Exploring Skyrmion Deformation in Antiferromagnetic Systems: A Pathway to Next-Generation Memory Devices

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Magnetic skyrmions possess a unique topological protection property, making them highly promising candidates as information carriers in advanced recording and memory technologies. However, these carriers can experience deformation when subjected to high current densities, potentially disrupting stable data transmission. In this study, we investigate skyrmion deformation across various magnetic systems, including ferromagnetic (FM), ferrimagnetic (FiM), and antiferromagnetic (AFM) systems, to assess their viability in memory applications. Through micromagnetic simulations and theoretical analysis, we focus on AFM skyrmions, which show the least susceptibility to deformation. Our analysis involves deriving a canting term from the Thiele equation, highlighting a critical factor that accounts for the reduced deformation observed in AFM systems. This insight underscores the superior stability of AFM skyrmions, positioning them as an optimal choice for skyrmion-based memory devices. The findings suggest that AFM systems can enhance the reliability and efficiency of skyrmion-driven information storage and transmission, advancing the fundamentals of recording and memory technologies.

***Index Terms*—Skyrmion, antiferromagnetic system, information storage, memory**

I. Introduction

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The magnetic skyrmion presents a transformative potential for advanced recording and memory applications, such as racetrack memory devices, [1]–[5] transistor-like devices, [6], [7] and neuromorphic computing systems. [6] Key attributes of skyrmions that make them suitable for these applications include their topological stability, [8]–[11] nanoscale dimensions, [8], [12]–[14] and the ability to be manipulated by lower current densities compared to domain walls. [15]–[17]

Several control mechanisms are available for skyrmions, including spin current, [18], [19] magnetic field gradients, [20] spin waves, [21] and temperature variations. [22] Among these, current-driven manipulation is prevalent due to its high efficiency and technological compatibility.

In ferromagnetic (FM) systems, skyrmions tend to deform and disintegrate under high current densities, [1], [12], [15], [23] limiting their effectiveness in memory devices. Antiferromagnetic (AFM) systems offer promising alternatives, characterized by weak stray fields [24], [25] and terahertz spin dynamics, [26], [27] which can mitigate skyrmion deformation. [28]–[33] A schematic illustrating AFM skyrmion deformation is presented in Fig. 1(a). The commensurate spins in AFM eliminate skyrmion Hall effect (SkHE), [34], [35] which leads to the deflection of the skyrmion's trajectory and a higher risk of boundary annihilation. We use Mumax3 [36], [37] to simulate the FM, FiM, and AFM systems. The simulation results indicate that increasing the applied current density causes a skyrmion to gradually deform from a circular shape to an elliptical shape, expanding until it ultimately breaks down, as shown in Fig. 1(b). Our simulations reveal that AFM skyrmions possess larger stiffness, meaning that they are more resistant to current-induced deformation.

This study investigates skyrmion deformation across FM, FiM, and AFM systems using micromagnetic simulations, highlighting transitions from strong to negligible Magnus forces. Our findings reveal that AFM skyrmions exhibit minimal deformation. Theoretically, we examine skyrmion deformation through force balance analysis, identifying magnetic canting as a crucial factor enhancing AFM skyrmion stability. We quantify skyrmion deformation in terms of stress, size, shape, and orientation, [28], [29], [31], [38] comparing AFM and FM skyrmions. Our numerical simulations closely align with analytical solutions, underscoring AFM systems' potential in revolutionizing recording and memory technologies. And we could use the δ term to define the skyrmion deformation:

$$\delta = \frac{1}{(2D/w + 2A/R^2)} \left(\frac{A\boldsymbol{\delta}_0}{w^2} + \alpha \frac{M_S}{\gamma} \frac{\boldsymbol{v}}{R} \right) \cdot \hat{\boldsymbol{\varphi}}. \tag{1}$$

where $\boldsymbol{\delta}_0 = \tau_{\mathrm{ad}} M_S \hat{\boldsymbol{\imath}}/2K\gamma$, refers to the AFM domain canting far from the skyrmion, $\boldsymbol{v}$ is the moving speed of skyrmion caused by the current. Normally the relation between skyrmion radius and domain wall width is $R \gg w$, and under such condition δ can be approximated as $\delta \approx (A/2Dw)\boldsymbol{\delta}_0 \cdot \hat{\boldsymbol{\varphi}}$. On the contrary, the canting in FM skyrmion is given by $\delta_{\mathrm{FM}} = -v_r M_S/2D\gamma$. Comparing the canting between AFM and FM systems provides a clearer insight into why the deformation in AFM is considerably smaller:

$$\begin{aligned} \delta_{\mathrm{AFM,max}} &\approx \frac{A|\boldsymbol{\delta}_0|}{2Dw} \approx \frac{1}{2} \cdot \left(\frac{w\tau_{\mathrm{ad}} M_S}{2D\gamma} \right), \\ \delta_{\mathrm{FM,max}} &\approx \left(\frac{\pi}{\alpha} \right) \cdot \delta_{\mathrm{AFM,max}}. \end{aligned} \tag{2}$$

where $\delta_{\mathrm{AFM,max}} \ll \delta_{\mathrm{FM,max}}$ as the damping $\alpha < 1$.

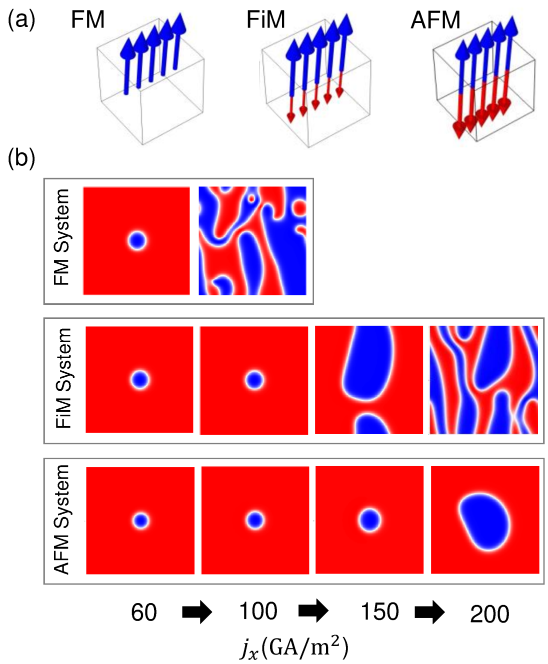

Fig. 1. (a) Schematic structure of the AFM skyrmion deformation. (b) The skyrmion deformation under different applied current densities in different systems. The skyrmion breaks down at 60 $\mathrm{GA/m^2}$ and 150 $\mathrm{GA/m^2}$ in the FM and FiM system respectively, but it still remains stable at 200 $\mathrm{GA/m^2}$ in the AFM system.

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