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Interface adjustment and exchange coupling in the IrMn/NiFe system

F. Spizzo, M. Tamisari, F. Chinni, E. Bonfiglioli, L. Del Bianco*

Dipartimento di Fisica e Scienze della Terra and CNISM, Università di Ferrara, I-44122 Ferrara, Italy

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ABSTRACT

The exchange bias effect was investigated, in the 5–300 K temperature range, in samples of IrMn [100 Å]/NiFe [50 Å] (set A) and in samples with inverted layer-stacking sequence (set B), produced at room temperature by DC magnetron sputtering in a static magnetic field of 400 Oe. The samples of each set differ for the nominal thickness (t_{Cu}) of a Cu spacer, grown at the interface between the antiferromagnetic and ferromagnetic layers, which was varied between 0 and 2 Å. It has been found out that the Cu insertion reduces the values of the exchange field and of the coercivity and can also affect their thermal evolution, depending on the stack configuration. Indeed, the latter also determines a peculiar variation of the exchange bias properties with time, shown and discussed with reference to the samples without Cu of the two sets. The results have been explained considering that, in this system, the exchange coupling mechanism is ruled by the glassy magnetic behavior of the IrMn spins located at the interface with the NiFe layer. Varying the stack configuration and t_{Cu} results in a modulation of the structural and magnetic features of the interface, which ultimately affects the spins dynamics of the glassy IrMn interfacial component.

1. Introduction

A main requirement for the technological application of giant or tunneling magnetoresistive devices, as read-heads or in magnetic random access memories (MRAMs), is to achieve a fine control of the magnetization reversal process in the ferromagnetic (FM) electrodes [1]. To this aim, the most commonly used method is coupling the FM layer to an antiferromagnetic (AFM) one by magnetic exchange interaction [2], so as to give rise to an unidirectional anisotropy for the FM spins (exchange anisotropy) because of the torque action exerted on them by the AFM spins. As a consequence, a horizontal shift of the hysteresis loop of the AFM/FM system is experienced (exchange bias, EB, effect expressed by the exchange field parameter H_{ex}) [3], which is almost invariably accompanied by a coercivity (H_C) enhancement [4,5]. Hence, it is well established that the effective magnetic anisotropy of the FM layer can be tailored by acting on several parameters, such as the AFM magnetic anisotropy and the FM and AFM layer thickness [6]. Some articles contributed to elucidate the origin of the EB phenomenon reporting about exchange biasing through a non-magnetic spacer at the AFM/FM interface [7–11]. Several models have been proposed for the exchange coupling mechanism and some of them assign a crucial role to the magnetic stability of the AFM nanograins, generally assumed as non-interacting [11–13]. A similar description was also used to account for the change of H_{ex} with time observed in IrMn/CoFe samples subjected to He ion bombardment that altered the structure and the anisotropy of the AFM component [14].

Recent studies have demonstrated the existence of AFM regions with spin-glass like magnetic properties at the interface with the FM phase, originating from the concomitance of structural disorder and existence of competing magnetic interactions as a consequence of the lack of structural periodicity [13,15,16]. In particular, we coherently explained the EB properties of IrMn/NiFe samples, in form both of continuous films and of dot arrays, considering the glassy magnetic behavior of a structurally disordered IrMn region located between the FM phase and the 'bulk' of the AFM layer, clearly detected by high-resolution transmission electron microscopy analyses [17,18]. The glassy magnetic nature of these AFM regions implies a complex magnetic dynamics of AFM spins, governed by intertwined parameters such as temperature, anisotropy energy barriers distribution and length of magnetic correlation [18–21]. In this context, in this research work, we will show that it is possible tuning the EB properties of IrMn/NiFe samples, i.e. H_{ex}, H_C and their thermal dependence, by adjusting the AFM/FM interface, namely its position in the layer-stacking sequence and its extension, through the insertions of Cu islands. The results are explained considering that this interface modulation ultimately affects the magnetic dynamics of the glassy AFM component.

* Corresponding author.
E-mail address: lucia.delbianco@unife.it (L. Del Bianco).

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2. Experimental

Samples deposition was carried out at room temperature by DC magnetron sputtering in a 2 mTorrAr atmosphere, in a static magnetic field $H_{dep}=400$ Oe. The FM and AFM phases were $Ni_{80}Fe_{20}$ (NiFe) and $Ir_{25}Mn_{75}$ (IrMn), respectively. The films were grown on a naturally oxidized Si substrate, covered by a 5 nm-thick Cu underlayer to favor crystalline order and texture and thus enhance the EB effect [22,23]. We prepared two sets of samples differing for the stack sequence: i) set A, with structure Si/Cu (50 Å)/IrMn (100 Å)/Cu (t_{Cu})/NiFe (50 Å), where t_{Cu}, the nominal thickness of the Cu layer, was 0, 0.5, 1, 2 Å; and ii) set B with structure Si/Cu (50 Å)/NiFe (50 Å)/Cu (t_{Cu})/IrMn (100 Å), with $t_{Cu}=0$, 1 and 2 Å. Hence, in set A the FM layer is grown at the top of the stack whereas it is at the bottom in set B, apart from the Cu underlayer. With reference to the set and to t_{Cu}, the samples were labeled with the general notation *set_nameCu-*t_{Cu}.

The magnetic properties were investigated by measuring hysteresis loops at temperature T in the 5–300 K range, using both a superconducting quantum interference device (SQUID) magnetometer and a longitudinal magneto-optic Kerr effect (MOKE) apparatus with the polarization modulation technique. SQUID and MOKE measurements were carried out on all the samples immediately after deposition. In the as-deposited state at $T=300$ K, all the samples appeared substantially saturated (in no sample the difference between the remanent magnetization and the saturation magnetization exceeded 10%) and horizontally shifted by exchange anisotropy. Then, the samples were stored at room temperature in a vacuum of ~10^{-3} mbar and their magnetic properties at $T=300$ K were checked by MOKE during about one year. At the end of this aging period, SQUID measurements were performed again on all the samples and no variation in their magnetic moment at saturation was detected. This is a hint that no oxidation took place during the aging period, but it is to be expected that oxygen passivation occurred when the samples were extracted from the deposition chamber.

3. Results and discussion

3.1. Magnetic structure of the interface in samples with no Cu

In this section, we describe the EB properties of samples ACu-0 and BCu-0, namely belonging to sets A and B respectively and without Cu spacer. Fig. 1(a) shows a typical hysteresis loop shifted by exchange anisotropy (in particular, it has been measured at $T=300$ K on the as-deposited ACu-0 sample). We define the exchange field H_{ex} and the coercivity H_C as positive parameters in this way: $H_{ex}=-(H_{right}+H_{left})/2$ and $H_C=(H_{right}-H_{left})/2$, H_{right} and H_{left} being the points where the loop intersects the field axis.

In Fig. 1(b), H_{ex} and H_C measured at $T=300$ K in sample ACu-0 as-deposited (time=0 days) and during a period of 300 days are reported. A marked increase in H_{ex}, passing from ~140 Oe to ~285 Oe is experienced during the first 42 days of aging; after 300 days the total variation of H_{ex} amounts to ~124%. During the whole period, H_C undergoes just a very small decrease and the final value is ~100 Oe. In Fig. 2(a), the thermal dependence of H_{ex} and H_C is shown for the sample aged 2 and 300 days. The difference in the values of H_{ex} reduces more and more with decreasing T below 300 K and is negligible at the lowest temperature. Irrespective of aging, H_{ex} and H_C decrease with increasing T, especially in the 5–100 K range, as revealed by the analysis of the derivative curves (Fig. 2(c)). This thermal evolution of the two parameters was already observed in IrMn/NiFe bilayers, independently of the position of the NiFe layer in the stack, and it was explained through a simplified model based on the existence of a structurally and magnetically disordered IrMn region interposed between the FM phase and the 'bulk' of the AFM layer [17,18]. The latter was found to consist of nanograins [18], supposed magnetically independent or just weakly interacting. It is worth recalling the main conclusions descending from such a description. Two different magnetic regimes characterize the magnetothermal behavior of the IrMn/NiFe system. At $T=5$ K, the interfacial IrMn spins are frozen in a long-range correlated glassy magnetic state and collectively involved in the exchange coupling with the NiFe spins, which results in a maximized EB effect. At $T=5$ K, H_{ex} ~860 Oe in ACu-0; the high value of H_C (~530 Oe), in comparison with that of a single 5 nm-thick NiFe reference film (~20 Oe), reveals the presence of AFM spins, which are dragged by the FM ones during the magnetization reversal (often indicated as rotatable spins in literature [24]), probably because of a lower local anisotropy within the frozen state. With increasing T above 5 K, thermal effects reduce the length of magnetic correlation among interfacial AFM spins as well as their effective anisotropy [25], leading to a marked decrease in both H_{ex} and H_C. $T=100$ K can be schematically indicated as the temperature where the collective frozen state of the interfacial AFM component breaks up, resulting in a collection of spins magnetically uncorrelated (or correlated on a very short length, i.e. small clusters). In this regime, only the AFM interfacial spins that, under the polarizing action of the bulk AFM spins, are tightly anchored to the AFM nanograins may have an effective anisotropy strong enough to produce the EB effect. Hence, for $T>100$ K, the

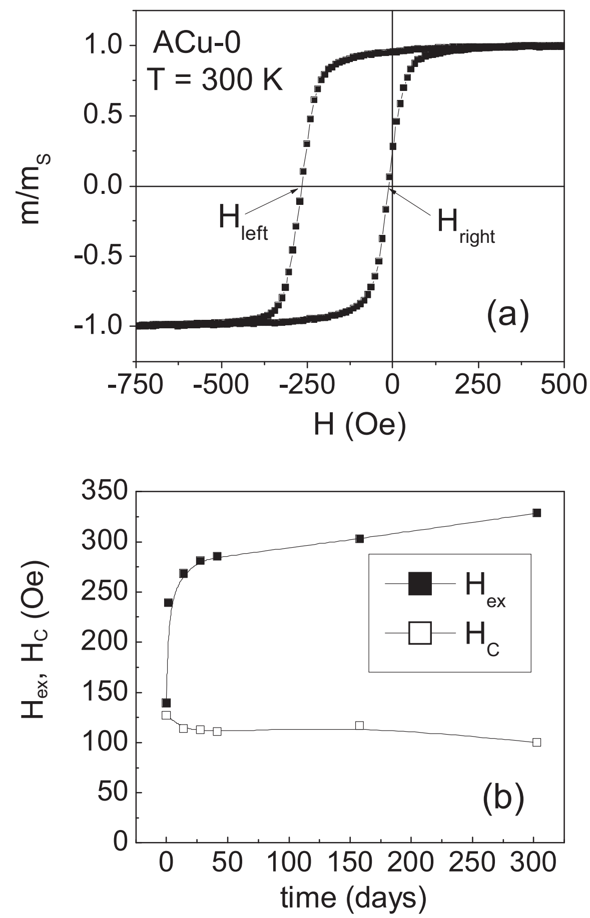

Fig. 1. (a) Hysteresis loop measured at $T=300$ K on sample ACu-0 as-deposited (normalized to the magnetic moment at saturation m_S). (b) Evolution of the exchange field H_{ex} (full symbols) and of the coercivity H_C (open symbols) with time in sample ACu-0, measured at $T=300$ K. Time=0 corresponds to the day of deposition of the film by DC magnetron sputtering. The error bars are smaller or comparable to the size of the dots. Solid lines are guides to the eye.