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Single skyrmion induced by external magnetic field in CoFeB ferromagnetic alloy nanodisks

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ABSTRACT

In this paper, we study the magnetization behavior in $Co_{40}Fe_{40}B_{20}$ nanodisks with Dzyaloshinskii-Moriya interaction, which is induced by a Pt layer. The known giant perpendicular magnetic anisotropy (PMA) in thin films elaborated from this kind of materials improves the topological structures nucleation. Our work consists in investigating the skyrmions apparition and stability in amorphous CoFeB nanodisks. The detected skyrmions are not spontaneously nucleated. Their nucleation is induced by an applied external field. We also study reversal magnetization of CoFeB and we elucidate skyrmions nucleation and annihilation.

1. Introduction

Nowadays, the spintronic is one of the most attractive research fields. It held the interest of a large number of researchers and therefore released a noticeable success in electronic devices construction and data storage [1]. Many efforts were deployed to elaborate non-volatile memories which are less expensive in energy and with a huge capacity of data storing [2].

With thin films technology, the first MRAM (Magnetoresistive Random Access Memory) was constructed successfully [3,4]. This class of memories requires a tunnel junction [5,6], such as in two ferromagnetic layers separated by a non-magnetic isolating layer; the electron transfer is generated by the quantum tunneling process. This discovery has motivated researchers to continue their trays in improving data storing devices.

The emergence of topological structures, such as magnetic skyrmions and vortices gave a great push in memories construction [7,8]. Skyrmions are observed in specific materials where the inversion symmetry is broken. In this type of systems, a ferromagnetic layer is deposited on a heavy metal layer or the inverse, for example Pt/$Co_{70.5}Fe_{4.5}Si_{15}B_{10}$/Ta [9] or Ta/Co2FeAl [10], or B20 compounds like MnSi [11,13] and FeGe [12] where skyrmions were observed for the first time. The main responsible for skyrmions apparition is Dzyaloshinskii-Moriya interaction (DMI) [14]. It's viewed as an asymmetric exchange interaction where the magnetization takes a rotational continuous form. The DMI is due to the chirality and the strong spin–orbit coupling (SOC) [15] of the system. Beside the existence of the bulk Dzyaloshinskii-Moriya interaction, there is the interfacial Dzyaloshinskii-Moriya interaction (iDMI), which is due to the symmetry breaking at the interface between the heavy metal layer and the ferromagnetic layer. In addition to DMI, the perpendicular magnetic anisotropy has an important contribution in skyrmions apparition.

Magnetic anisotropy plays a key role on magnetization changes and depends mainly on the size and the dimension of the system. For ferromagnetic films, the anisotropy constant can be expressed by K_{tot} where $K_{tot} = K_1 + \frac{2K_s}{t} - \frac{1}{2}\mu_0 M_s^2$ in ultra-thin films and $K_{tot} = K_1 - \frac{1}{2}\mu_0 M_s^2$ for thicker films.

If $K_{tot} < 0$, in-plane magnetic anisotropy takes place, while for $K_{tot} > 0$, it becomes perpendicular magnetic anisotropy (PMA) [16]. Materials where both PMA and DMI are contributing provide a good environment for skyrmion emergence.

In this work, we aim to investigate topological structures nucleation and annihilation, and their stabilization in amorphous ferromagnetic nanodisks. The ferromagnetic film CoFeB is deposited on a Pt nanodisk. This kind of samples are well known by their strong PMA and high iDMI values ($0 < D < 0.45\,mJ/m^2$) depending on the platinum layer thickness [17] that allows favorable conditions for skyrmions creation.

In the next section, we present the phenomenological continuum model displayed to characterize the chiral states in the system putting down the micromagnetic energy and describing the structure and geometry of the chosen multilayer, then we explain our simulation conditions, summarize and discuss the main results. Finally, we give our conclusions and perspectives.

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2. Model description

Among several numerical methods to investigate magnetization in ferromagnetic materials, we use micromagnetic calculation [18] to study numerically the magnetization behavior in CoFeB nanodisks.

The system energy is given by:

$$E_M = \int A_{exch}(\nabla.\ \boldsymbol{m}(r))^2 d^3r + \int D\boldsymbol{m}.\ (\nabla \times \boldsymbol{m})d^3r + \int d^3r K_{eff}(1-\cos^2(\theta)) + \left(-\frac{\mu_0 M_s}{2}\right)\int \boldsymbol{m}(r).\ \boldsymbol{H_d} d^3r + (-\mu_0 M_s)\int \boldsymbol{m}(r).\ \boldsymbol{H_{ext}} d^3r \quad (1)$$

where the first term is the symmetric exchange, the second is the Dzyaloshinskii-Moriya contribution, the third is the magneto-crystalline anisotropy, the fourth is the shape anisotropy part and the last is the external field energy.

The effective anisotropy constant writes:

$$K_{eff} = K_1 + \frac{2K_S}{t} \quad (2)$$

where K_1 is the bulk magneto-crystalline anisotropy constant, K_s is the surface anisotropy and t is the ferromagnetic layer thickness, M_S is the saturation magnetization and $\boldsymbol{\mu}_0$ is the vacuum permeability.

The used geometry is marked by the strength of demagnetization field "shape anisotropy" tending to keep magnetization in the plane of the sample which is expressed by:

$$H_d = -[N]M \quad (3)$$

where $[N]$ is the demagnetizing tensor reduced for the present nanodisk to:

$$[N] = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad (4)$$

The magnetization configurations of the CoFeB nanodisks are obtained by the Landau-Lifshitz-Gilbert (LLG) dynamic equation:

$$\frac{dM}{dt} = -\gamma M \times H_{eff} + \frac{\alpha}{M_s} M \times \frac{dM}{dt} \quad (5)$$

where γ is the gyromagnetic ratio, α is the dimensionless damping parameter and $\boldsymbol{H_{eff}}$ is the effective field, which is given by:

$$H_{eff} = \frac{2A_{exch}}{\mu_0 M_s^2}\nabla^2 M - H_d + \frac{2D}{\mu_0 M_s^2} M.\ (\nabla \times M) + \frac{2K_{eff}}{\mu_0 M_s^2}(M.\ e_z)e_z - H_{ext} \quad (6)$$

The effective field is the functional derivative of the energy density.

The amorphous ferromagnetic alloy nanodisk CoFeB studied here is inserted in the stack presented in Fig. 1 (where its thickness was fixed in 2 nm and platinium thickness in 1.3 nm) and has the following concentrations: 40% of Co, 40% of Fe and 20% of B. This alloy is known by its good magnetic and electric properties [19]. Indeed, in term of magnetic properties, exchange stiffness constant known by $A_{ex} = \frac{JS^2}{a}$ (J is the exchange integral, S is the spin value and a is the lattice constant) is around 1×10^{-11} J/m [20]. The calculated value of CoFeB saturation Magnetization was $M_S = 0.4 \times M_S$ (Co) + $0.4 \times M_S$ (Fe) = 1.24×10^6 A/m, which is in the same range of experimental values such as 1.19×10^6 A/m [9] and 1.23×10^6 A/m [17].

The exchange length measuring the width of the transition between magnetic domains and defined by $\lambda_{ex} = \sqrt{2A_{ex}/\mu_0 M_S^2}$ has the value of 3.24 nm for our alloy.

Here, to perform micromagnetic analysis, Mumax3 which is a GPU-accelerated micromagnetic simulation program developed by A. Vansteenkiste & al. [21] is used to run simulation. The software resolves equations using finite difference method that subdivides space into many small cuboids [22], the output data is automatically stored in the directory for specific treatments.

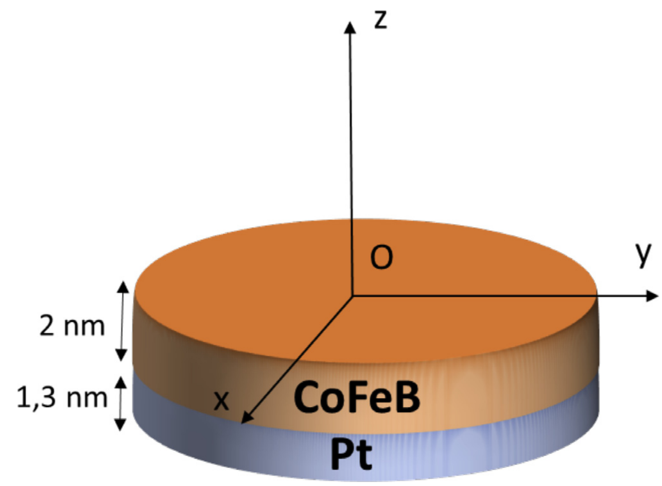

Fig. 1. Schematic representation of the simulated stack.

Micromagnetic simulation parameters are taken from a real experiment of BLS technique measurement of iDMI releasing by Tacchi & al [17]. Key inputs are: $M_S = 1.23 \times 10^6$ A/m, , *thedamping*, the damping coefficient is $\alpha = 0.012$ and interfacial Dzyaloshinskii-Moriya interaction is *.Thecellsizes*. The cell sizes were chosen as $2 \times 2 \times 2\,\text{nm}^3$ less than exchange length value of $\lambda_{ex} = 3.24$ nm [23]. Magnetocrystalline anisotropy parametrization will be shown later.

To begin discussion about skyrmions, let's consider the two magnetic phases of ferromagnetic materials: the paramagnetic phase and the ferromagnetic phase (aligned moments) separated by a critical temperature. Other singular phases (skyrmions) can appear in a ferromagnetic material. These types of rotating magnetizations are mainly induced by the anisotropic interaction of Dzyaloshinskii-Moriya or a competitive behavior between two or more interactions. Topological structures present a circular magnetic moments form, the magnetization in this case is analytically parametrized by:

$$m = \sin\theta\cos\varphi\ e_\rho + \sin\theta\ \sin\varphi\ e_\varphi + \cos\theta\ e_z \quad (7)$$

where θ and φ are the angle between magnetization and the z axis and the in plane angle. The various values of these two angles describe the type of topological structure configuration [24]. To distinguish between topological textures, we need to know the value of topological charge [25] which is defined by:

$$Q = \frac{1}{4\pi}\int^m . \left(\frac{\partial \mathbf{m}}{\partial x} \times \frac{\partial \mathbf{m}}{\partial y}\right)dxdy \quad (8)$$

where $\mathbf{m}$ is the magnetization and x and y are the in plane coordinates. Skyrmions are obtained if $Q = \pm 1$ whereas vortices and merons are characterized by $Q = \pm\frac{1}{2}$ [30].

3. Results and discussions

In this section, we present the main results and discuss different magnetization states induced by magnetic excitation. We aim in this work to elucidate in addition to magnetization ground state the excited state, by applying an out-of-plane external magnetic field.

Magnetocrystalline anisotropy is an important factor on skyrmions formation. It is influenced by many factors such as amorphization degree [26], substrate type and deposition method. Therefore, we study several magnetizations ground states by giving different values to magnetocrystalline anisotropy.

In order to investigate all ground state possibilities, we performed calculations for different initial configurations (random, vortex, uniform). Fig. 2 shows the ground states relaxed for different anisotropy constant values and initial configurations. In Fig. 2-a, at low anisotropies, the system keeps a vortex state; as we know, vortex state is a