

Micromagnetic simulation of two-body magnetic nanoparticles

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Abstract. Field-induced magnetization dynamics was investigated in a system of two magnetic nanoparticles with uniaxial anisotropies and magnetostatic interaction. By using the micromagnetic simulation, ultralow switching field strength was found when the separation distance between the two particles reaches a critical small value on nanometer scale in the perpendicular configuration where the anisotropic axes of the two particles are perpendicular to the separation line. The switching field increases sharply when the separation is away from the critical distance. The same results were observed when varying the radius of particles. The micromagnetic results are consistent with the previous theoretical prediction where dipolar interaction between two single-domain magnetic particles was considered. Our present simulations offered further proofs and possibilities for the low-power applications of information storage as the two-body magnetic nanoparticles could be implemented as a composite information bit.

1. Introduction

Nanomagnetism has attracted wide attention for potential applications in information storage industry, such as hard disk technology, magnetic memory, and logic devices [1, 2]. The magnetization switching of Stoner particles which are believed to be advantageous for high-density information storage has been numerously studied and made significant progress in recent years, both theoretically and experimentally [3-14]. For example, an energy surface model was introduced into the micromagnetic simulation for a single-domain particle and a reversal field below the famous Stoner-Wohlfarth limit was observed [15]. When the nanoparticles were fabricated in array patterns [6, 16-19] the magnetostatic interaction among particles plays an important role and will significantly affect the magnetization switching behaviors. Two-body Stoner particles system could be the simplest one to investigate the magnetostatic interaction on the magnetic switching [20-26]. The dipolar interaction between two particles can assist the switching and influence their hysteresis loops in the two-body system, which was numerically explored in Ref. [20, 23]. In the previous work [27], we have predicted that a critical switching field appears to be dramatically low, almost to the zero-field regime by



omitting thermal fluctuation, with simply considering the magnetic dipolar interaction between the two particles. Our present work is desire to verify it with the more realistic micromagnetic simulation.

In this work, we have studied the magnetization switching of the two-body system and verified our previous results [27] by using the micromagnetic simulation OOMMF package [28]. An ultralow switching field strength (about 20mT) was found when the separation between the two Cobalt particles of 10nm-radius reaches a critical small value (about 23nm). Moreover, varying the radius of nanoparticles the same results were observed. The micromagnetic results verified our theoretical predictions [27], which shall be believed to offer further possibilities for the low-power applications of information storage.

2. Model

The dynamics of magnetization of each particle in a system of two magnetic nanoparticles can be described by the Landau-Lifshitz-Gilbert (LLG) equation [7, 27],

$$\frac{\partial \vec{M}_i}{\partial t} = -\gamma |\vec{M}_i| \times \vec{H}_{i,eff} + \frac{\alpha}{M_s} \left(\vec{M}_i \times \frac{\partial \vec{M}_i}{\partial t} \right). \quad (1)$$

Here $\vec{M}_i$ is the magnetization vector of the i th particle ($i = 1, 2$). $M_s = |\vec{M}_i|$, γ and α are the saturation magnetization of each particle, the gyromagnetic ratio and the Gilbert damping coefficient, respectively. $\vec{H}_{i,eff}$ is the effective magnetic field acting on the i th particle. The material parameters are for Cobalt ($M_s = 1.4 \times 10^6 \text{ A/m}$, $A = 1.3 \times 10^{-11} \text{ J/m}$, $K_i = 10^5 \text{ J/m}^3$). Damping coefficient $\alpha = 0.5$ is chosen bit larger for accelerating the simulation speed in our static simulation without loss of accuracy. Both particles are in spherical shapes with the same radius, and the mesh cell size is $1\text{nm} \times 1\text{nm} \times 1\text{nm}$. The two-body system consists of two identical magnetic nanoparticles with uniaxial anisotropies (see inset in Figure 1). According to our previous results [27] perpendicular configuration is a more promising candidate of a composite information bit, in which the connecting unit vector $\vec{n}$ between the centers of the two particles is perpendicular to the anisotropy easy-axes (EA) of each particle, referred to as PERP configuration.

3. Results and discussion

At the first step we considered the PERP configuration with particles of 10nm-radius and the varying separation d . The initial magnetization directions of the system were set to along the easy axis (x-direction) and the external fields were applied antiparallel to the initial magnetization directions [see inset in Figure 1(b)]. Figure 1(a) shows the magnetic hysteresis loops of magnetization for the varying separation distances ranging from 22nm to 120nm. The curves clearly show that the coherent rotation is satisfied with a large range of separations. Figure 1(b) shows the dependence of the switching fields on the varying separations. An ultralow switching field strength of about 17mT was observed for the separation chosen as $d = 23\text{nm}$. The corresponding magnetic vector distribution snapshots within particles are shown in Figure 2(b) which corresponds to the two locations D (no magnetization reversal), E (both particles reversed) in Figure 1(a) (red color). The behaviors for other larger separations are similar. For $d < 23\text{nm}$, the switching fields abruptly become large where two metastable states appear as shown in the hysteresis curve of $d = 22\text{nm}$ in Figure 1(a) (black color). Two midst plateaus of zero total magnetization of the two particles can be clearly observed in the figure. The switching field for totally reversing the two particles is found at about 186mT. The corresponding magnetic vector distribution snapshots within particles for the metastable state are shown in Figure 2(a) which corresponds to the three locations A (no magnetization reversal), B (one particle reversed), C (both particles reversed) in Figure 1(a) (black color), respectively. It implies that one of two particles reverses its magnetization first, and then the other particle reverses. This phenomenon could be interpreted as the enhancement of the magnetostatic interaction with the very close distance between the two particles.

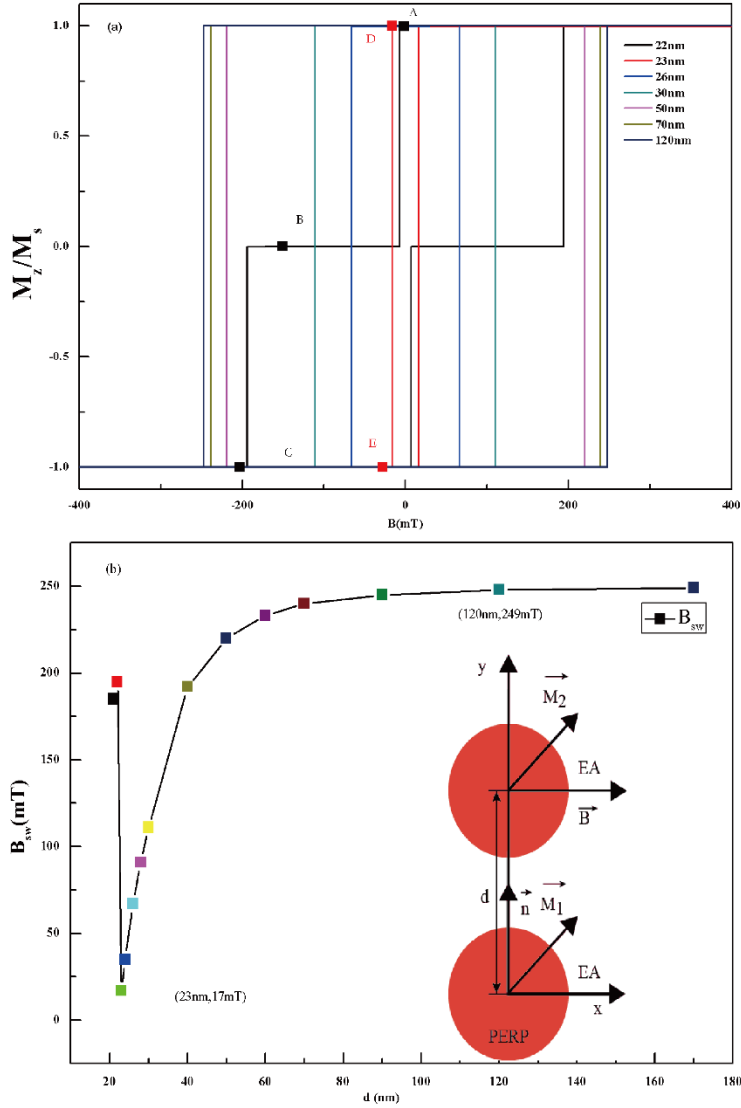


Figure 1. (Color online) (a) The hysteresis loops of magnetization for different separations d in the PERP configuration. (b) The critical switching field versus the separations d ranging from 21nm to 170nm when magnetic fields are applied along the x-direction shown in the lower right inset. The system parameters are $K_i = 10^5 \text{ J/m}^3$, and $\alpha = 0.5$.

On the other hand, the switching field increases in saturation with the rising separations ranging from 23nm to 120nm. It approaches to a constant value of 250mT for larger separations. The value is closely equal to the switching field required for a single nanoparticle under the same parameters observed in our simulation. The increasing trend of the switching field is due to the competition between the magnetostatic interaction and the exchange interaction which are significant when the separations between the two particles are much closer. Nevertheless, both of them can be negligible when two bodies are separated far away. Thus, the far-away behavior of the two-body system will behave as a single particle.

Figure 3 reveals that the critical switching fields versus the separations for different radius of particles. As shown in the figure, the minimum switching fields can be found in certain separations that is 18nm, 23nm and 28nm corresponding to the radius of 8nm, 10nm and 12nm, respectively. These results are consistent with the previous theoretical prediction with the critical separation distance $d_c = \left(\frac{\pi \mu_0 M_s^2}{2\pi K} \right)^{1/3} r$ [27]. Consequently, a ultralow magnetic field is sufficient to switch the magnetization in a system of two-body particles from initial state to the antiparallel state. More detailed physical significance about the above critical condition has been illustrated in Ref. [27].

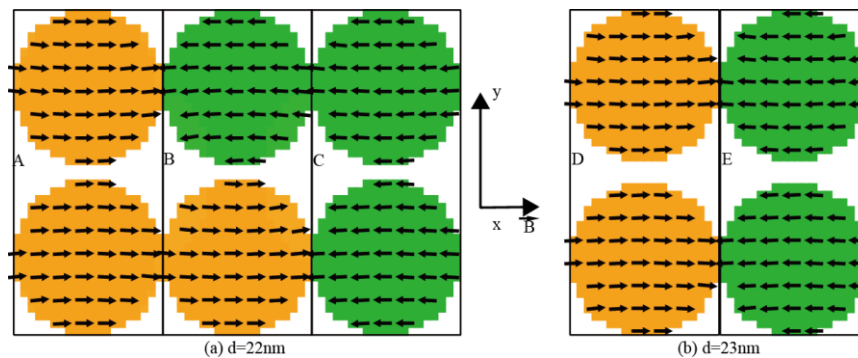


Figure 2. (Color online) The magnetic vector distribution snapshots inside the particles for (a) $d = 22\text{nm}$ and (b) $d = 23\text{nm}$. Each single snapshot from A to E corresponds to the marked locations in Figure 1(a). Orange and green color depict with magnetization reversal and without reversal, respectively.

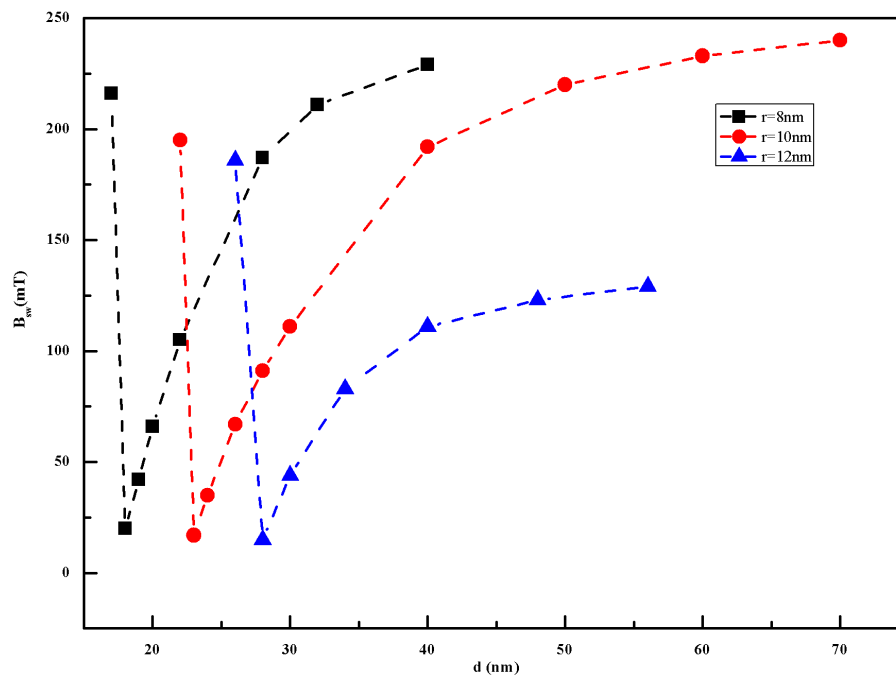


Figure 3. (Color online) The critical switching field versus the separations d for radius of 8nm, 10nm and 12nm of particles in PERP configuration

The present work has the advantages over the previous studies with taking into account the more realistic micromagnetic simulation case. In the simulation, the magnetostatic interaction is adopted in place of the simplified dipolar interaction in the previous analytical calculations. Thus the ultralow field switching behavior could be more realistic and be tested in real experiments. Additionally, we have also simulated the magnetization switching of the system with the initial magnetic states of two particles antiparallel to each other along the easy-axes. The results were similar which implies that the choices of the initial states will not affect much on the ultralow magnetization switching behaviors.

4. Summary

In conclusion, we have investigated magnetization switching of two-body magnetic nanoparticles by using micromagnetic simulation. Owing to the competition between magnetostatic interaction and magnetic exchange interaction, an ultralow magnetization switching field was found in the perpendicular configuration for a critical separation distance between two particles. A metastable state of the two particles was also observed below the critical distance. The switching fields increase with the increasing separations beyond the critical distance and finally reach a saturated value because the contribution of magnetostatic interaction and exchange interaction is getting weaker as the two particles separate far away. Moreover, varying the radius of particles shows the same behaviors. It should be pointed out that our simulation neglects the thermal fluctuations. The micromagnetic simulation results have verified our previous theoretical predictions and could offer more possibilities to new magnetic information storage applications.

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