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Magnetization reversal via a Stoner–Wohlfarth model with bi-dimensional angular distribution of easy axis

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ABSTRACT

A numerical extension of the simple Stoner–Wohlfarth model to the case of bi-dimensional angular distributions of easy axis is provided. The results are particularized in case of step-like, Gaussian-like and user defined distributions. In spite of its simplicity, the model can be applied to magnetically textured thin films and multilayers with in-plane magnetic anisotropy, independently on the texture source. Exemplifications are provided for a simple ferromagnetic textured FeCo film as well as for a FeMn/FeCo/Cu/FeCo spin valve structure.

1. Introduction

There are more than 60 years since E.C Stoner and E.P Wohlfarth published their model about the magnetization reversal of single-domain ferromagnets [1,2]. Despite its simplicity, the Stoner–Wohlfarth (S–W) model is still of actual interest while it provides results in good concordance with experimental observations for many system of technological impact. That is due to the fact that the presently developing nanotechnology deals frequently with assemblies of magnetic nanoentities respecting the condition of magnetic monodomains [3] (to be mentioned here biomedical and catalytic applications of magnetic nanoparticles [4,5] or applications related to magnetic recording or sensoristics [6–9] involving patterned thin films, multilayers and nanowires). The model has the great advantage that, due to its simplicity, analytical expressions can be derived in particular cases transparent to intuitive physical explanations. Moreover, the case of magnetic assemblies can be analyzed via usual statistical means of non-interacting entities with further extension to the perturbation effect of possible interactions. The most evident example is the case of magnetic monodomain nanoparticle assemblies which behavior can be easily explained starting from the S–W model of a nanoparticle [3,10]. Very interesting is that the S–W model with related corrections can also provide in a first approximation the description of more complex effects connected to the interfacial interactions leading to exchange-spring and exchange bias phenomena, which are of large technological impact in our days [3,9,11–14]. This is the reason for a permanent developing of the model in different versions, taking into account different additional energy contributions or suitable averaging processes. Excellent reviews of the model in respect to different applications and present achievements were provided, among others, by Radu and Zabel [15] and Tannous and Giewaltowski [16]. At this point it is to mention that only numerical solutions are suitable for a general treatment of the S–W problem, especially in case of magnetic assemblies (even in interaction), but however the involved numerical analysis is more simple, efficient and transparent as compared to the case of complex micromagnetic simulations, which on the other hand may take into account additional microstructural aspects and specific interactions among components.

As the main hypothesis of the model is the fact that all the local spins (magnetic moments) of the magnetic entity are oriented in the same preferred direction and are rotating coherently under an applied magnetic field. Hence, just one rotating representative macrospin is associated to the magnetic entity, which means that the exchange energy is infinite with respect to other magnetic energy terms and can be considered as a constant in the energy expression. As it will be shown in the next section, the magnetization reversal of the macrospin is depending on the direction of the applied field with respect to a preferred direction, which is called easy axis (EA) of magnetization. A quite realistic case of assembly of magnetic entities is the one involving an angular easy

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axis distribution (EAD), which can cover the limits from a unique direction (Dirac type angular distribution) to randomly distributed directions in the whole space. An angular distribution centered along a given direction reflects the case of a higher/lower magnetic texture depending on the distribution width. There are different possibilities for obtaining experimentally appropriate information about the EAD by using either Mössbauer spectroscopy [17,18] and specific magnetometry techniques, as for example, via Orientation Ratio (OR) measurements or Flanders and Shtrikman's principle [19,20]. However, all these methods present quit strong limitations [20] and except the last method, make apriori assumptions about the type of the EAD function. While the magnetic texture effects are clearly reflected in the shape of the hysteresis loop of the system, one may assume that the reciprocal approach of using suitably collected hysteresis loops in order to get an as much as complete information about the distribution of easy axis might be also very effectively. For example, Kronmuller et al. have already shown and carefully analyzed different effects induced by magnetic texture and Gaussian EADs related to grain orientation on nucleation and coercive fields, in case of oriented sintered Nd–Fe–B magnets [21–23].

In this respect, the present work deals with a general numerical solution of the S–W model for bi-dimensional angular distribution of EAD. The model can be extended to different types of EADs and is consistent with the case of bi-dimensional magnetic systems, as for example thin films and multilayers presenting in plane magnetic anisotropy. In order to respect the model hypothesis, the real magnetic structures should not allow the formation of magnetic domains, fulfilling therefore conditions related to either specific thicknesses (assuring also the in plane anisotropy) or a specific island-like morphology. It is worth to mention that such a tri-dimensional type of growth (Volmer–Weber growth mode) leading to the formation of uniform nanogranular films with small oriented island-like morphologies with lateral size of a few tenths of nanometers and behaving as magnetic single domains were usually reported in case of thin films and multilayers obtained by either sputtering or thermo-ionic arc methods [24–26]. Moreover, there is a growing interest in deposition of nanoparticle-assembled thin films by femtosecond pulsed laser deposition in vacuum [27,28] which in certain conditions can be alternative physical supports for the described model.

2. Model and simulations

2.1. Algorithm

The starting point of the algorithm is based on the simple S–W model of a magnetic monodomain bidimensional entity, which also assumes: (i) an in plane applied field, H, (ii) an enhanced in plane shape anisotropy in order to allow the in plane reversal process and (iii) an in plane uniaxial anisotropy (anisotropy constant K_F). To note that such a simplified model infers a specific physical system consisting of well-shaped bidimensional magnetic grains (e.g. circular, with in plane uniaxial magneto-crystalline anisotropy or ellipsoidal, with shape dominating uniaxial anisotropy) and without surface deterioration (to avoid spatial variations of the anisotropy constant and other microstructural effects). In addition, such magnetic grains should not interact either by dipolar or exchange interactions. Although such ideal conditions are never realized, real systems can approach them enough in order to allow a homogeneous rotation model for non-interacting entities, but with appropriate corrections for the involved parameters, as discussed later.

Only two contributions have to be considered to the magnetic energy of the system (infinite and constant exchange energy is assumed) with spontaneous magnetization M_F:

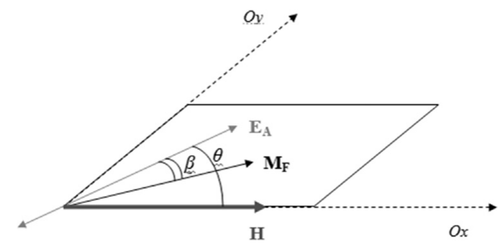

Fig. 1. Typical configuration for a S–W bidimensional model. If the magnetic field is applied along the Ox axis maxing angle θ with the EA, the macrospin (or the spontaneous magnetization) will rotate progressively along the field direction, as counted by either angle β or $\theta-\beta$.

$$E = -\mu_0 H M_F \cos(\theta - \beta) + K_F \sin^2\beta \tag{1}$$

In the above expression, the first term is the Zeeman energy and the second is the uniaxial anisotropy energy whereas θ and β are the angles between EA and H and between EA and M_F, respectively (see Fig. 1). The typical solution of the S–W problem is to find the angle β which places the system in a stationary state under a given applied field (e.g. magnitude and orientation versus the EA), that is to find that specific value of β leading to an energy minimum for a given H and θ. This can be done either analytically or numerically. The first way is not suitable for general use because the analytical solutions can be found only for a few particular cases. For example, angle β could be simply obtained as satisfying the typical two conditions $\partial E/\partial\beta = 0$ and $\partial^2 E/\partial\beta^2 > 0$ (starting from saturation, only the first equation has to be fulfilled). Evidently, β will be the solution of a trigonometric equation of type $f(H, \theta, \beta)=0$, which in turn can be solved also numerically (and hence the whole magnetization reversal process will be numerically described). If just the coercive field H_C is desired, it can be searched as the field where the magnetization component along the field, $M_F \cos(\theta-\beta)$, drops to zero, involving the additional angular condition $\theta-\beta=\pi/2$. By introducing this condition in the above equation, $f(H_C, \theta, \beta)=0$, the coercive field can be expressed as $H_C = (K_F/\mu_0 M_F)\sin 2\theta$, which however should be considered with high caution. The above expression for the coercive field is valid only for $\pi/2>\theta>\pi/4$, involving a progressive rotation of magnetization, whereas for $\pi/4>\theta>0$ one deals with a sudden jump of magnetization from the EA direction to the field direction (under a negative applied field), with the coercive field coinciding to the nucleation (switching) field [29].

Contrary, a full numerical approach of Eq. (1) provides, down to a reasonable sampling, a general solution with respect to all possible parameters (magnetic field and angles θ) and in addition is susceptible to be easily extended to the case of many EAs (either discretes or with different angular distributions).

In order to provide the numerical general solution, is more conveniently to write (1) as:

$$E_R = -2H_R\cos(\theta - \beta) + \sin^2\beta \tag{2}$$

where $H_R=H/H_a$ with $H_a=2K_F/(M_F\mu_0)$ known as the anisotropy field and $E_R=E/K_F$. In this way one can work with relative (adimensional) parameters expressing the energy in units of K_F and the applied field in units of anisotropy field. The variation of the energy versus angle β for a simple S–W system with unique EA and under different applied relative fields, H_R, oriented along the EA ($\theta=0°$) is shown in Fig. 2 (left side). Similar results but obtained for an applied field perpendicular to the EA ($\theta=90°$) are shown in the same Fig. 2 (right side). It may be observed in the first case that starting from very high applied fields (H_R»1), the system is in a minimum energy state for $\beta=0°$ (this is the starting point after saturation in positive field) and in the second case for $\beta=90°$. By decreasing the applied field, it may be seen in the first