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EXCHANGE ANISOTROPY IN NiO/Co BILAYERS

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40 nm-NiO/d_{Co}-Co bilayers ($0 < d_{Co} < 40$ nm) were prepared onto $SiO_2(101)/Si(100)$ and glass substrates using UHV RF/DC magnetron sputtering. Results showed that the exchange coupling effects, i.e. unidirectional anisotropy field, H_s (shift of the hysteresis loop), and broadening of the hysteresis loop, ΔH_c, are inversely proportional to the Co thickness down to 2 nm. Furthermore, no significant difference in H_s and ΔH_c was observed between as deposited and field cooled bilayers. Practically no contraction of the successive hysteresis loops (training effects) was also observed at room temperature. On the other hand, the interface exchange coupling effects strongly depend on the preparation conditions. A maximal coupling energy for the NiO–Co interface was estimated as 0.04 mJ/m^2 at room temperature for the samples prepared onto $SiO_2(101)/Si(100)$ substrates.

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1. Introduction

Magnetic layered structures containing transition metal oxides have received considerable interest in recent years due to exchange biasing effect [1, 2]. From the technological point of view, this phenomenon plays an important role in magnetic domains stabilisation in magnetoresistive devices, for instant, such as spin valves [3]. Exchange coupling at the interface of a ferromagnetic (FM) and antiferromagnetic (AFM) layer can produce an unidirectional anisotropy field in the ferromagnet, which causes a shift (H_s) and broadening (ΔH_c) of the hysteresis loop. Practically these features appear after cooling through the Néel temperature of the antiferromagnetic layer with an applied magnetic field which single-domains the ferromagnetic layer and results in a field shift of the hysteresis loop [4, 5]. The unidirectional exchange anisotropy (UEA) was first discovered by Meiklejohn and Bean for Co particles embedded in their native antiferromagnetic oxide (CoO) [4, 5]. The UEA was observed in many different systems containing ferromagnetic-antiferromagnetic interfaces, such as small particles, inhomogeneous materials, ferromagnetic thin films on antiferromagnetic bulk single crystals and thin films [6]. UEA and related effects have also been observed in other types

of interfaces containing ferrimagnets, such as antiferromagnetic–ferrimagnetic or ferrimagnetic–ferromagnetic [6].

The spin structure of bulk NiO single crystal below the Néel temperature is relatively simple [7]. On the other side, large number of domain configurations and domain walls in a multidomain polycrystalline sample is to be expected. Bulk NiO has a cubic fcc NaCl crystal structure above its Néel temperature ($T_N = 250°C$) [7]. Below the Néel temperature there is a slight distortion of the NiO lattice in a [111] direction. The contraction axis defines sheets of ferromagnetically aligned (non-compensated) spins in the (111) planes [7]. On the other hand, metallic cobalt is well known ferromagnet.

In general, the microscopic mechanism of exchange anisotropy is still not fully recognised. Especially, the exchange coupling energy calculated for perfect non-compensated AFM–FM interface is typically two orders of magnitude stronger compared to that measured experimentally [1, 4–6]. The above disagreement could be explained by domain formation in the AFM below the AFM/FM interface, resulting from a 90° coupling between AFM and FM moments [8]. In this paper we report on the unidirectional exchange anisotropy field (H_s) and broadening of the hysteresis loop (ΔH_c) in the Co/NiO bilayers.

2. Experimental

NiO/d_{Co}-Co bilayers were prepared onto SiO_2(101)/Si(100) and glass substrates using UHV (5×10^{-10} mbar) RF/DC magnetron sputtering. The Co-layers ($2 \leq d_{Co} \leq 40$ nm) were deposited using a DC source in an Ar atmosphere. The NiO-layer ($d_{NiO} = 40$ nm) was prepared using an RF source in Ar + O_2 atmosphere. The deposition rates of Co and NiO are individually checked by a quartz thickness monitors. The thicknesses of individual sublayers were controlled by varying the deposition times. Typical deposition rate for the Co and NiO layers was equal to 0.1 and 0.05 nm/s, respectively. The distance between sputtering targets and substrate was about 20 cm. The purity of the Co and Ni targets was equal to 99.998% and 99.9998%, respectively. After preparation of Si(111) substrate with native SiO_2(101) surface layer [9], we have first deposited NiO layers. The Co layers were then grown immediately onto the NiO. The top Co layers had a step-like wedge form. Wedge-shaped Co layers were grown by steeply moving a shutter in front of the substrate during deposition. Finally, 5 nm-Cu cap layer was deposited to prevent the oxidation of the Co layer. The chemical composition and the cleanness of all layers was checked *in situ*, immediately after deposition, transferring the bilayers to an UHV (4×10^{-11} mbar) analyse chamber equipped with Auger and X-ray photoelectron spectroscopy (AES, XPS). From the exponential variation of the XPS Co-2p and NiO-2p integral intensities with increasing layer thickness we conclude that the Co and NiO layers grow homogeneously. The structure of the samples was examined *ex situ* by standard θ–2θ X-ray diffraction with Co K_α radiation. The thicknesses of individual Co and NiO layers were determined using X-ray fluorescence analysis (XRF). The magnetic characterisation of the wedged and constant-thickness NiO/Co bilayers was carried out at room

temperature using the magnetooptical Kerr effect and a vibrating sample magnetometer (VSM), respectively. The coercive (H_c) and unidirectional anisotropy fields (H_s) were determined from the in-plane hysteresis loops measurements. The samples were first measured without field cooling (as deposited) and then after cooling in a high vacuum (10^{-7} mbar) from above Néel temperature of bulk NiO (250°C) to room temperature in a magnetic field of 5 kOe. The exchange coupling energy at the NiO–Co interface was determined for bilayers prepared in the same conditions, in which the top Co layer was deposited in a step-like wedge form.

3. Results and discussion

For the Co/NiO bilayers with $d_{Co} > 20$ nm the high-angle X-ray diffraction patterns show an appreciable (111) texture of fcc Co and NiO. The average Co and NiO crystallite sizes in direction perpendicular to the substrates, determined from the Scherrer equation, are comparable to their respective sublayer thicknesses.

Figure 1 shows typical hysteresis loop, measured at room temperature for the NiO/Co bilayer with Co layer thickness $d_{Co} = 2.5$ nm. The hysteresis loop is strongly displaced from the origin and broadened compared to that measured for the single 2.5 nm-Co film protected against oxidation by a 5 nm-Cu cap layer. The value of this displacement (H_s) defines directly the UEA field. As origin of these effects, the exchange coupling between the spins of the ferromagnetic Co atoms and the spins of the Ni ions in the antiferromagnetic NiO is invoked.

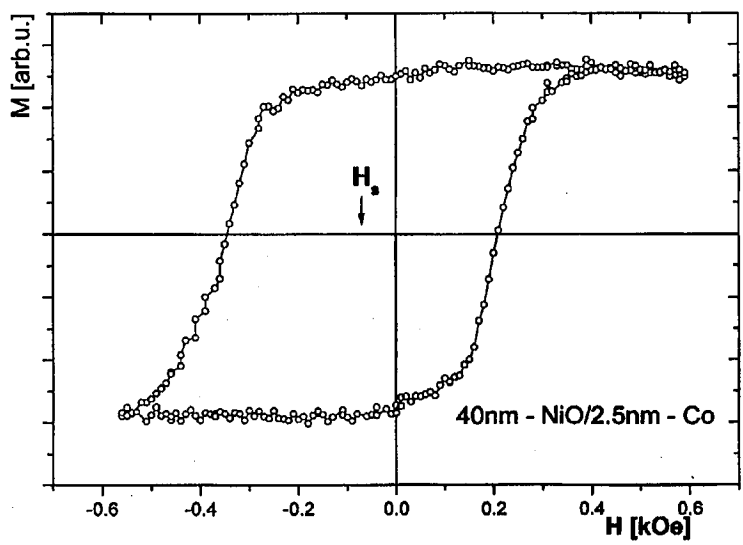

Fig. 1. Typical hysteresis loop of the exchange coupled 40 nm-NiO/2.5 nm-Co bilayer prepared onto $SiO_2(101)/Si(100)$ substrate at 20°C. Measurements were performed at room temperature.

Figure 2 shows the UEA field, measured at room temperature, as a function of the inverse Co layer thickness for the Co/NiO bilayers prepared onto $SiO_2(101)/Si(100)$ substrates at 20°C. The linear dependence of H_s on $1/d_{Co}$ revealed the interfacial origin of the observed UEA field [10]. We have also observed a qualitatively similar $1/d_{Co}$ thickness dependence for broadening of the hysteresis loop ΔH_c, measured on the same samples. The interfacial origin of the UEA field (linear dependence as a function of $1/d_{FM}$) was already experimentally confirmed for Co/CoO [1], FeNi/FeMn [10], and other FM/AFM interfaces [6]. A similar $1/d_{FM}$ thickness dependence was also observed for the uniaxial interface (surface) anisotropy in magnetic multilayers composed of ferromagnetic and nonmagnetic metals [11].

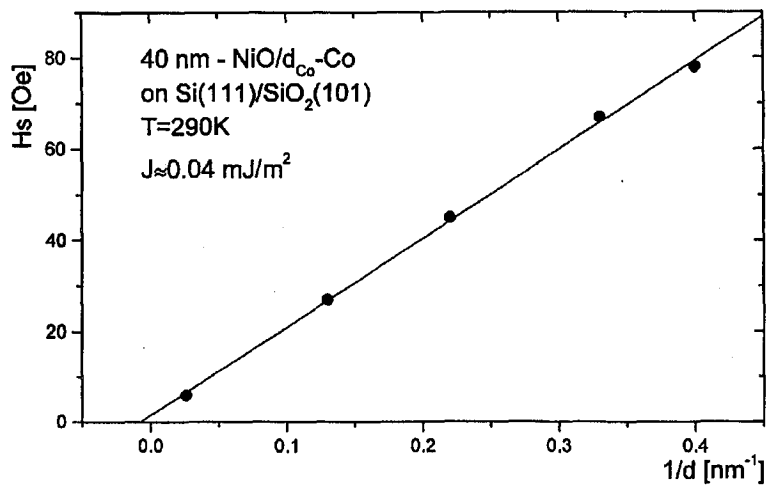

Fig. 2. Unidirectional exchange anisotropy field (H_s) as a function of $1/d_{Co}$ for 40 nm-NiO/d_{Co}-Co bilayers prepared onto $SiO_2(101)/Si(100)$ substrates at 20°C. Measurements were performed at room temperature.

Practically no contraction of the successive hysteresis loops (training effects) was observed at room temperature. Furthermore, no significant difference in H_s and ΔH_c at room temperature was observed between as deposited and field cooled bilayers. The above behaviour is probably associated with grow induced uniaxial (not unidirectional) anisotropy in Co layer due to grain deformation during the deposition process [12]. In our case the Co source is mounted at an angle of about 20° from the normal to the substrate. Such a sputtering configuration could induce deformation of the deposited Co grains in a preferred direction in such a way that the easy axis of the uniaxial anisotropy is placed along the grains [12]. In that case, the Co layer is in a single domain state immediately after deposition (local temperature of NiO/Co bilayer comparable with T_N of NiO) and therefore the field cooling procedure cannot change the spins configuration at the NiO–Co interface.

According to the single spin model of the FM/AFM interface [4, 5], the average exchange coupling energy at the interface is given by $J = \boldsymbol{H}_s \cdot \boldsymbol{M} d_{Co}$

(M denotes average magnetisation of the Co layer). We have previously showed that the magnetisation of ultrathin Co layer is practically equal to the bulk value [9, 13, 14]. Using the above equation and the data obtained for the samples prepared onto $SiO_2(101)/Si(100)$ substrates at 20°C (see Fig. 2), we have estimated a coupling energy for the NiO–Co interface as $J = 0.04\ mJ/m^2$ at room temperature. On the other hand, the estimated J value at room temperature for NiO/Co bilayers prepared onto glass substrates at 100°C and 20°C was equal to 0.02 mJ/m^2 and 0.03 mJ/m^2, respectively. The significantly lower value of the UEA energy for the samples prepared onto glass substrates could be related with greater roughness of the NiO–Co interface. This is in agreement with recent results obtained by Takano et al. [15] showing a strong dependence of the UEA on the roughness of the AFM–FM interfaces and the role of uncompensated interface spins in the AFM [15].

In conclusion, results showed that the exchange coupling effects (H_s and ΔH_c) are inversely proportional to the Co thickness down to 2 nm. The NiO/Co bilayers showed no training effects and relatively high unidirectional anisotropy field (up to 80 Oe) at room temperature. On the other hand, the interface exchange coupling effects strongly depend on the preparation conditions. A maximal coupling energy for the NiO–Co interface was estimated as 0.04 mJ/m^2 at room temperature for the samples prepared onto $SiO_2(101)/Si(100)$ substrates.

Acknowledgments

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