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The universal criterion for switching a magnetic vortex core in soft magnetic nanodots

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The universal criterion for ultrafast vortex core switching between core-up and -down vortex
bi-states in soft magnetic nanodots was empirically investigated by micromagnetic
simulations and combined with an analytical approach. Vortex-core switching occurs
whenever the velocity of vortex core motion reaches a critical value, which is $\nu_c = 330 \pm 37$
m/s for Permalloy, as estimated from numerical simulations. This critical velocity was found
to be $\nu_c = \eta_c \gamma \sqrt{A_{ex}}$ with $A_{ex}$ the exchange stiffness, $\gamma$ the gyromagnetic ratio, and an
estimated proportional constant $\eta_c = 1.66 \pm 0.18$. This criterion does neither depend on
driving force parameters nor on the dimension or geometry of the magnetic specimen. The
phase diagrams for the vortex core switching criterion and its switching time with respect to
both the strength and angular frequency of circular rotating magnetic fields were derived,
which offer practical guidance for implementing vortex core switching into future solid state
information storage devices.
In magnetic thin films [1,2] and patterned magnetic elements of submicron (or smaller) size [3], a nontrivial spiral magnetization (M) configuration occurs and has been experimentally observed in both static and dynamic states. This magnetic nanostructure, the so-called “magnetic vortex” has an in-plane curling M along with an out-of-plane M at the core area stretching over of a few tens of nm in size [3]. Owing to a high thermal stability of this static structure [4] as well as the bi-state M orientations of the tiny vortex core (VC), the magnetic vortex has been received considerable attention as an information carrier of binary digits “0” and “1” in nonvolatile information storage technologies [4]. Furthermore, very recently, experimental, theoretical, and simulation studies have explored a rich variety of the dynamic properties of the magnetic vortex, including ultrafast VC switching by linearly oscillating [5-8] and circularly rotating [9-11] in-plane magnetic fields or spin-polarized currents [12,13], with extremely low-power consumption. The underlying mechanism and physical origin of ultrafast VC switching have also been found [8,14]. These rich dynamic properties stimulate continuing intensive studies of patterned nanodots in the vortex states targeting towards a fundamental understanding of their dynamics and real applications to a new class of nonvolatile random access memory and patterned information storage media. Such new conceptual devices using ultrafast, low-power VC switching becomes an emerging issue in the research areas of nanomagnetism and M dynamics.

Although, the fundamental understanding of VC reversal and vortex gyrotropic
motion dynamics has been much advanced recently, the universal criterion for VC switching, its phase diagram, and VC switching time still needs clarification. Moreover, these are technologically essential parameters for the manipulation of VCs, such as VC switching as basic component in future information storage devices.

In this Letter, we report that there is a critical velocity $\nu_c$ of the VC motion, which serves as the universal criterion required for VC switching, as found by micromagnetic simulations and analytical calculations. The constant value of $\nu_c$ only depends on the intrinsic material parameter of the exchange stiffness $A_{ex}$ and does not vary with the dimension or geometry of a given nanodot as well as external driving force parameters. Based on the universality of $\nu_c$ we derive technologically useful phase diagrams of the VC reversal and the switching time with respect to the external force parameters.

In the present study, we chose as a micromagnetic simulation approach the OOMMF code [15] that utilizes the Landau-Lifshitz-Gilbert equation of motion [16] because this approach is a well established, optimized tool, and reliable enough to investigate $M$ dynamics of vortex states of magnetic dots up to a few hundred nm in spatial and on the > 10 ps temporal scales. In addition, we used an analytical approach to determine the threshold of driving forces required for VC switching and the VC switching time with respect to external magnetic field parameters, based on the linearized Thiele equation [17] of motion of the VC position in the dot plane. We used Permalloy (Py) nanodots as a model system, each dot with
a different radius $R$ ranging from 150 to 600 nm and a different thickness $L$ ranging from 10 to 50 nm [see Fig. 1(a)].

To excite the vortex gyrotropic motion up to its VC switching, we used a specially designed driving force of counter-clockwise (CCW) circularly rotating magnetic fields in the film plane with the angular frequency $\omega_{\text{H}}$ and the strength $H_{0}$, denoted as $\mathbf{H}_{\text{ccw}} = H_{0} [\cos(\omega_{\text{H}} t)\hat{x} + \sin(\omega_{\text{H}} t)\hat{y}]$ [18]. The reason for selecting this CCW rotating field is that it is the eigenbasis and most efficient process for the resonantly excited eigenmotion of the core-up vortex state, as demonstrated in earlier theoretical and simulation [10,19], and experimental studies [11]. An example of the resonant vortex gyrotropic motion and VC switching driven by the CCW rotating field with a condition of $H_{0} = 20$ Oe and $\nu_{\text{H}} = \omega_{\text{H}}/2\pi = \omega_{D}/2\pi = 580$ MHz (where $\nu_{D} = \omega_{D}/2\pi$ is the vortex eigenfrequency) [20,21] is represented by the orbital trajectories of the earlier transient and steady-state motions of the initial up core and its reversed down core along with their velocities following their individual orbital trajectories, as shown in Fig. 1(b). It is empirically found that the up-core switches to the down-core when the velocity of the up-core motion reaches a threshold velocity of $\nu_{C} = 330$ m/s for the Py dot [right panel in Fig. 1(b)].

To confirm the universality of this definite value of $\nu_{C} = 330$ m/s (see also Refs. [10,13,14]), we conducted additional simulations to obtain the VC velocity-versus-time curves versus both $H_{0}$ (10 to 350 Oe) and $\nu_{\text{H}}$ (0.1 to 2 GHz) for a Py dot of $R = 150$ nm.
and $L = 20$ nm, as shown in Fig. 2(a). It is evident that the value of $\nu_c = 330 \pm 37$ m/s is not affected by the external field parameters of $\omega_H$ and $H_0$, as well as the size of the Py dot, as evidenced by the independence of $\nu_c$ on the dot size shown in Fig. 2(b). Furthermore, in order to examine the impact of intrinsic material parameters on the constant value of $\nu_c = 330 \pm 37$ m/s, we performed simulations for a circular dot of a fixed geometry, namely $R = 150$ nm and $L = 20$ nm (artificially) varying the values of the saturation magnetization $M_s$, $A_{ex}$, and the gyromagnetic ratio $\gamma$, using $M_s/M_{s,Py} = 1.0 \sim 2.0$, $(A_{ex}/A_{ex,Py})^{1/2} = 0.75 \sim 1.5$, and $\gamma/\gamma_{Py} = 0.5 \sim 1.75$, where $M_{s,Py} = 860$ G, $A_{ex,Py} = 1.3$ $\mu$erg/cm, $\gamma_{Py} = 2.8 \times 2\pi$ MHz/Oe correspond to the values of Py. The simulation results in Figs. 2(c) and 2(d) display a linear increase of $\nu_c$ with $(A_{ex}/A_{ex,Py})^{1/2}$ with an equal slope for different values of $M_s$, and a linear increase with $\gamma/\gamma_{Py}$, respectively.

All the simulation results lead to an explicit analytical form of $\nu_c = \eta_c \gamma \sqrt{A_{ex}}$ with the proportional constant $\eta_c$, the value of which is estimated to be $1.66 \pm 0.18$ using just the simulation result of $\nu_c = 330 \pm 37$ m/s for Py. It is interesting to note, that $\nu_c$ is not determined by the other intrinsic parameter such as $M_s$. This fact can be understood from the physical origin of the VC switching. As reported previously [14], the VC gyrotropic motion driven by an external force induces the so-called gyrofield which originates from a dynamic deformation of $\mathbf{M}$ concentrated around the moving VC. This $\mathbf{M}$ deformation yields a large and spatially non-uniform excess effective field that acts against the $\mathbf{M}$ deformation, so that a
further $\mathbf{M}$ deformation suppresses the gyrofield. Thus, the resultant $\mathbf{M}$ deformation is
determined by the balance between the gyrofield and the excess effective field. When the
gyrofield reaches a sufficiently enough critical value to overcome the excess effective field,
the resultant $\mathbf{M}$ deformation leads eventually to the VC switching via pure dynamic processes
of the nucleation and annihilation of a vortex-antivortex pair [5-8]. Owing to the dramatic $\mathbf{M}$
deformation employed in a few nm area, the dominant contribution to the critical value of
gyrofield is the short-range exchange field. Since the gyrofield is proportional to the VC
velocity, $A_{ex}$ is the dominant parameter in determining $\nu_c$. Following the same argument, the
long-range dipolar interaction is a negligible contribution to $\nu_c$, so that the dimension and
shape of a given dot, as well as $M_s$ do not affect $\nu_c$, as expressed in the form of
$\nu_c = \eta_c \gamma \sqrt{A_{ex}}$.

To summarize, $\nu_c$ only depends on $A_{ex}$, but neither geometry nor any driving force
parameters such as $\omega_{H}$ and $H_0$. Consequently, one arrives at VC switching phase diagram
and switching time diagram in the $\omega_{H}$-$H_0$ plane. Figure 3 shows the simulation results on
the criterion boundary diagram where VC switching (gray) and non-switching (white) areas
are separated by different symbols for the several different dimensions of the Py dots, $[R
(nm), L (nm)] = [150, 20], [150, 30], [300, 20], \text{ and } [450, 20]$. The criterion boundaries for all
different dimensions of the dots are found on almost the same line, which reflects again the
fact that $\nu_c$ does not vary with the size of a given Py dot. Owing to the resonant excitation
of the VC motions at \( \omega_h = \omega_d \), the velocity can reach \( \nu_c \) in VC motion even it is driven by
only an extremely small field strength [5,10,11]. Resonant VC motions yield a valley in the
criterion boundary in the vicinity of \( \omega_h = \omega_d \) and the threshold strength of \( H_0 \) required for
VC switching is thus a minimum at \( \omega_h = \omega_d \).

In addition, we theoretically derived more general explicit analytical equations
representing the criterion boundary which distinguishes the event of VC switching and non-
switching based on the linearized Thiele’s equation of motion. A detailed derivation is
described in the supplementary online material [22]. Here we chose CCW rotating fields
necessary for the up- to down-core switching [10,19]. From the general solution of VC
motions in the linear regime, the velocity of the up-core motion driven by \( \mathbf{H}_{CCW} \) is written
as

\[
\nu(t) = \frac{\gamma R H_0}{3 \sqrt{\left(\frac{g^2 + \rho^2}{\tilde{G}^2} - \Omega^2 \right)^2 + \frac{g^2}{\tilde{G}^2} \Omega^2}} \sqrt{\Omega^2 + F(\Omega, t)},
\]

(1)

with the gyrovector \( \mathbf{G} = -G \hat{z} \), the diagonal damping tensor \( \tilde{D} = D \hat{I} \) with the identity
matrix \( \hat{I} \), the damping constant \( D \), and \( \Omega = \omega_h / \omega_d \). The function \( F(\Omega, t) \) represents the
time variable velocity term of the transient VC motions. This explicit form also allows us to
analytically construct the criterion boundary \( RH_0^C \) diagram of VC switching on the \( \Omega - RH_0 \)
plane, using Eq. (1) by setting \( \nu = \nu_c = \eta_c \gamma \sqrt{A_{ex}} \), as written by Eq. (2) below.

\[
RH_0^C = \frac{3 \nu_c}{\gamma} \sqrt{\left(\frac{g^2 + \rho^2}{\tilde{G}^2} - \Omega^2 \right)^2 + \frac{g^2}{\tilde{G}^2} \Omega^2} \Omega^2 + F_\nu(\Omega),
\]

(2)
where $F_m(\Omega)$ has the maximum at $t \approx \pi/|\omega_h - \omega_0|$. The numerical calculation of Eq.(2) using $\nu_c = 330 \pm 37$ m/s for Py estimated from simulations is displayed by the thick yellow region in Fig. 3. On resonance ($\Omega = 1$), the minimum value of $RH_0^C$ is $3|\partial|/\nu_c / \gamma)$, where $|\partial| = \alpha \left[ 1.193 + \ln(R)/2 - \ln(L)/6 - \ln(\sqrt{2A/M_s})/3 \right]$ [23], indicating that $H_0^C \sim 3|\partial|/\nu_c / \gamma)/R$ at $\Omega = 1$ is the lowest field strength required for VC switching [24]. The analytical solution (thick yellow region) is somewhat in discrepancy with the micromagnetic simulations (symbols), although they are similar in shape/trend. This discrepancy can be associated with the fact that the present simulations of VC switching imply a nonlinearity of VC gyrotropic motions near its switching event [25], whereas Eq. (2) assumes only linear-regime vortex motions. However, this nonlinear effect could be compensated by multiplying a scaling factor $S_F = + 1.4$ to Eq. (2) that was derived based on the linearized Thiele’s equation of the vortex motion. Recent experimental results by Curcie et al. [11] support well our results. They reported $H_0^C = 3.4$ Oe and $\nu_c = 190$ m/s for a square dot of 500 width and 50 nm thickness, being in quite good agreement with our estimated value of $H_0^C = 4.1$ Oe from $\left[ 3|\partial|/\nu_c / \gamma)/R \right] \cdot S_F$ on resonance for the assumption of $R = 250$ nm, $\nu_c = 190$ m/s, and the scaling factor $S_F = 1.4$.

Using Eq. (1), the diagram for the switching time $t_s$, i.e., the time when the VC switching is completed (or upon $\nu$ reaches $\nu_c$) was numerically calculated with respect to both $\omega_h$ and $H_0$. For the resonance case $\Omega = 1$, $t_s$ is analytically expressed as

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\( t_s = \left( \frac{\theta}{k_B T} \right) \ln \left[ 1 - \left( \frac{H_s^C}{H_0} \right) \right] \) for \( H_0 > H_s^C \) (non-switching for \( H_0 < H_s^C \)). For all the cases of \( \Omega \neq 1 \), \( t_s \) can be numerically calculated by putting \( \nu = \nu_c \) from Eq. (1) along with the correction of the nonlinear effect of VC switching, as shown in Fig. 4(a), for example, for a Py dot of \( R = 150 \text{ nm} \) and \( L = 20 \text{ nm} \). For the cases of \( H_0 \gg H_s^C \), \( t_s \) is \( \sim 1 \text{ ps} \), and does not much vary with \( \omega_\mathbf{\Pi} \), but as \( H_0 \) decreases close to \( H_s^C \), \( t_s \) markedly increases and varies with \( \omega_\mathbf{\Pi} \). At \( \Omega = 1 \), it appears that the lower \( H_s^C \), the longer \( t_s \) [26].

For faster VC switching, larger values of \( H_0 \) and \( \omega_\mathbf{\Pi} > \omega_d \) are more effective. For \( \omega_\mathbf{\Pi} / \omega_d = 0.6, 1.0, \text{ and } 1.6 \), those corresponding \( t_s \)-versus-\( H_0 \) curves were plotted along with the simulation results (symbols) [Fig. 4(b)], both being in good agreement. It should be pointed out, that the switching time diagram will be technologically useful in the optimization of driving force parameters that reliably control ultrafast VC switching. Note that this switching is a pure dynamical process, which does not involve overcoming any energy barriers as in the classical Neel-Brown case [1].

In conclusion, by conducting micromagnetic simulations and analytical calculations we have found that the universal criterion for vortex core switching is the critical velocity of vortex-core gyrotropic motion, which is expressed as \( \nu_c = \eta_c \gamma \sqrt{A_{ex}} \) with \( \eta_c = 1.66 \pm 0.18 \), and exhibits a constant value of \( \nu_c = 330 \pm 37 \text{ m/s} \) for Py. From this criterion, the VC switching diagram and switching time diagram for VC switching with respect to the driving force parameters were constructed, which will provide guidance for practical
implementations of an array of dots in vortex state to information storage devices in terms of information storage, writing, and reading operations. They are also technologically useful in the design of the dot dimensions and proper choice of materials as well as to optimize external driving forces for reliable ultrafast VC switching at extremely low power consumption.

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[18] A linearly oscillating field can be decomposed into the CCW and CW rotating fields with the same \( H_0 \) and \( \omega_0 \) [10].


[22] See EPAPS Document No. XXX for detailed descriptions. For more information on
EPAPS, see http://www.aip.org/pubservs/epaps.html.


[24] For the CW rotational field, $RH_0^C$ has the constant value of $3\nu_c/\gamma$ which indicate $RH_0^C \gg RH_0^C$ for $p = +1$. Very recently, these asymmetric switching behaviors has been verified experimentally [11].


[26] From the results of micromagnetic simulation for the 150 nm (300 nm) radius and 20 nm thickness Py nanodot, the minimum field amplitude required for VC switching is only 14 Oe (7 Oe) whereas the switching time is 17 ns (33 ns).
FIG. 1 (color online). (a) Magnetic vortex structure with either upward or downward core \( \mathbf{M} \) orientation. The rotation sense of the local in-plane \( \mathbf{M} \)s around the VC is counter-clockwise (CCW). (b) Orbital trajectories (left) and velocity-versus-time curve of the up (red line) and down (blue line) cores in a circular Py nanodot of \( R = 150 \text{ nm} \) and \( L = 20 \text{ nm} \) driven by the indicated CCW rotating field \( \mathbf{H}_{\text{CCW}} \) (inset) with \( \omega_u / \omega_d = 1 \) and \( H_0 = 20 \text{ Oe} \). The horizontal line (right) denotes the value of \( v_c = 330 \text{ m/s} \) with an estimated error value of \( \pm 37 \text{ m/s} \) (gray-color region).

FIG. 2 (color online). (a) VC velocity \( v \) in the Py dot of \( R = 150 \text{ nm} \) and \( L = 20 \text{ nm} \) for different values of \( H_0 \) and \( \Omega = \omega_u / \omega_d \) of the \( \mathbf{H}_{\text{CCW}} \) (b), (c), and (d) show the dependence of \( v_c \) on the dimensions of the Py dot, the material parameters of \( A_{\text{ex}} \) and \( M_s \), and \( \gamma \), respectively. All the results were obtained from micromagnetic numerical simulations. The gray-colored region with the line indicates the critical velocity with its error range.

FIG. 3 (color online). Criterion boundary diagram of VC switching driven by \( \mathbf{H}_{\text{CCW}} \) with respect to the \( \Omega - RH_0 \) plane. Blue circle, green triangle, orange square, black diamond symbols correspond to the micromagnetic simulation results with \( [R \text{ (nm)}, L \text{ (nm)}] = [150, 20], [150, 30], [300, 20], [600, 20], \) respectively. Yellow colored area indicates the criterion boundary obtained using the analytical Eq. (2) for Py dots with \( R = 50 \sim 5000 \text{ nm} \) and \( L = 20 \)
~ 80 nm, based on the estimated value of $v_c = 330 \pm 37$ m/s for Py. The light purple colored area is the result of the multiplication of 1.4 to Eq. (2) (yellow colored area). The blue colored axis indicates the results corresponding to a specific Py dot of $[R \text{ (nm)}, \ L \text{ (nm)}] = [150, 20]$.

FIG. 4 (color online). (a) Contour plot of VC switching time $t_s$ on the $\omega_H - H_0$ plane for the Py dot with $R = 150$ nm and $L = 20$ nm. (b) $t_s$-versus-$H_0$ curves for specific values of $\omega_H / \omega_D = 0.6, 1.0$, and 1.6, along with the corresponding simulation results.
FIG. 1

(a)

(b) $\omega_u / \omega_D = 1, H_0 = 20 \text{ Oe}$

$t = 0 - 16 \text{ ns}$
Supplementary Documents

Derivation of Eq. (1)

To obtain the velocity of VC motions in the linear regime, we derived the general solution of VC motions including the earlier transient and later steady state motions [1] based on the linearized Thiele’s equation [2] for the VC position \( X = (X, Y) \):

\[-G \times \dot{X} - \dot{\Omega} \times \dot{X} + \partial W(X, t)/\partial X = 0 \]

with the gyrovector \( G = -G \hat{z} \), and the damping tensor \( \dot{D} = D \hat{I} \) with the identity matrix \( \hat{I} \), the damping constant \( D \) and the potential energy function \( W(X, t) \) [1,3]. To solve elementary rotating eigenmotions of a VC in a circular dot driven by the CCW- and CW- circular rotating fields [4,5], it is useful to describe the VC position using a complex variable \( S = X + iY \) where the real and imaginary values indicate the \( x \)- and \( y \)-positions of the VC, respectively. For the case of \( H_{ccw} \) for a selective switching from the up- to down-core, the general solution in the linear regime is given as

\[ S = [S(0) - S_o] \exp(i \omega_d t) \exp(\omega_D t |G|) + S_o \exp(i \omega_h t) \]

[6] with \( \omega_D = \kappa |G|/(G^2 + D^2) \) [7]

where \( \kappa \) is the stiffness coefficient of the potential energy \( W(S, t) \), \( S_o = i \mu H_o/(\kappa - \omega_h G - i \omega_h D) \), and \( S(0) = X_0 + i Y_0 \). \( X(0) = (X_o, Y_o) \) is the VC position at \( t = 0 \). From the time derivation of this general solution, the velocity of the up core motion driven by \( H_{ccw} \) is written as
\[\nu(t) = \frac{\gamma R H_0}{3\sqrt{\left(\frac{G^2}{G} - \Omega\right)^2 + \frac{\Omega^2}{G^2}} + F(\Omega, t)},\]

with the transient term

\[F(\Omega, t) = \frac{G^2 + D^2}{G^2} \exp\left(2 \frac{D\omega_{b} t}{|G|}\right) - 2\Omega \exp\left(\frac{D\omega_{b} t}{|G|}\right) \left[ \cos\left((1 - \Omega)\omega_{b} t\right) + \frac{D}{|G|} \sin\left((1 - \Omega)\omega_{b} t\right) \right],\]

where \(\Omega = \omega_{H}/\omega_{D}\). For a sufficiently large value of \(t\), the function \(F(\Omega, t)\) converges to 0, i.e., the vortex motion arrives at a pure steady state (the earlier transient state disappears).

The vortex motion becomes a steady-state motion (non time dependence), thus its velocity turns into

\[\nu = \frac{\gamma R H_0}{3\sqrt{\left(\frac{G^2}{G} - \Omega\right)^2 + \frac{\Omega^2}{G^2}}} \Omega.\]

References


