Nonadiabatic spin-torque and damping effects on vortex core switching triggered by a single current pulse*

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Switching the orientation of a vortex core by spin-polarised pulse current introduces a promising concept for the reliable addressing of a single nanodisc element inside dense arrays. In this paper, micromagnetic simulations are employed to study the vortex core switching behaviour excited by a short in-plane Gaussian current pulse. We find that both the switching mechanism and the switching time are not sensitive to changes in the phenomenological parameters of spin-torque nonadiabaticity and Gilbert damping. The switching time, however, strongly depends on the current strength. In addition, we have theoretically predicted the parameter range of current pulses to achieve a single switching event.

Keywords: magnetic vortex, spin torque, micromagnetic simulation
PACC: 7000, 7500, 7570P, 7540M

1. Introduction

A magnetic vortex is a fundamental magnetic state which can be formed in a broad range of diameters of ferromagnetic thin film elements.[1] The vortex state consists of an in-plane curling magnetisation around a $\sim$ 10 nm central core magnetised perpendicular to the plane (up- or down-core orientation, defined by vortex polarity).[2−4] Recently, the spin dynamics of magnetic vortices has attracted considerable attention because it involves fundamental interest and possible applications in logic and memory elements.[5−12] The binary states could be identified by the polarity of the vortex core (VC)[5] or the vortex circulation.[6] A traditional approach to switching the polarity of VC is done by using a magnetic field perpendicular to the sample plane, but the required field is as large as 250 mT.[7] Recently, it was discovered that an easy core reversal concept could be realised by using an oscillating in-plane magnetic field under the excitation of vortex gyration mode.[8] In this case, the field is only a few millitesla. The underlying physical mechanism of the VC switching has been clarified by the micromagnetic technique, revealing that it involves a vortex–antivortex (V–AV) pair creation and annihilation process.[9,10] Such a switching process has been confirmed by a very recent experiment with direct imaging of high-resolution time-resolved magnetic x-ray microscopy.[11]

Various excitation methods to switch the VC of nanodiscs have been explored either by in-plane resonant or pulsed magnetic fields,[8−10,12−14] or by a resonant spin-polarised current.[15,16] Based on the micromagnetic simulation, we have predicted that a single spin-polarised current pulse could also drive the VC switching,[17] which has been experimentally confirmed recently.[18]From a technological point of view, the current-driven switching is quite advantageous for data storage, e.g. vortex-based memory elements,[19]because the reliable addressing of a single nanodisc inside dense arrays by electric current is much easier than that by magnetic field. On the other hand, the switching process (within one nanosecond) in the pulse excitation mode is faster than the resonant excitation mode, since the resonance (linearly or circularly oscillating) excitation mode first requires a few nanoseconds to bring the vortex core to its gyrotropic orbit before the creation of a newborn V–AV pair.

Theoretically, the current-induced magnetisation

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dynamics is modelled by including the adiabatic and nonadiabatic spin-torque terms into the Landau–Lifshitz–Gilbert equation[20−22]

$$\frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t} = -\gamma \boldsymbol{M} \times \boldsymbol{H}_{\mathrm{eff}} - \frac{\alpha}{M_{\mathrm{s}}} \boldsymbol{M} \times \frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t} - \frac{a_J}{M_{\mathrm{s}}^2} \boldsymbol{M} \times \left(\boldsymbol{M} \times \frac{\partial \boldsymbol{M}}{\partial \boldsymbol{x}} \right) - \frac{\beta a_J}{M_{\mathrm{s}}^2} \boldsymbol{M} \times \frac{\partial \boldsymbol{M}}{\partial \boldsymbol{x}}, \quad (1)$$

where the current is applied along the x-axis, $\boldsymbol{H}_{\mathrm{eff}}$ is the effective field containing the exchange and the demagnetising field,[23] M_{s} is the saturation magnetisation, α is the Gilbert damping constant, β is the dimensionless constant describing the degree of nonadiabaticity. The quantity of the spin-torque is $a_J = P\mu_{\mathrm{B}} g j_{\mathrm{e}} / 2eM_{\mathrm{s}}$, where P is the spin polarisation, μ_{B} the Bohr magneton, j_{e} the electric current density, g the Landé splitting factor, and e the electron charge.

Although current pulse mode excited VC switching possesses great advantages over its alternatives, the observed multiple reversals are still undesired.[17] Therefore, carefully tuning the pulse parameters to achieve a single switching event of VC is of crucial important for data storage. In addition, some fundamental questions regarding the dependence of VC switching behaviour on the phenomenological parameters of α and β remain unanswered. In this paper, micromagnetic modelling is used to study the parameter dependence of the core switching. In particular, we have obtained the proper parameter range of current pulses that allows a single event of VC switching.

2. Simulation model and results

We consider a permalloy (Py) nanodisc of $2R = 200$ nm in diameter and $L = 20$ nm in thickness. In our model system, the initial vortex configuration possesses counterclockwise circulation of the in-plane magnetisation and a positive polarity (up-core orientation, $p = +1$). The standard material parameters for permalloy are used: $A = 1.3 \times 10^{-11}$ J/m (exchange constant), $\mu_0 M_{\mathrm{s}} = 1.0$ T, $K = 0$ (anisotropy constant), $P = 0.7$. The discretization element cell size is about 3 nm which is smaller than the exchange length (~ 5.6 nm). The applied current is taken from the Gaussian shaped pulse, $J = J_0 \exp[-(t-\mu)^2/2\sigma]$, where J_0 is the current strength, σ is a parameter associated with pulse width, the corresponding full width at half maximum (FWHM) of the pulse is $\sim 2.35\sigma$.

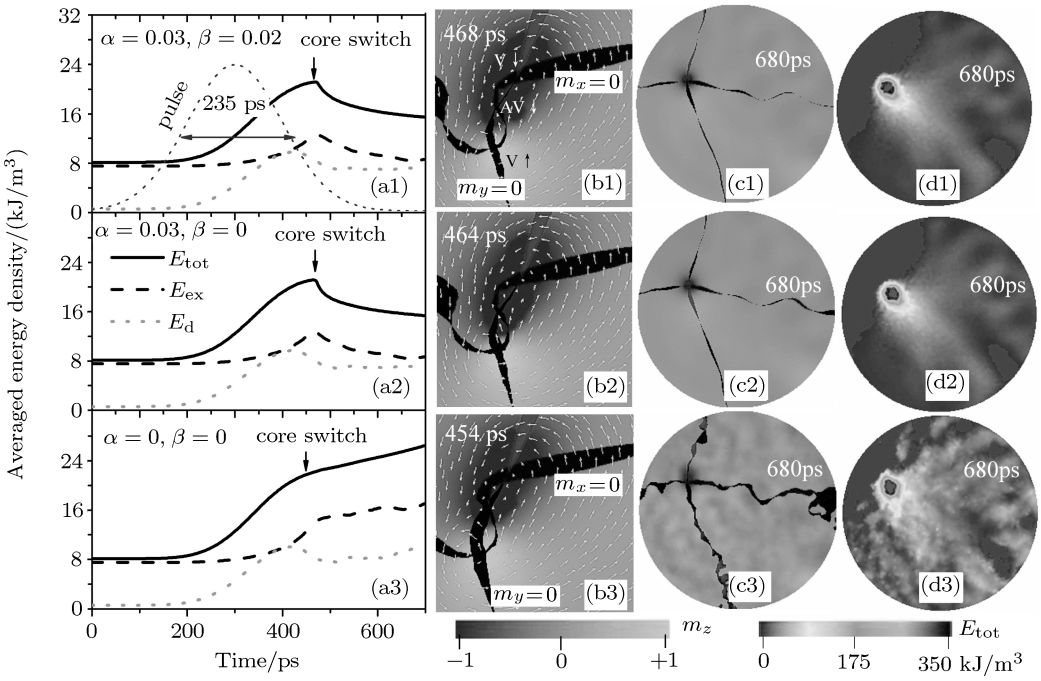


Fig. 1. (a1)–(a3) Temporal evolutions of the total, exchange, magnetostatic energy densities respectively for single core switching for different values of α and β. The dotted Gaussian curve shown in (a1) characterises the applied current pulse with a strength of $7.4{\times}10^8$ A/cm^2 and width $\sigma = 100$ ps. (b1)–(b3) Snapshots of magnetisation for a small region around the VC, where a V–AV pair nucleates. The white arrows represent the in-plane magnetisation directions. The colour bar displays the z component of the magnetisation. The two ribbons are the $m_x = 0$ and $m_y = 0$ isosurfaces, respectively. (c1)–(c3) show the snapshots of the z component of magnetisation at a time of 680 ps and (d1)–(d3) are the corresponding energy distributions.

We first discuss how the core switching mechanism depends on the phenomenological parameters of the Gilbert damping α and the nonadiabatic spin-torque factor β. Figures 1(a1)–1(a3) show the temporal evolutions of the sample's spatially averaged energy densities (the exchange energy $E_{\rm ex}$, magnetostatic energy $E_{\rm d}$, and their sum $E_{\rm tot}$) for three different combinations of α and β. The strength of the applied current pulse is 7.4×10^8 A/cm^2 and the width is $\sigma = 100$ ps (FWHM=235 ps). The simulated results show that the temporal evolution of the averaged magnetostatic energy is almost the same for all three cases. In the cases of $\alpha = 0.03$ and $\beta = 0.02$ [Fig. 1(a1)] or $\beta = 0$ [Fig. 1(a2)], both the exchange and total energy densities increase until VC reversal is achieved, at which the snapshots for magnetisation configuration around the core region are shown in Figs. 1(b1) and 1(b2). Note that an identical transient coexistence state containing an original vortex (V↑) and a pair of newborn V–AV (V↓–AV↓) are clearly observed. Subsequently, the antivortex (AV↓) annihilates with the original vortex (V↑) and the newborn vortex (V↓) remains. Such a so-called V–AV pair mediated VC switching mechanism has been intensively studied.[8−19] After the annihilation process, the sum of the internal total energies will suddenly decrease due to the release of the strong exchange energy between the AV↓ and original V↑. The core reversal moment corresponds to a sharp peak in the temporal curves of the total energy [Figs. 1(a1) and 1(a2)].

In contrast, the energy curves in the case of $\alpha = 0$ and $\beta = 0$ demonstrate different behaviours, showing no clear evidence (without a peak) in the total energy curve to identify the occurrence of core reversal [Fig. 1(a3)]. But our simulations reveal that the core switches in the same way, as shown in Fig. 1(b3). As a result, we conclude that the V–AV pair mediated VC switching process is a universal mechanism, which is independent of the parameters of α and β. This conclusion has been further confirmed by the simulations performed for more different parameter combinations of α and β, as shown in Fig. 2.

After the core switching, the energy dissipates into the surrounding area through spin-wave propagation. However, in the case of $\alpha = 0$ (without Gilbert damping, therefore, less energy dissipation), the system after switching still has a large amount of unreleased exchange energy [Fig. 1(a3)], leading to the relatively large local energy [Fig. 1(d3)] and fluctuant magnetisation configuration [Fig. 1(c3)]. In contrast, in the cases of non-zero α, the spin waves are quickly damped with the Gilbert term, resulting in the relatively small energy distribution in the surrounding areas of the discs [Figs. 1(d1) and 1(d2)].

Another interesting behaviour shown in Fig. 1 and Fig. 2(a) is that the VC switches at almost the same time ($\sim$ 470 ps) when α varies from 0.01 to 0.03 and β from 0 to 0.02, implying that the β term of the spin-torque plays a minor role in the VC switching. When α is set to zero, the core is switched in a slightly earlier time ($\sim$ 453 ps) [Fig. 1(b3)]. We attribute this small change to the smaller energy dissipation (without damping term) during the vortex procession. Similar to the critical velocity of the core switching,[13,15] there exists a critical total energy to switch the VC, e.g., for a disc of $2R = 200$ nm and $L = 20$ nm, the critical energy is ~ 18.8 kJ/m^3 (the shadow boundary in Fig. 3(a)). Therefore, the system without damping is a little faster than that with damping to reach the critical energy.

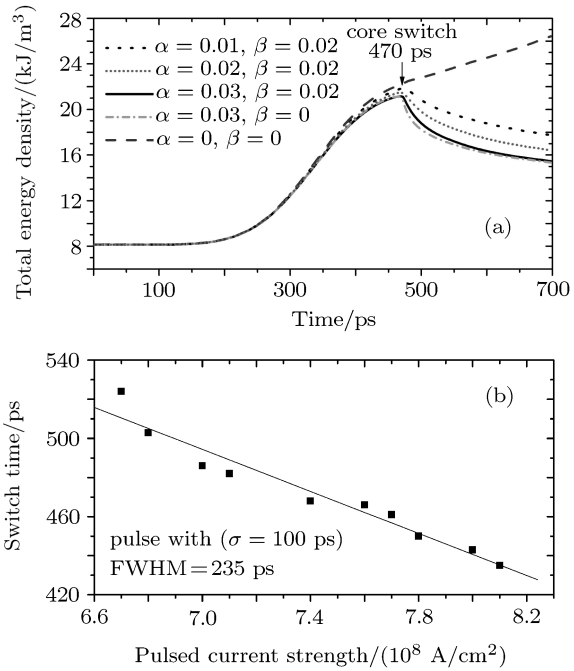


Fig. 2. (a) Evolution of the total energy densities for different values of α and β. (b) Switching time as a function of pulsed current strength.

Although the VC switching time is not sensitive to the phenomenological parameters of α and β, it strongly depends on the pulse parameters. Figure 2(b) displays the core switching time as a function of the current strength ranging from 6.7 to 8.1×10^8 A/cm^2, where $\alpha = 0.03$, $\beta = 0.02$, the pulse width is fixed at $\sigma = 100$ ps (FWHM=235 ps) and the current reaches

its maximum at $t = 300$ ps. The switching time shown here is defined as the time interval from the pulse starting moment ($t = 0$) to the moment at which the core reversal is fully completed. Simulations indicate that the switching time rapidly decreases with the increase of current strength and a single VC reversal event triggered by the current pulse can be achieved within a few hundreds of picoseconds. From this viewpoint, the current pulse excitation mode provides a promising prospect in the ultrafast switching route of the VC over its alternatives (linear or circular resonance excitations).

As mentioned before, a controllable single event of VC reversal is of crucial important for data storage. However, the in-plane polarised current pulse could excite undesired multiple switches of VC.[17] Figure 3(a) shows the switching behaviour as a function of current strength, where the pulse width is fixed at $\sigma = 100$ ps. The simulation results indicate that very weak pulses ($J < 6.5 \times 10^8$ A/cm^2) cannot trigger the core reversal while too strong a pulse could yield multiple switches [e.g. double switches occur at $J = 8.1 \times 10^8$ A/cm^2, see Fig. 3(a)]. Finally, very strong pulses (for example, a pulse with a strength of $14{\times}10^8$ A/cm^2) will push the core out of the sample (not shown). Therefore, it is necessary to predict a proper parameter range of current pulses to achieve a single event of VC reversal. Figure 3(b) summarises the phase diagram of VC switching behaviour (on the current strength and pulse width). Note that the single event of core reversal only occurs in a relatively narrow region with special combinations of pulse width and strength, and the pulse strength decreases with the increase of pulse width. Our simulated critical current strength is larger than the experimental value ($J_c = 1.3 \times 10^8$ A/cm^2 at a pulse duration of 2–3 ns).[18] This could be ascribed to the much shorter pulse used in our simulations (FWHM$<$ 500 ps). It should be pointed out that the selectable switching schemes of VC orientation could also be realised by using in-plane circular-rotating field and current[19,24] as well as by a DC spin-polarised current perpendicularly flowing through a spin-valve pillar.[25,26]

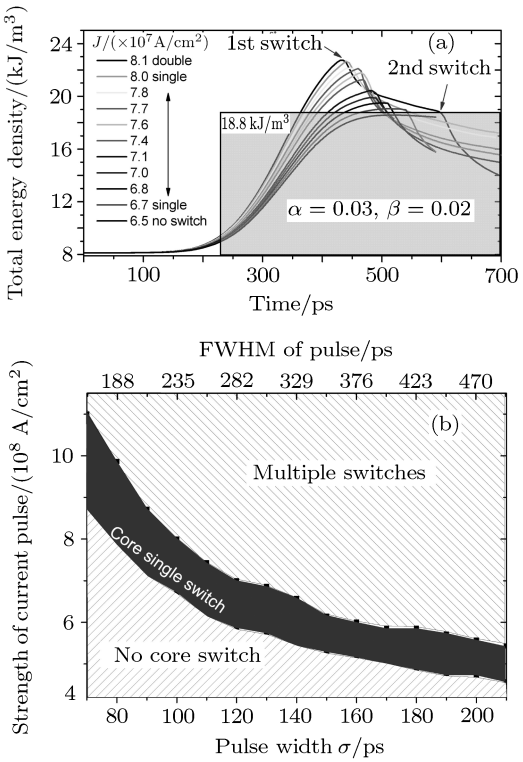


Fig. 3. (a) Switching behaviours as a function of current strength for a fixed pulse width of $\sigma = 100$ ps. (b) Phase diagram of the VC switching as a function of the current strength and pulse duration. The current pulse width is indicated either by σ (the bottom x-axis) or by the full width at half maximum (FWHM, the top x-axis). Three different regimes denote no core switch, core single switch and multiple switches.

3. Conclusion

In summary, a spin-polarised current pulse could trigger VC switching. We show that not only the switching route but also the switching time are insensitive to the phenomenological parameters of α and β. The ultrafast switching time is reduced when the current strength is increased whilst the pulse width is fixed. We have derived a pulse parameter phase diagram for a controllable single event of core switching.

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