ORIGINAL PAPER

BASIC CONCEPTS ON MAGNETIZATION REVERSAL IN NANOSTRUCTURES: MAGNETIC FIELD AND TEMPERATURE INFLUENCE*

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Abstract. *In this lecture, we will address the problem of magnetization reversal in thin films and nanostructures. This topic is at the basis of most studies in the fields of magnetism and spintronics and is of particular relevance for applications in magnetic memories. We will review the different models that explain and describe the magnetic field induced magnetization reversal, from the simplest coherent rotation to domain wall nucleation and propagation induced reversal. In a second part, a special focus will be given to the influence of temperature, which induces slow time scale dynamics in the reversal (superparamagnetism in nanoparticles, creep motion of domain walls).*

Keywords: *magnetic nanostructures, magnetization switching, slow dynamics.*

1. INTRODUCTION

In most studies in magnetism, field induced magnetization reversal is one of the first question to address. The variation of the magnetization versus field (M-H curve), together with its eventual hysteretic properties is generally the first approach to infer the sample magnetic characteristics. However, this problem is more complicated than it looks. Since the pioneering work of Stoner and Wohlfarth [1] who first related the hysteresis loop with magnetic anisotropy in a coherent reversal model, several attempts have been made to quantitatively link the material parameters with the magnetization switching properties. Micromagnetism theory plays a great role in order to overcome the simple uniform magnetization rotation, particularly introducing the notion of magnetic domain and domain wall propagation induced magnetization reversal. Defects in samples, even with a very low density and strength, can become crucial in understanding the magnetization switching properties and generally need to be considered. Furthermore, most of the experiments and application being performed at room temperature, temperature influence on the magnetization is to be considered. This has given rise to the description of superparamagnetism in nanoparticles by Néel and Brown [2, 3], latter on the description of domain nucleation and domain wall motion in thin films.

In this lecture, we will address the problem of magnetization reversal in thin films and nanostructures, where efficient models can now link the magnetic parameters to the switching

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properties. We will first address the static problem of field induced switching, starting from the simple uniform rotation model, up to the more elaborated models. In a second part, we will focus on the effect of temperature, which induces a slow time scale dynamics and particularly address the problem of superparamagnetism and creep domain wall motion.

2. FIELD INDUCED SWITCHING

The simplest model to explain magnetization switching is the coherent rotation model, first described by Stoner and Wohlfarth [1], where all the atomic spins are forced to be collinear. This gives rise to the simple equation for the energy density E of the system:

$$E = -\mu_0 M_S H \cos(\theta + \varphi) + K \sin^2 \varphi \quad (1)$$

where M_S is the material spontaneous magnetization, H the applied field and K is the anisotropy energy density, φ and θ the angles between the easy magnetization axis and respectively the magnetization and the applied field. This problem is rather rich and is generally used in a first approach. It introduces the anisotropy field $H_K = 2K/\mu_0 M_S$, which compares the strength of the anisotropy energy and the Zeeman energy. However, in real life, this model is rarely relevant and predicts coercive fields several order of magnitude higher than the experimental ones, an effect known as Brown's paradox [4]. Only in the last 15 years, it founded a good agreement for nanoparticles, with dimensions much smaller than any micromagnetic characteristic length scales and where the magnetization can be replaced by a single giant spin (macrospin model) [5, 6].

In order to go beyond uniform magnetization, and restore some degree of freedom, micromagnetism theory [7,8] has to be used. It introduces two characteristic length scales: the exchange length $\Lambda = (2A/\mu_0 M_S^2)^{1/2}$ (with A the exchange constant) and the Bloch domain wall width $\delta = (A/K)^{1/2}$ which compare the strength of the exchange energy with respectively the dipolar couplings and the magnetic anisotropy. In a material with dimensions larger than those lengths, non collinearities in the magnetization direction may be allowed, giving rise to more complex magnetization reversal schemes. In the limit of large nanoparticles or thin films, magnetization reversal generally occurs with nucleation of small domains, eventually followed by domain wall propagation [3, 9]. However, the complexity in increased and all the models become rather specific to the structure considered. Modeling the defects (soft magnetic inclusions, sample edges, domain wall pinning centers) for domain nucleation becomes crucial in order to obtain a quantitative understanding of the magnetization reversal.

3. TEMPERATURE EFFECT AND SLOW DYNAMICS

Considering thermal effects in magnetization reversal is generally essential. Indeed, for experiments which occur on long time scales (much larger than the precession period), the thermal energy may help overcoming small energy barriers and then reduce switching fields.

This is particularly obvious in nanoparticles. In the macrospin framework, the energy to switch the magnetization from up to down direction at zero field is KV (where V is the

particle volume). A small volume then means a small switching energy so that such samples are subject to magnetic relaxation [2, 3], the magnetization initial direction being lost on a time scale $t = \tau_0 \exp(KV/kT)$ (where $\tau_0 \sim 1$ ns). This effect is crucial for the future of magnetic recording at higher density and motivates an intense research for high magnetic anisotropy nanoparticles. We will give a complete description of this phenomena illustrated by state of the art experiments [5]. The presentation will not be restricted to macrospin model as it is usual. We will show how thermal magnons confined in the nanoparticles may fasten the magnetization relaxation [10] and will address the case of larger particle systems, where domain nucleation is allowed (the energy barrier is then $s\sigma$ with s the particle section and σ the domain wall energy) [11].

In a different domain, temperature is also essential to understand magnetization reversal in thin films. Both domain nucleation and domain wall propagation can be subjected to thermal activation. We will particularly discuss the case of domain wall motion at low field, which give rise to the so called creep phenomenon [12]. When the magnetic films slightly disordered, the domain wall movement is strongly influenced by low pinning centers and it move in a random energy landscape. The competition between domain wall elasticity and pinning give rise to a scaling law for the velocity v of the type $\ln(v) \sim H^{-1/4}$. The domain wall propagation is strongly chaotic and gives rise to domain wall roughness, avalanche phenomenon.

4. CONCLUSIONS

In this lecture, all essential bases to understand magnetization reversal at low frequencies are given. The macrospin, despites its simplicity and limits, provides an important and basic model, in particular when dealing with nanostructures with significant magnetic anisotropy, and forms a good base to approach switching phenomena. Many phenomenons can be first approached with this model and it is (maybe too?) widely used in applied systems (hard drive magnetic media, MRAM cells…). Its extension to high frequency to understand precessional magnetization switching is the natural following of this lecture, and will be given later in the lecture by U. Ebels.

However, one has to keep in mind the strong hypothesis and limits of the macrospin model: large dimension, thermal effects… may cause severe deviations with significant reduction of the switching field that must be taken into account, in most sophisticated and complicated models.

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