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The Role of Interfaces in CoFe/IrMn Exchange Biased Systems

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A trilayer system consisting of an IrMn layer exchanged coupled to two CoFe layers of equal thickness has been studied. A single stage reversal was observed over a wide range of temperatures. Two bilayers with the same thicknesses of the pinning layer but different ferromagnetic thicknesses were also studied. By comparing the magnetic properties of these three stacks the effect of the interfacial area on the exchange field and the coercivity has been determined. We find that the interfacial area has a very minor effect on the exchange field H_{ex} and the blocking temperature (T_B) but causes a doubling of the coercivity (H_c). This indicates that H_c is dominated by the interface whereas the exchange bias is controlled by volumetric effects.

***Index Terms*—Exchange bias, interface, thermal activation.**

I. Introduction

Since its discovery in 1956 most of the work reported on exchange bias systems relates to bilayers. However, there have been several studies where the antiferromagnet (AF) is "sandwiched" between two ferromagnetic (F) layers. Sankaranarayanan *et al.* [1] reported on a systematic study of the variation of the exchange field H_{ex} as a function of the thickness of all layers in Ta/NiFe/FeMn/NiFe trilayers. They found a greater exchange bias for the bottom NiFe layer. Single reversal of both F layers was only achieved in a few particular cases when for example the thickness of the FeMn layer was varied. Above 5 nm two independent reversals were observed. Similar behavior was observed by Schanzer *et al.* [2] when studying FeCoV(20nm)/NiO(t_{AF})/FeCoV(20 nm) by polarized neutron reflectivity. For $t_{NiO} < 20$ nm the reversal occurs via a single transition.

The difference between the exchange coupling at the two F/AF interfaces in trilayer structures has been the subject of several studies, e.g., [3]. In most of the studies, either the pinned material or its thickness was changed so the reversal corresponding to each interface could be easily identified. Ambrose *et al.* [3] observed four different spin structures in exchange coupled NiFe/CoO/NiFe trilayers where the two NiFe layers were 30 and 60 nm thick.

In this work we present a study of the magnetization reversal of a trilayer stack where the thicknesses of the constituting layers have been tuned in order to observe a single transition. By comparing the behavior to the reversal of two single bilayers with the same (and half the) amount of ferromagnetic material, the effect of the interface on H_{ex} and H_c is given.

II. Sample Preparation

Three polycrystalline samples were grown using a HiTUS sputtering system [4]. The system employs an RF antenna (0–2.5 kW) to ionize the Ar sputter gas. The gas pressure together with the RF controls the number of ions in the plasma. The energy of the ions is controlled by the DC bias voltage. These parameters determine the growth rate of the films which in turn controls the grain size. The samples were grown on Si 5 mm by 5 mm precut substrates. All the substrates were plasma cleaned prior to deposition. Due to the Cu seed layers the samples are not expected to be textured. A magnetic field of 300 Oe was applied during the deposition of the layers in order to induce unidirectional anisotropy. The base pressure was 1.5×10^{-7} mbar and the process pressure 2.7×10^{-3} mbar. The structure of the samples is shown in Fig. 1. All the layers were grown using the same sputtering conditions.

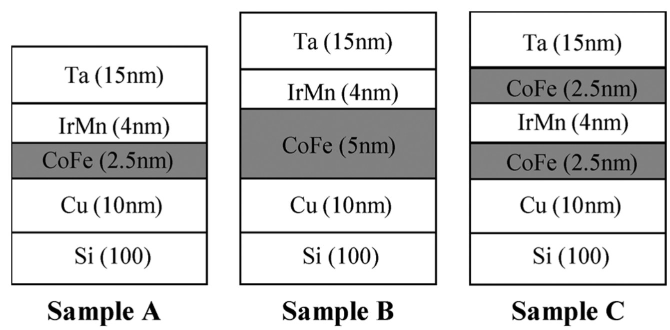

Fig. 1. Schematic diagram of the samples studied.

Samples A and B have the same interfacial area between the F and the AF whilst sample C has twice this area. Sample B and C have the same volume of CoFe and hence moment, while sample A has half of the magnetic moment. Therefore, we can compare the contribution of the interfacial area and the ferromagnetic layer thickness (t_F) on H_{ex} and H_c.

III. Measurement Protocol

The samples were measured using a vibrating sample magnetometer (VSM) with a noise base of 5×10^{-6} emu. The temperatures were stable to ± 0.2 K/hour. The time constant was 100 ms and the sweep rate 60 Oe/minute. The measurement protocol used has been described in detail previously [5]. Prior to measurement the AF was reset by heating to 373 K for 90 min

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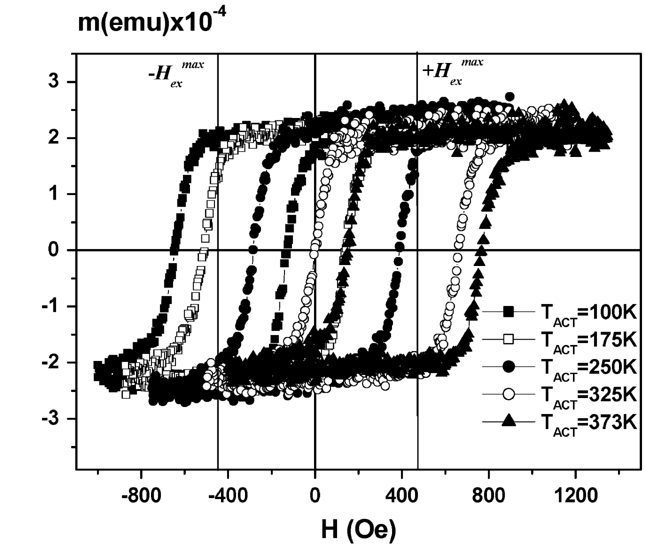

Fig. 2. Hysteresis loops for sample B (5 nm CoFe) at different $\mathrm{T_{ACT}}$.

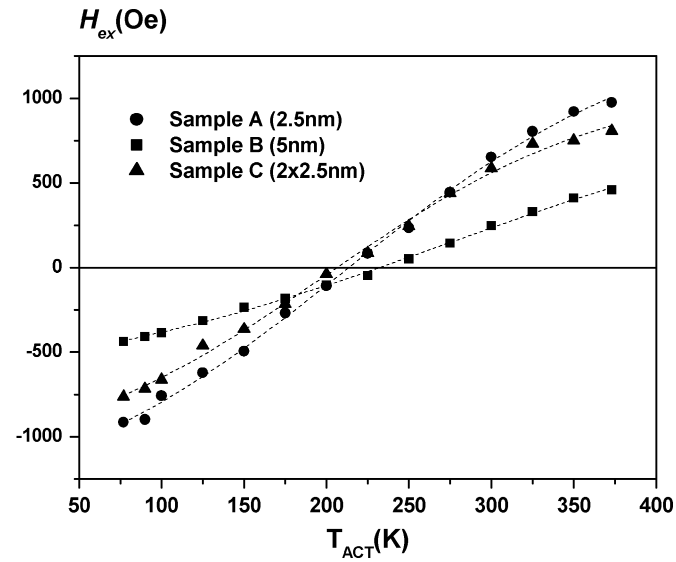

Fig. 3. Variation of $H_{\rm ex}$ with $\mathrm{T_{ACT}}$.

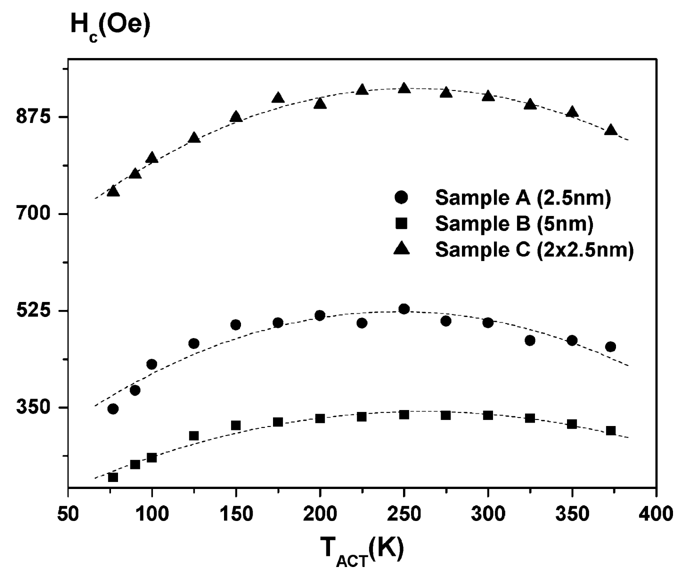

Fig. 4. Variation of $\mathrm{H_c}$ with $\mathrm{T_{ACT}}$.

in a positive saturating field. This way, we ensure that the AF is always in the same state of order prior to each measurement. The temperature is then quenched to a temperature where we establish by experiment that the AF is free of thermal activation $(\mathrm{T_{NA}})$. The field is reversed so the F is saturated in the negative direction, and the sample is then heated to an activation temperature $\mathrm{T_{ACT}}$ for 30 min. After this period the sample is cooled to $\mathrm{T_{NA}}$ and the loop is measured. Note that all the measurements are made at the same temperature $\mathrm{T_{NA}}$ of 77 K and that we first measure the ascending branch of the loop. This protocol ensures that thermal effects are reproducible and that the AF spin reorientation effect that gives rise to training is removed [6].

IV. Experimental Results

The exchange field of exchange biased systems is dependent upon thermal activation of the AF [5] and spin reorientation [6]. In our case, spin reorientation is removed by reversing the field after resetting the AF. Therefore, in this experiment the exchange field depends only on the intrinsic coupling at the interface and thermal effects. By increasing $\mathrm{T_{ACT}}$, the amount of AF material that undergoes reversal during the conditioning time increases. This way, we can shift the hysteresis loop from $-H_{\rm ex}^{\rm max}$ to $+H_{\rm ex}^{\rm max}$ reproducibly by increasing $\mathrm{T_{ACT}}$. Examples of the hysteresis loops for sample B are shown in Fig. 2.

Fig. 3 shows the variation of $H_{\rm ex}$ with $\mathrm{T_{ACT}}$ for the three different samples. All the lines are guides to the eye. Here $H_{\rm ex}$ is the field from the centre of the loop to $\mathrm{H} = 0$ measured at 77 K for the second hysteresis loop, i.e., after removal of spin reorientation of the first loop [6]. Sample C shows a single reversal over the whole range of temperatures. A comparison of the values of $H_{\rm ex}^{\rm max}$ for samples A and B indicates the well known variation of H_{ex} with $1/\mathrm{t_F}$ [7].

Sample C has two interfaces and, assuming columnar growth, we would expect one AF grain in a 4 nm thick layer. This grain would be exchange coupled to two equal F grains. When the F is at negative saturation twice the area of the AF interface is exposed to a negative exchange field. This way, the amount of AF material that undergoes reversal during the conditioning time will be larger, leading to a greater reduction of $H_{\rm ex}$ in comparison with the sample with only one interface. The slight change in the average value of $\mathrm{T_B}$, which is the activation temperature at which $H_{\rm ex}$ is zero, is probably due to slight variations in the films due to preparation conditions. This indicates that the interface area plays only a small role in the value of $H_{\rm ex}$.

Fig. 4 shows the variation of the $\mathrm{H_c}$ with temperature for the three samples. In contrast to the effect of the interfaces on H_{ex} the value of $\mathrm{H_c}$ doubles indicating that it is dominated by interfacial effects. We also note from Fig. 4 that for each sample there is a broad maximum in the coercivity which, whilst being close to the value of the average blocking temperature as seen as Fig. 3, does not exactly coincide with the average blocking temperature. We have reported on the noncoincidence of the coercivity peak with the average blocking temperature previously [5].

From our data the exact origin of the coercivity in all three systems cannot be discerned. The CoFe ferromagnetic layers used in these samples have an intrinsic coercivity at this grain size of the order of 120 Oe which is much smaller than the values obtained here [8]. Therefore, in addition to the exchange anisotropy there must be an additional mechanism present which gives rise to the dramatic increase in coercivity. Given that the coercivity in soft CoFe systems is dominated by domain wall pinning effects, the role of the interfaces on the coercivity is expected to be significant.

Reference to the literature, e.g., [9], [10] shows that there is no clear understanding of the mechanism of coercivity enhancement in exchange biased systems. Quality experimental data taken at low temperatures where there is not expected to be significant thermal activation [9] generally shows a variation of $\mathrm{H_c} \propto 1/t_F^n$. However this data is for hybrid epitaxial/polycrystalline systems and different mechanisms may be occurring.

Our data also shows a variation in $\mathrm{H_c}$ consistent with a $1/t_F^n$ variation. In our case the value of n is of the order of 0.65 at low temperatures falling to 0.55 when the sample has been activated at temperatures close to the maximum blocking temperature. This is in contrast with values of 1.5 predicted theoretically [11] and 1.0 and 2.0 reported for the experimental work [9]. Thus these results must call into question our understanding of coercivity in exchange biased systems.

The fact that both layers reverse in a single step in C suggests that the AF spin configuration at both interfaces is the same. We could assume that this is due to a 360° domain wall propagating along the AF thickness. The energy associated with this domain wall would be $E_{\mathrm{DW}} = 16\sqrt{AK_{\mathrm{AF}}}$ where A is the AF exchange stiffness and K_{AF} its anisotropy constant. Using typical values from the literature ($A \approx 10^{-6}$ erg/cm and $K_{\mathrm{AF}} = 1.8 \times 10^6$ erg/cc [12]) gives a value for E_{DW} of 21.5 erg/cm^2. However, if a granular reversal process is assumed, the energy/area would be given by $K_{\mathrm{AF}}\mathrm{D}_m$ where D_m is the AF mean grain size. In order to calculate $\mathrm{D_m}$ a sample with composition Cu(10 nm)/CoFe(2.5 nm)/IrMn(4 nm) was grown on a TEM grid. Plan view TEM images in bright field mode at 200 keV and $\times$ 60 k magnification were obtained using a JEOL JEM-2010 TEM. The diameter of 600 particles were measured and fitted to a log-normal distribution. $\mathrm{D_m}$ was calculated using the cumulative percentage method giving a value of 7.9 nm. Using this result, the energy per unit area associated with the process is 1.4 erg/cm^2. Therefore, a granular process is more energetically favorable than a domain one.

Thus in conclusion we have shown that the interfacial area between an AF and an F layer in exchange bias systems is capable of modifying both the exchange field and the coercivity. However our results and previous data [13] show that the value of the exchange bias is dominated by thermal activation of the AF grains whereas the coercivity is only affected by those spins at the interfacex.

Acknowledgment

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