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Journal of Magnetism and Magnetic Materials 290–291 (2005) 153–156
Journal of magnetism and magnetic materials
www.elsevier.com/locate/jmmm

Magnetic properties of Fe/NiO/Fe(0 0 1) trilayers

P. Biagioni[a,*], A. Brambilla[a], M. Portalupi[a,b], N. Rougemaille[b], A.K. Schmid[b], A. Lanzara[b,c], P. Vavassori[d], M. Zani[a], M. Finazzi[a], L. Duò[a], F. Ciccacci[a]

[a]*INFM - Dipartimento di Fisica, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy*
[b]*Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*
[c]*Department of Physics, University of California at Berkeley, Berkeley, CA 94720, USA*
[d]*INFM - Dipartimento di Fisica, Università di Ferrara, Via Paradiso 12, 44100 Ferrara, Italy*

Available online 7 December 2004

Abstract

We have investigated the magnetic properties of epitaxially grown Fe/NiO/Fe(0 0 1) trilayers, for different thicknesses of the NiO spacer. Magneto Optical Kerr Effect has been exploited to study the in-plane magnetization reversal processes in the iron layers. We found that the NiO thickness t_{AFM} has a critical value t_C for the magnetic coupling between the Fe layers: for $t_{AFM} < t_C$ the magnetization directions align perpendicularly, with zero applied field, while the alignment is collinear for thicker spacers. A phenomenological model has been developed to reproduce and discuss the results. Complementary information has been obtained by means of spin polarized low energy electron microscopy.

PACS: 75.60.Jk; 75.70.Cn; 75.50.Ee

Keywords: Exchange coupling - interlayer; Magnetization - reversal; Thin films - trilayer

The coupling between ferromagnetic (FM) layers separated by a nonferromagnetic spacer has attracted many efforts in the last years [1–3]. The case of trilayers where two FM films are separated by a thin insulating antiferromagnetic (AFM) spacer can be of particular interest, because the indirect interaction due to conduction electrons is ruled out, and one would expect a large contribution coming from direct nearest-neighbour exchange across the spacer and the interfaces.

Here we report measurements of the magnetic properties of Fe(0 0 1)/NiO(0 0 1)/Fe(0 0 1) trilayers, epitaxially grown on MgO(0 0 1) substrates. Samples were prepared in an ultra high vacuum chamber (5×10^{-11} Torr base pressure) by Molecular Beam Epitaxy on an MgO(0 0 1) single crystal substrate [4]. The thickness of the NiO spacer and Fe overlayer was in the few nanometers range, while the substrate iron film was always a bulk-like thick film (about 300 nm). Cleanliness and surface reconstruction have been checked for each layer by means of X-ray Photoemission Spectroscopy and Low Energy Electron Diffraction (LEED).

The magnetization reversal processes of the two FM layers and the interlayer coupling have been studied by means of Magneto Optical Kerr Effect (MOKE) [5,6] for Fe(7 nm)/NiO(t_{AFM})/Fe(300 nm) trilayers, as a function of the NiO thickness t_{AFM}. All MOKE samples were capped with about 2 nm of Au. MOKE measurements were performed in air and at room temperature, with the external field applied along one of the in-plane easy axis of the Fe layers. A simple numerical model based on coherent rotation of the magnetic moments has been developed in order to

*Corresponding author. Tel.: +39 02 23996170; fax: +39 02 23996126.
E-mail address: paolo.biagioni@polimi.it (P. Biagioni).

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doi:10.1016/j.jmmm.2004.11.170

simulate the magnetization reversal and get a better insight in the physics involved.

Two distinct magnetization reversal behaviours are observed at different interlayer thicknesses, with a critical thickness t_C of about 4 nm for the transition between the two regimes. Below this value the relative alignment between the magnetization of the iron layers in zero applied field is perpendicular, and above it switches to collinear. No exchange bias has been detected, as expected in low-anisotropy NiO-based systems [7].

In the upper panel of Fig. 1 we show the experimental hysteresis loops for the Fe(7 nm)/NiO(1.4 nm)/Fe(300 nm) trilayer, i.e. for $t_{AFM} < t_C$. Both the in-plane longitudinal (parallel to $\vec{\mathbf{H}}$, $M_{\parallel}$) and transverse (perpendicular to $\vec{\mathbf{H}}$, $M_{\perp}$) loops are shown. No out-of-plane component has ever been observed. In the longitudinal loop, the inner narrow loop, with a coercivity of about 5 Oe, can be attributed to the Fe substrate, while the more complex behaviour of the outer loops, with the two lateral steps and a coercivity of about 230 Oe, comes from the contribution of the thin Fe overlayer. For the latter, at low applied fields, the overlayer magnetization is oriented perpendicularly to the substrate, as confirmed by the transverse ($M_{\perp}$) hysteresis loop, which shows a non-zero transverse component of the in-plane magnetization vector at correspondence with the intermediate plateaux of the longitudinal loop: they represent a possible intermediate state where the spins are directed perpendicularly to their initial and final directions, as a consequence of the fourfold symmetry of the Fe(0 0 1) magnetocrystalline anisotropy [8].

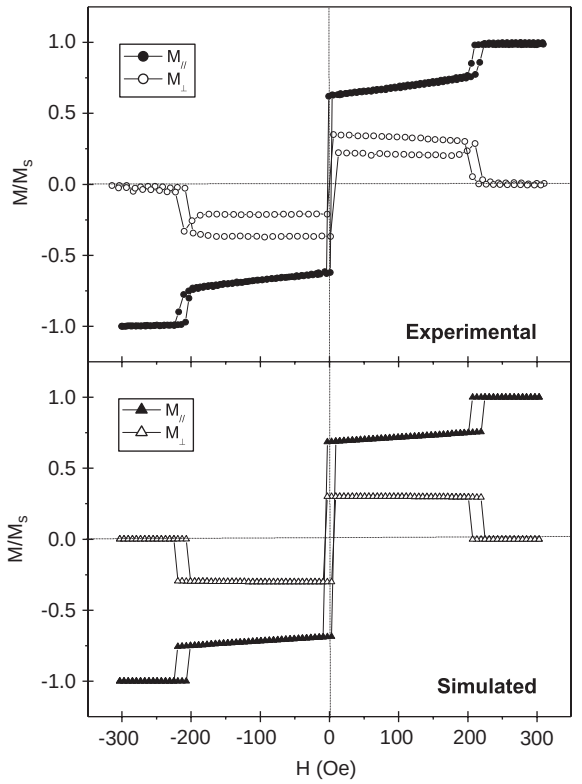

Fig. 1. Experimental and simulated hysteresis loops for the Fe(7 nm)/NiO(1.4 nm)/Fe(300 nm) trilayer.

In the numerical simulation, the coupling between the two FM layers is described with a bilinear term favouring collinear alignment, and a biquadratic term favouring perpendicular alignment [3]. Since one Fe layer is much thicker, it follows the applied field and drives the magnetization reversal of the coupled thinner layer. We consider energy barriers for the nucleation of 180° domains, both in the iron substrate and overlayer. For the latter, we also allow for the formation of 90° domains, as confirmed by the experimental data. The values for all the energy barriers are taken directly from the observed experimental loops. The hypothesis underlying the simulation is that the sample can always be considered to be in a single domain state, as confirmed by the sharp transitions in the observed hysteresis loops [8].

The expression for the total energy per unit surface is the following:

$$\begin{aligned} E_{\mathrm{tot}} &= E_{\mathrm{sub}} + E_{\mathrm{ov}} \\ &= -HM_S t_{\mathrm{sub}} \cos(\vartheta - \varphi_1) + \frac{1}{4} K_4 t_{\mathrm{sub}} \sin^2(2\varphi_1) \\ &\quad - HM_S t_{\mathrm{ov}} \cos(\vartheta - \varphi_2) + \frac{1}{4} K_4 t_{\mathrm{ov}} \sin^2(2\varphi_2) \\ &\quad + C_1 \cos(\varphi_2 - \varphi_1) + C_2 \cos^2(\varphi_2 - \varphi_1), \end{aligned}$$

where H is the applied field, M_S the saturation magnetization (taken to be 1742 emu/cm^3, as in bulk Fe), ϑ is the angle between $\vec{\mathbf{H}}$ and the [1 0 0] axis, t_{sub} and t_{ov} are the Fe substrate and overlayer thicknesses, φ_1 and φ_2 are the angles between the magnetization directions and the same easy axis in the Fe substrate and overlayer, respectively. The cubic anisotropy constant K_4 has been experimentally measured to be 4.8×10^5 erg/cm^3, as in bulk Fe, while the coupling coefficients C_1 and C_2 are fitted to the experimental data.

The best fit for the Fe(7 nm)/NiO(1.4 nm)/Fe(300 nm) trilayer is shown in the lower panel of Fig. 1, and is obtained with $C_1 = 4.35 \times 10^{-2}$ erg/cm^2 and $C_2 = 2.05 \times 10^{-1}$ erg/cm^2. There is actually a difference in the height of the plateaux in the transverse loop between the experimental data and our simulation: we tentatively attribute this behaviour to the possibility that the Fe overlayer is broken into several 90° domains, rather than into a single one. This fact is not accounted for by our coherent rotation model.

Let us now turn our attention to spacer thicknesses above t_C. The hysteresis loop for the Fe(7 nm)/NiO(10 nm)/Fe(300 nm) trilayer is shown in Fig. 2.

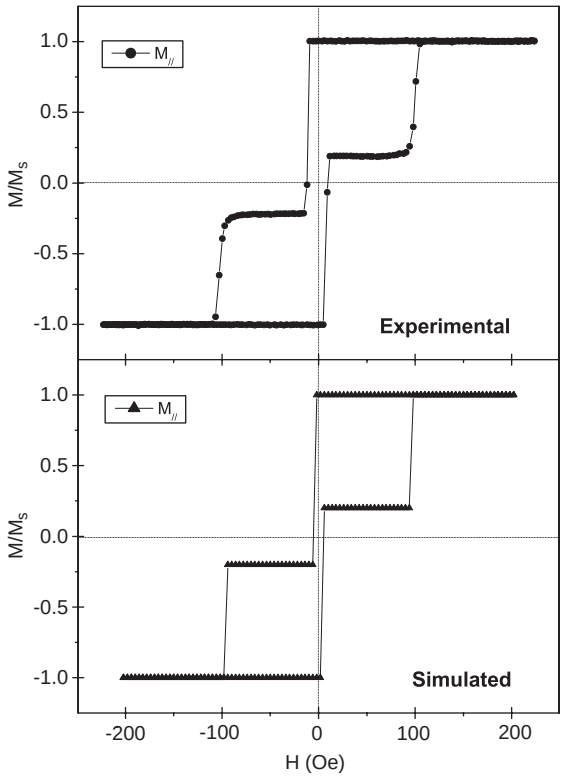

Fig. 2. Experimental and simulated hysteresis loops for the Fe(7 nm)/NiO(10 nm)/Fe(300 nm) trilayer.

For this trilayer no significant transverse component of the magnetization vector has been detected. The intermediate plateaux in the loop reveal therefore a situation where the magnetization vectors of the two layers are antiparallel, as they switch at different coercive fields.

We find that an increase in spacer thickness gradually decreases the value of the coupling constant for perpendicular alignment between the magnetic moments. We indeed fit our experimental data with $C_1 = 4.35 \times 10^{-2}\,\mathrm{erg/cm^2}$ and $C_2 = 0$.

The analysis of a thinner Fe overlayer is not easily accessible to a MOKE experiment, since the top layer contribution is masked by the overwhelming bulk Fe substrate signal. In order to study this case we utilized spin polarized low energy electron microscopy (SPLEEM) [9,10], where the magnetic contrast is usually dominated by the first few atomic layers. Sample preparation is the same as described above; cleanliness and surface reconstruction have been checked for each layer by Auger spectroscopy and LEED. The measurement procedure is the following: first we measure the remanent direction of the substrate, which would be inaccessible after the subsequent depositions of the NiO and Fe overlayers. Then, after the depositions, we measure the top layer magnetization, for Fe overlayer thicknesses ranging from 0.7 to 2.1 nm.

SPLEEM images for collinear and perpendicular alignment between the magnetization vectors of the two Fe layers are shown in Fig. 3: the overlayer is measured *as-grown*, before any external magnetization, and consequently clearly shows multidomain patterns, where all the domain magnetization vectors have the same direction but can lay antiparallel to each other. Again, we find that below a critical thickness of the NiO spacer the coupling in zero applied field is perpendicular and above is parallel. The critical thickness is strongly reduced compared to the case of a thick Fe overlayer, a fact that can be attributed to a reduction of the anisotropy in the thin overlayer with respect to the MOKE samples. This observation definitely deserves further investigation.

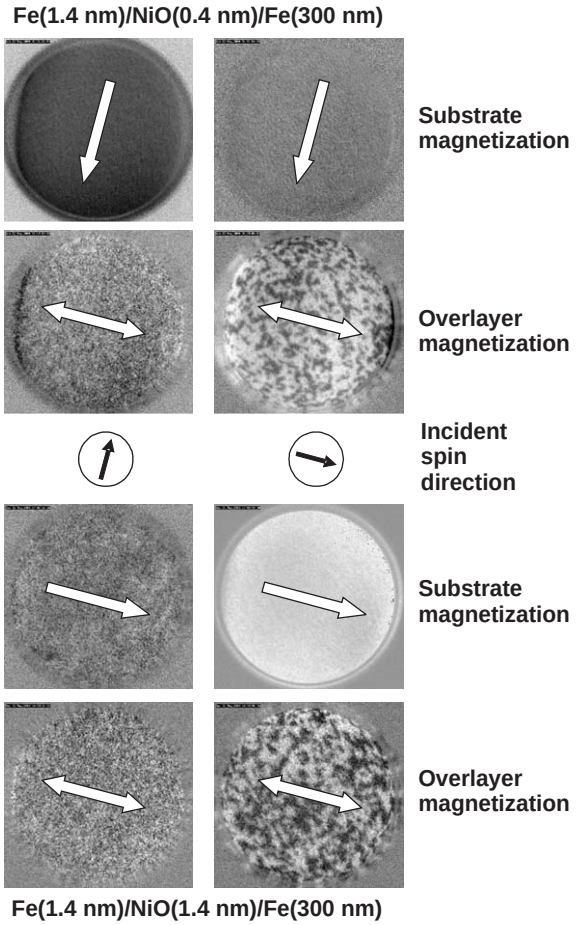

Fig. 3. SPLEEM images for the Fe(1.4 nm)/NiO(0.4 nm)/Fe(300 nm) trilayer (upper) and the Fe(1.4 nm)/NiO(1.4 nm)/Fe(300 nm) trilayer (lower). The arrows in the middle circles indicate the incident electrons spin direction, the arrows on the images indicate the magnetization directions of the Fe substrate and overlayer.

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