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Scalable magnetic skyrmions in nanostructures

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ABSTRACT

Magnetic skyrmions are going to be the prospective candidate for next generation ultra-high density data storage due to their tunable dimension down to few *nm* and requirement of low current density for their motion. This paper presents the stabilization of skyrmion and various ways of scaling skyrmion dimension in magnetic nanostructure with perpendicular magnetic anisotropy. The micromagnetic energetics of the system has been explained as an additive contribution due to the Heisenberg exchange, Dzyaloshinskii-Moriya interaction, anisotropy and Zeeman field. Emphasis has been provided towards the understanding of the complex interplay between the energy parameters in response to the modification of asymmetric exchange, anisotropy and their effect in magnetization reversal for circular nano-disks of different dimensions. Fine tuning of skyrmion diameter is shown with the presence of magnetic defect in the nanostructure. Stabilization of single skyrmion and symmetric multi skyrmion lattice from a ferromagnetic multi domain state has been explained for the nanostructures in the light of subtle balance of the energies, arising due to the Dzyaloshinskii-Moriya interaction and out-of-plane magnetic field.

1. Introduction

Symmetry breaking together with the spin-orbit coupling presents many intriguing phenomena in condensed matter physics. One of the recent examples is the existence of chiral spin textures which give rise to the emergence of magnetic skyrmion, a localized and topologically stable spin configuration. The skyrmion was named after the particle physicist Tony Skyrme who constructed a topological configuration of a four dimensional vector field in space and time [1]. Although the existence of the original skyrmion-like soliton has still been debated in high energy physics, its counterpart in the spin-space has drawn a considerable attention to the contemporary magnetism research community. Skyrmions are interested from the point of view of fundamental physics as well as its technological applications. The diameter of the skyrmions can be scaled down to few nm and behave like a particle that can be nucleated, propagated and annihilated. These properties make them suitable candidate for information storage and logic technologies. Comparably, the dimension of skyrmion is much smaller than that of conventional domain wall and the current induced motion of requires a current density almost 10^5 times smaller compared to the domain wall motion. Thus smaller dimension and requirement of smaller amount of current for motion project skyrmion to be the future carrier for ultra high density data storage with faster and energy efficient data transfer.

The broken space-inversion symmetry in non-centrosymmetric magnetic compounds gives rise to a non-collinear exchange interaction between the neighboring spins, known as the Dzyaloshinskii-Moriya interaction (DMI) that can be expressed as:

$$E_{DMI} = -\sum_{i,j} \overrightarrow{D_{ij}}\cdot(\overrightarrow{S_i} \times \overrightarrow{S_j}) \tag{1}$$

and for interface DMI,

$$\overrightarrow{D_{ij}} = D_{ij}\cdot(\hat{z} \times \overrightarrow{u_{ij}}) \tag{2}$$

$\overrightarrow{D_{ij}}$ is the DMI vector, governed by the crystal symmetry whereas $\overrightarrow{S_i}$ and $\overrightarrow{S_j}$ are the neighboring spin moments. $\hat{z}$ and $\overrightarrow{u_{ij}}$ are the unit vectors, respectively perpendicular to the interface in the direction of the magnetic layer and pointing from site *i* to site *j*. DMI is a site-specific exchange interaction where the energy flips its sign under the inversion operation of the mid-point of two sites S_i and S_j and hence proves the breaking of space inversion symmetry. The energy due to the DMI is minimized when the neighboring spins are situating in the plane normal to $\overrightarrow{D_{ij}}$ and perpendicular to each other. This is in contrast with the symmetric Heisenberg exchange which governs the magnetism of generic ferromagnets and favors parallel spin alignment. Thus, the presence of DMI causes the neighboring spins to extend over a finite angle with respect to each-other which is responsible for the non-collinear stable and localized spin textures. For $D_{ij} > 0$, DMI favors anti-

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clockwise rotation of spins from S_i to S_j and vice versa in order to minimize the E_{DMI}.

Typically, there are two types of skyrmions, Néel and Bloch types, which differ by the symmetry of the interaction between the spins, resulting in different direction of rotations. In the context of non-collinear spin textures, the topology maps the spatial distribution of the magnetic moment. Each topology class is characterized by an integer Q (mathematically known as winding number), called the skyrmion number which essentially describes the number of times spins wind around a unit sphere. For skyrmion, Q is quantized and can be expressed as:

$$Q = (1/4\pi) \iint \overrightarrow{M}\cdot(\partial_x\overrightarrow{M} \times \partial_y\overrightarrow{M})dxdy = \pm 1 \tag{3}$$

where $\overrightarrow{M}$ is the magnetization vector. The value of Q varies depending upon the spin chirality and hence a skyrmion can be differentiated from a magnetic bubble domains, stabilized by strong dipolar interaction. Thiaville et al. reported numerical and analytical micromagnetic results on the existence of domain wall (DW) structure, stabilized by DMI in ultrathin films with perpendicular magnetic anisotropy (PMA) [2]. The tilting of DW and the modification in DW dynamics have been shown using large DMI in magnetic nanotracks with PMA [3]. The torque exerted by DMI on DW can also lead to an exchange of linear momentum between spin wave and the DW which plays a leading role on DW motion [4]. The idea of hybrid device made of skyrmion and DW was proposed by Zhou et al. where they micromagnetically predicted the writing and reading of information by DW and the other functional control by skyrmion [5]. A recent report shows a continuous phase transition between topologically non-trivial magnetization states namely, vortex, Bloch and Neel-type skyrmions by gradual change in the strength of PMA and DMI in magnetic nanodot [6]. Interestingly, the stabilization of skyrmion ground states has also been theoretically predicted by Dai and colleagues for Co/Ru/Co nanodisk without DMI [7].

The swirling spin textures were first discovered by identifying hexagonal symmetry in bulk MnSi single crystal [8]. New proposition for skyrmion phase control by mechanical stress has also been reported by Nii et al., where the advantage lies on the little consumption of energy compared to applying electric or magnetic biases [9]. Characterizing the existence of skyrmion requires spin sensitive real-space experimental techniques. There are existence of direct imaging of skyrmion along with the field and temperature dependent transition from single skyrmion to multiple skyrmion lattice using Lorentz microscopy technique [10,11]. Apart from that use of X-ray based imaging [12–15] and scattering techniques [16], spin polarized scanning tunneling microscopy [17], neutron scattering [18] and magnetic force microscopy [19] are equally popular to characterize skyrmions. The other important aspect is the skyrmion dynamics. The current-driven skyrmion Hall effect [20] due to spin-orbit torque, nucleation and propagation of skyrmion in magnetic racetrack [19] in response to current and resonant modes arising from the local topological features [14] have also been investigated experimentally.

Micromagnetic and analytical simulation tools play a key role in predicting the stability and dynamics of skyrmion. The pioneering work by Sampaio et al. essentially brought the fundamental concept of isolated magnetic skyrmions and its dynamics in nanostructures [21]. The current and microwave magnetic field induced dynamics of skyrmions in different constricted nanostructures such as racetrack [22,23], nanodisks [24–26], nanostrips [27], nanodots [28,29] can be found in existing literature. From the point of view of pinning of skyrmions into the defect sites, probably simulation is the best tool to study the role of defect in nucleation and dynamics of skyrmion. Iwasaki et al. considered a constricted geometry where the current induced skyrmion motion is controlled by the geometrical boundaries [30]. Consideration of defect and its effect on the modification of the ground state magnetization and the skyrmion trajectories was explained by Zhang et al., using model of spin transfer nano-oscillator [31]. A recent study presents a detailed theoretical understanding about the preferred pinning loci of the skyrmions as a function of its nominal size and type of the defect to reveal the manipulation of skyrmion core in the vicinity of the defect [32]. It is also interesting to observe theoretical observation of skyrmion in films with spatial variation of thickness [33] and with varying anisotropy as well as tilted magnetic field [34]. The review on the recent experimental and theoretical development of skyrmion research can be found else-where [35–38].

In this paper, we are going to present a micromagnetic study on the scalability of magnetic skyrmion in circular nanodisks of variable diameter. We have focused on the material properties such as, disk dimension, anisotropy and the strength of DMI. Emphasis has been given towards understanding the role of defect in the formation and tunability of skyrmion in ultrathin nanostructure. Finally, we have shown the role of external magnetic field, DMI and the disk dimension in the transformation from ferromagnetic multi-domain state to an isolated skyrmion and its further conversion to symmetric triangular lattices.

2. Material and methods

In this work we have considered circular nanodisk of ultrathin (0.6 nm) Co film with strong PMA on a Pt substrate as mentioned in [21]. The interfacial DMI is induced by the substrate. In a continuous magnetization model, the energy due to DMI can be expressed as:

$$E = D\cdot(M_z\partial_x M_x - M_x\partial_x M_z + M_z\partial_y M_y - M_y\partial_y M_z) \tag{4}$$

here M_x, M_y and M_z are the x, y and z components of magnetization respectively. D is the DMI energy per unit area, related to the modulus of $\overrightarrow{D_{i,j}}$ divided by the lattice constant times thickness [21]. Now, the total magnetic energy per unit volume of the system can be expressed as:

$$E_{total} = -\sum_{i,j} J_{ij}(\overrightarrow{S_i}\cdot\overrightarrow{S_j}) - \sum_{i,j} \overrightarrow{D_{ij}}\cdot(\overrightarrow{S_i}\times\overrightarrow{S_j}) - \sum_i K_{disk}(\overrightarrow{S_i}\cdot\hat{z})^2 - \mu_0\sum_i \overrightarrow{\mu_i}\cdot\overrightarrow{H} \tag{5}$$

where the first term expresses the contribution due to Heisenberg exchange interaction with J_{ij} as the exchange integral. The second term represents the energy due to DMI, as explained before. The third term denotes the anisotropy energy where K_{disk} is the effective anisotropy (PMA) constant of the disk with $\hat{z}$ normal to the film surface. The Zeeman energy is expressed in the last term where the external magnetic field (H) direction has been considered along $\hat{z}$ with $\overrightarrow{\mu_i}$ as the magnetic moment at the i-th site. The ground state energetics of the system has been obtained by solving Landau-Lifshitz-Gilbert equation using micromagnetic simulations with OOMMF code [39] including DMI [40]. The time driver was used with a stopping condition of $dM/dt = 0.01$ where M denotes the magnitude of the total magnetization of the system. The input parameters used for the simulations include, $K_{disk} = 0.51 \times 10^6\, J/m^3$, exchange stiffness constant $A = 1.6 \times 10^{-11}\, J/m$, saturation magnetization $M_s = 1.1 \times 10^6\, A/m$. The Gilbert damping constant has been chosen to be 0.5, which is very close to the value for Co/Pt system [21]. As we want to study the ground state properties of the considered system, so the role of α is restricted only to control the simulation time. The value of D has been varied to check the formation and tunability of skyrmion in the nanostructures. Micromagnetic simulations provide the flexibility of choosing the input parameters, which can be controlled by different experimental techniques in reality. The dimension of the individual cell is taken to be $1\ nm \times 1\ nm \times 0.6\ nm$, which is much lower compared to the dimension of the skyrmion, investigated here. The effect of variation of D has been studied in the formation of skyrmion and magnetization reversal of the system as a function of disk diameter (d_{disk}), K_{disk}. D can be tuned by changing the thickness whereas anisotropy of a magnetic material can be modified by different external perturbations such as, ion-beam