Magnetic reversal of double-layer patterned nanosquares

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The magnetic reversal process of double-layer patterned nanosquares was studied by means of micromagnetic simulations. Different types of hysteresis loops were observed, depending on the thickness ratio of the two layers and the interlayer distance. Antiparallel state was induced by different mechanisms, either through the differential magnetostatic fields or through the differential coercitivies of the two layers. It is revealed that the interlayer magnetostatic interaction is the key factor that determines the reversal behavior. In this study, we constructed a diagram for the dependence of the types of hysteresis loops on thickness ratios and interlayer distances. The switching dynamics for the double-layer patterned nanosquares were also investigated. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1866498]

INTRODUCTION

Magnetic mutilayer systems have been extensively studied for the last 20 years, revealing many interesting properties, such as giant magnetoresistance (GMR) and perpendicular magnetic anisotropy (PMA).[1,2] Recently nanofabrication technology[3] offers powerful capabilities in patterning material into submicron scale, which allows us to achieve unique magnetic properties that do not exist in a thin-film or bulk material. Lithographically patterned magnetic multilayer elements, such as magnetic tunneling junctions (MTJs) and pseudospin-valve (PSV) elements, have been used in high-density magnetoresistive random access memory (MRAM) devices.[4,5] These PSV or MTJs consist of two asymmetric ferromagnetic layers with a nonmagnetic metallic spacer. The reversal behavior of PSV elements has been studied both experimentally[6–8] and theoretically.[9–11] While most studied patterned magnetic multilayer elements have rectangular or elliptical shapes, recently square magnetic double-layer nanodots have also been developed.[12,13] Due to their unique domain structures and magnetic properties, different magnetic reversal behaviors have been found by Maicas *et al.*,[14] who numerically investigated the stable domain structures and switching mechanisms of double-layer nanosquares with equal thickness. In this paper, the magnetic reversal behavior of double-layer patterned nanosquares was studied by micromagnetic simulations. Our emphasis is on the effects of thickness ratio and interlayer distance of the two layers. We also study the switching dynamics of the two layers.

MODEL AND COMPUTATIONAL DETAILS

Three-dimensional micromagnetic simulations of the double-layer patterned nanosquares (Fig. 1) were carried out by numerically solving the Landau–Lifshitz–Gilbert (LLG) equation

$$(1+\alpha^2)\frac{\partial \mathbf{M}}{\partial t} = -\gamma_0 \mathbf{M}\times\mathbf{H}_{\mathrm{eff}} - \frac{\gamma_0\alpha}{M_s}\mathbf{M}\times(\mathbf{M}\times\mathbf{H}_{\mathrm{eff}}), \quad (1)$$

where M_s is the saturation magnetization, γ_0 is the gyromagnetic ratio, α is the damping constant, and $\mathbf{H}_{\mathrm{eff}}$ is the effective magnetic field. In our simulations, we take into account four main energetic contributions: exchange, anisotropy, magnetostatic, and Zeeman energies. To study the magnetic reversal properties, an external field is applied. The amplitude of the field varies stepwise with an interval of 5 Oe. For each step, the equilibrium distribution of magnetic moments, and thus the average magnetization are obtained from the LLG equation. Magnetic parameters are chosen to correspond to the isotropic permalloy, which has been commonly used in patterned magnetic structures,[15,16] i.e., the saturation magnetization is $M_s = 800$ emu/cc, the exchange constant is $A_{\mathrm{ex}} = 1.05\times10^{-6}$ erg/cm, and the gyromagnetic ratio $\gamma_0 = 0.017\,59\ \mathrm{Oe}^{-1}\,\mathrm{ns}^{-1}$. For the damping constant, value $\alpha = 0.5$ is used for the static configuration while $\alpha = 0.2$ is used for dynamic study. The system is modeled by discretizing it into a three-dimensional array of cubic cells. In order to assure a good description of the magnetic details, the size of the cell is chosen to be smaller than the exchange length $l_{\mathrm{ex}} = \sqrt{2A_{\mathrm{ex}}/\mu_0 M_s^2} \approx 5.11$ nm. The LLG equation is solved using the Gauss–Seidel projection method.[17]

RESULTS AND DISCUSSIONS

Double-layer patterned nanosquares with an edge length of 60 nm were simulated for different thickness ratios and

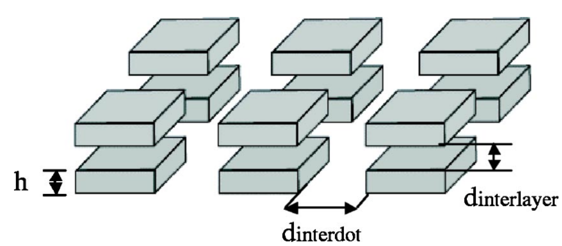

FIG. 1. Geometry of the patterned double-layer nanosquares. The layer thickness (h), interdot distance (d_{interdot}), and interlayer distance ($d_{\mathrm{interlayer}}$) are shown.

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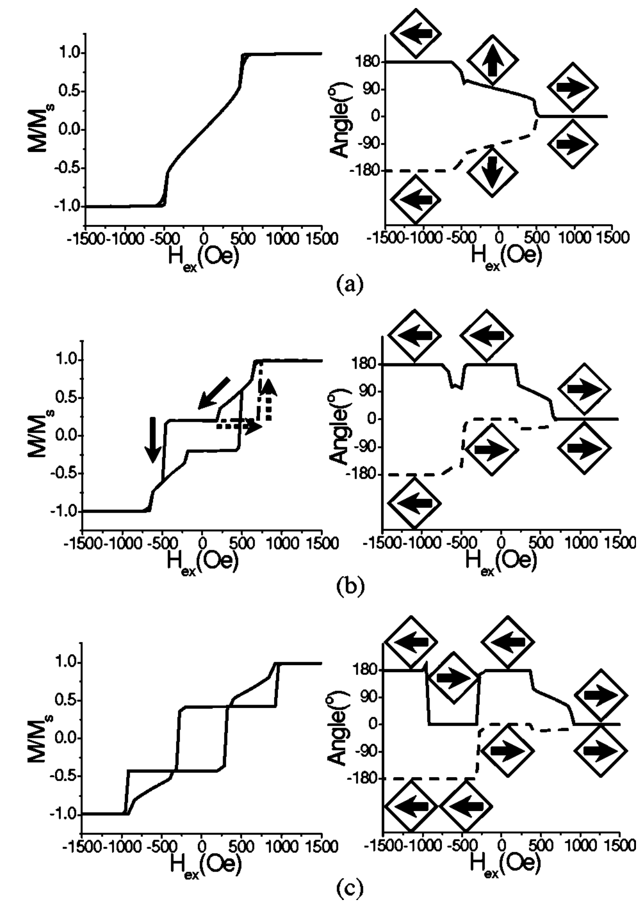

FIG. 2. Hysteresis loops (left side) and the mean magnetization direction evolution to the applied field (right side: solid line is that for the thin layer and the dash line is that for the thick layer) of double-layer nanosquares with different thickness ratios: (a) 1:1, (b) 1:1.5, (c) and 1:2.5. The dash dot line in (b) shows the back switching of the thin layer. (Edge=60 nm, $h_{\text{thinlayer}}$ =7.5 nm, and $d_{\text{interlayer}}$=7.5 nm.)

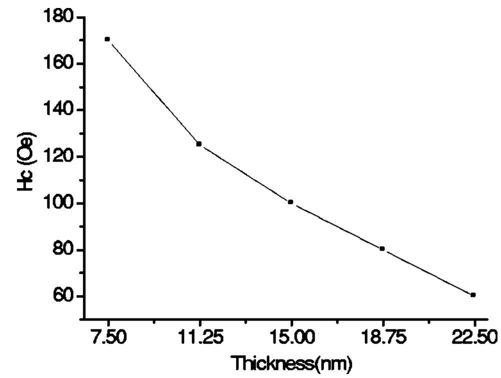

FIG. 3. The coercive field (H_c) of single-layer nanosquare as a function of layer thickness. (Edge=60 nm).

interlayer distances. Here, we assume that the nanodots are spaced by a sufficiently large interdot distance (two times of the edge length of the nanodots) that magnetostatic interactions among dots within a single layer are relatively weak and can be ignored. We also ignored the exchange coupling between the layers, as our study focus on the effect of magnetostatic interaction, and the exchange coupling effect is weak for the interlayer distances that we studied.[12] The magnetic field was applied parallel to the patterned layer and in a diagonal direction of the nanosquare.

In Fig. 2, the left side shows the hysteresis loops for the double-layer nanosquares with different thickness ratios of the two layers, and the right side shows the mean magnetization directions of the two layers to the applied field. For double-layer nanosquares with equal thickness, as the applied field decreases from the saturation value, the two layers symmetrically rotate to the opposite directions from the parallel saturation state, which originates from the magnetostatic interaction between the two layers. The hysteresis loop obtained was similar to earlier studies of Maicas *et al.*[14] The antiparallel state [Fig. 2(a)], with the magnetization direction perpendicular to the applied field, was attributed to its fourfold configurational anisotropy,[18] unlike the shape anisotropy found in rectangles or ellipses that only exhibit uniaxial (twofold) symmetry. When the thickness ratio is not equal to 1, quite different hysteresis loops were observed, as shown in Figs. 2(b) and 2(c). For the normal PSV elements with rectangular or elliptical shapes, the antiparallel state was obtained by introducing different coercivities of the two layers through the use of differential layer thickness or layer materials. In this case, the soft layer switches before the hard layer, providing a range of applied field for which the two layers are antiparallel. While for the double-layer nanosquares, it is surprising to see that the thin (hard) layer reverses first to form an antiparallel state [configurational anisotropy decreases with the thickness for the range of thickness we studied (Fig. 3)], implying that the antiparallel state was not induced by the differential coercivites but the differential magnetostatic fields of the two layers. As the applied field decreases, the two layers rotate to opposite directions but with different angles [Fig. 2(b)]. The thin layer rotates with a larger angle since the magnetostatic field produced by the thick layer exceeds that produced by the thin layer. At a certain field, the thin layer overcomes the external and anisotropy fields, reverses first. We notice that at this time the thick layer rotates back to its original direction, thus an antiparallel configuration was obtained, whose direction parallels to the applied field. For double-layer nanosquares with a large thickness ratio (1:2.5), an additional antiparallel state was observed as shown in Fig. 2(c). In this case, the magnetostatic field of the thick layer becomes so strong that the thin layer reverses again simultaneously when the thick layer reverses. For the application of patterned magnetic multilayer elements in MRAM, the back switching field is also important,[19] which requires that the thin layer need to be switched back easily from the high resistant state (antiparallel state). We studied the back switching behavior of the thin layer by applying an increasingly positive field from the remanent state as the dash dot line shown in Fig. 2(b). The obtained switching field of the thin layer is 720 Oe, which is higher than that of the thick layer (around 500 Oe). The difference of these two switching fields comes from the differential anisotropies and differential magnetostatic fields of the two layers. While for the normal PSV elements with rectangular or elliptical shapes, the thin layer switches back and forth by a small field without changing the magnetization direction of the thick layer, which is necessary for application in MRAM to read the storage state without modifying it.

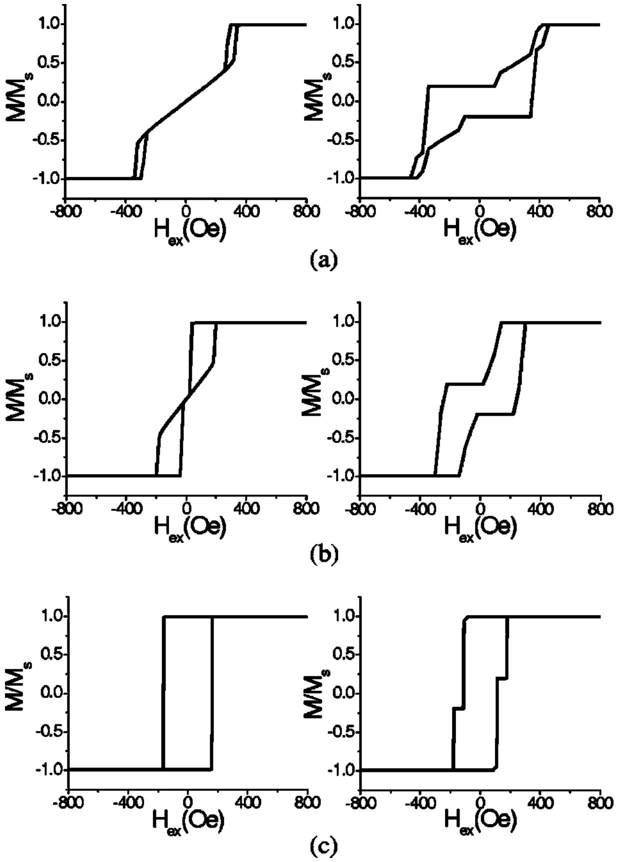

FIG. 4. Hysteresis loops for double-layer nanosquares with different interlayer distances, (a) 15, (b) 30, and (c) 120 nm. Left side: thickness ratio =1:1, right side: thickness ratio=1:1.5 ($h_{\mathrm{thinlayer}}$=7.5 nm, edge=60 nm).

Therefore, the double-layer nanosquares are not appropriate to be used in MRAM at least with present technology.

Figure 4 shows the hysteresis loops of double-layer nanosquares for different interlayer distances. As expected, the shorter the interlayer distance is, the stronger the magnetostatic interactions between the layers are. For double-layer nanosquares with equal thickness (Fig. 4 left side), with the increase of the interlayer distance, the applied field range of the nonparallel state decreases as the magnetostatic interactions disfavor the parallel state. When the interlayer distance is sufficiently large that the magnetostatic interactions between the layers become relatively weak, a square loop was obtained [Fig. 4(c)], which is typical for single-layer nanosquares. For the double-layer nanosquares with unequal thickness, the applied field range of the antiparallel state

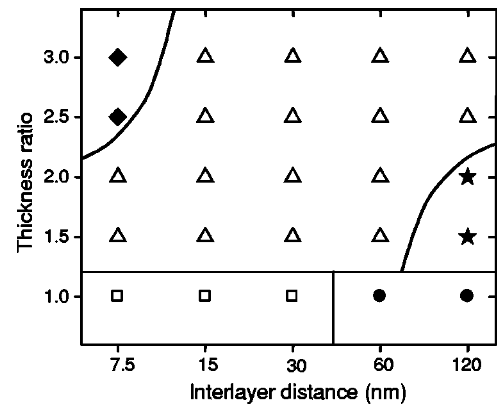

FIG. 6. Phase diagram of the hysteresis loop types for double-layer nanosquares. □ indicates P-AP (perpendicular to applied field)-P, ● indicates P-P, △ indicates P-AP (positive magnetization)-P, ★ indicates P-AP (negative magnetization)-P, ◆ indicates P-AP (positive magnetization)-AP (negative magnetization)-P. P: parallel, AP: antiparallel.

shrinks with an increase of the interlayer distance (Fig. 4 right side). It is interesting to note that, for large interlayer distances with relatively weak magnetostatic interactions [Fig. 4(c)], the thick (soft) layer reverses first, leading an antiparallel state with negative magnetization. As in this case, the anisotropy effect becomes dominant, the antiparallel state was induced by the differential coercivities of the two layers. For the double-layer nanosquares with two antiparallel states (Fig. 5), the additional antiparallel state disappears with the increase of interlayer distance since the magnetostatic field of the thick layer is not strong enough to reverse the thin layer.

As a summary, Fig. 6 shows the dependence of the types of hysteresis loops on the thickness ratio and interlayer distance. As we discussed it earlier, the double-layer nanosquares with equal thickness have unique reversal behavior due to its symmetric structure. For short interlayer distances, an antiparallel state with a direction perpendicular to the applied field can be obtained due to its fourfold configurational anisotropy. While for larger interlayer distances, a square loop will be obtained instead. For double-layer nanosquares with unequal thickness, there are three kinds of hysteresis loops, depending on the thickness ratio and inter-

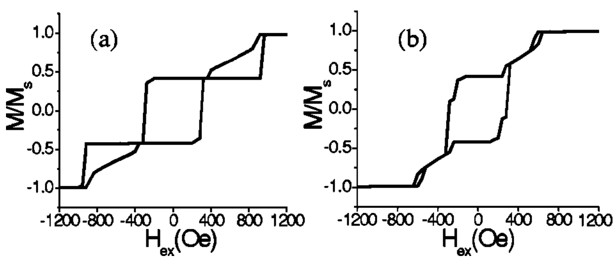

FIG. 5. Hysteresis loops for double-layer nanosquares with different interlayer distances, (a) 7.5, and (b) 15 nm. ($h_{\mathrm{thinlayer}}$=7.5 nm, thickness ratio =1:2.5, and edge=60 nm.)

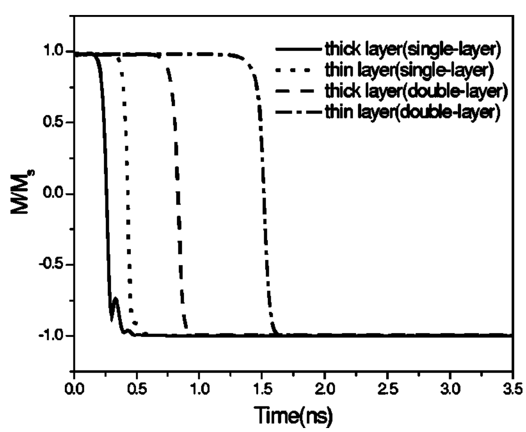

FIG. 7. Time evolution of the average magnetization for double-layer nanosquares and single-layer nanosquare during the switching process. (edge=60 nm, $h_{\mathrm{thinlayer}}$=7.5 nm, $h_{\mathrm{thicklayer}}$=11.25 nm, and $d_{\mathrm{interlayer}}$=7.5 nm.)

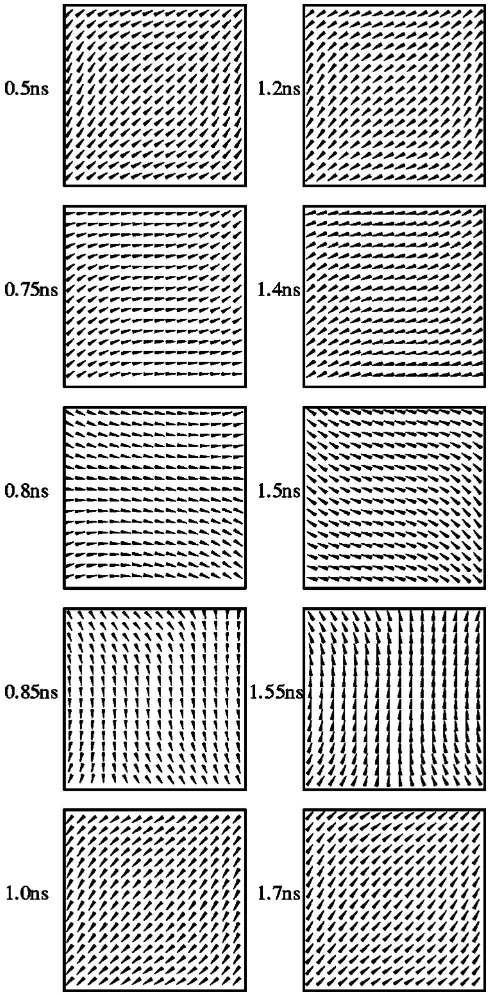

FIG. 8. Magnetization configurations during the switching process for double-layer nanosquares. Left side: thick layer; right side: thin layer ($d_{\text{interlayer}}=7.5$ nm, $h_{\text{thinlayer}}=7.5$ nm, $h_{\text{thicklayer}}=11.25$ nm, and edge=60 nm).

layer distance. For high thickness ratio and low interlayer distance, a hysteresis loop with two antiparallel states is obtained, as the thin layer will reverse three times due to the strong magnetostatic field from the thick layer. With the decrease of the thickness ratio or increase of the interlayer distance, the magnetostatic interactions decrease and the additional antiparallel state will disappear. For larger distances with very weak interlayer magnetostatic interactions, the anisotropy field becomes more important. A different antiparallel configuration with negative magnetization was obtained due to the different coercivities of the two layers.

The switching dynamics of the thin layer and thick lyer have been investigated for double-layer nanosquares with thickness ratio of 1:1.5. The remanent state [antiparallel state, as shown in Fig. 2(b)] has been taken as the initial state. Instantaneously external fields with 800 or −800 Oe were applied to reverse the thin layer or the thick layer. In Fig. 7, the time evolution of average magnetization during the switching process was plotted. For comparison, the switching process of single-layer nanosquare with the same thickness was also plotted. For the double-layer nanosquares, the switching time of the thin layer is longer than that of the thick layer due to the higher switching field of the thin layer originating from both anisotropy and magnetostatic interaction. And both the two layers in double-layer nanosquares have longer switching time than their counterparts in single-layer nanosquares, due to the magnetostatic interactions between the two layers. Figure 8 shows some snapshots of the magnetization configuration during the reversal process. As can be observed, the switching mode is quasicoherent rotation, which is the same as that of single-layer nanosquares.[20]

SUMMARY

The reversal behavior of double-layer nanosquares was studied by micromagnetic simulations. It is shown that different thickness ratios and interlayer distances lead to different hysteresis loops. Antiparallel states were induced by different mechanisms, either through the different magnetostatic fields or through the differential coercitivies of the two layers, depending on the thickness ratio and interlayer distance. The switching dynamics of the two layers was also investigated, which reveal that the switching process was delayed by the magnetostatic interaction between the layers compared to that of single-layer nanosquares.

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