Various excitation phenomena of a skyrmion in ultrathin magnetic nanodisk induced by Spin Hall Effect

Takayuki Shiino[1,*], Ki-Suk Lee[2], Byong-Guk Park[1]
[1]Department of Materials Science and Engineering, KAIST, Daejeon, 305-701, Republic of Korea
[2]School of Materials Science and Engineering, Ulsan National Institute of Science and Technology, Ulsan 689-798, Republic of Korea

1. Introduction

Magnetic skyrmions have been considered as promising candidates of the information carriers in future spintronic devices because of their small size and of ultralow current densities required to drive them. Recent studies have suggested that skyrmions can be found in a magnetic ultrathin film sandwiched by a nonmagnetic insulating layer and a heavy metal layer with large spin-orbit interaction. The existence of the skyrmions can be explained by the interfacial Dzyaloshinskii-Moritya interaction (DMI), which originates from the lack of inversion symmetry and from large spin-orbit coupling, and gives a chirality to the magnetization configuration of a ferromagnetic layer [1]. Also, current-induced spin-orbit torques, namely, the spin Hall effect (SHE) and the Rashba effect, can give a new way to control the magnetic configuration of a ferromagnetic layer which is adjacent to a nonmagnetic metallic layer with strong spin-orbit interactions. Recently, several micromagnetic simulation studies have predicted that a magnetic skyrmion can be nucleated and stabilized in a nano-sized ultrathin magnetic disk in the presence of the interfacial DMI [1-3]. However, it has not been reported so far the study on the current-induced skyrmion motion in a magnetic circular disk. In this study, we focused on the simulation of current-induced skyrmion motion in a nano-sized ultrathin magnetic circular disk, which demonstrates three interesting excitation phenomena depending on the excitation frequency.

2. Simulation scheme

We conducted micromagnetic simulations for a magneticdisk of 0.6 nm in thickness and 80 nm in diameter using the OOMMF code [4] with the DMI extension [3]. The material parameters are as follows: the saturation magnetization $M_s = 1.13 \times 10^6$A/m, the exchange stiffness constant $A = 1.6 \times 10^{-11}$J/m, the DMI constant $D = 3.0 \times 10^{-3}$J/m^2, the perpendicular magnetocrystalline anisotropy energy $K_u = 1.28 \times 10^6$J/m^3, and the damping constant $\alpha = 0.015$. The mesh size was set to $1.0 \times 1.0 \times 0.6$nm^3. The governing equation of the simulation is the Landau-Lifshitz-Gilbert (LLG) equation with the time-varying SHE term,

$$\frac{\partial \vec{m}}{\partial t} = -\gamma_0 \vec{m} \times \vec{H}_{\text{eff}} + \alpha\, \vec{m} \times \frac{\partial \vec{m}}{\partial t} + \gamma_0 \vec{m} \times \left(\vec{m} \times H_{\text{SHE}} \sin(2\pi f_{ac} t)\, \vec{e}_y\right) \qquad (1)$$

where $\vec{m} = \vec{m}(t, x)$ is the dimensionless unit vector of the local magnetization. The first and second terms of the right side of the equation (1) are the conventional LLG equation, while the third term indicates the time-varying SHE term (H_{SHE} is the amplitude and f_{ac} is the excitation frequency) on the assumption that the alternating current is applied along the in-plane x direction [5]. Here, we assumed only the SHE as a major driving force, and neglected other possible effects such as the Rashba effect and spin-transfer torque.

3. Results and discussion

When ac current is applied to the disk, three distinctive excitation phenomena were observed depending on the driving frequency of the ac current. Figure 1 (a) shows the snapshots of the regular resonant gyrotropicmotion excited at f_{ac} = 0.26 GHz, and Fig. 1 (b) shows the corresponding trajectory of the steady-state gyrotropic motion. The gyration frequency f_g was same as the excitation frequency of 0.26GHz, and this resonant gyrotropic mode has been observed in the magnetic vortices [6]. Second, when ac current of f_{ac} = 2.8 GHz was applied, we observed excitation of resonant breathing mode whose frequency was f_s = 5.6 GHz as shown in Fig. 1 (c). During the breathing motion, the skyrmion showed small elliptic gyrotropic motion in the proximity of the disk center as shown in Fig. 1 (d). We have found that the resonant breathing mode excitation can occur through the elliptic gyrotropic motion of f_g = 2.8 GHz. Third, the simultaneous excitation of two gyrotropic and breathing modes were observed in the frequency range of 4.8~6.2 GHz. As shown in Figs 1(e) and 1(f), the breathing mode of f_s = 6.32 GHz and the gyration resulted from an anharmonic superposition between circular gyrotropic motion with f_g = 0.32 GHz and an elliptical gyrotripc mode with f_{ac} = 6.0 GHz are excited by a single ac current with f_{ac} = 6.0 GHz. Interestingly, we found that these hybridizedgyrotropicand breathing modesare always satisfied the relation $f_s = f_g + f_{ac}$ and which reveals that there is a strong coupling among those modes and thus, they are hybridized mediated by a single harmonic ac current.

Such novel phenomena of hybridization among gyrations and breathing mode can provide a different view angle to understand the inertial mass of a skyrmion in a confined system.

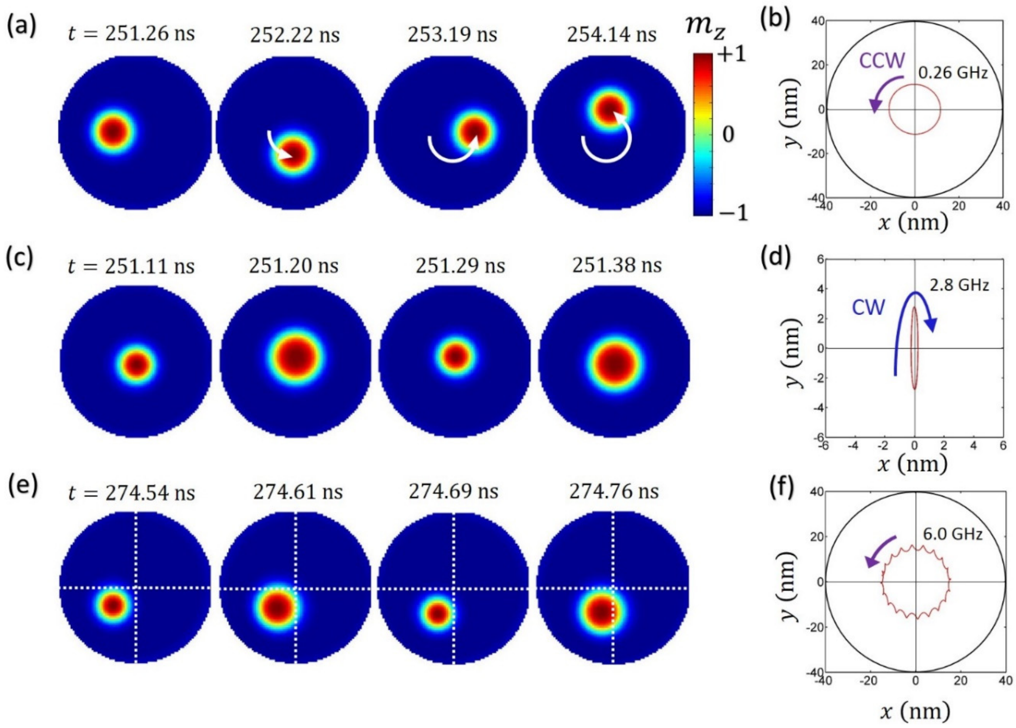

Fig. 1. The snapshot images and the trajectory (a), (b) for the steady-state gyrotropic motion excited at f_{ac} = 0.26 GHz, (c), (d) for the breathing motion excited at f_{ac} = 2.8 GHz, and (e), (f) for the simultaneous excitation of breathing mode and trajectioy of the gyrations for f_{ac} = 6.0 GHz, respectively. The amplitude of the applied SHE-based current was $H_{SHE} = 0.1(2.69) \times 10^4$A/m with the MHz (GHz) driving frequencies.

4. References

[1] A. Fert et al. Nature Nanotechnology 8, 152-156 (2013).

[2] J. Sampaio et al. Nature Nanotechnology 8, 839-844 (2013).

[3] S. Rohart and A. Thiaville Phys. Rev. B 88, 184422 (2013).

[4] M.J. Donahue and D.G. Porter, OOMMF User's Guide, Version 1.0, Interagency Report NISTIR 6376, National Institute of Standards and Technology, Gaithersburg, MD (Sept 1999).

[5] Eduardo Martinez et al. Appl. Phys. Lett. 103, 072406 (2013).

[6] Ki-Suk Lee et al. Phys. Rev. B 78, 014405 (2008).