Magnetization Reversal in Submicron Disks: Exchange Biased Vortices

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Submicron, circular, ferromagnetic-antiferromagnetic dots exhibit different magnetization reversal mechanisms depending on the direction of the magnetic applied field. Shifted, constricted hysteresis loops, typical for vortex formation, are observed for fields along the exchange bias direction. However, for fields applied close to perpendicular to the exchange bias direction, magnetization reversal occurs via coherent rotation. Magnetic force microscopy imaging together with micromagnetic simulations are used to further clarify the different magnetic switching behaviors.

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The rapid advancement in lithography methods for fabricating nanostructures with controlled dimensions and geometry has triggered increased research in magnetic nanostructures [1,2]. When the size of a magnetic element becomes of the same order as magnetic length scales, such as the domain wall width or the critical single domain size, the multidomain structure encountered in the bulk material becomes energetically unfavorable and either single domain or inhomogeneous magnetization configurations develop instead [1–4]. A case of particular interest is the formation of vortex states in circular or ring-shaped soft magnetic nanostructures [5–8]. When the Zeeman energy becomes sufficiently low, the magnetization curls up along the edges of the nanostructure to minimize the lateral stray fields, leading to a flux closure arrangement. This vortex formation results in a sudden drop of the magnetization at the so-called nucleation field. Towards the center of the vortex the magnetization turns out of plane, forming the vortex core. As the applied field is changed to negative saturation, the core moves perpendicularly to the field until it is expelled from the dot at the so-called annihilation field, where the vortex transforms back into a single domain [4].

In almost all magnetotransport devices, i.e., spin valves or tunnel junction structures, ferromagnetic (FM)—antiferromagnetic (AFM) exchange biased bilayers constitute an essential part [9]. Exchange bias, \( H_E \), is defined as the shift of the hysteresis loop along the magnetic field axis typically observed in exchange coupled FM-AFM materials [10–13]. Many models attribute this effect to the formation of domains either in the FM or in the AFM layer [14–17]. Hence, apart from its crucial technological importance, the study of exchange bias in nanostructures is interesting from a fundamental point of view since the reduction of the lateral dimensions is likely to cause significant alterations to the domain structure of each layer [18–25].

In this Letter, we investigate the influence of the unidirectional FM-AFM coupling on the magnetization reversal of submicron circular Permalloy (Py)-IrMn dots. A constricted hysteresis loop (due to the formation of a vortex state), shifted along the magnetic field axis, is observed along the exchange bias direction. Beyond a critical angle the vortex no longer nucleates but, instead, the magnetization is found to reverse by “coherent” rotation of a so-called \( S \) state.

A continuous film with the composition Ta(5 nm)/Py(12 nm)/IrMn(5 nm)/Pt(2 nm) (where Py is FM and IrMn is AFM) was deposited onto a thermally oxidized Si wafer by dc magnetron sputtering. For comparison, a sample without the AFM, Ta(5 nm)/Py(12 nm)/Pt(2 nm), was also prepared. From the continuous films, arrays of circular dots with diameter of 400 nm and 800 nm periodicity were fabricated by e-beam lithography and subsequent ion etching [26]. For this geometry dipolar interactions are negligible [27]. To induce exchange bias, the as-prepared samples were field cooled (FC) from \( T = 500 \text{ K} \) under an applied field of 3 kOe. Hysteresis loops were subsequently measured at room temperature with fields applied at several angles from the FC direction (which defines \( 0^\circ \)), using a transverse magneto-optic Kerr effect (MOKE) setup. The magnetic configurations were investigated by magnetic force microscopy (MFM) under magnetic fields, in standard phase detection mode, with a lift height of 80 nm, using CoPtCr low moment probes. Micromagnetic simulations were performed using a Landau-Lifshitz-Gilbert micromagnetic solver [28] with saturation magnetization of bulk Py, \( M_S = 8 \times 10^{-5} \text{ A/m} \), exchange stiffness constant \( A = 1.05 \times 10^{-11} \text{ J/m} \), and using a cell size of approximately \( 6 \times 6 \text{ nm}^2 \). The magnetocrystalline anisotropy was neglected. The exchange bias field arising from the FM-AFM coupling (\( H_E = 65 \text{ Oe} \)) was simulated as an additional static field, applied along \( 0^\circ \). Full hysteresis curves were calcu-
lateral for external field directions ranging from 0° to 90° in plane.

The hysteresis loop of the circular uncoupled Py dots (without IrMn) is shown in Fig. 1(a). The constricted loop shape is typical of magnetization reversal via a vortex state [5–8]. For this sample, no significant differences in the loop shape were observed when measuring at different in-plane angles, indicating that the anisotropy of the shape of the loop were observed when measuring at different angles from the FC direction, as it occurs in the vortex state, results in an increase of the exchange energy. Nevertheless, when the applied field effectively compensates the unidirectional coupling, the vortex state appears as the most energetically stable configuration.

When the measuring angle deviates from the FC direction, vortexlike hysteresis loops are still observed, up to an angle of 75° [see Fig. 1(c)]. However, beyond a critical angle, located between 75° and 80°, the hysteresis loops start to resemble hard axis loops, i.e., without constriction, indicating that the vortex no longer nucleates but, instead, the magnetization tends to reverse by coherent rotation [see Figs. 1(d) and 1(e)].

Selected MFM images corresponding to different values of the applied field, as indicated in the hysteresis loops of Fig. 1(b)–1(e), are shown in Fig. 2. The top left panel of Fig. 2(a) is the atomic force microscopy image of a single dot. The subsequent panels are MFM images acquired under different magnetic fields [as indicated in Fig. 1(b)] applied parallel to the exchange bias direction (i.e., 0°). (b) MFM images of the exchange biased dots, with the external field [as indicated in Fig. 1(e)] applied perpendicular to the exchange bias direction (i.e., 90°).

FIG. 1. Hysteresis loops of: (a) the circular dots with composition Ta/Py/Pl (i.e., without AFM); (b),(c),(d),(e) the FM-AFM dots, with composition Ta/Py/IrMn/Pl, measured with the magnetic field applied (b) along the FC direction, 0°, (c) at 75°, (d) at 80°, and (e) at 90° with respect to the FC direction. The nucleation and annihilation fields, \( H_N \) and \( H_A \), of the vortex state are indicated in (a).
lutions confirm that the magnetization reversal occurs via nucleation and annihilation of a vortex state when the field is applied along the exchange bias direction, whereas a vortex state is absent for the perpendicular direction. Actually, in the simulations, along the 90° direction and intermediate field values, the unidirectional exchange favors the formation of a so-called S state, where the spins in the FM tend to orient in a shape reminiscent of the letter “S” [4]. In general, as the magnetic field is reduced, a dot will take on a curled magnetization state to minimize stray fields at the dot edges. The simulations show that if an exchange bias field is superimposed at an angle from the applied field then the perpendicular component of the exchange bias selects a preferred edge-magnetization direction, hence resulting in the S state.

The experimental exchange bias loop shift $H_E$ of the dots can be evaluated either from the two nucleation or the two annihilation fields. Figure 4(a) shows the angular dependence of $H_E$ for the two cases, which follows closely a $H_E(\theta) = H_E(0) \cos(\theta)$ relationship. A similar angular dependence is observed for continuous Py/IrMn films [19]. As the applied field is rotated from the FC direction, both the measured nucleation and annihilation fields progressively decrease with angle, i.e., the loops become overall narrower [see Figs. 1(b) and 1(c)]. The angular dependencies of the nucleation fields, for both the descending ($H_{N1}$) and ascending ($H_{N2}$) branches of the hysteresis loops are plotted in Fig. 4(b). It is noteworthy that although $H_{N2}$ strongly decreases with angle, $H_{N1}$ is quite insensitive to the direction of measurement. The average nucleation field, $H_N = (H_{N1} - H_{N2})/2$, is plotted as a function of the measuring angle in Fig. 4(c), while Fig. 4(d) shows the angular dependence of the average annihilation field, $H_A$.

As the angle $\theta$ from the exchange bias direction increases, both $H_N(\theta)$ and $H_A(\theta)$ progressively decrease with respect to $H_N(0)$ and $H_A(0)$, which are the fields necessary to nucleate/annihilate the vortex if there was no exchange bias. Indeed, as a first approximation, one can consider that the unidirectional exchange coupling with the AFM can be represented by the exchange bias field, $\tilde{H}_E$. The hysteresis loops measured along the FC direction lead directly to the “real” average nucleation field of the vortex, since the applied field directly compensates the exchange bias field. If $\tilde{H}_E$ is oriented at an angle from the applied external field, the vortex will nucleate when the absolute value of the effective field $\tilde{H}_{\text{eff}} = \tilde{H}_{\text{appl}} + \tilde{H}_E$ becomes equal to the nucleation field of the vortex, $H_N(0)$ [see inset Fig. 4(c)]. Consequently, using simple geometric calculations, one can estimate $H_{N1}$ and $H_{N2}$ (which, to be accurate, are the external fields that need to be applied, so that $|\tilde{H}_{\text{eff}}| = H_N(0)$), as follows:

$$H_{N1}(\theta) = H_N(0) \cos(\theta) + \sqrt{H_N^2(0) - H_E^2(0) \sin^2(\theta)}$$

These calculated fields are plotted as lines in Fig. 4(b). In our case, since $H_N(0) = H_E(0)$, Eq. (1) correctly predicts that $H_{N1} = 0$ and is almost independent of $\theta$. From Eq. (1), the average nucleation field, $H_N(\theta)$, is $H_N(\theta) = \sqrt{H_N^2(0) - H_E^2(0) \sin^2(\theta)}$, shown by the line in Fig. 4(c).

With a similar argument one would expect $H_A(\theta) = \sqrt{H_A^2(0) - H_E^2(0) \sin^2(\theta)}$, which should be almost constant.

![FIG. 3. Simulated hysteresis loops, measured along 0° and 90° with respect to the field cooling (i.e., exchange bias) direction, together with spin configurations corresponding to selected values of fields, as indicated in the loops.](image-url)
Since $H_A(0) \gg H_E(0)$. However, this simple geometrical argument does not properly account for the angular variation of $H_A(\theta)$, as can be seen in Fig. 4(d). In fact, the micromagnetic calculations suggest that the decrease of $H_A$ from 400 to 200 Oe is correlated with changes in the intermediate magnetization structure during the reversal process. In the calculations the vortex nucleation proceeds with increasing angle first via a $C$ then via an $S$ state with a tendency to nucleate two vortices, and finally for the largest angles the vortex nucleation is completely suppressed. The magnitudes of the calculated $H_A$ at low and high angles are comparable to the experimental value; however, the exact angular dependence varies with the modeling parameters, which makes a quantitative comparison with the experimental data difficult. Equation (1) also predicts the existence of a critical angle, $\theta_C = \arcsin[H_N(0)/H_E(0)]$, beyond which the vortex nucleation does not occur. Taking into account that $H_E(0)$ is just slightly larger than $H_N(0)$, $\theta_C$ is indeed found to be close to $80^\circ$, as observed experimentally. It should also be noted that angular variations in $H_N$ and $H_A$ have already been reported in the literature for arrays of circular dots with strong interdot magnetostatic interactions [6,27,30], where an interaction field is superimposed on $H_N$ and $H_A$, or for elliptical dots [31,32]. In the latter case, either $S$ states or double vortices are observed when measuring along the long axis of the ellipses, whereas a $C$ state or a single vortex are obtained along their short axis, thus evidencing that different magnetization reversal mechanisms can occur in anisotropic systems depending on the field direction [31,32]. The coupling with an AFM is in some sense similar since the exchange bias also breaks the symmetry of the circular dots in a manner analogous to the interdot interactions or the elliptical shape. For sufficiently large exchange bias fields, the FM-AFM coupling can even induce completely different magnetization reversal modes, depending on the angle of measurement. The actual reversal mechanism depends on the interplay between the different energies (i.e., magnetostatic, exchange) involved in the system. Finally, it should be noted that exchange bias is a complex phenomenon, and thus it may not be fully described by an extra field superimposed onto the applied external field. Hence, although our simple analysis provides an understandable description of the system’s general behavior, the underlying microscopic mechanisms are considerably more complex, as shown, for example, by the behavior of the annihilation field.

In summary, the magnetization reversal mechanisms of circular FM-AFM dots with submicron diameter have been found to depend on the direction of the applied field. Along the exchange bias direction, the magnetization reversal occurs via vortex formation. If the magnetic field is applied at an angle to the FC direction, the measured nucleation field progressively decreases. When the magnetic field is applied beyond a critical angle, in our case $\theta_C \sim 80^\circ$, the vortex state no longer nucleates. This is confirmed by MFM imaging together with micromagnetic simulations. Our results show that the magnetization reversal of submicron disks is significantly more complex when the magnetostatic energies have to compete with additional interactions.

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