nm* (with vortex state). (b) Magnetization plot for single domain state and vortex state of nanomagnet.

magnet to its neighboring nanomagnet. In order to enhance the dipole-dipole interaction, the inter element spacing should be small (smaller than the element size). This requirement is in contrast to high density storage applications. Furthermore, to exploit the dipole-dipole interaction, each nanomagnet should be single domain state with high charge density at the edges of the nanomagnet, which results strong dipolar field rather than vortex state, with no charge distribution around the edges and hence little dipolar field interaction.

II. MICROMAGNETIC SIMULATION DISCUSSION

The micromagnetic simulations were carried out by solving the Landau-Lifshitz-Gilbert (LLG) equations, using the micromagnetic software^{4,5}.

$$\frac{d\mathbf{M}}{dt} = -\gamma\mathbf{M} \times \mathbf{H}_{\text{eff}} - \frac{\alpha\gamma}{M_s}[\mathbf{M} \times \mathbf{M} \times \mathbf{H}_{\text{eff}}] \quad (1)$$

Here, \mathbf{M}_s is the saturation magnetization of the material, γ is the gyromagnetic ratio, and α is a damping constant. The effective magnetic field (\mathbf{H}_{eff}) is the average magnetic field experienced by the magnetic moment, and it is the sum of externally applied field (\mathbf{H}), the dipole field and the uniaxial anisotropy field

$$\mathbf{H}_{\text{eff}}^i = \mathbf{H} - \mathbf{H}_{\text{dp}}^i + 2\mathbf{K} \frac{\mathbf{M} \cdot \mathbf{u}}{M_s^2} \mathbf{u} \quad (2)$$

TABLE I. Magnetic properties of permalloy material used in simulation study.

Material parameters used in simulation	
Saturation Magnetization (M_s)	800 A/m
Exchange stiffness constant (A)	1.3×10^{-12} J/m
Anisotropy Constant (K)	5×10^2 J/m ³
Damping constant (α)	0.5

where \mathbf{u} is a unit vector in the direction of the magneto-crystalline anisotropy and K is the strength of the anisotropy. The dipole field on the i -th nanomagnet is given by

$$\mathbf{H}_{\text{dp}}^i = \sum_{j \neq i} \left[\frac{\mathbf{M}_j}{r_{ij}^3} - 3 \frac{(\mathbf{M}_j \cdot \mathbf{r}_{ij})}{r_{ij}^5} \right] \quad (3)$$

The software approximates the continuum micromagnetic theory, where continuous magnetization distribution of a magnetic material is approximated by a discrete magnetization distribution consisting of equal volume cubes (3-D). The cubic cell size in all the simulations were kept 5 nm, which is smaller than the characteristic exchange length of permalloy⁶, $l_{ex} = [2A_{ex}/(\mu_0 M_s^2)]^{1/2} \approx 5.2$ nm. In this study, we have studied the magnetization configuration of nanomagnet that results from the minimization of the free energy. In all the simulations $\alpha = 0.5$ that successfully capture the correct convergence and accelerate the computation process. We used permalloy material with magnetic properties shown in Table I.

III. RESULTS AND DISCUSSION

Nanoscale structures behave differently than the bulk material. At nanoscale, the interaction between competing magneto-static energy and quantum mechanical exchange energy, causes the nanomagnet to behave as single spin. There are two possible stable states for single domain nanomagnet. One is the single domain state where all the moment align in one direction either up or down at ground state. Second is the vortex state, first demonstrated by Shinjo et al.⁷, where moments with curling spin configuration has the low energy configuration and magnetization can be clock-wise or counter clock-wise. Our micromagnetic numerical simulation study plays an essential role in understanding and designing nanoscale element. It is important to understand fundamental properties of individual and interacting

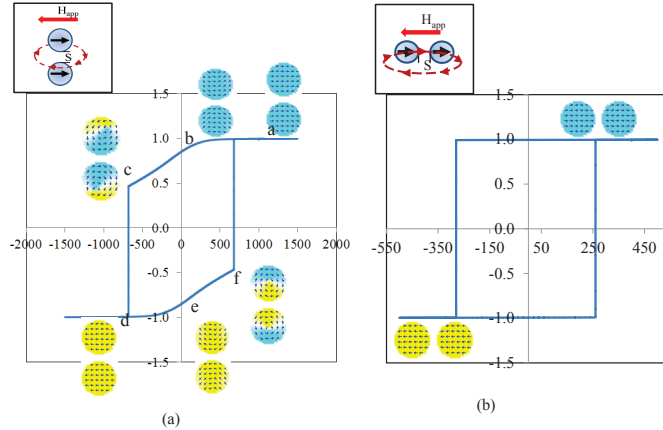


FIG. 2. Magnetization transition process in (a) Transverse arrangement and (b) Longitudinal arrangement.

nanomagnet elements with reduced dimensions to be able to design larger computing structures with them. Generally for given material and geometry, the size and lateral dimension determines the transformation of one magnetization configuration into another. Our first study involves the determination of the parameter space boundary between single domain and vortex states of isolated circular nanomagnet. We have simulated permalloy circular nanomagnet with diameters in the range $100 - 300 \text{ nm}$ and thickness in the range $5 - 20 \text{ nm}$. For each simulation, a uniformly magnetized state in X-axis, 10 degree away from the ground state direction was used as the initial condition. Our results for isolate nanomagnet match with the previous studies³, as shown in FIG. 3.

In order to capture, to first order, the effect of the dipolar interaction on the magnetization state, we examine two single domain nanomagnets at (a) longitudinal arrangement, where magnetic moments are parallel to each other and also to their separation and (b) transverse arrangement, where magnetic moments are parallel to each other but perpendicular to their separation. In longitudinal arrangement, the dipolar interaction between two nanomagnets is parallel and anti-parallel to the direction of applied field as shown in the inset of FIG. 2 (b). While in transverse arrangement, the dipolar interaction between two nanomagnet is anti-parallel and it is parallel to the applied field as shown in the inset of FIG. 2 (a). In order to elaborate the dipolar interaction on the magnetization transition state, a simulation was carried out for both arrangements with 100 nm diameter nanomagnet. The simulation results shows a clear difference in the magnetization transition between

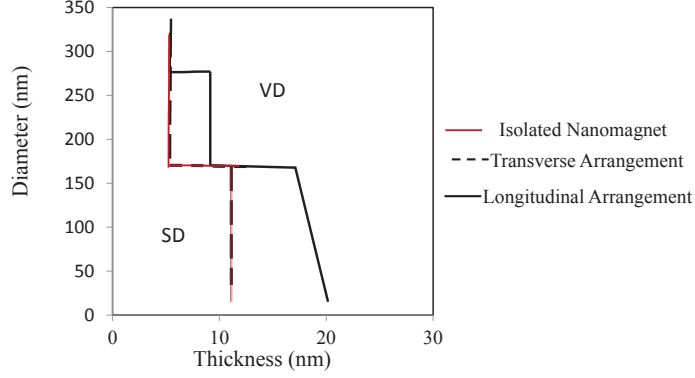


FIG. 3. A phase diagram of numerical simulation results for isolated and coupled nanomagnet, as a function of element size and thickness. The solid red line shows the boundary between the single domain state (SD) and vortex state (VD) for isolated nanomagnet. The solid black line is the boundary for longitudinal arrangement, while dashed black line is the boundary for the transverse arrangement.

longitudinal and transverse arrangements. Nanomagnets with longitudinal arrangement, at spacing 20 nm , goes through coherent reversal with one step switching, as shown in FIG.2 (b), while for transversely arranged nanomagnets, the reversal takes place gradually through vortex formation. The simulation experiment is repeated for different diameters and thicknesses. The results are represented in the form of phase diagram. It is evident that nanomagnets with 20 nm thickness and 100 nm diameter in longitudinal arrangement stays in single domain state during switching, which is not the case when nanomagnets of same dimension is isolated or in transverse arrangement, as shown in FIG. 3. So, in general the phase plot of longitudinally coupled nanomagnet moves upward as compared to the transverse and single nanomagnet. It is noteworthy that the dipolar interaction between two single domain nanomagnets that is sufficient to produce collective rotation of magnetic spin during magnetization reversal, depends on their thickness and diameter. Apart from the dimension and inter-element distance, another important factor that influences the dipolar interaction is the number of nearest nanomagnets in an array. In order to visualize the effect of dipole-dipole interaction in 2D array, we carried out simulation for different size arrays (3×3 and 5×5). The diameter and inter-element separation is kept constant at 100 nm and 20 nm respectively, while thickness is varied between $5 - 20 \text{ nm}$. The saturation field of 100 mT along the array edge is applied. The magnetic moments of nanomagnet rotates

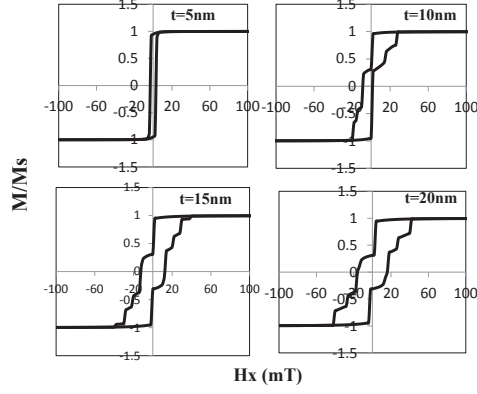


FIG. 4. Simulated hysteresis loop for 3 x 3 array of 100 nm diameter with different thickness indicated above the loop.

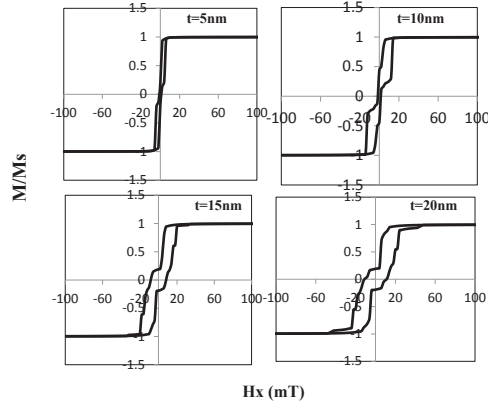


FIG. 5. Simulated hysteresis loop for 5 x 5 array of 100 nm diameter with different thickness indicated above the loop.

in order to minimize the magneto-static energies due to uncompensated nanomagnets. A change in remanent magnetization and the area A_h enclosed by the hysteresis loop, with respect to thickness during reversal process is observed as shown in FIG. 4 and FIG. 5. It is evident from the magnetization curve that due to dipolar interaction, the reversal tends

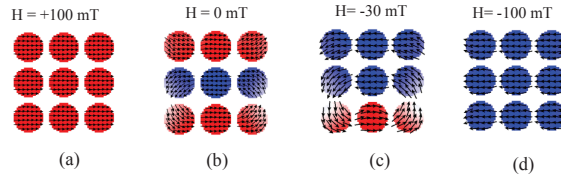


FIG. 6. Spin Configuration of 3 x 3 array at different field, during reversal process.

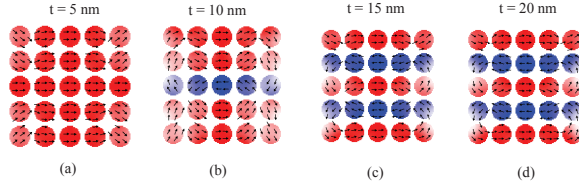


FIG. 7. Spin Configuration of 5 x 5 array at remanence with different thickness.

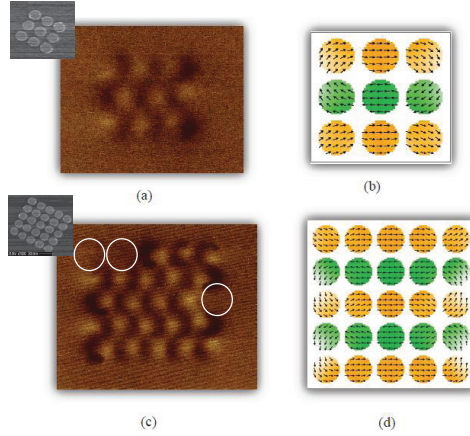


FIG. 8. (a) MFM image of 3 x 3 array, at remanence (b) Simulated spin configuration, (c) MFM image of 5 x 5 array, at remanence. MFM tip couldn't capture the image of the nanomagnets showed by white circles due to very low magnetization of the nanomagnet and (d) Simulated spin configuration.

to occur by jumps rather than by reversible rotations. Also reversal in an array takes place hierarchically, starting with the inner most row and proceeding to the outer row as shown in FIG. 6. The dipolar interaction between the nanomagnets is increased with increase in thickness of nanomagnets as substantiated by simulation results. Illustrated in FIG. 7 is the equilibrium spin configuration for 5 x 5 array with different thickness. Clearly, magnetization for array with thickness 5 *nm* and 10 *nm* are not aligned in anti-ferromagnetic order as shown in FIG. 7 (a) and (b). This configuration indicates that nanomagnets in the array are weakly coupled as opposed to the array of nanomagnets with thickness 15 *nm* and 20 *nm*, where nanomagnets are strongly coupled and attain the anti-ferromagnetic order as shown in FIG. 7 (c) and (d). We have fabricated arrays of 100 *nm* diameter circular nanomagnet with thickness 15 *nm* to validate some of the findings. We were able to achieve edge to edge spacing of 20 *nm* by E-beam lithography and this indicates that it is possible to fabricate

nano-size magnet with such a small separation. FIG. 8(a) and (c), shows the MFM images of 3 x 3 and 5 x 5 array, at remenance, after saturating the array and reducing the field back to zero. The images reveals that all the nanomagnets are in single domain state. These results are correlated with the numerical simulation as shown in FIG. 8(b) and (d).

IV. CONCLUSION

We have studied the magnetization state transition in coupled nanomagnets, for two basic configurations namely, longitudinal and transverse. The phase diagram between vortex state and single domain state was produced for both the configurations. We find that single domain state in longitudinal arrangement is present over a large range of thickness as compared to the transverse and isolated nanomagnet. This is useful to know when we design computing system where switching through a single state is desirable. Further, we studied theoretically and experimentally the magnetization state of the finite arrays. The study predicted that the array of diameter 100 *nm* and thickness 15 – 20 *nm*, stays in single domain state with one step reversal, which results in sharp switching and is ideal for computation applications.

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