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EXCHANGE-BIASED $Fe_{4.6}CO_{70.4}Si_{15}B_{10}$/NiO BILAYERS

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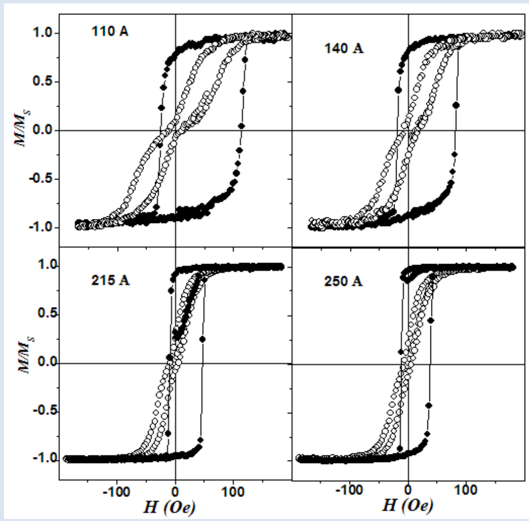

ABSTRACT

We report on experimental evidence of exchange bias between the amorphous ferromagnetic (FM) $Fe_{4.6}Co_{70.4}Si_{15}B_{10}$ and an antiferromagnetic (AF) NiO film, grown onto single crystalline Si(001) wafers. Surface Magneto-optic Kerr Effect (SMOKE) has been used to measure the hysteresis loop shift, and coercivity, as functions of the azimuthal angle, φ_H, and the FM layer thickness, t. The measurements reveal the presence of induced unidirectional and uniaxial symmetries following a complex cosine dependence, and thickness dependence proportional to $1/t$, typical of interfacial effects.

Keywords: Exchange-bias; Unidirectional anisotropy; Surface Magneto-optic Kerr Effect; ferromagnetic-antiferromagnetic bilayers..

BICAPAS $Fe_{4.6}Co_{70.4}Si_{15}B_{10}$/NiO CON POLARIZACIÓN DE INTERCAMBIO

RESUMEN

Reportamos evidencia experimental de polarización de intercambio entre una película ferromagnética (FM) de $Fe_{4.6}Co_{70.4}Si_{15}B_{10}$ y una de NiO antiferromagnética (AF), depositadas sobre substratos de Si(001). Se obtuvieron las curvas de histéresis utilizando la técnica de Efecto Kerr Magnetoóptico de Superficie (SMOKE), y medimos el desplazamiento de las curvas y el campo coercitivo en función del ángulo acimutal, φ_H, y el espesor de la película FM, t. Las medidas revelan la presencia de anisotropías unidireccional y uniaxial, cuyas asimetrías corresponden a funciones complejas de cos(φ_H), y dependencia con el espesor proporcional a $1/t$, típica de los efectos de interface.

Palabras Claves: polarización de intercambio; anisotropía unidireccional; Efecto Kerr Magneotóptico de superficie; películas dobles ferromagnéticas-antiferromagnéticas.

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1. INTRODUCTION

Since the discovery of the exchange anisotropy by Meiklejhon and Bean in 1956 on Co-CoO particles [1], systems consisting of a ferromagnetic (FM) material in contact with an antiferromagnetic (AF) material have attracted much attention during the last decade. The term exchange anisotropy, H_{EB}, was coined to describe the magnetic interaction between the magnetic moments of the FM, and the magnetic moments of the AF just at the interface. The main features of these structures are a shift of the hysteresis curve along the applied field, an unusual increase in the coercivity, H_C, of the FM compared with the bulk value, rotational hysteresis, and torque curves following purely sinusoidal symmetry. More recently, ferromagnetic resonance (FMR) profiles displaying an unidirectional anisotropy superposed to the usual uniaxial symmetry, has been reported [2]. By the mid 1970´s, almost all significant research on AF-FM exchange coupling was reported on materials involving monoxide magnetic particles, until the seminal paper by Hempstead et al in 1978 [3]. They reported that depositing γ-FeMn films onto Py films, larger loop shifts were produced, with significant ratios H_{EB}/ H_C. They also noted that as the exchange anisotropy increased, no Barkhausen noise was observed, and then, higher GMR values were measured. These remarkable properties make AF/FM thin films unique candidates for applications in high density magnetic memories, and magnetic recording devices [4, 5].

Experimentally, a diversity of materials and methods has been employed to investigate the exchange bias phenomenon in magnetic bilayers and nanostructures. This is because, in general, the magnetic properties of these systems are highly affected by growth conditions and sample treatment, purity of the alloys, substrate temperature, film thickness, roughness, chemical stability of the alloys, interdiffusion of atoms at the interface, etc. The most extensively studied AF/FM bilayers are those based on the antiferromagnetic compound FeMn [6], however, is in general difficult to obtain, corrodes easily, and crystallizes in different phases. Besides FeMn, other compounds such as NiO, CoO, PtMn, IrMn, are also employed as AF layer [7-10]. This is because these materials may exhibit chemical stability, relatively simple crystalline structure, corrosion resistance, and are magnetically harder than FeMn. As FM layer, NiFe or CoFe, are commonly used due to their soft magnetic properties, and because are easy to obtain [9, 10]. More recently, some other intermetallic alloys such as $Sm_{1-x}Gd_xAl_2$ [11], $BiFeO_3$ [12], $NdMnO_3$ [13], have been proposed to be employed as alternative materials in exchange-biased heterostructures and artificial interfaces. On the other hand, although several techniques are available to measure the magnetic properties, most of these experiments yield contradictory results regarding the value of the exchange coupling field between the AF and the FM layer [14]. This intriguing property of exchange-biased AF/FM systems has led to classify the measuring techniques into reversible and irreversible, such as FMR and magneto-optic Kerr effect (MOKE), respectively. These discrepancies are indicative that the physical mechanisms responsible for the inter-film coupling at the AF/FM interface are actually not well understood, are that there is a need of more realistic models addressing the physics of exchange bias.

In this paper, we report on the magnetic properties of exchange-biased $Fe_{4.6}Co_{70.4}Si_{15}B_{10}$/NiO bilayers grown by dc magnetron sputtering onto Si(001) substrates. Amorphous $Fe_{4.6}Co_{70.4}Si_{15}B_{10}$ has been chosen as the FM layer because exhibit very soft magnetic properties, exhibits giant magnetoimpedance (GMI) [15], and with a saturation magnetization of about 10.0 kOe [16], giving this material interesting properties for technological applications in magnetoresistive sensors. Besides this, it is known that magnetron sputtering provides facilities for growing $Fe_{4.6}Co_{70.4}Si_{15}B_{10}$ thin films on Si wafers [17]. Although this, there is no report on literature about FM/AF bilayers based on this material. The samples hysteresis curves were obtained by Surface magneto-optic Kerr effect (SMOKE), and then the exchange field and coercivity studied as function of the azimuthal angle, and FM layer thickness.

2. EXPERIMENTAL PART

The samples were grown by dc magnetron sputtering, onto single crystalline Si(001) substrates commercially obtained. The substrates were first cleaned in ultrasound baths of acetone and methanol for 10 min each, and then dried in flowing nitrogen. A NiO layer was then deposited onto the substrate by means of reactive sputtering of Ni in an argon:oxygen atmosphere at a rate 10:2, and in the sputter-up configuration with distance target-substrate held at 9 cm. With this, a texturized NiO(001) layer is expected. For the targets, amorphous ribbons of $Fe_{4.6}Co_{70.4}Si_{15}B_{10}$ were previously produced by the melt-spinning technique, within the conditions described in ref [15]. The ribbons are powder-processed, and finally machining the resulting target (for a review of the powder processing techniques for thin films applications see ref [18]). The amorphous $Fe_{4.6}Co_{70.4}Si_{15}B_{10}$ alloy was then deposited on top of the NiO film. The base pressure of the system was 1.2×10^{-7} Torr and the work pressure of the Argon was 3.3×10^{-3} Torr. The samples were prepared keeping the thickness of the AF layer fixed at 375 Å, while the FM layer thickness, *t*, varied from 40 Å to 280 Å, with deposition rates ~0.6 and 1.6 Å/s for NiO and $Fe_{4.6}Co_{70.4}Si_{15}B_{10}$, respectively. The thickness of the films was measured using a calibrated quartz crystal sensor.

The magnetization curves were measured by Surface magneto-optical Kerr effect (SMOKE) in the longitudinal geometry. In this configuration, the detected signal is proportional to the magnetization parallel to the aplied magnetic field. The ligth of a 2.0 mW He-Ne laser (632.8 nm), was linearly polarized at 45° with respect to the plane of incidence, and modulated at 50 kHz by a photoelastic modulator, striking the surface of the film at an angle of incidence of about 60°. Before detection, the reflected radiation passes through an analyzer in order to select the corresponding magnetization component. In order to measure hysteris loops with respect to in-plane angle, φ_H, the sample was mounted on a goniometer that allowed us to rotate the plane of the film with respect to the applied magnetic field. All measurements were performed at room temperature.

3. RESULTS AND DISCUSSION

The hysteresis loops of $Fe_{4.6}Co_{70.4}Si_{15}B_{10}$/NiO, taken at φ_H= 0° (closed symbols) and φ_H=90° (open symbols) are shown in Fig.1 for several thicknesses of the ferromagnetic layer. These loops are shifted from the origin, with a maximum field shift and maximum coercivity at φ_H= 180°, and zero field shift and minimum coercivity at φ_H= 90°. From these curves the values of the exchange bias field (field shift from the origin), H_E, and the coercive field, H_C, are obtained as functions of the azimuthal angle, φ_H, and FM layer thickness, *t*. For thickness, *t*, below ~100 Å, H_E and H_C show no obvious angular dependence, however, as the thickness was increased a defined symmetry is triggered, as shown in Fig. 2, for the samples with 140 Å and 180 Å. The exchange field exhibits the expected unidirectional symmetry, $H_E(\varphi_H) = H_E(-\varphi_H) = -H_E(\pi \pm \varphi_H)$ with a period of 2π, whereas the coercivity is uniaxial, $H_C(\varphi_H) = H_C(-\varphi_H) = H_C(\pi \pm \varphi_H)$ with a period of π. This confirms that the intrinsic properties of the exchange bias are preserved. At the vicinity of φ_H = 180°, we note an anomaly in the value of H_E and a flattening of the coercivity curve, leading to angular dependences far from being pure sinusoidal and sine-squared. Instead, this behavior can be qualitatively described by a Fourier series with odd and even terms [17],

$$H_E(\varphi_H) = H_{E0} \sum_{n=0} a_{2n+1} \cos(2n+1)\varphi_H \quad (1)$$

$$H_C(\varphi_H) = H_{C0} \sum_{n=0} b_{2n} \cos(2n)\varphi_H \,. \quad (2)$$

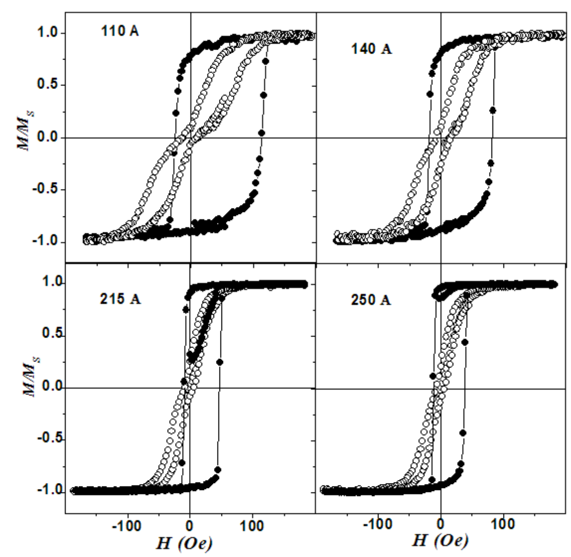

Figure 1. SMOKE magnetization curves for $Fe_{4.6}Co_{70.4}Si_{15}B_{10}$(140 Å)/NiO(375 Å)/Si(001), taken with the magnetic field at φ_H=90° (open symbols), and φ_H=180° (closed symbols)

The experimental results shown in Figs. 2(a)-(b) are reasonably described by the functions $H_E(\varphi_H)$=37.6 [-$cos(\varphi_H)$+0.17$cos(3\varphi_H)$] Oe, $H_C(\varphi_H)$=29.50 [1+$cos(2\varphi_H)$ +0.6 $cos(4\varphi_H)$] Oe, for *t*=140 Å, and $H_E(\varphi_H)$=22.50 [-$cos(\varphi_H)$+0.20$cos(3\varphi_H)$] Oe, $H_C(\varphi_H)$=20 [1+0.7$cos(2\varphi_H)$ +0.25$cos(4\varphi_H)$] Oe, for *t*=180 Å, as shown by the solid curves. Such angular dependences have been previously reported in $Co_{65}Mo_2B_{33}$/CoO [19], Py/CoO [20], and Py/Au/CoO [21]. On the other hand, both the field shift and coercivity vary from sample to sample. This variation gives suitable information about the interfacial nature of the magnetic anisotropies of the system.

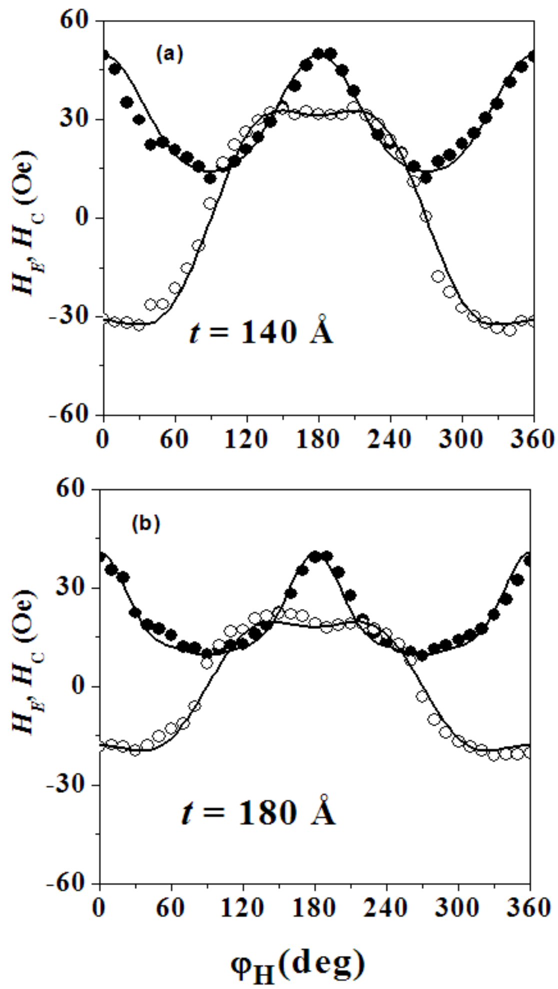

Figure 2. Angular dependence of the exchange-bias field (open symbols), H_E, and coercivity (closed symbols), H_C, for two typical samples. The solid curves are calculated with Eqs (1) and (2)

In Fig. 3 we plot the field shift measured at φ_H = 180°, H_E(180°), and the amplitude of the coercivity curve, $\Delta H_C = H_C(180°) - H_C(90°)$, as functions of the FM film thickness. It is noted that the value of H_E(180°) and ΔH_C increases gradually as the FM film thickness is decreased, reaching a maximum field shift of about 115 Oe for the sample with $t \approx 40$ Å. Similar magnitudes for H_E have been reported previously in CoFe/IrMn bilayers [10]. The solid line is the best fit using a function of the type $H(t)=H_0+H_S/t$, which demonstrates that the exchange bias coupling in these systems is purely of interfacial nature. Also note that $H_E(180°) \approx \Delta H_C$ over the entire film thickness. This feature may be of technological interest and have not been explored up to date.

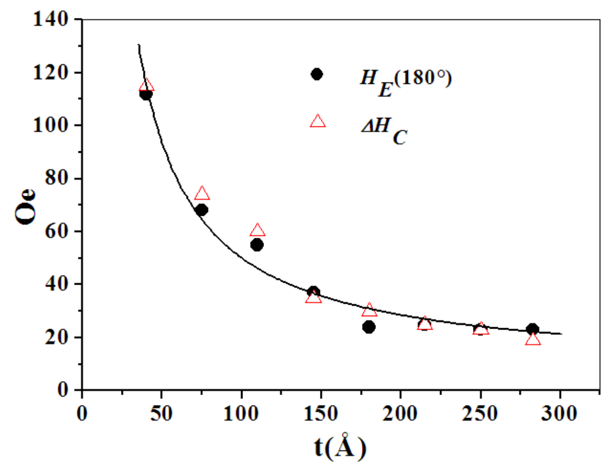

Figure 3. Thickness variation of the maximum value of the exchange-bias field (open symbols), $H_E(\varphi_H=180°)$, and coercivity amplitude (closed symbols), ΔH_C.

4. CONCLUSIONS

In summary, we have grown exchange-coupled FM/AF bilayers using amorphous $Fe_{4.6}Co_{70.4}Si_{15}B_{10}$ as ferromagnetic layer, and NiO as the antiferromagnet layer. The exchange bias field and coercivity exhibit anomalous in-plane unidirectional and uniaxial symmetries, with angular dependences different from the simple $sin\varphi_H$ and $sin^2\varphi_H$. The thickness dependence of both exchange field and coercivity follows the inverse thickness law, indicating that this is a pure interfacial phenomenon. Our results suggest that amorphous ferromagnetic $Fe_{4.6}Co_{70.4}Si_{15}B_{10}$ can be used as an alternative material for application in exchange-biased based spintronics and related devices, were NiFe alloys where previously employed.

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