Critical velocity for the vortex core reversal in perpendicular bias magnetic field

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For a circular magnetic nanodot in a vortex ground state, we study how the critical velocity v_c of the vortex core reversal depends on the magnitude H of a bias magnetic field applied perpendicularly to the dot plane. We find that, similarly to the case $H=0$, the critical velocity does not depend on the size of the dot. The critical velocity is dramatically reduced when the negative (i.e., opposite to the vortex core direction) bias field approaches the value, at which a *static* core reversal takes place. A simple analytical model shows good agreement with our numerical result. © *2010 American Institute of Physics*. [doi:10.1063/1.3291064]

A magnetic vortex is a curling magnetization distribution in flat magnetic submicron dots, with the magnetization pointing perpendicularly to the dot plane within the 10 nm size vortex core. The vortex ground state corresponds to a deep energy minimum when the dot lateral sizes fit the conditions for vortex stability.[1] This unique magnetic object has attracted much attention recently because of the fundamental interest to specific properties of such a nanoscale spin structure. The direction of the core polarization ("up" or "down") can store a bit of information, and this is of considerable practical interest for applications in magnetic memory technology. Several approaches can be used to switch the bit, i.e., to reverse the vortex core. It has been shown that a static magnetic field can reverse the core, if its magnitude reaches sufficiently large values, typically of several kilo-oersteds.[2,3] The reason for that is a large energy barrier between the vortex states with up or down core polarizations. Alternately, the magnetic core can be switched at zero static magnetic field, if it is excited by a variable (oscillating or pulsed) in-plane field or by a spin-polarized current.[4–7] The reversal occurs if the core velocity reaches a certain critical value v_c, which is defined solely by the magnetic parameters.[8] Very recently, the vortex core switching has been observed at intermediate experimental conditions in Ref. 9. In this work, a static perpendicular magnetic field together with a small oscillating in-plane field was applied to a nanodot in the vortex state. The frequency of the excitation was swept and the resonant vortex motion was detected. At a given magnitude of the exciting field, the vortex core was switched when the static bias magnetic field reached a critical value.

In our study, we calculate numerically the critical velocity of the vortex core reversal as a function of a static out-of-the plane magnetic field. We find that this critical velocity, similarly to the case of zero applied field, is independent of the dot sizes, but depends on the magnetic parameters of the dot material. The critical velocity drops significantly with the

increase in the magnitude of the negative (opposite to the vortex core direction) bias magnetic field.

We consider a circular magnetic nanodot in the vortex ground state. A static bias magnetic field is applied perpendicularly to the dot plane (along the z-axis). It is considered to be positive if parallel (and negative if antiparallel) to the initial direction of the vortex core (or vortex core polarization), see the inset to Fig. 1. The vortex motion is excited by a dc spin polarized current flowing perpendicular to the plane.[10] The spin polarization of the current is along the z-axis. Two dots with the diameter $2R=300$ nm and thicknesses $w=20$ and 30 nm are considered in the simulations.[11] Magnetic parameters mimic those for NiMnSb used in Ref. 9 as follows: $\mu_0 M_s=0.69$ T for the saturation magnetization, the easy plane anisotropy field $H_A=-0.185$ T, the exchange stiffness $A=10$ pJ/m, and the Gilbert damping $\alpha=0.01$. The mesh cell size is $1.5 \times 1.5 \times 5$ nm^3.
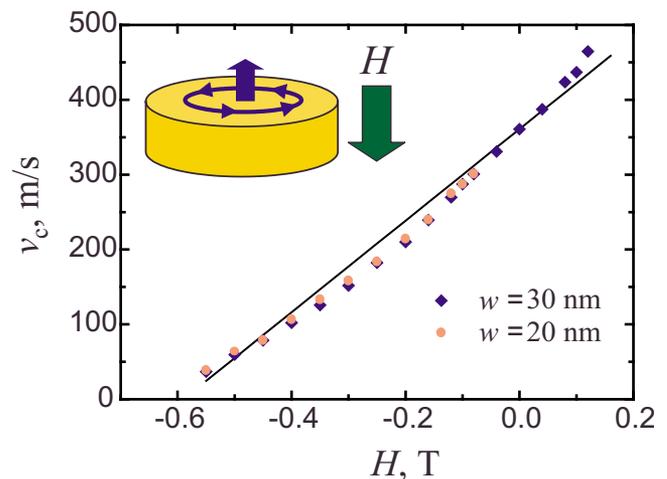

FIG. 1. (Color online) Symbols: critical velocity v_c as a function of the magnitude of the bias magnetic field applied perpendicularly to the dot plane for dots with thickness $w=20$ and 30 nm. Solid line: analytical prediction by Eq. (1).

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Due to the excitation by the spin current, the vortex core starts to gyrate with gradually increasing amplitude.[12] Correspondingly, the core velocity is increasing until the core eventually reverses. Prior to the reversal, a region with negative values of M_z component (a "magnetic dip") is formed at the inner part of the core trajectory. When the core velocity reaches the critical value, this dip splits into a vortex with negative polarization and an antivortex.[6] The antivortex annihilates with the original vortex core, and in the end only the vortex with a negative polarization remains. After the core reversal the spin-polarized current starts to damp the core gyration, thus slowing the core motion and, eventually, bringing the reversed core to the equilibrium position in the dot center.[12]

The critical velocity v_c is determined as the maximum core velocity on the gyration trajectory. This maximum is reached just before the core switching. The core velocity is calculated as the time derivative of the core position, which in its turn is extracted from the magnetization distributions printed out each 0.05 ns. At fields larger than 0.12 T for the dot with $w=30$ nm (correspondingly, larger than -0.04 T for the dot with $w=20$ nm) the core is expelled from the dot prior to the switching. At fields smaller than -0.55 T, the mesh we use becomes insufficiently fine to be able to calculate the vortex dynamics accurately. The static switching field H_c is equal to -5.9 kOe for the both dot thicknesses.[13] This approximate numerical value for H_c is used below in our analytical calculations of the dependence of the critical velocity on the bias field. The results of this calculation are shown by a solid line in Fig. 1.

The simulation results for the two dots are summarized in Fig. 1 (symbols). The critical velocity at $H=0$ is $v_c = 360$ m/s for both dots. $v_c(H)$ increases for increasing positive fields ($v_c=460$ m/s for $w=30$ nm at $H=0.12$ T). However, it diminishes significantly for negative fields ($v_c =40$ m/s at $H=-0.55$ T for both the dots). At moderate fields ($|H|<2$ kOe) v_c scales linearly with H, and the slope is approximately 670 m(s T)$^{-1}$.

We find that for all the field values, when they can be calculated, the critical velocities determined for the two dots coincide. This fact is rather nontrivial as, owing to different thicknesses, many parameters of the vortex (such as the profile of the potential energy $W(\mathbf{X})$, where $\mathbf{X}$ is the core position;[14] the separation of the vortex from the dot center and edges at the switching; the shape of the core) are very different for the two dots and depend differently on the field. From these results we conclude that, similarly to the case $H=0$, for nonzero H, v_c depends only on local properties of the vortex core spin structure.[15]

The zero-field value of the critical velocity for both dot thicknesses, $v_c=360$ m/s, is in perfect agreement with the analytical expression found in Refs. 8 and 16, taking into account the easy-plane anisotropy constant $K=M_sH_A/2$ of NiMnSb: $v_c(0)=1.66\gamma M_s\sqrt{2\pi A/(2\pi M_s^2+K)}$, which gives $v_c=340$ m/s (γ is the gyromagnetic ratio). In the following, we investigate the underlying physics responsible for the $v_c(H)$ behavior presented in Fig. 1. The vortex core dynamic reversal, as it was shown in Ref. 8, originates from the self-induced dynamic gyrotropic field or gyrofield. This field is induced by the vortex motion and its amplitude is proportional to the ratio v/ρ, where v is the velocity of the moving vortex and ρ is the vortex core radius. When the gyrofield
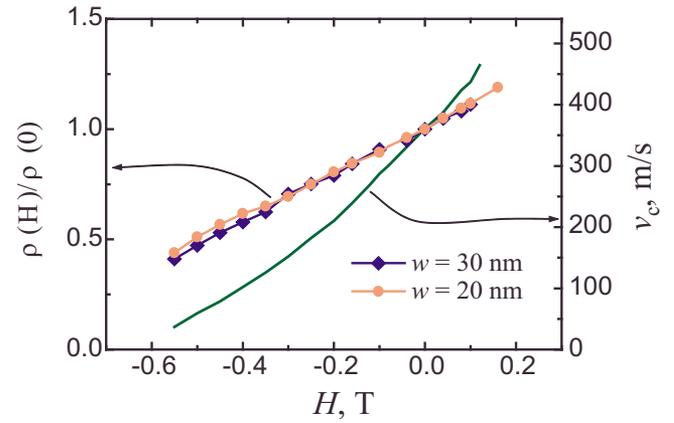

FIG. 2. (Color online) Symbols: radius of the vortex core in equilibrium ρ as a function of magnetic field H, for two dots. Solid line: critical velocity for the dot with $w=30$ nm.

reaches a critical value $H_g^{cr} \propto v_c/\rho$, the vortex core very rapidly reverses.

We study how ρ scales with H for the two dot thicknesses. We analyze magnetization distribution profiles for a static vortex in equilibrium at different fields to extract the dependence $\rho(H)$.[17] We find that although $\rho(H)$ is different for the two dots (e.g., at $H=0$, $\rho=20$ nm for the dot with $w=30$ nm and correspondingly $\rho=18$ nm for $w=20$ nm), to the precision of our calculation, $\rho(H)/\rho(0)$ coincides for the two thicknesses, as can be seen on Fig. 2. From this result we conclude that the critical value of the gyrofield $H_g^{cr} \propto v_c/\rho$ scales equally with the field H for the two dots. It also indicates that at nonzero external field the critical velocity $v_c(H)$ relies on the same vortex core reversal mechanism than at zero field, i.e., it is mainly determined by a competition of the gyrotropic and exchange fields within the core. The gyrofield deforms the core magnetization profile, whereas the exchange field tries to create a more uniform magnetization distribution suppressing the core deformation.

As can be seen from Fig. 2, the slopes of v_c and ρ as functions of the perpendicular magnetic field are different; indeed, $v_c(H)$ decreases noticeably more rapidly than $\rho(H)$ at negative H. This means that the critical value of the gyrofield H_g^{cr} decreases with negative H increasing. This feature can be attributed to the fact that the deformation of the core by the perpendicular bias field H leads to a decrease in the effective potential barrier that the gyrofield has to surpass to induce the vortex core reversal. Therefore, the bias field provides two different actions on the vortex which help to switch the core. One is that, at a given core velocity v, the amplitude of the gyrofield H_g increases with negative H increasing as long as ρ is reduced. Second is that the critical value of the gyrofield H_g^{cr} that is required to switch the core becomes smaller at higher negative fields. For any field H, the vortex core reversal mode is an axially *asymmetric* mode like it was found for $H=0$.[5,6] That is very different from the axially symmetric reversal path involving the Bloch point (BP) found in the simulations for static reversal.[3] We also see this axially symmetric mode and the BP formation in our simulations of the static core reversal. But this axially symmetric BP mechanism is an idealization, which leads to higher values of H_c. It can not be realized practically due to unavoid-

able spontaneous symmetry breaking in real systems, e.g., induced by the thermal fluctuations. This is the vortex gyrotropic mode with a finite **X** that is responsible for the axial symmetry breaking. That is why the critical velocity $v_c(H)$ of the moving vortex is important.

We can get a simple analytical expression for the $v_c(H)$. Let us consider a dot with static switching field H_c. The value of the core radius at this field $\rho_c(H_c)$ is finite. The physical sense of $\rho_c(H_c)$ is the following: the vortex with positive polarization becomes unstable in the point $H=H_c$ when decreasing H. From the other side, it is reasonable to assume that the dependence $v_c(H)$ goes to 0 when H approaches the static core reversal field H_c, i.e., we can assume that $v_c(H)$ is proportional to $(1-H/H_c)$ near H_c. That immediately leads to the dependence

$$v_c(H) = v_c(0)(1 - H/H_c). \qquad (1)$$

The static field reversal and dynamic reversal mechanisms help each other leading to descending dependence of $v_c(H)$. Thus, the analytically estimated slope of the dependence $v_c(H)$ is $dv_c/dH = -v_c(0)/H_c = 610$ m/s T (shown as a solid line in Fig. 1), that is close to the numerically simulated slope of 670 m/s T. These speculations explain the main features of our simulations of $v_c(H)$, $\rho_c(H)$ presented in Figs. 1 and 2.

In summary, our numerical study has demonstrated that there are two contributions to the process of the vortex core reversal in a magnetic dot subjected to a perpendicular bias magnetic field as follows: the static reversal mechanism related to the instability of the vortex core with polarization directed against the bias field and the dynamical reversal mechanism related to the vortex core deformation. While the first mechanism keeps the axial symmetry of the vortex magnetization distribution, the second one breaks this axial symmetry and creates an "easy" core reversal path. Thus, the perpendicular bias magnetic field applied oppositely to the vortex core direction reduces the critical velocity of the vortex core reversal and facilitates the dynamical reversal process, which was demonstrated experimentally in Ref. 9.

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[10] dc spin-polarized current can excite the vortex motion for whatever the vortex eigenfrequency is. Thus, it is more convenient for the calculations than the *resonant* excitation by the in-plane ac field like in Ref. 9. We have checked, however, that the vortex critical velocity does not depend on the way the vortex motion is excited.

[11] Our micromagnetic code SPINPM performs numerical integration of the LLG equation using the forth order Runge–Kutta method with an adaptive time-step control. The magnitude of the spin transfer term is (σJ) $=6$ mT in terms of Ref. 12. The Oersted field generated by the current is disregarded in the simulations.

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