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Shape-tuned dynamic properties of magnetic nanoelements during magnetization reversal

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ABSTRACT

We study the dynamic properties of magnetic nanoelements with tapered ends by using micromagnetic simulations. It is found that the spin-wave modes can be effectively manipulated by the element shape. With the increase of the end sharpness (described by tapering parameter h), the frequency of the spin-wave edge mode increases rapidly and its oscillation areas in the both ends of element gradually increase and move toward to the central area. Finally, the edge mode completely merges into the fundamental mode. During the magnetization reversal processes, the edge mode experiences one or two softening depending on $h \leq 60$ nm or $60\text{ nm} < h < 100$ nm. When $h > 100$ nm, it is the fundamental mode that goes to zero at the switching field. The evolution of the spin-wave modes reflects the change of the micromagnetic structures of the elements during the reversal. It is the softening of the edge mode that triggers the magnetization reversal in elements with $h < 100$ nm. The quasi-uniform reversal in the elements with $h > 100$ nm is induced by the softening of the fundamental mode, where the edge mode is completely suppressed. The results presented in this work demonstrate that the dynamic properties and the magnetization reversal can be effectively tuned by changing the shape of the nanoelements and may be useful for designing the nanoscale magnetic devices.

1. Introduction

The magnetization reversal of magnetic nanostructures has attracted considerable attention during the last few years due to its relation to the performance of magnetic data storage and spintronic devices. Depending on the shape, size and magnetic parameters, the nanomagnets may reverse via different paths. For example, in ring-shaped elements, the magnetization reversal is realized by the domain nucleation processes and domain wall motion [1–3], or by the formation and motion of complex multi-domain states [3–7], depending on the ratio of inner to outer diameter of the ring and the thickness of the ring. For magnetic soft square or circular elements, it was found that the magnetization switching is accomplished through the formation and motion of the vortex structure [8–10]. As regards the rectangular element, the magnetization reversal is achieved by means of nucleation of revised domains at the two ends of element and subsequent domain wall movement. But, depending on whether the configuration of the edge domains is the so-called "*C*-state" or "*S*-state", the switching field is greatly different, which leads to a wide range of distribution of the switching fields in arrays of rectangular elements [11–14]. Recently, it was found that if the ends of the rectangular element are tapered, the reversal may initiate in the interior of the structures and spread out to the ends. This eliminates the influence of edge effect and in certain degree suppresses the distribution of the switching fields [14–16]. From the viewpoint of application, a fast magnetization reversal with low switching field is always favorable for ultrafast and low-power consumption devices. The control of the magnetization reversal according to the actual requirement of devices is an important issue.

The magnetization reversal is closely related to the magnetization dynamics of magnets, especially the dynamics in the vicinity of the switching field [17–20]. Garanin and Kachkachi [21] showed that the magnetization reversal can be achieved via internal spin waves. Montoncello et al. [22–24] found that the occurrence of magnetization reversal is always accompanied by softening of one of the spin wave modes (its frequency goes to zero at switching field). The symmetry of the soft mode determines the reversal path. Moreover, by exciting certain spin waves, one can not only reduce the switching field greatly but also choose a desirable magnetization reversal process [25–27]. Therefore, fully understanding of the magnetization dynamics and its inherent relation with the magnetization reversal is essential

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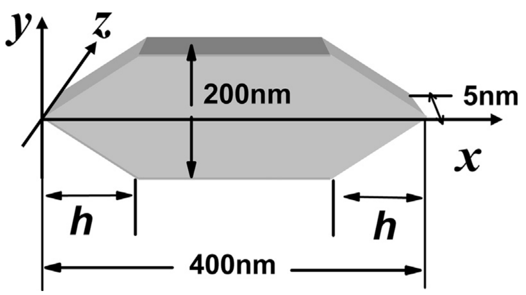

Fig. 1. Illustration of the tapered magnetic nanoelement with the geometry and dimensions.

for realizing the controllable reversal process.

In this paper, we present our detailed study about the shape-controlled dynamic properties and magnetization reversal of magnetic nanoelements with tapered ends by micromagnetic simulations. By changing the tapering degree, several reversal processes are observed and their relation with the dynamic properties is revealed by looking into the evolution of spin wave modes during the reversal processes.

2. Micromagnetic simulation details

The magnetic nanoelement with tapered ends studied in this work is 400 nm long in the x-direction, 200 nm wide in the y-direction, and 5 nm thick in the z-direction as presented in Fig. 1. The tapering degree of the nanoelement is represented by h, which changes from 0 to 200 nm. The magnetic parameters chosen for micromagnetic simulations corresponding to Permalloy are: saturation magnetization $M_s = 8.6 \times 10^5$ A/m, exchange stiffness $A_{ex} = 1.3 \times 10^{-11}$ J/m and magnetocrystalline anisotropy $K = 0$. Simulations are performed with the micromagnetic code OOMMF [28]. The simulation cell size is set to be $2 \times 2 \times 5$ nm^3.

To simulate the magnetization reversal, we first magnetize the elements to saturation under an external field ($H = 100$ mT) applied along the positive x-direction and then gradually reduce the field in step of 1 mT to $H = -100$ mT (negative x-direction). For the simulations of the dynamical properties, a sinc-function field $h_0 \sin(2\pi \nu_H t)/(2\pi \nu_H t)$ along the z axis with $h_0 = 10$ mT and $\nu_H = 30$ GHz is applied on the element to excite the magnetization oscillation. The temporal evolution of the magnetization in each cell is recorded every 5 ps. The local FFT power is computed for each cell by performing a Fourier analysis and then summed over the whole element. Thus, the magnetic resonance spectrum with frequency from 0 to 30 GHz can be obtained and the spatial distribution of the resonance oscillation can be imaged.

3. Results and discussion

We first simulated the demagnetization curves of the magnetic elements with different tapered ends as shown in Fig. 2. The equilibrium magnetization configurations (on the right side of the curves) and the transient configurations during the irreversible reversal process (on the left side of the curves) are also presented as insets of the figure. The magnetization reversal of the rectangle and elliptical elements and nanowires has been studied extensively [11–16]. Depending on the shape of the magnet, the magnetization reversal can be achieved via two different ways. One starts through the nucleation of reversal domains in the end areas and their succedent expansion through the domain wall

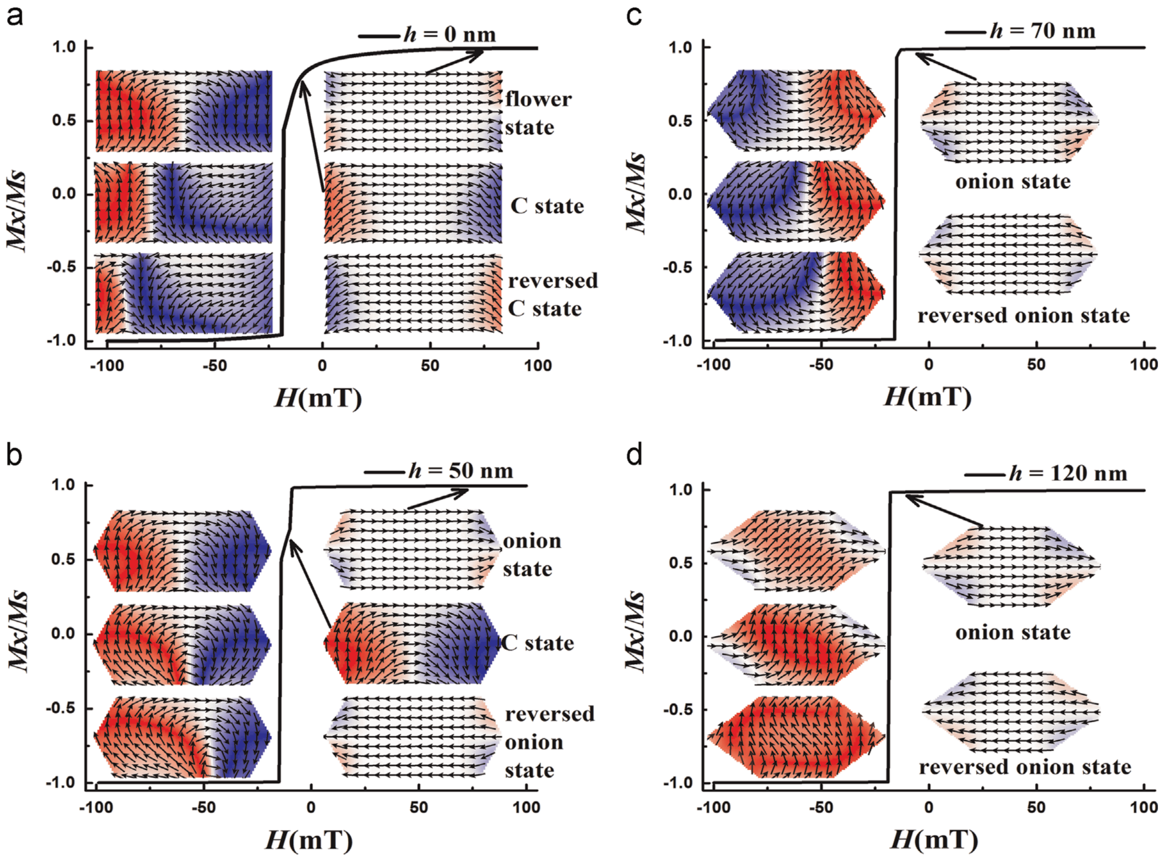

Fig. 2. The demagnetization curves of the tapered magnetic elements with $h = 0$ nm (a), 50 nm (b), 70 nm (c), and 120 nm (d). The equilibrium magnetization configurations (on the right side of the curves) and the transient configurations during the irreversible reversal process (on the left side of the curves) are presented as insets of the figure.