Switching Time of Vortex-core Reversals in Soft Magnetic Nanodots

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1. Introduction

The magnetic vortex structure in patterned magnetic elements of micrometer or smaller size is one of the most prominent candidates for future nonvolatile magnetic solid-state memory devices [1] owing to its very stable binary ground states of the core orientation. Recently, low-power driven vortex core (VC) switching by in-plane oscillating (or rotating) magnetic field or current has been experimentally demonstrated and its fundamental dynamic properties have been explored from many simulation and theoretical studies [2-7]. Other essential issues to remain are, from technological point of view, to understand switching time of the VC reversal respect to the driving force parameters of in-plane oscillating (or rotating) magnetic field or current. In this presentation, we report on micromagnetic simulation and analytical calculation results of VC switching time with respect to the field amplitude and frequency of circular rotating fields [3].

2. Micromagnetic Simulations

We performed micromagnetic simulations for a model system of Permalloy (Py) circular dot with radius R = 150 nm and thickness L = 20 nm, usingthe OOMMF code [8]. We applied counter-clockwise circularly rotating fields of various field amplitudes and frequencies for switching the upward core orientation [5,6].

As shown in Fig. 1(a), the VC switching occurs through several serial processes with their characteristic duration times: the VC starts to gyrate about its equilibrium position [see the VC trajectory in Fig. 1(a)] and then it reaches its critical velocity during time period of Δt_g, and after that, the dynamic deformation of the entire magnetization of the initial VC is maximized during Δt_d, and, finally, the VC switching is completed by a nucleation and annihilation process of avortex-antivortex (V-AV) pair during $\Delta t_{V\text{-}AV}$. As a result, the entire switching times T_s, the time period necessary for the VC switching to complete itself from an initial equilibrium VC position, consists of the above three duration times, as expressed by $T_s=\Delta t_g+\Delta t_d+\Delta t_{V\text{-}AV}$.

Fig. 1(b) shows Δt_g, Δt_d, $\Delta t_{V\text{-}AV}$, and Ts as a function of field strength H0 for the case of a resonant excitation, the angular frequency $\omega_H = \omega_D$, where ω_D is the angular eigenfrequency. For the higher field strengths (H_0 > 0.5 kOe), Δt_g reaches a few ps, being much less than Δt_d (～50 ps) and $\Delta t_{V\text{-}AV}$ (～30 ps), and thus, $\Delta t_d+\Delta t_{V\text{-}AV}$ represents T_s. However, for the low field strengths (H0 < 0.4 kOe), Δtg (～ns) is much longer than both Δtd and $\Delta t_{V\text{-}AV}$ and therefore, the Δt_g can stand for T_s. Since the VC gyrtoropic motion can be described by an analytical equation of motion, for such low field strength case, the T_s can be estimated from its analytical form, as described below.

3. Analytical calculation

Based on the Thiele's equation of VC motion [9], we derived an explicit analytical equation of the instantaneous velocity of VC motion, $\upsilon(t)$ under a given circularly rotating magnetic field with H0 and wH. Using an analytical equation of the critical velocity (υ_{cri}), we calculated Δtg by putting $\upsilon(t)=\upsilon_{\mathrm{cri}}$. For a resonant excitation, the explicit analytical equation of Δtg as a function of field strength was derived. In Fig. 1(b), this analytical equation (indicated by gray line) shows in a good agreement with the micromagnetic simulation result of Ts for low field strengths (H_0 < 0.4 kOe). Moreover, we constructed the phase diagram of Δt_{g} in the ω_{H}-H_0 plane by solving numerically the analytical equation of $\upsilon(t)$ for the switching condition of $\upsilon(t)=\upsilon_{\mathrm{cri}}$ for different values of ω_{H} and H_0.

4. Conclusion

We derived an analytical expression of the switching time of the vortex-core reversal with respect to the amplitude and frequency of circularly rotating magnetic fields, which is in good agreement with simulation result. The constructed phase diagram is 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 with extremely low-power consumption.

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5. References

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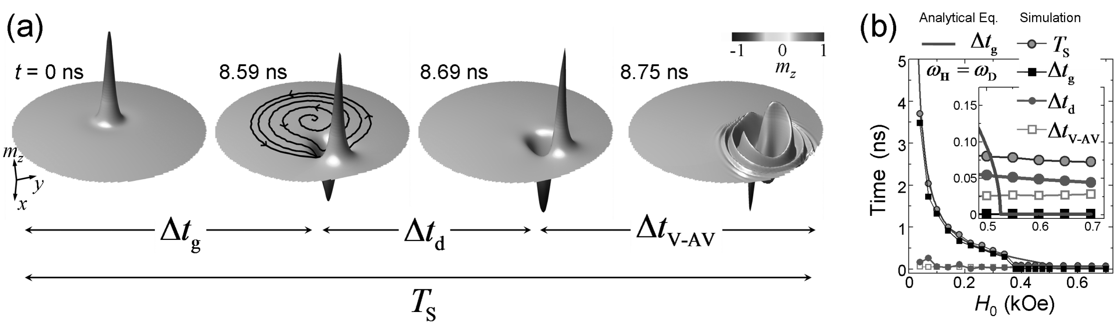

Fig. 1. (a) Serial dynamic processes of VC switching. (b) Time periods for the individual indicated processes of VC switching in the Py dot of R = 150 nm and L = 20nm.