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Effect of the Perpendicular Magnetic Field and Nonadiabatic Spin-transfer Torque on the Vortex Dynamics

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The effect of the perpendicular field on the trajectory of a vortex core driven by spin-transfer torque was investigated using micromagnetic simulations. The trajectory of the vortex core was staggered due to distortions of the moving vortex core. The core trajectory was affected by both the perpendicular field and β value, which is the relative magnitude of nonadiabatic spin torque to the adiabatic spin torque. This suggests that the effect of the perpendicular field should be considered when examining a vortex core trajectory affected by β.

Keywords : micromagnetic calculation, vortex dynamics, spin transfer torque

1. Introduction

The progress of fabrication techniques has led to the availability of nano-patterned magnetic structures with various shapes. There has been considerable interest in submicron disks, particularly because it can fulfill the need for high density magnetic data storage devices. It was found both theoretically and experimentally that the magnetic vortex state is energetically favored in such a disk structure [1]. The vortex state has in-plane spiral magnetization (chirality) and out-of-plane magnetization (polarity) at the center of the disk due to energy competition between the exchange and demagnetization energies. The vortex state can be excited by both the magnetic field and spin-polarized current [2, 3]. A spin-polarized current can exert torque onto the vortex by transferring spin-angular momentum, which is called spin-transfer torque [4, 5]. The vortex state shows steady state precession and core reversal when the current is sufficiently high. The dynamic response of the vortex due to spin-transfer torque is one of the most attractive subjects in both theoretical and application points of view.

The spin-transfer torque consists of two terms: adiabatic and nonadiabatic terms. The adiabatic term occurs when the projection of conduction electron spin on the film plane follows the direction of local magnetization, whereas the nonadiabatic term arises from a misalignment of these two components [6-8]. The value of β, which is the relative ratio of the nonadiabatic term to the adiabatic term, is attracting increasing interest because it is related to the threshold current density of the domain wall motion in a nanowire [9-12]. Despite the importance in determining the magnitude of β, the value of β is still unsolved both theoretically and experimentally. The analytical approach predicts that the trajectory of the vortex core has a relationship with β. It was reported that a small in-plane Oersted field induced by the current alters the vortex core trajectory [13]. However, there are no reports on effects of the perpendicular field on the vortex gyration. This study examined the effect of the perpendicular magnetic field on the trajectory of the vortex core in order to determine the value of β by observing the trajectory of the vortex core.

2. Micromagnetic Simulation

A micromagnetic simulation was performed to understand the vortex dynamics induced by spin transfer torque. The simulation was performed using the Landau-Lifshitz-Gilbert (LLG) equation including spin transfer torque terms (Eq. (1)).

$$\frac{\partial \mathbf{M}}{\partial t} = -\gamma \mathbf{M} \times \mathbf{H}_{eff} + \frac{\alpha}{M_S} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t}$$

$$-\frac{u_0}{M_S^2} \mathbf{M} \times (\mathbf{M} \times \nabla \mathbf{M}) - \frac{\beta u_0}{M_S} \mathbf{M} \times \nabla \mathbf{M} \qquad (1)$$

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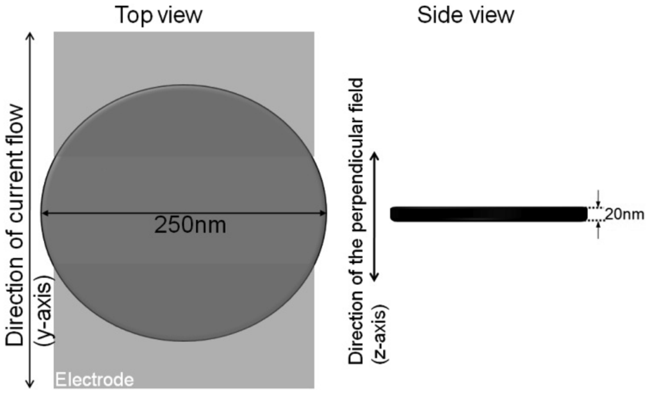

Fig. 1. Schematic diagram of the modeling system.

where H_{eff} is the effective field containing the external, magnetostatic, exchange, perpendicular Oersted field and current-originated Oersted field. α is the Gilbert damping constant, γ is the gyromagnetic ratio and u_0 ($=\mu_B JP/eM_S$) is the magnitude of spin transfer torque.

The model system is a circular Permalloy disk, 20 nm in thickness and 250 nm in diameter (Fig. 1). The cell size was $2 \times 2 \times 20$ nm^3. The perpendicular magnetic field was applied along the +z-axis with the magnitude ranging from -300 Oe to +300 Oe. The ac current was assumed to flow uniformly along the y-axis. The resonance frequency of the applied ac current was 586 MHz, as determined by the micromagnetic simulation. The maximum current density and spin polarization (P) were 1.25×10^7 A/cm^2 and 0.7, respectively. The standard material parameters for Permalloy are used: saturation magnetization $M_S = 800$ emu/cm^3, gyromagnetic ratio $\gamma = 1.76 \times 10^7$ sec^{-1}Oe^{-1}, Gilbert damping constant $\alpha = 0.01$ and exchange constant $A = 1.3 \times 10^{-6}$ erg/cm.

3. Result and Discussion

The dynamics of the vortex core excited purely by the ac current were first examined in order to observe the trajectory of the vortex core when a perpendicular magnetic field is not applied. When the spin-polarized current was injected, the vortex core was shifted instantly toward the direction of electron flow. The trajectory of the vortex core was tilted in the counter-clockwise direction due to its polarity, as predicted and previously reported [14]. Finally, the vortex core showed gyration motion, as shown in Fig. 2.

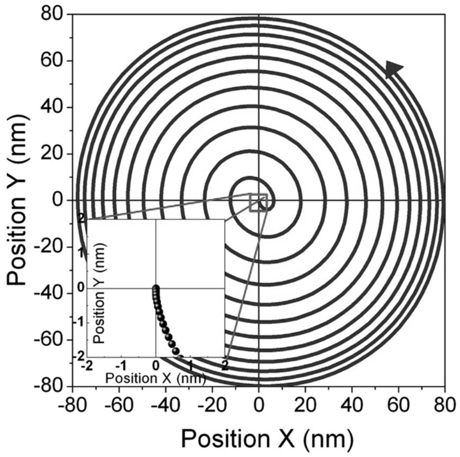

Fig. 2. The trajectory of the vortex core excited by the ac current without a perpendicular magnetic field. The inset shows the initial trajectory of the vortex core for 20 ns. The dot is marked every 20 ps.

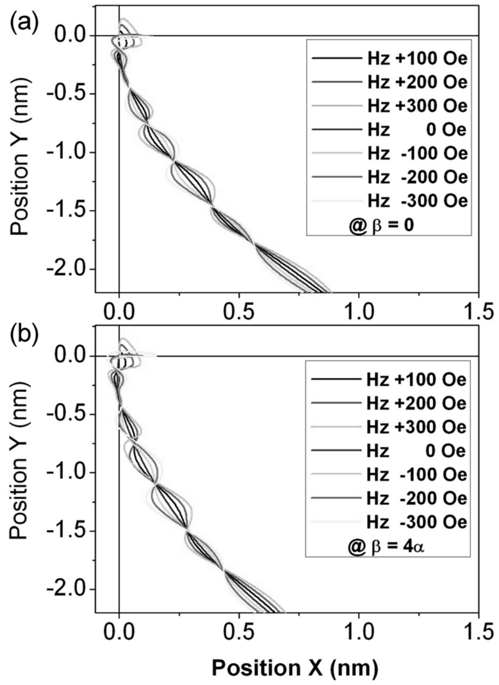

Fig. 3. The trajectory of the vortex core was drawn when perpendicular magnetic field was applied. The value of β was assumed to be (a) zero, and (b) 4α.

Fig. 3 shows the effect of the perpendicular magnetic field on the trajectory of the vortex core excited by the ac current. The trajectory of the vortex core was similar to the zero magnetic field case. However, the detailed trajectory was slightly different from those of the zero magnetic field case. In particular, the vortex core at the early time motion was quite strange. Unlike the zero field case, the vortex core did not move toward the direction of electron flow. The trajectory of the vortex core showed staggered gyration motion. The degree of staggering corresponds to the value of the magnetic field. One possible reason may be distortion of the vortex core. The vortex core begins to distort its shape when a perpendicular field is applied to the vortex core (Fig. 4). The distorted vortex

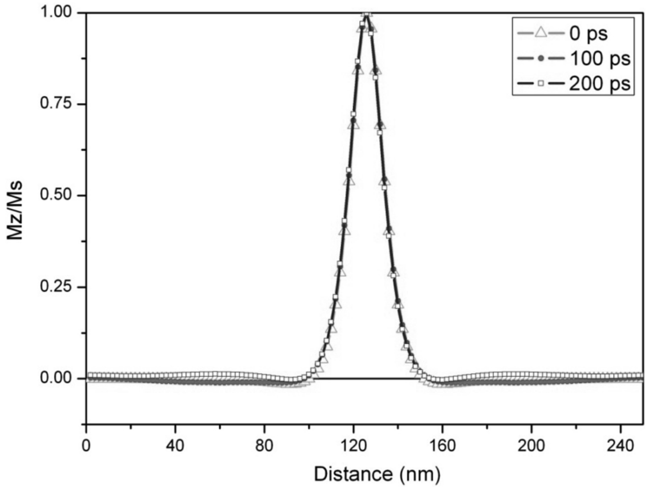

Fig. 4. The distortion of the vortex core when a perpendicular magnetic field is applied.

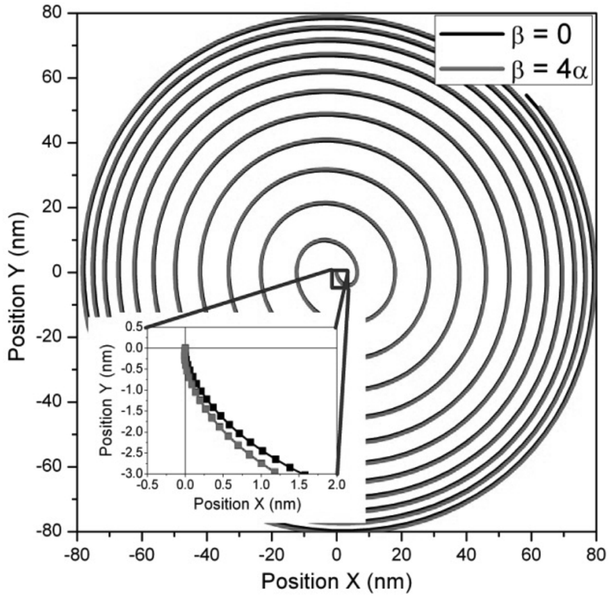

Fig. 5. The trajectories of the vortex core with different values of β; $\beta = 0$ and $\beta = 4\alpha$. The inset shows the initial trajectory of the vortex core.

core leads to a change in the potential profile, which results in a change in the trajectory of the vortex core.

The trajectory varied in the case of different values of β (0 and 4α), as shown in Figs. 3 and 5. The tilted motion of the vortex core varied according to the value of β (Fig. 3a), and b)). The vortex core with a larger β shows a tendency for the trajectory to incline toward the outer side, which is the left side in the figure. This rule applies regardless of whether a perpendicular field exists or not. The degree of staggered trajectory appears similar but the trajectory is tilted, as shown in zero-field case. It appears that β does not affect the steady-state gyration motion but causes a phase difference in the trajectory [15].

4. Conclusion

The trajectory of the vortex core driven by spin transfer torque showed spiral gyration. In the case of a perpendicular field, the vortex trajectory roughly follows a spiral but locally distorted trajectory due to a change in the vortex shape. These results suggest that a perpendicular field can strongly affect the vortex core trajectory driven by an ac current. Therefore, the effect of the perpendicular field needs to be considered when the current density is high or the electrode generates an undesired perpendicular field, particularly in cases of dealing with the vortex core trajectory related to β.

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