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Influence of Cu seed layer on the magnetization reversal in exchange-biased FeMn/FeCo systems

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Abstract. Magnetization hysteresis loops are measured on FeMn/FeCo bilayers. The existence of the exchange bias effect up to room temperature is guaranteed by the presence of copper as a seed layer. We demonstrate that the choice of the growth parameters for Cu allows the control of the magnetic response of the structure, tuning the coercivity and the exchange field. The switching field distribution suggests different magnetization reversal mechanisms during the ascending and descending branches of the hysteresis loop. The evident noisy character of the data, during the reversal of the magnetization with respect to the initially set orientation, supports the picture of domain wall motion involving pinned states at magnetic defects, contrasting with the coherent magnetic moments rotation along the opposite branch.

1 Introduction

Exchange Bias (EB), first discovered in 1956 [1], is a phenomenon utilized nowadays in many spintronics devices, which consists in a shift of the hysteresis loop along the magnetic field axis in ferromagnetic/antiferromagnetic (FM/AFM) coupled arrangements. Among the technological applications exploiting the properties of EB systems, we mention spin valves present in magnetic recording read heads and MRAM memories, based on the phenomenon of giant or tunnel magneto-resistance.

Although many theories have been proposed to explain this important magnetic phenomenon, no definite and universal model can account, so far, for all the observations made on the many different systems that have been studied: nanoparticles, epitaxial films, polycrystalline structures, etc. [2].

Therefore, the work of theorists and experimentalists has proceeded in parallel since the EB constitutes a very challenging subject for both applicative and speculative points of view [3].

Clearly, in order to use this phenomenon in a real device, it is fundamental that it shows up at room temperature (RT).

To pursue such a goal, we have devoted an extensive study on a promising system, namely the FeMn/FeCo bilayer system [4]. In fact, FeMn is an AFM material with bulk Néel temperature of about $T_N = 500$ K. This guarantees a good magnetic stability of the AFM-FM exchange interaction at RT. Moreover, the FM FeCo alloy is also interesting for its magneto-elastic properties, which are promising for possible applications. This makes it important to know the specific magnetic properties of this particular system. We examined a large series of samples with the intent of exploring how the details of the growth conditions influence the coercive and EB fields (H_C and H_B). We varied thickness and growth rate of each individual layer, in order to optimize the magnetic response and enhance H_B.

In this paper we report the results for a selected choice of the samples, after some of the growth parameters had been already optimized. We show how the parameters H_C and H_B can be in principle tuned by varying the growth conditions of the seed layer underneath the AFM/FM stack and how it is possible to evidence some details on the irreversibility mechanisms leading to the exchange bias phenomenon.

A more extensive study on the entire series of samples and on a deeper characterization will be published elsewhere [5].

2 Sample preparation and experimental details

Different Si(100)/Cu/FeMn/FeCo/Cu multilayers were grown by rf magnetron sputtering, at room temperature. The presence of Cu as underlayer is due to the fact that it facilitates the growth of FeMn [4]. The Cu capping layer protects the multilayer from oxidation. FeCo and FeMn layers were grown from $Fe_{50}Co_{50}$ and $Fe_{50}Mn_{50}$ alloyed targets at a rate of 1.5 Å/s and 7 Å/s, respectively. The nominal thicknesses were 16 nm and 10 nm for FeCo and FeMn, respectively. These values were chosen after several attempts had been made until an appreciable EB effect was observed up to RT.

During the growth, the film was exposed to a magnetic field, along the substrate plane, of about 700 Oe. Immediately after, each sample was heated at 250°C for 30 minutes and then slowly cooled down in presence of a magnetic field of about 500 Oe, in the same orientation as the previous field. The field cooling (FC) procedure at a temperature above T_N guarantees to set the AFM/FM interface in order to trigger the EB effect.

In table 1 we report the description of the samples discussed in this work.

Table 1. Samples characteristics of the Si(100)/Cu/FeMn /FeCo /Cu multilayers. The growth parameters of FeMn and FeCo are common to all samples (see text). The growth parameters in columns 2 and 3 refer to the Cu buffer layer. The magnetic parameters indicated in the last two columns are room temperature values.

sample	Cu rate (Å/s)	Cu thick-ness (nm)	H_C (Oe) (RT)	H_B (Oe) (RT)
A	7.0	10	23	41
B	6.5	50	26	70
C	14.6	50	45	66
D	20.6	50	69	73

The four samples differ only for the underlayer Cu growth characteristics, as indicated. In sample A the Cu underlayer is sensibly thinner than the other samples. Samples B, C, and D are in ascending order of the Cu growth rate.

Hysteresis loops where recorded using a magneto-optical (MO) apparatus, measuring the change in polarization of a reflected laser beam, initially linearly polarized (s-polarization), incident at 45% on the sample surface. The magnetic field was varied along the film plane, in the same direction as the growth and FC fields. This geometry corresponds to the so called longitudinal MO Kerr effect (MOKE). This apparatus can operate in the temperature range between 4 and 320 K.

We also made use of an alternated gradient magneto-meter (AGM) (Micromag 2900 - Princeton Corporation) for hysteresis measurements, which operates at room temperature but with a much finer field increment (depending on the swept interval of the magnetic field), which allows a better observation of the magnetization reversal mechanisms.

3 Experimental results and discussion

Figure 1 shows an example of the MOKE hysteresis loops measured for sample D. The two curves were collected at 300 K and 30 K, respectively. Both loops present high squareness and high remanence/saturation ratio. The EB effect is evident, as well a decrease of both H_C and H_B with increasing temperature. Nevertheless, an appreciable EB effect persists at RT with coercivity well above the commonly found values for the soft FeCo alloy.

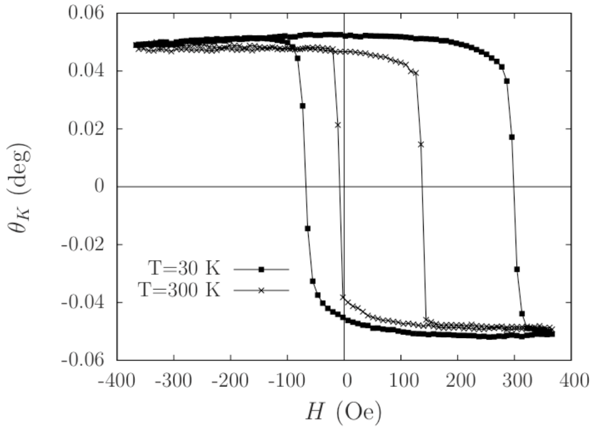

Fig. 1. MOKE hysteresis loops for sample D at low and high temperature. The exchange bias effect persists up to room temperature.

Hysteresis loop data were collected for all samples at various temperatures, and for each loop the coercive and EB fields were calculated. The complete evolution of these two parameters is shown in figure 2 as a function of temperature for all samples. There is a qualitative typical tendency for both parameters to decrease with increasing temperature. However, it is important to notice how the details differ from sample to sample also that EB is preserved at RT.

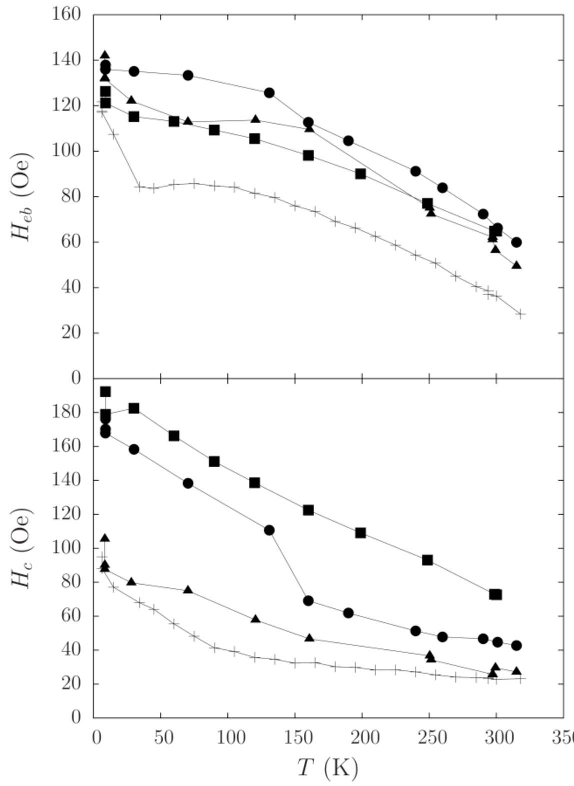

Fig. 2. Temperature dependence of the EB (top) and coercivity (bottom) for samples A (crosses), B (triangles), C (circles), and D (squares). As shown in table 1, they differ for the growth parameters of the Cu underlayer.

Values of H_B and H_C at RT are also reported in the last two columns of table 1. It is evident that the Cu buffer layer thickness mainly influences the exchange bias, whereas the Cu growth rate affects mostly the coercivity, with an almost linear dependence, at RT, between the rate and the magnetic parameter. From a more accurate observation of the temperature dependence, we emphasize that H_B is very similar for all the samples at T = 7 K, with a sudden linear drop of this value for sample A up to T = 30 K. Assuming a granular character for our samples, this indicates that the size distribution of the AFM layer is strongly influenced by the Cu underlayer thickness. In fact, a thicker Cu layer may induce the presence of larger FeMn grains in the AFM layer which will be more magnetically stable at higher temperatures maintaining the exchange interaction with the upper FM layer [6]. In this respect, the linear drop at low temperature of the bias field for sample A must correspond to a significant small size component in its grain size distribution, not present in the other three samples. Moreover, the dependence of coercivity on Cu growth rate could be related to the degree of disorder in the AFM layer induced by a similar disorder in the Cu layer. This is consistent, for example, with partial domain-wall models which interpret the enhanced coercivity in terms of wall pinning at magnetic defects [7]. These defects decrease locally the anisotropy and lead to an overall reduction of the AFM energy providing an energy barrier for wall motion and consequent pinning of the domain walls at such positions, contributing to the coercivity. The irreversible rotation of magnetization in the ferromagnet, due to a combination of wall pinning and depinning transitions, gives rise to the observed asymmetric hysteresis loops. Therefore, the growth parameters of the seed layer control, indirectly, the details of the exchange interaction at the AFM/FM interface and the irreversible character of the magnetization inversion of the FM layer.

In order to explore this aspect, we also made a very preliminary study trying to understand the magnetization reversal mechanisms which govern the details of the hysteresis curve shapes. For this investigation we measured RT loops using the AGM apparatus incrementing the magnetic field in very fine steps. The reversal of magnetization is better highlighted if the derivative of the magnetization with respect to the external magnetic field H is plotted as a function of H. This so called switching field distribution (SFD) is shown in figure 3 for sample D (bottom-left). Qualitatively similar plots are found also for the other samples. The top plot refers to the original magnetization hysteresis loop from which the SFD has been calculated. On the right, for comparison, we report the results obtained from a Si(100)/Cu/FeCo/Cu sample, with identical growth parameters as for sample D except that it does not contain the AFM layer and, therefore, without EB.

Contrarily to what observed for the sample without exchange bias, there is a clear asymmetry between the two peaks in the SFD of sample D, not only in the position (related to the EB field), but also in the shape. Both branches reveal distinct profiles, suggesting a different reversal magnetization mechanism in the two

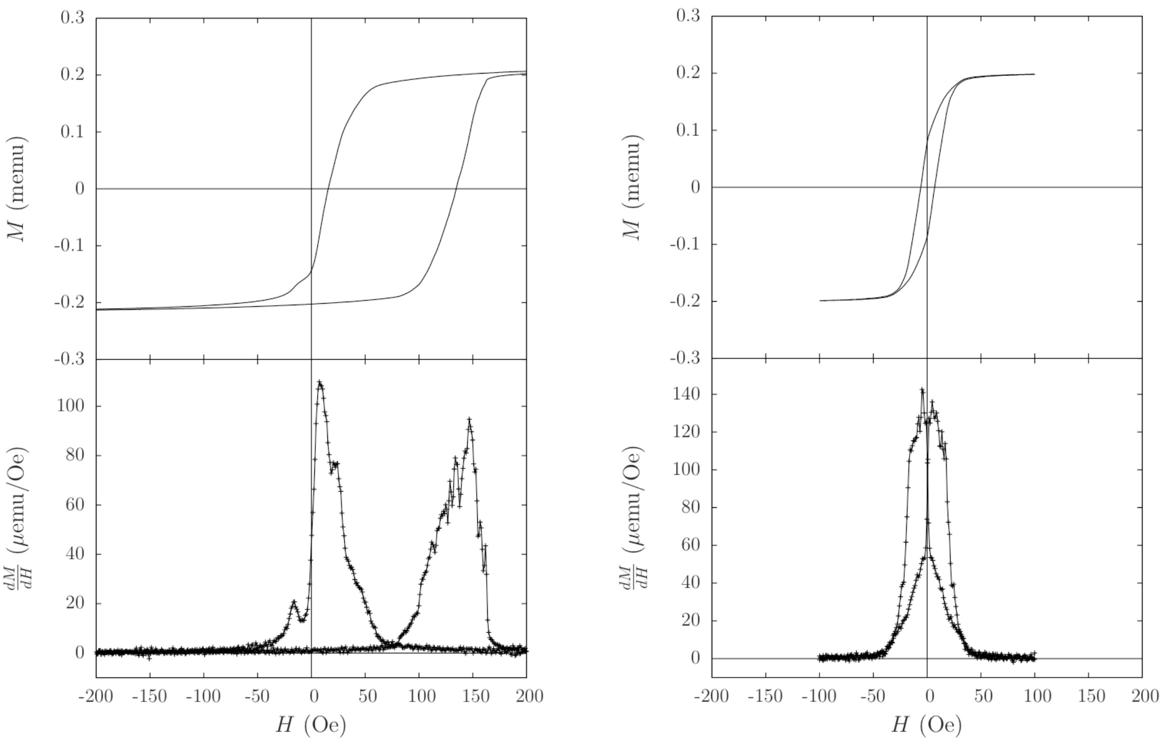

Fig. 3. Magnetization hysteresis loops (top) and corresponding switching field distributions (bottom) obtained with the AGM apparatus . The plots for sample D (left) are compared with the results (right) on a sample obtained with the same growth parameters except for the absence of the FeMn layer.

cases besides a structured grain size distribution. This remark is even more strengthened if we observe that the right peak, which originates when the magnetization switches from the initial orientation that minimizes the exchange energy at the AFM/FM interface toward the opposite orientation, is much more noisy than the other. It is conceivable to think that this behaviour originates from sudden consecutive breaking of domain walls and consequent jumps from a pinning magnetic defect to the next one, whereas the smoother SFD observed when the magnetization switches back to the initial more stable orientation is related to a coherent rotation of the magnetic moments. This conjecture is consistent with similar conclusions derived from polarized neutron reflectivity, anisotropic magneto-resistance and Kerr microscopy on CoO/Co bilayers [8, 9].

4 Conclusions

In this paper we showed that FeMn/FeCo bilayers grown by rf magnetron sputtering on silicon, using Cu as a seed layer, can exhibit exchange bias at room temperature. The coercive and exchange bias fields can be tuned by adjusting the growth parameters of the Cu layer, without directly modifying the sputtering parameters during the growth of the AFM and the FM structures. This indirect action of the copper layer on the magnetic response may be potentially exploited in view of a practical application in a technological device since it allows adjusting the range of the operating magnetic field to the desired value.

We also showed some evidence of the different irreversible mechanisms controlling the inversion of the magnetization as the field is swept along the two distinct branches of the hysteresis loops. The observation of the peculiar noisy branch detected during switching from the initial more energetically stable magnetization orientation to the reversed state, suggests a mechanism of domain walls motion regulated by consecutive jumps and encourages to further investigate in detail such phenomenon which can give an important insight on the magnetic configurations and interactions, at a microscopic level, in proximity of the AFM/FM interface which are responsible for the macroscopic parameters of the exchange bias effect.

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