Contribution of magnetostatic interaction to magnetization reversal of Fe$_3$Pt nanowires arrays: A micromagnetic simulation

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**Abstract**

Using the micromagnetic simulations, we have investigated the magnetization reversal and magnetostatic interaction of Fe$_3$Pt nanowires arrays with wire diameters lower than 40 nm. By changing the number of interacting nanowires, $N$, interwire distance, $a$, and wire diameter, $D$, the effects of magnetostatic interaction on coercivity and remanence are investigated in detail. According to the simulated results, the contribution to the stray field induced by surface perpendicular magnetization at the end of wires is established.

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**1. Introduction**

The ordered arrays of magnetic nanowires fabricated by electrodeposition have attracted much attention due to their possible application on perpendicular magnetic recording media. Recently, several papers have reported that the magnetostatic interaction between nanowires could be treated as a dipole–dipole interaction [1–5]. Although the dipole–dipole interaction is much weaker than the direct exchange interaction for ordered magnetic nanostructures, it still plays an important role in determining the magnetic properties. In our previous work [6], we have simulated the hysteresis loop of Fe$_3$Pt nanowire arrays with diameter $D = 10$ nm. The simulation results demonstrate that the calculated coercivity for one single nanowire is much larger than the measured one of Fe$_3$Pt nanowire arrays. This suggests that the magnetostatic interaction between nanowires cannot be neglected. Although the contribution of magnetostatic interaction has been generally simulated by changing the number of interacting nanowires, $N$, interwire distance, $a$, and wire diameter, $D$, the effects of these three parameters to the magnetization reversal of Fe$_3$Pt nanowires can be investigated separately by means of micromagnetic simulation via changing $N$, $a$ and $D$, respectively. In this work, we have investigated the magnetostatic interaction of Fe$_3$Pt nanowire arrays on the basis of micromagnetic simulations. Moreover, the contribution of the magnetostatic interaction derived from the stray field of Fe$_3$Pt nanowire arrays has been established.

**2. Simulation model**

The micromagnetic simulations were performed using the object-oriented micromagnetic computing framework (OOMMF) [9]. All nanowires in the simulation are assumed to have exactly the same geometry. According to scanning electron microscopy images, the geometry of the closely packed magnetic nanowires was employed as the simulation parameters [10].

A hexagonal cell array of Fe$_3$Pt nanowires was established with number of nanowires $N$ varying from 1 to 16 in order to investigate the magnetostatic interaction by changing the number of the neighboring wires. Considering about our previous studies on the Fe$_3$Pt nanowires arrays, the centre-to-centre distances of 40 nm between the wires would almost exceed the effective range of the magnetostatic interaction. Therefore, we only focus on Fe$_3$Pt nanowires arrays with the wire diameter lower than 40 nm and the centre-to-centre interwire distance between 10 and 40 nm in...
order to determine the significant influence of the interwire spacing on the magnetostatic interaction. The length of the nanowires is 400 nm. A unit cell used in this simulation was defined as \((X \times Y \times Z) = 1.25 \text{ nm} \times 1.25 \text{ nm} \times 10 \text{ nm}\), in order to compromise the precision of the calculation and the computational time. The exchange stiffness of \(A = 25.79 \times 10^{-8} \text{ erg/cm}\) and the saturation magnetization of \(M_s = 1250 \text{ emu/cm}^3\) obtained from bulk Fe$_3$Pt were used during the simulation [11]. The magnetocrystalline anisotropy could be neglected because the strong shape anisotropy plays a dominant role in Fe$_3$Pt nanowires arrays [6,10]. The used parameters for simulation are summarized in Table 1.

### 3. Results and discussion

The contribution of magnetostatic coupling between nanowires to magnetization reversal was investigated via placing an increasing number of nanowires on hexagonal arrays. Fig. 1 illustrates the simulated hysteresis loops of Fe$_3$Pt nanowire arrays along easy axis with different numbers of interacting wires. On the basis of experimental results [6,10], the diameter of \(D = 10 \text{ nm}\) and interwire distance of \(a = 40 \text{ nm}\) were selected for simulation. For comparison, the measured hysteresis loop for Fe$_3$Pt nanowires was also plotted in Fig. 1. Although the present data are not sufficient to convincingly extrapolate a value of coercivity for the case \(N \to \infty\), our simulation result indicates that the value of \(H_c = 2.86 \text{ kOe}\) for \(N = 16\) approaches well the experimental value \((H_c = 2.76 \text{ kOe})\) of Fe$_3$Pt nanowires arrays [6]. One can see that in the experiment the nanowires have no more a typical square shape hysteresis loop as the simulations. The different shape in the experimental situation comes from irregular boundary for the surface magnetization at the end of actual nanowires, as well as their size distributions.

The coercivity and the remanence of Fe$_3$Pt nanowires parallel to the wires axes with various interwire distance \(a = 10–40 \text{ nm}\) as a function of the number of interacting nanowires, \(N\), are plotted in Fig. 2(a) and (b), respectively. The diameter is fixed \(D = 10 \text{ nm}\). In Fig. 2(a), it can be seen that a single nanowire possesses a significantly higher coercivity of 3.7 kOe than the measured value of 2.76 kOe. The coercivity decreases roughly with increasing the interacting wire number in the arrays, except for the nanowire arrays with \(N = 4\) and \(a = 10 \text{ nm}\). Since four wires cannot form a periodic hexagonal array, the array with \(a = 10 \text{ nm}\) exhibits a minimum of coercivity due to the boundary effect of simulation model. Similar results were also calculated by Hertel and Rahman in Ni nanowires [7,8]. With decreasing the interwire distance \(a\), the coercivity decreases owing to the increase in the magnitude of magnetostatic coupling between nanowires. For the interwire \(a = 10 \text{ nm}\), the nanowires are almost directly connected, a significant decrease of coercivity is expected. The magnetostatic interaction between nanowires results in not only a reduction of coercivity, but also a decrease of remanence (Fig. 2(b)). The decrease of remanence is more evident for the larger number of nanowires and smaller interwire distance; although the influence of magnetostatic interaction on remanence, however, is weaker than that on coercivity, which is attributed to the small number of nanowires used for calculation.

After learning the contribution of interacting number and interwire distance of nanowires to the coercivity as well as the remanence of Fe$_3$Pt nanowires arrays, the effect of interwire distance on the detailed magnetization reversal process of Fe$_3$Pt nanowires arrays was simulated for \(4 \times 4\) arrays. Fig. 3(a) shows the easy axis demagnetization curves of \(4 \times 4\) arrays with different interwire distance. In the case of non-interacting wires,
the magnetization reversal was governed by the shape magnetic anisotropy of nanowires. The switching field of each wire is identical if their length and diameter are uniform. Consequently, a hysteresis loop of perfectly rectangular shape is expected. For the nanowires with larger interwire distance $a = 40 \text{ nm}$, the magnetostatic interaction between nanowires is relatively weak. Almost coherent magnetization reversal occurs. However, with further decreasing the interwire distance, the demagnetization curves indicate multi-step jumps in magnetization reversal process of individual nanowires. For example, the demagnetization curve for the $4 \times 4$ arrays with interwire distance $a = 10 \text{ nm}$ indicates clearly eight-step jump for normalized magnetization from $+1$ to $-1$, suggesting that the magnetizations of different nanowires in the $4 \times 4$ arrays reverse step by step when the magnetostatic coupling between the nanowires is strong enough. In the case of the interacting wires, the reversal process of magnetization for each wire is not only determined by the magnetic shape anisotropy itself, but also by the stray field originated from the surrounding wires. Since we have only employed $4 \times 4$ arrays, rather than periodic array consisting of infinite number of nanowires to simulate the demagnetization curves, the stray field applied on each wire is varied. Therefore, multi-step jumps were observed in magnetization reversal. Even the interacting number is just 4 or 11, whenever the interwire distance is in the range of 40 nm, we still could see those plateaus in their hysteresis loops no matter how small the field step we have taken. Similar multi-step loops were seen as the evident in interacting Ni wires in the experiment [12] and also in the simulation [13]. The stepped-demagnetization curve becomes sheared when the number of interacting wires approaches infinite. Size distribution, temperature or even other effects can also play a major role in smoothing the hysteresis loops in the experiments.

To give an insight into the magnetization state during the reversal, Fig. 3(b) and (c) presents the magnetic moment configurations for firstly reversed wires in the array (marked as blue) and the corresponding stray field configuration. A pair of firstly reversed wires in the center of array is outlined. The colors represent the $z$ component of the magnetization (b) or stray field (c). The blue arrows (point to the plane) imply that the magnetizations are switched while the red arrows (out-of-plane) suggest the magnetized state. It proves that a non-coherent magnetization reversal occurs in the interacting nanowires arrays. When the magnetizations of some interacting wires have been reversed by external magnetic field, the stray field also reverses, and hence acts against the external field in the neighboring regions. Therefore, the magnetizations in the wires involved in this region need a higher switching field (nearly more than 400 Oe additionally) to be reversed as shown in the stepped curves. Thus, the magnetostatic interaction in the array can be derived from the stray field between neighboring wires. As a result, the stray field changes the shape of the hysteresis loops significantly. Since the magnitude of the magnetostatic interaction is dependent upon the number of interacting wires and the interwire distance, the magnetostatic interaction of neighboring wires adds to the external field and leads to a higher local field to switch the magnetic moment, and consequently the coercivity decreases with increasing the number of neighboring wires and with decreasing the interwire distance.

The stepped-demagnetization curves were also observed in the interacting nanowires by increasing the wire diameter $D$ from 10 to 25 nm (Fig. 4). Although the center-to-center distance was fixed as 40 nm during the calculation, the increase in diameter results in a reduction of distance between the boundaries of wires. Therefore, the magnetostatic interaction between nanowires is enhanced and consequently, the multi-step jumps in demagnetization curves are still observed with increasing the diameter of nanowires.

Fig. 5(a) and (b) indicates the diameter dependence of coercivity and remanence of the arrays parallel to the wire axis with various number of interacting wires $N = 1–16$, respectively.
It can be seen clearly that regardless of the number of interacting wires, both coercivity and remanence decreases monotonously with increasing the diameter of nanowire. Compared with non-interacting nanowires, the magnetostatic coupling between nanowires results in a slightly decrease of coercivity, whereas a significant reduction of remanence when the diameter of nanowire increases.

Shtrikman and Aharoni have predicted that for perfectly infinite cylinders with different diameters, the magnetization reversal occurs by coherent rotation, magnetization curling and buckling mode [14,15]. Usually coherent or uniform rotation occurs when the nanowire diameters are smaller than the critical diameter $D_{coh} = \sqrt[3]{24 A/\mu_0 M_s^3}$ [16]. When the diameters are larger than critical diameter $D_{coh}$, the magnetization reversal process occurs by magnetization curling mode or buckling mode. For the magnetization curling mechanism, coercive fields decrease with increasing the diameter and could be written as

$$H_c = \frac{2\pi kA}{\mu_0 M_s} \frac{1}{D^2} + H_o,$$

where $A$ is the exchange stiffness, $k$ is the geometry-dependent parameter and $D$ is the diameter of the nanowires.

A linear relationship between $H_c$ and $d^{-2}$ was observed for the single nanowire (inset of Fig. 5(a)), which implies that the magnetization reversal shows curling mode of inhomogeneous rotation for the non-interacting wires. The curling mode is characterized by a vanishing stray field. For the interacting wires with $N>1$, however, the deviation from linear relationship between $H_c$ and $d^{-2}$ suggests that owing to the magnetostatic interaction between wires, the inhomogeneous rotation is mainly determined by buckling mode when the diameter is large enough.

The micromagnetic theory can explain the dependence of coercivity and remanence on the interwire distance and wire diameter. Within the framework of micromagnetic theory, the total energy in a ferromagnetic sample can be written as

$$E_{tot} = E_A + E_k + E_{zee} + E_s,$$

where $E_A$ is the exchange energy. For modeling, $E_A$ behaves as a short-range interaction which can only act on the neighboring cells inside a single wire. $E_s$ is the magnetocrystalline anisotropy energy, which can be neglected since the strong shape magnetic anisotropy plays a dominant role in these arrays [6]. $E_{zee}$ is the Zeeman energy and irrelevant with the interacting wires. $E_k$ is the dipolar stray field energy, which origins from the magnetostatic interaction between wires and can be obtained by solving these equations [17]

$$E_s = -\frac{1}{2} \int J_s d^3\mathbf{r},$$
$$H_s(r) = -\nabla U, \quad \Delta U = 4\pi \nabla \mathbf{M}_s,$$
$$U(r) = -\int_0^r \nabla \mathbf{M}_s(r') \, dr' + \int_0^r \mathbf{M}_s \, dr,$$
$$U^{(i)}(r_{ext}) = H_{ext}^{(i)} + 4\pi \mathbf{M}_s.$$

The first part of Eq. (5) forms the demagnetization field antiparallel to the magnetization through the magnetic moments inside the single wire, while the latter one so-called as stray field presents the demagnetization field caused by surface magnetic moments, existing both inside and outside of the single wire. Considering the surface magnetic moments and the stray field outside the wire, the boundary conditions (Eq. (6)) should be satisfied. Thus, the external stray field out of the wire depends on the sum of internal demagnetization field and the projection of the magnetization vector on the perpendicular direction of the surface. As for the cylinder wires, the stray field outside the wires could only be detected at the ends of wires if the applied field is along the wires axes since there is no perpendicular magnetization vector on the perpendicular direction of the surface existed in the midst of wire (see Fig. 3(b)).

When the applied field parallel to the wire axis is reversed to the opposite direction, on the one hand, the stray field from neighboring interacting wires causes a small nucleation field starting at the end of the wire. With increasing the external field, it activates a new domain nucleation in the nearest neighboring domains inside the wire, and finally the whole magnetization of this wire is reversed while this domain nucleation "avalanche" happens when the coercivity field reached. Thus, the buckling mode is favorable in magnetization reversal process for the interacting nanowires, which was confirmed in our previous work [6]. On the other hand, the stray field also adds to the external field and leads to a higher local field to switch the magnetic moment in this wire. The stray field strongly depends both on the distance between the boundaries of interacting wires (proportional to $1/r^2$, as shown in Eqs. (4) and (5)) and the number of the nearest neighboring interacting wires. Thus, the coercivity reduces remarkably when this stray field becomes stronger with increasing wire diameter, reducing interwire distance as well as increasing number of wires in the array. Furthermore, besides the reduction of coercivity, this stray field also facilitates the magnetic moments to lean from the direction of the saturation field in order to satisfy the equilibrium structures of the total energy in the remanence state, which results in a reduction of remanence as shown in Fig. 5(b).

4. Conclusions

We have simulated the contribution of magnetostatic interaction to magnetization reversal in Fe$_3$Pt by changing the number of interacting nanowires, $N$, interwire distance, $a$, and wire diameter, $D$. It was found that the stray field from the neighboring wires...
adds to the external field and leads to a higher local field to switch the magnetic moment, and consequently the coercivity decreases with increasing the number of neighboring wires and the diameter of nanowires, as well as decreasing the interwire distance. A slight decrease of remanence was also resulted from the magnetostatic interaction between nanowires.

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