Origin and evolution of positive exchange bias in epitaxial *(hcp)*Co/CoO bi-layer structures

A. K. Suszka, O. Idigoras and A. Berger

CIC nanoGUNE Consolider, Tolosa Hiribidea 76, E-20018 Donostia-San Sebastian, Spain
a.suszka@nanogune.eu

The phenomenon of unidirectional anisotropy of antiferromagnetic (AF)/ferromagnetic (FM) bi-layers, also referred to as exchange bias, is a prominent scientific and technological topic. Exchange biased magnetic thin films with uniaxial magnetic anisotropy (UA) are currently at the forefront of technology in magnetic recording and represent a challenge for scientific research. A relatively small number of experiments has been dedicated to study the exchange bias for systems with in-plane UA of the FM layer. Specifically, some recent studies focused on the competition of UA and exchange bias and revealed a distinct temperature dependence of uniaxial anisotropy at the interface of the FM layer that is in contact with the AF, for both out-of-plane [1] and in-plane magnetized thin films [2]. So far, however, very little work on the exchange bias has been done for Co/CoO structures in the presence of UA, even though Co/CoO-bilayers are the prototypical exchange bias system, and to our knowledge no previous work was dedicated to the study of (hcp) Co/CoO bi-layers with in-plane c-axis orientation [3].

Two types of multilayers with structure: Si-substrate/Ag(75nm)/Cr(50nm)/Co(12nm)/CoO(3nm) were grown by ultra high vacuum (UHV) sputtering. For one type of the multilayers, we modified the Co texture and consequently the UA by interrupting the epitaxial growth sequence in between the HF-etched Si-substrate and Ag underlayer, specifically by exposing the substrate to an ultra-low power SiO_2 plasma for 30s prior to Ag deposition [4]. In this way, we fabricated samples with uniaxial (epitaxial structure) and isotropic (polycrystalline structure) magnetic characteristics as shown in figs. 1(a) and (b) respectively. X-ray diffraction studies confirm the Si(110)/Ag(110)/Cr(211)/Co(10$\underline{1}$0) structure for samples without SiO_2 interlayer [4]. CoO was formed by natural oxidation in both types of multilayers. Samples were characterised using magneto-optical Kerr effect setup (MOKE), superconducting quantum interference device (SQUID), x-ray diffraction, ellipsometry and Kerr microscopy.

We measured hysteresis loops for epitaxial and polycrystalline samples as a function of temperature in the easy (EA) and hard axis (HA) magnetization direction. Epitaxial multilayer shows higher values of exchange bias (H_{ex}) and blocking temperature (T_B) in comparison with polycrystalline structures. In addition to that, a positive exchange bias is measured for the epitaxial structures in a certain temperature window while it is not observed in polycrystalline samples. Increasing the magnitude of the cooling field (FC) results in a decrease of the positive H_{ex} effect and causes a different transition temperature from positive to negative H_{ex}. We also find a direct relation between the asymmetry of the magnetization reversal process, and the enhancement of unidirectional anisotropy. Some previous reports suggested the existence of positive exchange bias due to anisotropic enhancement of the coercivity H_c [5]. This conclusion was originally supported by the existence of a peak in the coercivity around the positive H_{ex}. Here, we find a non-monotonous increase in the coercivity for the epitaxial sample. This is most pronounced in the hard axis magnetization direction (Figs. 2(a) and (b)). Changes in coercivity relate directly to the behavior of positive and negative switching fields as shown on figure 2 (c). Figure 2 (d) shows the extracted *d*m/*d*H of our hysteresis loops for different temperatures and reveals switching asymmetry near positive exchange bias. In current work we also analyze the magnetic characteristics of the EA for epitaxial structure and the exchange bias for polycrystalline sample. Each one of these cases shows different and unique evolution of exchange bias with varying temperature. The experimental results are analyzed in the framework of changes in magnetization states near interface of FM/AF and the influence of competition of uniaxial anisotropy and exchange bias on magnetization switching at various temperatures.

We acknowledge funding from the ETORTEK Program, Project No. IE06-172, the Spanish Consolider-Ingenio 2010 Program, Project No. CSD2006-53 and the Basque Government fellowships No. BFI09.284.

References

[1] E. Shipton, K. Chan, T. Hauet, O. Hellwig, and E. E. Fullerton, Appl. Phys. Lett. **95**, 132509 (2009)
[2] M. Grimisditch, A. Hoffmann, P. Vavassori, H. Shi, and D. Lederman, Phys. Rev. Lett. **90**, 257201 (2003)
[3] F. Radu, M. Etzkorn, R. Siebrecht, T. Schmitte, K. Westerholt, and H. Zabel, Phys. Rev. **B 67**, 134409 (2003)
[4] O. Idigoras, A. K. Suszka, J. M. Porro, P. Vavassori, and A. Berger, submitted to Phys. Rev. Lett.
[5] T. Gredig, I. N. Krivorotov, P. Eames and E. D. Dahlberg, Appl. Phys. Lett. **81**, 1270 (2002)
[6] O. Idigoras, P. Vavassori, J. M. Porro, and A. Berger, J. Magn. Magn. Mater. **320**, L57-L60 (2010)

Figures:

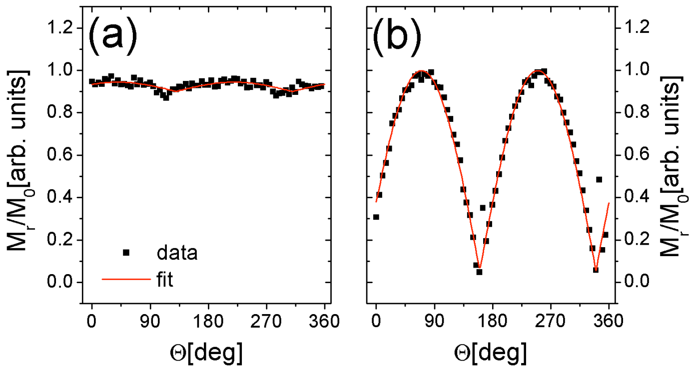

*Fig. 1: Normalized remanent magnetization (M_r/M_0) as a function of magnetic field orientation angle Θ for a polycrystalline (a) and an epitaxial (b) Co/CoO sample, measured at room temperature. Red line is a fit to the data (M_r/M_0=a*abs(cos(Θ-ϕ))+c) following reference [6].*

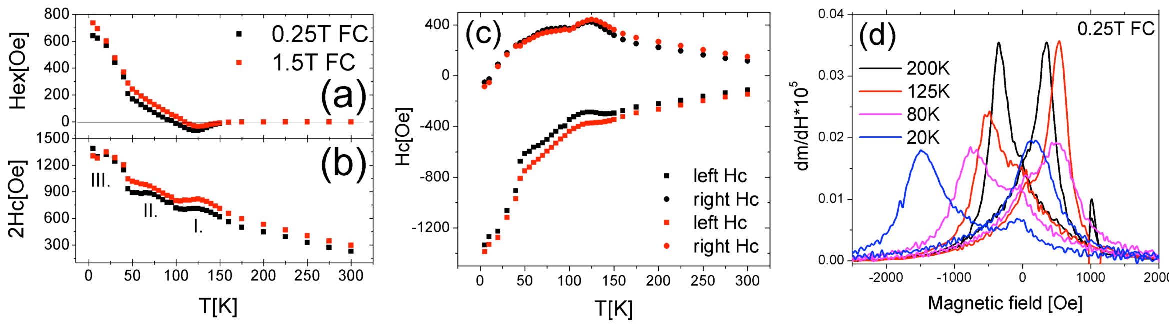

Fig. 2: Exchange bias (a) and coercivity (b) as a function of temperature measured in the hard axis magnetization direction on an epitaxial sample for two cooling field values (0.25T and 1.5T), (c) left and right coercivity as a function of temperature for the same sample and orientation cooled at 0.25T (black) and 1.5T (red). (c) field derivative of hysteresis loops for an epitaxial sample cooled at 0.25T at different temperatures, revealing a substantial switching asymmetry in the region of positive exchange bias.