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Thermally Excited Mag-Noise in Ferromagnetic Ring Structures

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As the dimension of magnetic devices drastically decreases to nanometer range, thermally excited mag-noise gradually becomes the dominant noise source. Thermally excited mag-noise plays an important role in ferromagnetic ring structures. By conducting micromagnetic simulation, the saturated state, triangle state, half triangle state, onion state, and vortex state are explored and studied, respectively. The mag-noise calculation shows that triangle state is the main reason for the mag-noise exhibiting $1/f$ tendency in both the low-frequency range and high-frequency range in relaxed state, while the onion state explains why a noise peak appears in high-frequency range in relaxed state. Meanwhile, it is proved that the area of the ferromagnetic rings is not the determining factor for the mag-noise distribution in saturated state. These results offer the theoretical framework for explaining the relation between domain structure and mag-noise, which is conducive to the future application of ferromagnetic ring structures as magnetic random access memory elements.

Index Terms—Ferromagnetic ring, mag-noise, ring domain, thermal.

I. INTRODUCTION

FERROMAGNETIC ring structures have been intensively investigated recently [1], [2] since they exhibit a number of different magnetic states and switching processes. The existence of well-defined remanent states in these thin-film rings offers the possibility of their utilization as data storage media in magnetic random access memories (MRAM) [3]–[6]. The investigation in micron-diameter rings has already revealed some distinct states such as vortex states with opposite chiralities (clockwise or counterclockwise), onion states, and twisted states. With the variation of ring-structure dimension in practical application, novel multidomain structures due to complex domain-wall nucleation and propagation are expected to emerge. Meanwhile, analytical analysis has suggested that the thermally activated magnetization fluctuation has become a source of noise comparable to that of Johnson noise as the volume of a magnetic sensor or magnetic storage cell shrinks. The thermally excited mag-noise in ferromagnetic ring structures acts an important role in application [7] since it overwhelms most other noise sources for micron- and submicron-diameter rings.

In this paper, we explore the thermally excited mag-noise properties under different ring-structure dimensions using micromagnetic simulation. The relation between domain structure and mag-noise is fully demonstrated. This relation is not only helpful to illustrate how the mag-noise is distributed but also beneficial to explain this distribution from the perspective of multidomain structure.

II. SIMULATION DETAILS

Fig. 1 shows the single-layer ferromagnetic ring structure used in our study, which is parameterized by its outer diameter

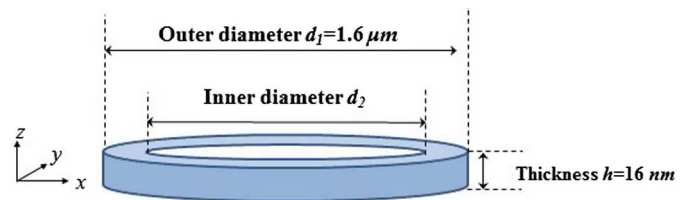


Fig. 1. Schematics of the ferromagnetic ring structure.

d_1 , its inner diameter d_2 , and its thickness h . The simulation is carried out on rings with outer diameters fixed at $1.6 \mu\text{m}$ [8] while the inner diameter is set at $0 \mu\text{m}$, $0.4 \mu\text{m}$, $0.8 \mu\text{m}$, and $1.2 \mu\text{m}$ respectively. The thickness is also fixed at 16 nm . The selected material is permalloy ($\text{N}_{80}\text{Fe}_{20}$). The ferromagnetic ring structure has saturated magnetization $M_s = 860 \text{ emu/cm}$ and exchange constant $A_{ex} = 1.3 \times 10^{-6} \text{ erg/cm}$.

The stochastic Landau-Lifshitz-Gilbert (LLG) equation is solved by utilizing object-oriented micromagnetic framework (OOMMF) [9] with the thermal fluctuation term

$$\frac{d\vec{M}}{dt} = -|\gamma|\vec{M} \times (\vec{H}_{eff} + \vec{h}_{fl}(t)) - \frac{\alpha}{M_s} \left(\vec{M} \times \frac{d\vec{M}}{dt} \right) \quad (1)$$

where $\vec{h}_{fl}(t)$ is the thermal field modeling the Gaussian random process, with the variance of each cell written as

$$V_{ar} = \frac{\alpha}{1 + \alpha^2} \frac{2k_B T}{\gamma \mu_0 M_s V} \quad (2)$$

where M_s is the saturation magnetization, V is the volume of each cell. Since the exchange length $l_{ex} = \sqrt{A/2\pi M_s^2}$ is around 5.3 nm , the mesh size is set as $4 \times 4 \times 4 \text{ nm}^3$. The damping constant is $\alpha = 0.02$. The thermal fluctuations are simulated at $T = 60^\circ\text{C}$ which is below the Curie temperature. It is well justified for the situation where the dynamics are adiabatic and close to equilibrium.

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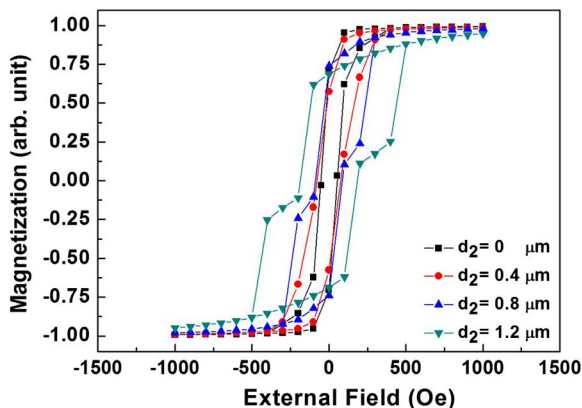


Fig. 2. Hysteresis loop for the ferromagnetic ring structure with inner diameter set as $0 \mu\text{m}$, $0.4 \mu\text{m}$, $0.8 \mu\text{m}$, and $1.2 \mu\text{m}$.

The magnetization configurations are simulated at each time step for a sufficiently long time (10^{-7} s) and collected every 10^{-11} s. The noise power spectrum density (PSD) is calculated by the fast Fourier transform (FFT) from the time-varying magnetization.

III. HYSTERESIS LOOP OF FERROMAGNETIC RINGS

The hysteresis loop as a function of applied field is depicted in Fig. 2 for ferromagnetic ring structures with different inner diameters. It is observed that for ring structures with relatively large inner diameter ($d_2 = 0.8 \mu\text{m}$ or $1.2 \mu\text{m}$), they are expected to exhibit discrete two-step magnetization switching behavior [1], [10]. As the ring magnetization is firstly relaxed from saturation, the onion state is formed due to the strong demagnetization field. The onion state is characterized with the feature that two head-to-head domain walls form along the direction of external field. When the external field turns to small reverse field around 0 Oe, the Zeeman energy in the system depends one of the two head-to-head domains to flip for 180° to another side of the ring, which leads to the formation of vortex state. When the reverse field is further increased to the opposite saturation, the second domain is also flipped and finally results in a reverse onion state.

However, as the inner diameter becomes relatively small ($d_2 = 0 \mu\text{m}$ or $0.4 \mu\text{m}$), this two-step magnetization switching behavior becomes continuous. It could be concluded that larger inner diameter would increase the coercivity and harden the ring structure to some extent, while small inner diameter is responsible for softening the ring structure.

IV. MULTIDOMAIN STRUCTURE IN FERROMAGNETIC RINGS

The representative domain structures are presented in Fig. 3 for ferromagnetic rings with different inner diameters. The structures in (a), (d), (g), and (j) are saturated states under external field (1000 Oe). The structures in (b), (e), (h), and (k) are relaxed states (zero external field in the hysteresis loop). The structures in (c), (f), (i), and (l) are all vortex states. When the inner diameter is $0 \mu\text{m}$, the ferromagnetic ring basically turns to a ferromagnetic disk structure. The relaxed state becomes a triangle state. The magnetic moment in this state is very large. However, the stray field is small because the magnetization follows the perimeter of the disk, which eliminates the possibility

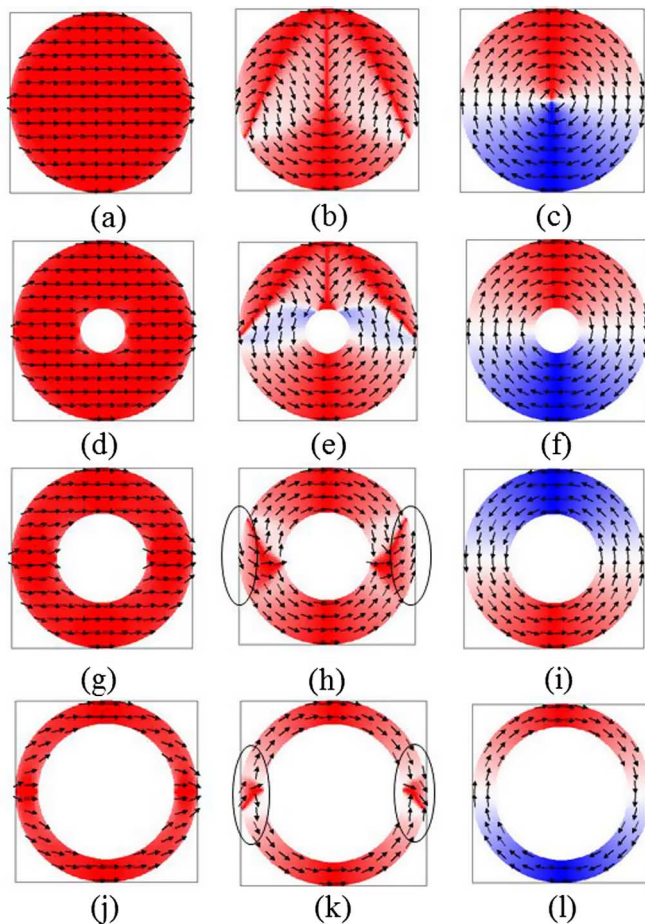


Fig. 3. Saturated state (first column), relaxed state (second column), and vortex state (third column) domain structure for inner diameter equal to $0 \mu\text{m}$ in (a), (b), and (c); inner diameter equals $0.4 \mu\text{m}$ in (d), (e), and (f); inner diameter equals $0.8 \mu\text{m}$ in (g), (h), and (i); inner diameter equals $1.2 \mu\text{m}$ in (j), (k), and (l).

of forming any “pole charges” [7]. Obviously, the stray field at the two edges of the triangle is large, which makes the magnetic energy mainly contributed by magnetostatic energy. When the inner diameter further increases to $0.4 \mu\text{m}$, the relaxed state sustains partial triangle. Due to the inner vacant space, the demagnetization field splits the two edges of the triangle into four domains. The two domains at the upper positions remain triangle patterns while the two domains at the lower positions begin to annihilate themselves to the saturated states as shown in Fig. 3(e). This tendency further increases the stray field at the triangle edges. When the inner diameter increases to $0.8 \mu\text{m}$, the two domains at the upper positions also annihilate themselves to the saturated state, which finally forms an onion state. However, in this onion state, two approximately symmetric transverse domain walls form at the left and right sides of the ring. The highlighted spins in Fig. 3(h) relax to a circumferential configuration to reduce the stray-field energy of the system. Meanwhile, the spins in these two parts point to the same direction around the ring, which causes the head-to-head onion state to gradually evolve to vortex state shown in Fig. 3(i). When the inner diameter increases to $1.2 \mu\text{m}$, the relaxed domain structure is more or less the same as the situation when the inner diameter is $0.8 \mu\text{m}$.

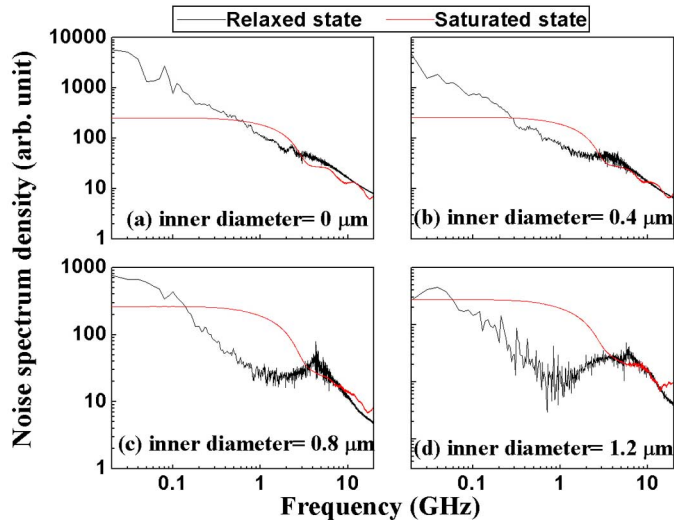


Fig. 4. Noise spectrum density of relaxed state and saturated state for ferromagnetic rings with inner diameter (a) $0 \mu\text{m}$, (b) $0.4 \mu\text{m}$, (c) $0.8 \mu\text{m}$, (d) $1.2 \mu\text{m}$.

V. MAG-NOISE OF SATURATED STATE AND RELAXED STATE IN FERROMAGNETIC RINGS

To further explore the noise behavior under thermal fluctuations, the mag-noise under relaxed state and saturated state is calculated as shown in Fig. 4 for ferromagnetic rings with different inner diameters. In Fig. 4(a), it is observed that the inner diameter equals $0 \mu\text{m}$ (disk structure), the mag-noise density in low frequency (0-1 GHz) for saturated state remains unchanged while a $1/f$ tendency with relatively larger amplitude emerges for the relaxed state (triangle state). As the frequency increases above 1 GHz, the saturated state and relaxed state share nearly the same $1/f$ tendency and amplitude. In Fig. 4(b) where the inner diameter increases to $0.4 \mu\text{m}$, due to the half triangle state in the relaxed state, the mag-noise density still exhibits $1/f$ tendency in both the low-frequency range and high-frequency range. In Fig. 4(c) where the inner diameter increases to $0.8 \mu\text{m}$, the triangle state is replaced by onion state. This replacement does not have much effect on the low-frequency mag-noise in the relaxed state. However, at higher frequency, a peak near 5 GHz appears. It is worth noting that the amplitude of the mag-noise in the relaxed state no longer overwhelms the mag-noise in the saturated state in low-frequency range. In Fig. 4(d) where the inner diameter increases to $1.2 \mu\text{m}$, the amplitude of the mag-noise in the relaxed state (onion state) minimally exceeds the saturated state in both low-frequency range and high-frequency range. It is interesting that although the low-frequency mag-noise in relaxed state still exhibits $1/f$ tendency, there is a large perturbation near 1 GHz. This perturbation is due to the large thermal fluctuation in the highlighted spins in Fig. 3(k).

In conclusion, the triangle state or half triangle state in the relaxed state would result in a $1/f$ mag-noise distribution in both low-frequency range and high-frequency range. The onion state would result in a $1/f$ mag-noise distribution only in the low-frequency range. At high-frequency range, a noise peak appears. Meanwhile, the onion state, as the relaxed state, would suppress the magnitude of the mag-noise when compared to the mag-noise in the saturated state.

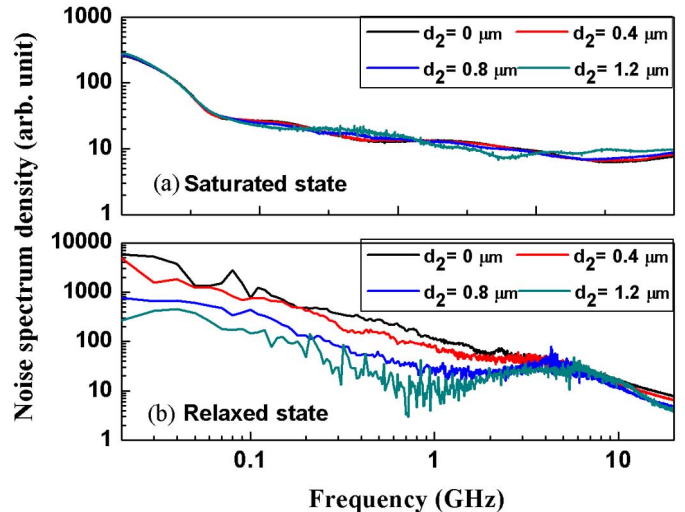


Fig. 5. Noise spectrum density of different inner diameter for ferromagnetic rings with (a) saturated state and (b) relaxed state.

In order to explore the influence of inner diameter on mag-noise in saturated state and relaxed state, we compare the mag-noise for various inner diameters in saturated state [Fig. 5(a)] and relaxed state [Fig. 5(b)]. In Fig. 5(a), it is observed that the difference in mag-noise between ferromagnetic rings with different inner diameters is negligible in low-frequency range. The difference in the high-frequency range is still very small. This reveals that the area of the ferromagnetic rings is not the decisive factor determining the mag-noise distribution for saturated state. For the relaxed state in Fig. 5(b), as the inner diameter increases, the mag-noise amplitude gradually decreases in the low-frequency range. On the other hand, the perturbation becomes much more remarkable when inner diameter increases. At high frequency, the inner diameter does not have significant effect on the mag-noise amplitude. The $1/f$ tendency in the high-frequency range retains good linearity with no perturbation appeared.

VI. CONCLUSION

In this paper, we have explored the magnetic configuration of ferromagnetic ring structures at micron-level with different inner diameters using micromagnetic simulation. At 1000 Oe external field, the ring structures all demonstrate saturated state with the magnetization direction points to the external field direction. In relaxed state where external field turns to zero, a variety of domain structures is formed including the triangle state, half triangle state, and special onion state (with symmetrical domain walls at two sides). As the external field direction reverses, the vortex state appears for all the ring structures. The mag-noise is calculated for both the saturated state and relaxed state under different inner diameters. The results reveal that triangle state is the main reason why the mag-noise exhibits $1/f$ tendency for both the low-frequency range and high-frequency range in relaxed state, while the onion state explains why a noise peak appears at high-frequency range in relaxed state. The discussion of the mag-noise in this paper has significant importance for the application of ferromagnetic ring structures as future MRAM

elements. The domain structures provide a framework of explanation of the mag-noise distribution which might help to offer some approaches to suppress the mag-noise in ring structures.

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