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Skyrmion core size dependence as a function of the perpendicular anisotropy and radius in magnetic nanodots

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ABSTRACT

A detailed analytical and numerical analysis of the skyrmion core size dependence as a function of the uniaxial perpendicular anisotropy and radius in magnetic nanodots has been carried out. Results from micromagnetic calculations show a non-monotonic behavior between the skyrmion core size and the uniaxial perpendicular anisotropy. The increment of the radius reduces the skyrmion core size at constant uniaxial perpendicular anisotropy. Thus, these results can be used for the control of the core sizes in magnetic artificial skyrmion crystals or spintronic devices that need to use a skyrmion configuration at room temperature.

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1. Introduction

In recent years, the study of the magnetic skyrmion configuration in structures such as disks, films, etc. has grown significantly due to the potential applications in magnetic storage devices of high density, spintronics, etc. [1–7]. A magnetic skyrmion configuration on a disk is a two-dimensional stereographic projection of a sphere with magnetization pointing outside in the form of a hedgehog [6]. There are two approaches from which we can obtain this magnetic configuration of a disk: the first one is to enter a Dzyaloshinskii–Moriya interaction due to the strong spin–orbit coupling between two materials [1,8] or the second is to include a uniaxial magnetic anisotropy perpendicular to the plane of the dot [9–11]. Therefore, there are two types of skyrmion configurations: the Néel-type and the Bloch-type skyrmions. In the Néel skyrmion configuration, the magnetic profile has a magnetic component different from zero in the radial direction. On the other hand, the Bloch skyrmion configuration does not have magnetic component in the radial direction. In addition the Bloch skyrmion can be stabilized by a uniaxial magnetic anisotropy perpendicular to the plane of the dot [9,11,12], but the Néel skyrmion configuration is necessary to include Dzyaloshinskii–Moriya interaction for the stabilization of this magnetic configuration [4,8].

The study of a skyrmion configuration in nanodisks with perpendicular anisotropy can be important since it could improve the artificial two-dimensional skyrmion crystal created by a combination of perpendicularly magnetized film, of the order of 400 kJ/m^3, and arrays of magnetic vortices that are geometrically confined within a nanodisk [13]. The magnetic uniaxial perpendicular anisotropy in the Co nanodot is added by varying the thickness of the Co layer in a Co/Pt stack [10]. Novais et al. observed that there are dots with perpendicular anisotropy of the order of 375 kJ/m^3 with core vortex radius and magnetization at the disk rim pointing down [9]. Guslienko also observed that it is possible to obtain a skyrmion configuration in a nanodisk with perpendicular anisotropy [11], by using the skyrmion ansatz of the solution of the nonlinear sigma model [14]. With that model, they observed that the skyrmion core size only decreases when the uniaxial perpendicular anisotropy of the dot increases.

In the present paper, we focus our attention on the skyrmion core size dependence as a function of the perpendicular anisotropy and radius in magnetic nanodots. Based on the micromagnetic calculation, we have carried out numerical calculations, which have identified a non-monotonic behavior between the core size radius and the perpendicular anisotropy. Also we observe that there is a dependence of the core size of the skyrmion configuration with the radius. This paper is organized as follows: in Section 2 we describe the approach we adopted in the present work, in Section 3 we present results and discussion, and in Section 4 conclusions are presented.

2. Theory

Our starting point is an ideal magnetic skyrmion configuration in a magnetic dot with radius R and height H. The magnetic dot has a magnetic uniaxial anisotropy perpendicular to the plane of

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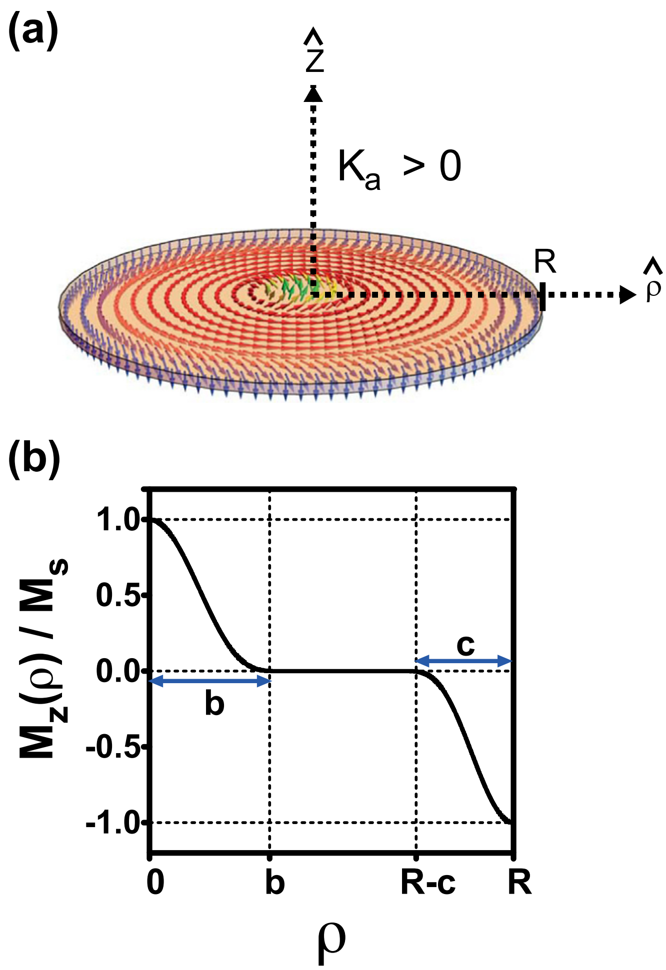

Fig. 1. Schematic representation of a skyrmion configuration with an uniaxial perpendicular anisotropy $\vec{K}_a$ in the nanodot (a). The core, *b*, and the end-width, *c*, sizes of a skyrmion configuration (b).

the dot, $K_a > 0$, see Fig. 1(a). With the purpose to study this magnetic configuration, we consider a simplified description of the magnetic system in which the discrete distribution of the magnetic moments is replaced by a continuous one, defined by a function $\vec{M}(\vec{r})$ such that $\vec{M}(\vec{r})\delta v$ gives the total magnetic moment within the element of volume δv centered at $\vec{r}$. For the skyrmion configuration, the magnetization can be written by $\vec{M}(\vec{r}) = M_s m_\phi(\rho)\hat{\phi} + M_s m_z(\rho)\hat{z}$, where M_s is the saturation magnetization of the dot and the magnetic profile, $m_z(\rho)$, is given by the ansatz obtained from Novais et al. [9]:

$$m_z(\rho) = \begin{cases} \left(1 - \frac{\rho^2}{b^2}\right)^4 & 0 < \rho \le b \\ 0 & b < \rho \le R - c \\ -\left(1 - \frac{(R-\rho)^2}{c^2}\right)^4 & R - c < \rho \le R \end{cases} \tag{1}$$

where *b* is the radius of the magnetic core of the skyrmion and *c* is the end-width of the magnetic skyrmion configuration, see Fig. 1 (b). The total energy for the magnetic skyrmion configuration, E_S, is given by the sum of the exchange, magnetostatic and anisotropy contributions, which now are taken from the continuum theory of ferromagnetism [15]. The exchange contribution for the skyrmion configuration, $E_{S,EX}$, is given by:

$$E_{S,EX} = E_{V,EX}(b, R-c, H) + 2\pi HA \int_{R-c}^{R} f(\rho)\rho d\rho \tag{2}$$

where $E_{V,EX}(b, R-c, H)$ is the magnetic exchange energy of a vortex configuration for a magnetic dot with radius $R-c$, height H, and magnetic vortex core radius equal b. $E_{V,EX}(b, R-c, H)$ is equal to [16]:

$$E_{V,EX}\left(b, R-c, H\right) = 2\pi HA\left[\frac{1}{2}\mathcal{H}(8) - 4\mathcal{H}\left(\frac{-1}{8}\right) + \ln\left(\frac{R-c}{b}\right)\right] \tag{3}$$

where A is the stiffness constant and $\mathcal{H}(z)$ is the harmonic number function of the complex variable z given by Euler's integral formula:

$$\mathcal{H}(n) = \int_0^1 \frac{1 - x^n}{1 - x}dx \tag{4}$$

The function $f(\rho)$ in Eq. (2) is:

$$f(\rho) = \frac{64(\zeta(\rho)^2 - 1)^6\zeta(\rho)^2}{c^2(1 - (\zeta(\rho)^2 - 1)^8)} + \frac{1 - (\zeta(\rho)^2 - 1)^8}{\rho^2} \tag{5}$$

where $\zeta(\rho) = (R - \rho)/c$. The magnetostatic interaction for the skyrmion configuration is $E_{S,M} = (\mu_0/2)\int \vec{M}(\vec{r})\cdot\vec{\nabla}U(\vec{r})\delta v$, where $U(\vec{r})$ is the magnetostatic potential [15]. If we use Eq. (1) for $\vec{M}$, we observe that the magnetostatic potential does not have volumetric charge ($\vec{\nabla}\cdot\vec{M}(\vec{r}) = 0$), then $E_{S,M}$ is given by:

$$E_{S,M} = \pi\mu_0 M_s^2 \int_0^\infty dq\left[F_1(q, b) + F_2(q, c, R)\right]^2(1 - e^{-Hq}) \tag{6}$$

where $F_1(q, b)$ and $F_2(q, c, R)$ are:

$$F_1(q, b) = \int_0^b \rho J_0(q\rho)m_z(\rho)d\rho = \frac{384 J_5(bq)}{b^3 q^5} \tag{7}$$

$$F_2(q, c, R) = \int_{R-c}^{R} \rho J_0(q\rho)m_z(\rho)d\rho \tag{8}$$

From Eq. (6), it is possible to observe that if $F_2(q, c, R) = 0$ (for instance $c \to 0$), then $\lim_{F_2 \to 0} E_{S,M} = E_{V,M}$, where $E_{V,M}$ is the magnetostatic energy for a magnetic vortex configuration with radius R, height H, and magnetic vortex core radius equal b.

For the anisotropy energy we have $E_A = -K_a \int m_z^2(\rho)dv$. In our case, the anisotropy contribution for the skyrmion configuration, $E_{S,A}$, is equal to:

$$E_{S,A} = -2\pi K_a H\left(\frac{b^2}{18} - \frac{c^2}{18} + \frac{32\,768}{109\,395}cR\right), \tag{9}$$

where the first term in Eq. (9) corresponds to the anisotropy term of a magnetic vortex configuration, $E_{V,A}(b, R, H)$, with radius R, height H, and magnetic vortex core radius equal b ($E_{V,A}(b, R, H) = -\pi K_a H b^2/9$).

Finally the total energy for the magnetic skyrmion configuration is equal to:

$$E_S = E_{S,EX} + E_{S,M} + E_{S,A} \tag{10}$$

If we want to have some physical interpretation of the skyrmion state, we need to compare the skyrmion energy with the energies of the other three magnetic states that could have a magnetic dot. These three configurations are the vortex, the in-plane and the out-plane magnetic configurations. Before continuing, we will call E_V the total energy of the magnetic vortex configuration, E_{IN} the total energy of the magnetic in-plane configuration, and E_{OUT} the total energy of the magnetic out-plane configuration. For the vortex configuration, the total energy is given by $E_V = \lim_{c\to 0} E_S$. The energy of the magnetic in-plane configuration can be obtained if we consider the magnetization $\vec{M}(\vec{r}) = M_s\hat{x}$, and the magnetic out plane configuration if we

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