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Exchange coupling mechanism for magnetization reversal and thermal stability of Co nanoparticles embedded in a CoO matrix

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Abstract

A model providing a semi-quantitative account of the magnetic behavior of Co nanoparticles embedded in a CoO matrix is presented. The results confirm that exchange coupling at the interface between ferromagnetic (FM) and antiferromagnetic (AFM) nanostructures could provide an extra source of magnetic anisotropy, leading to thermal stability of the FM nanoparticles. It is shown that perpendicular coupling between the AFM and FM moments may result in large coercivities. The energy barrier, which works against reversal is due to the AFM susceptibility anisotropy. The experimentally observed exchange bias is tentatively ascribed to pre-existing intrinsic canting of the AFM moments at the interface.

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1. Introduction

Today's interest in nanoparticle magnetism is stimulated by a variety of potential applications, ranging from soft to hard magnetic materials and from ultra-high-density information storage to medicine [1]. Thermal stability of the nanoparticle magnetization is one of the key issues for most applications and is particularly critical for magnetic recording [2]. Several experimental studies [3–8] have recently indicated that exchange coupled ferromagnetic (FM) and antiferromagnetic (AFM) nanostructures experience an improved thermal stability, as it has been theoretically suggested [9,10].

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We have recently reported an increase of the superparamagnetic blocking temperature of almost two orders of magnitude for Co nanoparticles (3–4 nm in diameter) embedded in AFM CoO matrix [3]. The studied nanostructure exhibits all the features of exchange-bias systems [11]: loop shift, along the field axis, of $\mu_0 H_{EB} = 0.74\,T$ and enhanced coercivity of $\mu_0 H_C = 0.76\,T$ at 4.2 K. In Ref. [3], we briefly introduced a model which provided a semi-quantitative account for the observed behavior, thus confirming that exchange coupling at the interface between FM and AFM nanostructures could provide an extra source of magnetic anisotropy, leading to thermal stability of the FM nanoparticles.

Here we present a more detailed description of the proposed model. Comparison with experimental data suggests that the so-called perpendicular coupling mechanism, instead of the usual parallel coupling, is the dominant mechanism involved in this type of nanostructures. The proposed model can be used when discussing exchange-coupled FM/AFM nanostructures, similar to the one described here.

2. The model

2.1. Basic parameters

Based on Meiklejohon and Bean rigid spin model, the classical expression of the bias field, H_{EB}, can be written as [12]

$$H_{EB} = J_{ex} S_{FM} S_{AFM} / A M_{FM} t_{FM}, \quad (1)$$

where S_{FM} and S_{AFM} are the individual FM and AFM spins, M_{FM} is the ferromagnetic magnetization, t_{FM} is the ferromagnetic layer thickness, and A is the surface area over which the exchange term is calculated. In CoO, the total Co moment is $3.8\mu_B$ and the orbital-to-spin ratio, $L/S = 0.95$, from which the AFM spin moment $\mu_{AFM} = 2.55\mu_B$ is derived. The parameter $J_{ex} S_{FM} S_{AFM}$, may be re-expressed as $\mu_0 \mu_{AFM} H_{exch}$, where H_{exch} is an effective exchange field created by the ferromagnetic spin moments. For Co/CoO, from the accepted value of $J_{ex} S_{FM} S_{AFM} = 143\,K$ [13], $\mu_0 H_{exch} = 84\,T$ can be derived (see Appendix A).

2.2. Parallel versus perpendicular coupling

A priori, two possible coupling mechanisms may be envisaged between the FM and the AFM moments at the interface.

(i) Usually, the FM moments are assumed coupled parallel to the uncompensated AFM moments. In principle, uncompensated moments (in an otherwise compensated AFM structure) could arise only on a flat surface, which is perpendicular to the propagation vector of the AFM structure. In the present case, the FM Co nanoparticles can be viewed as embedded inside small cavities of an AFM CoO single crystal (see Fig. 1). There is no reason for the AFM side of the interface to show strong uncompensation, except the one due to statistics. Considering that the surface per Co atom in the CoO structure is 0.072 nm [14] and assuming that the CoO shell at the surface of the metal core has an average diameter of 4.2 nm it is deduced that there are approximately 750 Co atoms at the AFM interfaces and the imbalance should be of the order of $\sqrt{750} = 27$ atoms $\approx 4\%$ of the total number of atoms. The interface coupling energy between the AFM and FM magnetization may thus be expressed as $-0.04\mu_0 H_{exch} M'$ where M' is the AFM magnetization, which is derived from μ_{AFM} and amounts to 0.76 T. The interface coupling energy, normalized to the volume V_{AFM} ($V_{AFM} = 10^{-26}\,m^3$) of one CoO atomic layer at the interface with the Co core, amounts to approximately $-0.2 \times 10^7\,J/m^3$.

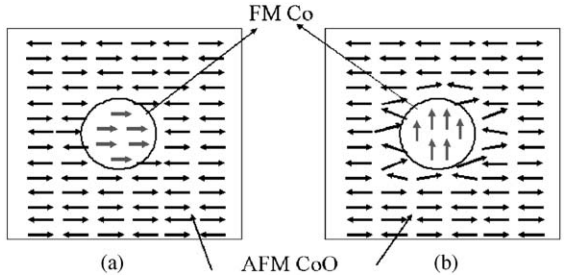

Fig. 1. Possible coupling schemes for magnetic moments of Co nanoparticles embedded in CoO: (a) uncompensated case—parallel coupling and, (b) compensated case—perpendicular coupling.