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The dependence of magnetic properties of Co/FeMn bilayer structure on the magnitude of magnetic field applied during the layer deposition

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Abstract. By measuring the angular dependence of ferromagnetic resonance field at room and low temperatures, it is demonstrated that the magnitude of magnetic field applied during magnetron deposition of Ta/Co/FeMn/Ta structures influences their magnetic properties such as uniaxial and unidirectional anisotropy, magnetization and the exchange bias blocking temperature. The deposition field effects on the bilayer structure are compared with the effects on a similar structure, but without antiferromagnetic layer. The exchange bias blocking temperature of investigated structures is found to be significantly lower than the Néel temperature of a bulk antiferromagnet. The origin of the observed effects is shortly discussed.

1. Introduction

In spite of more than 50 years history since the discovery and a high importance for development of magnetic information storage media, the exchange bias effect in a bilayer ferromagnet(F)/antiferromagnet (AF) structure still has a number of open issues. The exchange bias is normally detected by a shift of hysteresis loop. It can be induced in F/AF structures by layer deposition in magnetic field, first F-layer in the magnetically saturated state and then, on top of it, an AF-layer. The exchange bias also can be induced by thermal annealing at a temperature which is higher than the Néel point of the antiferromagnet transition into the paramagnetic state, but lower than the Curie point of the ferromagnetic layer, followed by cooling in magnetic field. In both cases the external magnetic field induces magnetic anisotropy and saturates the F-layer, which in its turn, induces the anisotropy in the AF-layer. In such a simplified picture, the magnetic moment of the F-layer plays a major role in the magnetic ordering and initiating the anisotropy of the AF-layer, while the magnitude of the external magnetic field is not of importance as soon as it is higher than the value for F-layer saturation. However, the experimental findings are not definite to support this picture. In fact, there is a number of evidences showing the field dependence of the magnitude and even the sign of the exchange bias (see a summary of the observations and references in the reviews [1, 2]). Shortly, the nature of the observed effects is unclear and experimental data are insufficient to make an
unambiguous conclusion about the role of the magnitude of the external field in appearance and strength of the exchange bias in F/AF bilayers.

This paper reports on the results of our study of the exchange bias generation in Co/FeMn bilayer structures during the layer deposition in presence of the magnetic field. The influence of the applied magnetic field magnitude on the magnetic properties of this bilayer structures is demonstrated and compared with that of a free Co layer.

2. Experimental techniques

The specimens were deposited by DC magnetron sputtering, using the magnetron sputtering system ATC ORION-5 produced by AJA INTERNATIONAL. The base pressure prior the deposition was of the order of $10^{-7}$ Torr and the pressure of argon atmosphere during the deposition was about 2.5 mTorr. Two permanent magnet plates were fixed on the specimen holder with the substrates being placed in the magnet poles gap. The magnitude of the magnetic field was varied by changing the gap width. To clean the surface and remove a native oxide, Si (100) substrates were dipped for 30 seconds in hydrofluoric acid before the sputtering. The multilayer structures Si/Ta/Co7nm/FeMn15nm/Ta were deposited onto the substrates in presence of 40, 420 and 1000 Oe magnetic field applied in plane of the substrate at ambient temperature. For comparison, also the structures Si/Ta/Co7nm/Ta, where F-layer did not contact with AF-layer (free Co-layer), in 40 and 420 Oe magnetic fields were deposited.

The magnetic properties of the structures were studied using the angular dependence of the ferromagnetic resonance (FMR) field. This method is characterized by a high sensibility, simplicity and possibility to investigate ferromagnetic layers covered by insulating, diamagnetic or antiferromagnetic layers that is hard to realize in MOKE and SQUID methods. The FMR is used for investigation of high-frequency properties of ferromagnetic materials [3], their anisotropy and saturation magnetization [4]. The FMR method can be also effectively used for exchange bias phenomenon investigation [5, 6, 7].

In this method the absorbed energy of microwave field, applied perpendicular to the direction of the external DC magnetic field is measured. The saturation magnetization $I_s$ and uniaxial anisotropy field $H_K$ can be obtained scanning the FMR DC field aligned along the easy (EA) and hard (HA) axes and using the Kittel equations [8]:

$$\omega^2 = \gamma^2 (H_{EA}^R + H_E) (H_{EA}^H + H_E + 4\pi I_s)$$ (1a)
$$\omega^2 = \gamma^2 (H_{HA}^R - H_E) (H_{HA}^H - H_E + 4\pi I_s)$$ (1b)

Here $\omega = 2\pi f$ - the frequency of RF field applied, $\gamma = ge/(2mc) \approx g \cdot 8.79 \cdot 10^6$ (G s$^{-1}$) - gyromagnetic constant, $H_{EA}^R$ and $H_{HA}^R$ - the value of resonance fields along the easy and hard axis, respectively. These equations could be also generalized for the case of an arbitrary orientation of the FMR DC field with respect to the vector of the unidirectional anisotropy field [4, 5, 9].

For a sample with a large saturation magnetization, $4\pi I_s > > H_s$, the resonance peak position $H_r$ is governed by intrinsic resonance field $H_{r0} = (\omega^2/4\pi I_s)$ of the Co-layer, bidirectional uniaxial crystallographic anisotropy field $H_K$ and unidirectional anisotropy field $H_{EB}$. If the sample is aligned with an angle $\theta$ between the unidirectional exchange bias field, which is parallel to EA of the F-layer, and the FMR DC magnetic field direction, then [4, 5]:

$$H_r = \frac{\omega^2}{4\pi I_s} - H_{EB} \cos \theta - H_K \cos 2\theta$$ (2)

Since the EA directions in our samples are set by the direction of the field during the deposition, in our experiment $\theta$ is the angle between the FMR DC magnetic field direction and the direction of deposition field.

The FMR investigations were carried out, using BRUKER ELEXSYS e500 setup with RF frequency of 9.65 GHz. A rectangle type resonator E$^{102}$ was used. The temperature dependence of the
specimens’ magnetic properties in the range of 115K to 300K was investigated by setting a cryostat into the resonator and cooling the cryostat by a liquid nitrogen vapor blowing.

3. Experimental results

3.1. Exchange bias
The exchange bias of 14 Oe was detected at room temperature only in the Co/FeMn sample deposited in presence of 1000 Oe magnetic field. The samples deposited in magnetic field of 40 Oe and 420 Oe did not exhibit exchange bias at room temperature. The temperature dependence of exchange bias for the sample deposited in 420 Oe field is shown in figure 1. The magnitude of exchange bias decreases with increasing of the measuring temperature. The blocking temperature at which the exchange bias vanished was about 250K, which is much lower than the Néel temperature for the bulk Fe$_{50}$Mn$_{50}$ ($T_N = 490$ K [1]).

![Figure 1. The temperature dependence of the uniaxial anisotropy (at the top) and of the exchange bias (at the bottom) for F/AF bilayer structure (squares) and free Co structure (circles) deposited in applied field of 420 Oe.](image)

3.2. Uniaxial anisotropy
The temperature dependences of uniaxial anisotropy for F/AF structure and free Co layer deposited in the magnetic field of 420 Oe are given in figure 1. While the value of $H_K$ for the free Co layer almost monotonically decreases when the temperature rises, the dependence of $H_K$ for F/AF system shows a peak shape with a maximum at the temperature where the exchange bias vanishes for this structure, i.e. at $T = T_B$. The higher the temperature the closer $H_K$ for the F/AF system to that for the free F-layer samples, however, these values do not become equal even above the blocking temperature. This comparison signalizes that with increasing the temperature the exchange interaction between F and AF layers weakens but does exist even above the blocking temperature.

The magnitude of the uniaxial magnetic anisotropy varied with alteration of the deposition field. The dependence shown in figure 2 reveals that the uniaxial anisotropy $H_K$ increases approximately linearly with increase of the deposition field. The field dependence of $H_K$ for the free Co layer, also
shown in figure 2, behaves in a similar way. With increasing of the deposition field the difference between $H_K$ for F/AF bilayer structure and for the free F-layer also increases.

![Figure 2. The dependence of the uniaxial anisotropy on the magnetic field applied during the deposition for F/AF bilayer (squares) and free Co (circles) structures.](image)

3.3. Intrinsic resonance field

The intrinsic resonance field $H_{r0}$ characterizes only ferromagnetic layer and is determined by its saturation magnetization via relation $H_{r0} = (\alpha/\gamma)^2/(4\pi I_s)$. The magnitude of $H_{r0}$ also depends on the magnitude of the magnetic field applied during the structures deposition. The field dependence of $H_{r0}$ (figure 3) is more complicated than field dependence of $H_K$. With increasing of the deposition field from 40 to 420 Oe the intrinsic resonance field slightly increases, then with the further increase of deposition field $H_{r0}$ sharply decreases. At the same time, the intrinsic resonance field of the free Co layer remains constant and is very close to that one of the Co layer deposited in absence of magnetic field, thus no field dependence was observed. This $H_{r0}$ value is also equal to the $H_{r0}$ value for the F/AF system deposited in absence of the magnetic field. This observation evidences the absence of exchange interaction between the F and AF layers in this case because of antiferromagnetic disorder on the interface.

![Figure 3. The intrinsic resonance field as a function of the deposition field for F/AF bilayer structures (squares) and free Co layer (circles).](image)

![Figure 4. The temperature dependence of the intrinsic resonance field for F/AF bilayer structure (squares) and free Co layer (circles) deposited in magnetic field of 420 Oe.](image)
In figure 4 the temperature dependences of $H_{r0}$ for the deposited in 420 Oe field F/AF and free-F structures are represented. One can see that such dependence for bilayer structure is not monotonic, while the intrinsic resonance field for the free-Co layer almost does not vary. One can also notice that the intrinsic resonance field of the bilayer structure remains at all temperatures higher than that for the free-F sample. Keeping in mind the inverse dependence of $H_{r0}$ on $I_s$, the saturation magnetization of the free-F layer remains higher that the saturation magnetization of the pinned F-layer in the F/AF structure.

4. Discussion

The fact that the exchange bias blocking temperature is below the Néel temperature of a bulk antiferromagnet is explained in a number of papers as a result of low-scaling effect [10]. According to this model the Néel temperature of AF nanofilms is lower than the Néel temperature of bulk AF and this temperature becomes lower while the AF film becomes thinner. But even taking into account this effect the Néel temperature still is not as low as blocking temperature we have obtained. It is essential to bear in mind that the Néel critical point marks the transition to paramagnetic state, while the blocking temperature marks the point of vanishing exchange bias, meaning an averaging out to zero balance of the magnetic moments of the AF layer at the interface in close contact with the F-interface layer. In other words, exchange interaction may exist even at temperatures above the blocking point, but not in average. Our results reported above give a certain evidence for this suggestion.

It is also important to notice that the blocking temperature normally has a certain local variation. As far as an ideal interface is an approximation and the interface roughness always reflects the layer thickness variation from point to point that is followed by widening of the blocking temperature local variation. It also seems to be true that as the roughness increases the average blocking temperature decreases. Our analysis did not reveal any correlation between the deposition field and the surface roughness of the samples. The largest roughness was observed for the sample deposited at 420 Oe. The sample deposited at 40 Oe was characterized by almost smooth surface, but the blocking temperature of this sample still remained below the room temperature. As for the structure deposited at 1000 Oe the surface was also almost smooth but the blocking point in this case was above the room temperature. From this we conclude that roughness is not the most important factor affecting the blocking temperature. In our case the blocking temperature variation is probably caused by variation of the grain size distribution in AF layer which may be somewhat different for different deposition field.

The comparison of the temperature dependences of uniaxial anisotropies of Co in F/AF system and of free Co structure shows that the interaction between the F and AF layers still remains even at temperatures above the blocking point. A persistent exchange interactions above the blocking temperature was also observed in comparison of coercivity of Co layer in contact with IrMn and of free Co layer [11].

The comparison of the field dependencies of the uniaxial anisotropies for the F/AF and free Co layer structures proves that the interaction between the F and AF layers becomes stronger for stronger deposition field. In the cases of layer deposition in magnetic field of 40 and 420 Oe the interaction between F and AF layers was too weak to withstand the thermal oscillation energy.

The fact that the intrinsic resonance field of the free Co layer is close to that of the bilayer structure deposited in absence of magnetic field proves that there is no exchange interaction between F and AF layers in this case. The magnetic properties of the structures deposited at 40 Oe are close to those of the structures deposited without magnetic field. With the increase of the deposition field the difference in $H_K$ and $H_{r0}$ also increases. These observations evidence that the increase of the deposition field leads to the enhancement of the exchange interaction between F and AF layers at the interface.
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