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# 나노디스크에서의 자기 소용돌이 핵의 3차원 동역학 연구

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전산모사를 이용하여, 자기소용돌이의 공진 주파수에 대한 두께 의존성을 조사하였다. 자기소용돌이의 공진 주파수는 2차원(2D)과 3차원(3D) 계산결과 모두 두께가 두꺼워짐에 따라 증가하는 경향을 보였다. 그러나 2D와 3D 계산 결과는 두께가 두꺼워짐에 따라 차이를 보였는데, 이는 3D 계산과 달리 2D 계산에서는 두께가 증가함에 따라 두께방향으로 발생하는 불균질한 자화 구조를 고려하지 않았기 때문이다.

**주제어** : 자기소용돌이, 자화거동, 미소자기학

# Three-Dimensional Dynamics of Magnetic Vortex Core in a Nanodisk

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**Using micromagnetic simulation, we investigated the effect of thickness of a nanodisk on a resonance frequency of vortex gyration. We observed that the resonance frequency increases with increasing thickness in both cases of 2-dimensional (2D) and 3-dimensional (3D) calculation. However, there is a difference in the increasing rate of resonance frequency between 2D and 3D modeling owing to dynamically developed inhomogeneous magnetic texture along the thickness direction of disk in 3D modeling.**

**Keywords :** magnetic vortex structure, magnetization dynamics, micromagnetics

## I. Introduction

A vortex state is a stable magnetic configuration for a patterned submicron disk made of a soft magnetic material. In a ground state, it has both in-plane curling magnetization, denoted by the chirality and out-of-plane magnetization at the center of vortex structure, denoted by the polarity $p$. The direction of curling in-plane magnetization can be clockwise (CW) or counterclockwise (CCW), and the magnetization of vortex core can point up ($p = +1$) or down ($p = -1$). Because of these bistable properties of vortex state, it is proposed for potential non-volatile memory called vortex-based random access memory using its polarity as information carrier [1, 2]. The simplest way to change the polarity is to apply a magnetic field along the opposite direction of core magnetization, but the field strength of a few kOe is needed for the core reversal in this way. Another and more energy-efficient way to reverse the core polarity is to use a resonance effect by applying a.c. magnetic field

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[3] or a.c. spin polarized current [4] at the resonance frequency. With the resonance excitation, a vortex core shows a gyrotropic motion [5, 6] that is the lowest excitation mode, and reverses its polarity when it reaches the critical velocity [7]. For this reason, the eigenfrequency of vortex gyration has been intensively studied both numerically and analytically in the limit of thin film [8], where the magnetization profile is uniform along the thickness direction. Recently, a study of 3D dynamics of the Landau structure revealed that its dynamics is different from the 2D dynamics, and pointed out the importance of 3D dynamics in case of a thick film [9]. In this paper, we examined the effect of film thickness on the resonance frequency of vortex gyration.

## II. Modeling

Micromagnetic simulation was performed to understand the effect of thickness on the resonance frequency of gyrotropic motion. The simulation was performed by solving the Landau-Lifshitz-Gilbert (LLG) equation (Eq. (1))

$$\frac{\partial \boldsymbol{M}}{\partial t} = -\gamma \boldsymbol{M} \times \boldsymbol{H}_{eff} + \frac{\alpha}{M_S} \boldsymbol{M} \times \frac{\partial \boldsymbol{M}}{\partial t}, \tag{1}$$

where $\boldsymbol{M}$ is the magnetization vector, $\boldsymbol{H}_{eff}$ is the effective field including the external, the magnetostatic, and the exchange field. In order to observe the effect of film thickness, we fixed the diameter of disk to 270 nm and changed the thickness of disk to 20, 30, 50 and 80 nm (Fig. 1). The resonance frequency for each case was calculated in the following way. An external magnetic field of 100 Oe was applied to the equilibrium vortex state along the x-axis, shifting the vortex core from the disk center. After 1 ns, the magnetic field was abruptly turned off and then the vortex core showed a gyrotropic free relaxation. During this free relaxation for 29 ns, the spatially averaged x-component (or y-component) of magnetization showed an oscillatory behavior with time and its resonance frequency was obtained by using Fourier analysis. In the micromagnetic modeling, standard material parameters of NiFe were used: the saturation magnetization $Ms = 800$ emu/cm$^3$, the gyromagnetic ratio $\gamma = 1.76 \times 10^7$ sec$^{-1}$Oe$^{-1}$, the Gilbert damping constant $\alpha = .01$ and the exchange constant $A_{ex} = 1.3 \times 10^{-6}$ erg/cm. In 2D modeling, the unit cell size was $2 \times 2 \times$ (20, 30, 50, and 80) nm$^3$ whereas in 3D modeling, it was $2 \times 2 \times 10$ nm$^3$. (Exchange length of Permalloy is about 5 nm, but 10~20 nm of cell thickness is generally used for reducing computation time.) A large $\alpha$ above 0.5 was used to get the initial equilibrium state.

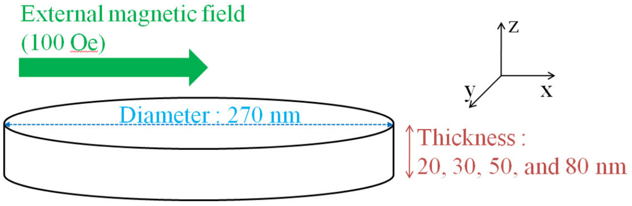

**Fig. 1.** (Color online) (a) schematic figure of modeling system.

## III. Results and Discussion

The thickness-dependence of resonance frequency is studied with various thicknesses (20, 30, 50, and 80 nm). Fig. 2 shows the resonance frequency as a function of the disk thickness obtained from 2D and 3D modeling. Firstly, it is observed that the resonance frequency of vortex gyration increases with increasing the disk thickness. Secondly, the resonance frequency in 3D modeling is always lower than in 2D modeling, and the difference of the resonance frequency between 2D and 3D modeling becomes larger as the thickness increases.

By using Thiele's approach [10], a gyrotropic motion of vortex core can be roughly described to damped harmonic oscillator model. A resonance frequency is given as $f = 1/2\pi\sqrt{k/m_{VW}}$, where $k$ is spring constant related with entire energy of vortex system and $m_{VW}$ is mass of vortex wall. It is known that the mass of domain wall is inversely proportional to $\lambda^2$, where $\lambda$ is domain wall width [11]. As a result, it is predicted that a resonance frequency shows a linear dependence to $\lambda$. Fig. 3(a) shows a resonance frequency (black) and relative radius of vortex core ($\lambda$, blue) as a function of disk's thickness in 2D modeling. Here, $\lambda$ is determined by isosurface representing $\boldsymbol{M}_z$ of

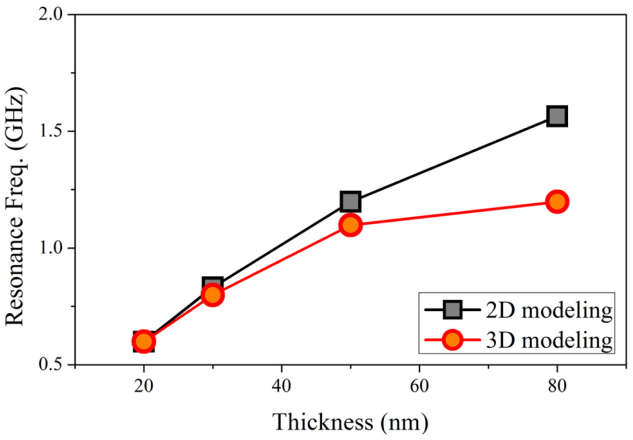

**Fig. 2.** (Color online) Resonance frequency as a function of time in the case of 2D (black color) and 3D (red color).

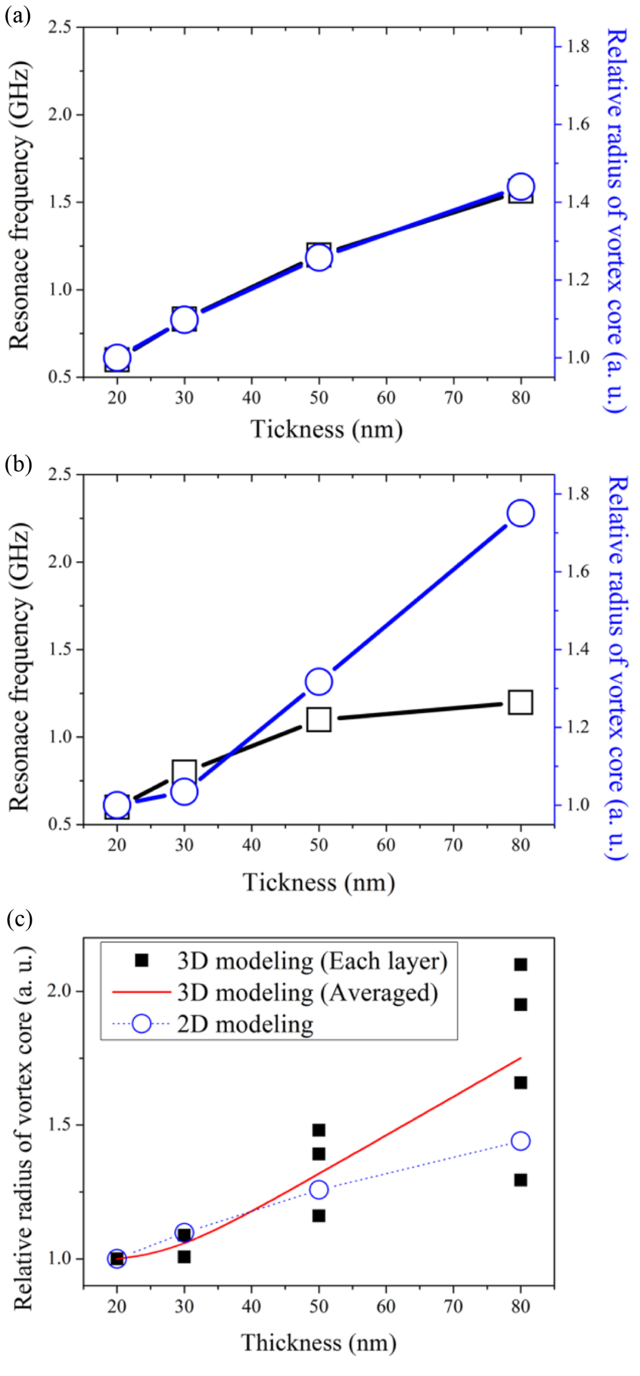

**Fig. 3.** (Color online) (a) Dependence of relative radius of a vortex core (blue) and resonance frequency (black) on film thickness is drawn for 2D modeling. (b) Dependence of relative radius of vortex core (blue) and resonance frequency (black) on film thickness is drawn for 3D modeling. (c) Relative radius of vortex core is drawn as a function of film thickness for 2D (blue) and 3D (black and red). Black symbol denotes the radius of vortex core in each layer and red line indicates averaged radius of vortex core through thickness.

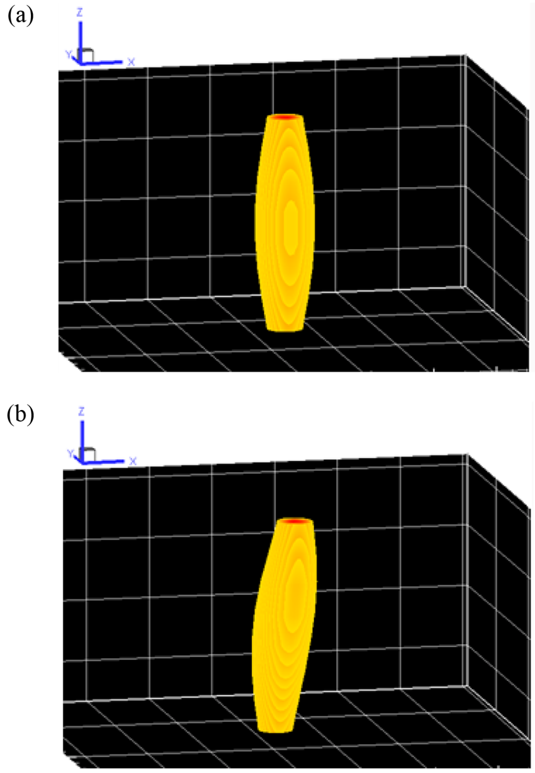

**Fig. 4.** (Color online) 3D magnetic texture of vortex core region in case of 80 nm of thickness: (a) in the ground state, (b) in the gyrotropic motion.

400 emu/cm$^3$ whose value is a half of $M_s$. It is observed that a trend of increasing rate of resonance frequency is well matched to that of $\lambda$ as predicted. However, in 3D modeling, an increase of resonance frequency is different from that of $\lambda$ as shown in Fig. 3(b).

To understand this difference, we first check the dependence of a core radius on the disk thickness in 2D and 3D modeling. Fig. 3(c) shows a relative radius of vortex core as a function of thickness in both 2D and 3D modeling. A radius of vortex core increases when the disk is thickened in both 2D and 3D modeling. However, an averaged core radius in 3D modeling (red) is large compare to 2D modeling (blue) and the relative core radius is not constant along thickness (black symbol). The relative radius of vortex core has the maximum value at inside of a disk, and is smaller at the top and bottom surfaces of the disk.

Next, we investigate the magnetic dynamics in 2D and 3D modeling in more detail. Fig. 4 shows 3D magnetic texture of vortex core region: (a) in the ground state, (b) in the gyrotropic motion. Even in a ground state, inhomogeneous magnetization profile is shown in the direction of thickness which is not taken into account in 2D modeling. When the vortex core is in the gyrotropic motion, an additional degree of freedom is developed: the distortion of vortex core along the thickness direction.

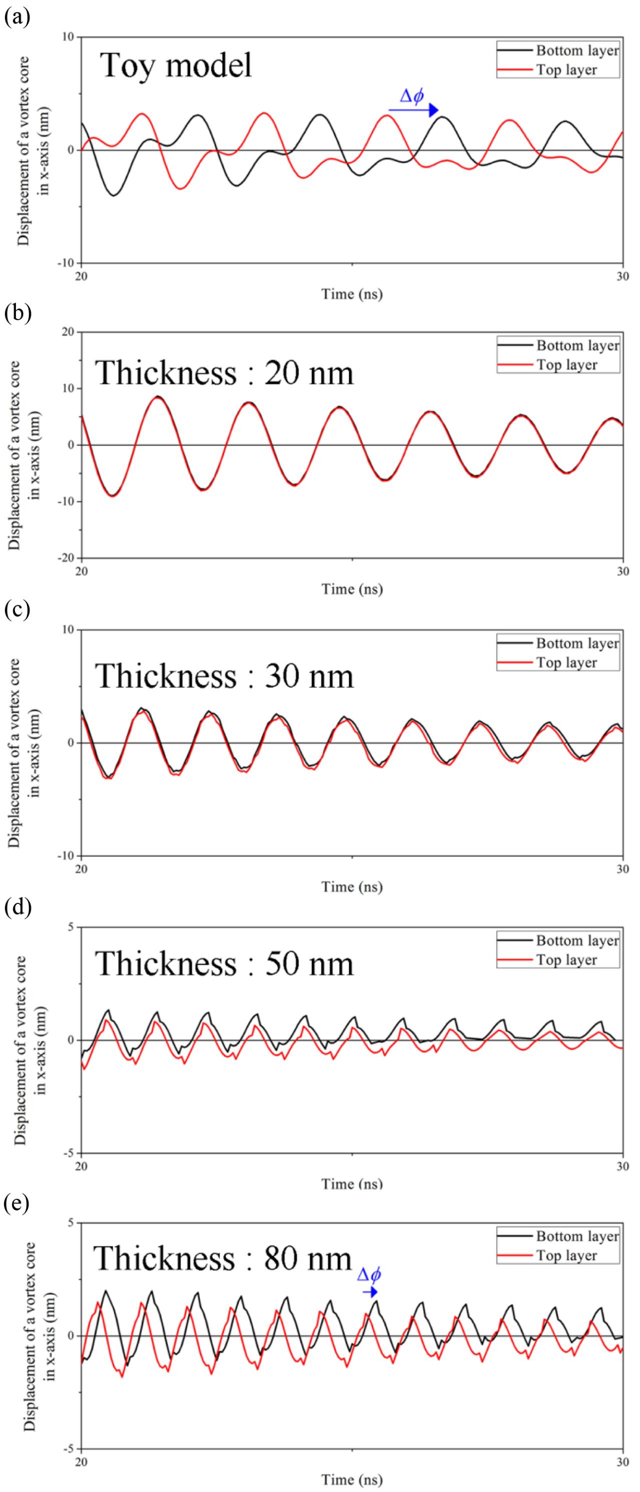

**Fig. 5.** (Color online) (a) Displacement of a vortex core in x-axis as a function of time when top and bottom layer in case of toy model. (b)~(e) displacement of a vortex core in x-axis as a function of time with given thickness (20, 30, 50 and 80 nm).

The center position of a vortex core at the top layer is not identical to that at the bottom layer. This additional degree of freedom in 3D modeling would act as an additional energy relaxation channel so that the resonance frequency can be lower compared to 2D modeling.

To maximized additional degree of freedom, a toy model was introduced by eliminating exchange coupling between the top and bottom layers. Nanodisks, which have the 20 nm of thickness and the 270 nm of diameter, are separated by an empty space (20 nm) in a toy model. Fig. 5(a) shows the displacement of a vortex core in x-axis as a function of time in case of toy model. We observed a phase difference ($\Delta\phi = \pi$) in toy model although there existed complex dynamics comes from coupled vortices. It is because toy model eliminates inter-disk exchange interaction, thus additional degree of freedom along the thickness direction can be exaggerated.

Fig. 5(b)~(e) show the displacement of vortex core in x-axis as a function of time with various thickness (20, 30, 50, and 80 nm) especially on top and bottom layer. In the case of 20 nm and 30 nm of thickness model (Fig. 5(b) and (c)), the difference in vortex dynamics between top and bottom layer is quite small, so magnetic dynamics of top and bottom layer shows almost synchronized behavior similar to 2D case. However in the case of 50 nm and 80 nm of thickness model (Fig. 5(d) and (e)), the difference in vortex dynamics seems large and there is a phase difference ($\Delta\phi$) of the magnetic dynamics between the top and bottom layer though the degree of phase difference ($\Delta\phi$) is small compare to toy model. The phase difference becomes significant with thickness and the property of additional degree of freedom becomes important in case of thick disk like as toy model. Thus, we attribute the discrepancy of resonance frequency between 2D and 3D modeling to the additional dissipation comes from phase difference between top and bottom layer.

## IV. Conclusion

The resonance frequency of vortex gyration is examined at various thickness of a nanodisk with a fixed diameter. Both 2D and 3D modeling show an increase of the resonance frequency with increasing the thickness of a nanodisk. However, an increasing rate of a resonance frequency shows a discrepancy between 2D and 3D modeling. This discrepancy is attributed to additional relaxation channel coming from inhomogeneous magnetic configuration along the disk thickness during the gyrotropic motion. When dealing with a resonance frequency in a nanodisk, thickness is an important factor because it changes its resonance frequency by making additional degree of freedom along thickness direction on vortex dynamics.

## Acknowledgment

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