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Influence of Magnetic Prehistory on The Exchange Bias in $Fe_{20}Ni_{80}/FeMn/Fe_{20}Ni_{80}$ Films

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Abstract

In this work peculiarities of the hysteresis properties formation in permalloy layers included in $Fe_{20}Ni_{80}/FeMn/Fe_{20}Ni_{80}$ films were investigated. Temperature dependencies of magnetization reversal parameters were analyzed in the temperature range 5-300 K for samples with various FeMn thickness (2÷4 nm). Conditions of the exchange bias emergence were determined. Magnetic history was shown to have a significant effect on the magnitude and the character of the exchange bias.

Keywords: films, exchange bias, thickness, temperature, antiferromagnet, anisotropy

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1. Introduction

Magnetic nanocomposites consisting of exchange coupled structural elements are the objects of increased interest within modern materials science [1]. Thin films containing ferromagnetic and antiferromagnetic contacting layers are the striking example of such composites. So-called unidirectional magnetic anisotropy, or exchange bias [2, 3], being functionally significant property for a number of magnetoelectronics devices is observed, in particular, in these structures [4]. Exchange bias manifested in the form of the hysteresis loop of a ferromagnetic layer by shifting the magnetic field axis by an amount H_e. H_e is dependent on the efficiency of the interlayer exchange coupling and thicknesses of the individual layers of magnetic properties, and also from the external environment, in which interlayer connection is formed. This work is devoted to the study of the temperature of the magnetic properties of membrane structures such as $Fe_{20}Ni_{80}/FeMn/Fe_{20}Ni_{80}$, containing FeMn antiferromagnetic layer of a variable thickness and having different magnetic prehistory.

2. Methods

Multilayer films $SiO_2/Ta/Fe_{20}Ni_{80}/FeMn/Fe_{20}Ni_{80}/Ta$ were obtained by magnetron sputtering in an Ar atmosphere. The base pressure was $1*10^{-3}$ torr. Residual gas pressure did not exceed $5*10^{-7}$ torr. The substrates were glass Corning, subjected during spraying to the high-frequency electric displacement. Deposition of films was held in a homogeneous technological magnetic field of an intensity of 150 Oe, oriented

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parallel to the plane of the substrate. The composition of the multilayer structure includes two ferromagnetic layers of permalloy $Fe_{20}Ni_{80}$ and layer of antiferromagnetic FeMn. Ta layers are additional and have a thickness of 5 nm. The inner layer of Ta, adjacent to the substrate, performed structure-function outer layer of Ta has a protective role. The thicknesses of layers of permalloy were fixed (inner layer – 5 nm, outer layer – 40 nm). The thickness L of FeMn layer was varied for different samples in the range of 2÷4 nm. Measurement of magnetic properties were performed using MPMS-XL-7 in a temperature range of 5 ÷ 300 K and magnetic field up to 7 T and the magneto-optical Kerr effect microscope (MOKE) at room temperature.

3. Results

It has been found that at room temperature in films with the specified thickness parameters unidirectional anisotropy is absent and the magnetization reversal is carried out by a single hysteresis loop. For example, loop for a sample with thickness L = 4 nm is shown in the inset of Figure 1. As can be seen, it has almost rectangular shape and a relatively large coercive force H_c. However, the coercive force decreases with decreasing FeMn layer thickness for more than an order of magnitude and at a thickness of $L \leq 2$ nm reaches the level of a typical permalloy films (Fig. 1). Due to the large difference in the thickness of layers of permalloy, their considerably varying properties influence on a hysteresis. Therefore, their combined reversal indicates a sufficiently strong interlayer coupling, and the symmetry of the magnetic field on the axis – the lack of action by fixing FeMn layer. This layer of the small thickness may have a lack of magnetic anisotropy to prevent magnetization reversal layer permalloy, or even be magnetically disordered. Based on the dependence H_c(L), one can assume that antiferromagnetism in the FeMn layer is present, but weakens in process decrease L. Otherwise, the existence of the paramagnetic layer between the ferromagnetic layers should lead to significantly lower values of H_c [5].

Decrease of temperature leads to a substantial change in the nature of magnetization reversal of film structures. For samples with $L \geq 3$ nm hysteresis loops acquire a stepped form (Fig. 2a) and overall are shifted by the magnetic field axis. This reflects a consistent reversal permalloy layers and magnetic fixing at the expense of exchange coupling with an antiferromagnetic layer of FeMn. The latter is characterized by the exchange bias fields H_{e1} and H_{e2} for layers with thicknesses of 40 and 5 nm, respectively. In films with less thickness L, separate magnetic reversal of the ferromagnetic layers is not observed, but the exchange bias is present (Fig. 2b).

Figure 3 shows the temperature dependence of the exchange bias field $H_{e1}(T)$ and $H_{e2}(T)$ for samples with split (curves 1-3) and $H_{e1}(T)$ for samples with associated (curves 4, 5) reversal permalloy layers. They were obtained from the hysteresis loops at MPMS –XL-7 by the following measuring procedure. Each sample was magnetized at room temperature in a superconducting solenoid to 70 kOe. Then, the current in the solenoid was reduced to zero and a sample was cooled to 5 K. In this case, the actual residual field in the solenoid was about 15 Oe. The measurement of hysteresis loops was carried out in the range of magnetic field from 2 kOe to -2 kOe at 5, 50, 100, 150, 200, 250,

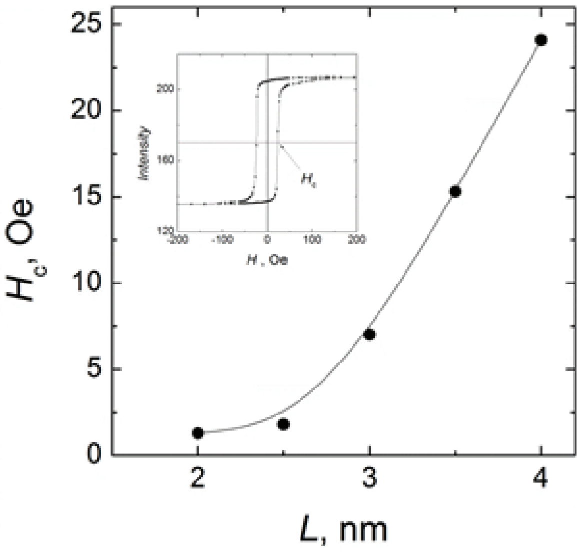

Figure 1: Dependences of coercivity H_c of films $Fe_{20}Ni_{80}$/FeMn/$Fe_{20}Ni_{80}$ vs. layer thickness of FeMn at room temperature. The inset shows the magnetooptical hysteresis loop of the sample with L = 4 nm.

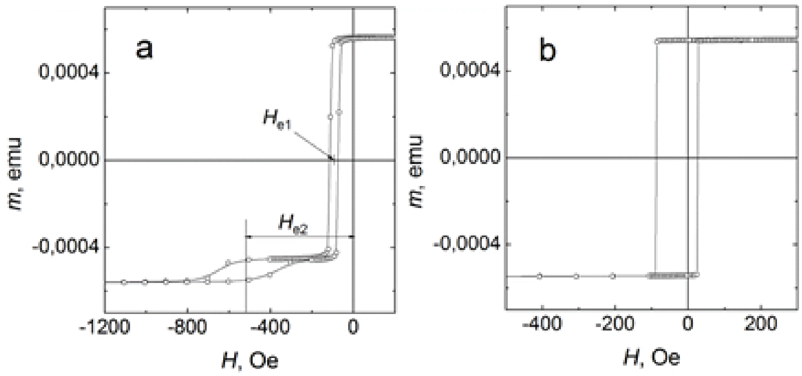

Figure 2: Magnetometer hysteresis loops measured at 5 K for samples with different thickness FeMn: a – 4 nm; b – 2 nm.

and 300 K. As can be concluded from the data presented in Figure 3, magnetic lock (the emergence of the exchange bias) was implemented in all studied samples, but the blocking temperature reduced with decreasing L. Probably, it reflects the change in the relationship between the anisotropy energy of the antiferromagnetic layer and the Zeeman energy of the ferromagnetic layers. In the case of a two-stage magnetic reversal, a big difference is seen between the fields of H_{e1} and H_{e2}, which is the result of differences in the thickness of the ferromagnetic layers. The temperature dependence of these fields is of the same character, showing a sharp increase in the exchange bias with decreasing temperature. But the thinner layers of FeMn are, the smaller the level of the exchange bias is.

To understand the causes of the observed changes in the exchange bias, it is reasonable to use a description with the help of the so-called exchange coupling constants K_s. It is calculated using the formula $K_s = | H_{e1} | L_1 M_s$, where L_1 and M_s are thickness and spontaneous magnetization of the ferromagnetic layer, correspondingly, and H_{e1} – field of its exchange bias. Figure 4 shows the dependence of K_s (L), resulting in a layer with

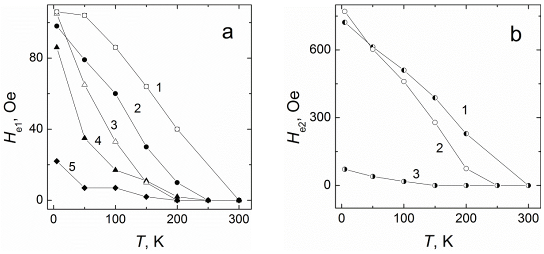

Figure 3: Dependence of the absolute values of the exchange bias field of temperature for samples with different FeMn layer thickness: 1 – 4 nm; 2 – 3.5 nm; 3 – 3 nm; 4 – 2.5 nm; 5 – 2 nm.

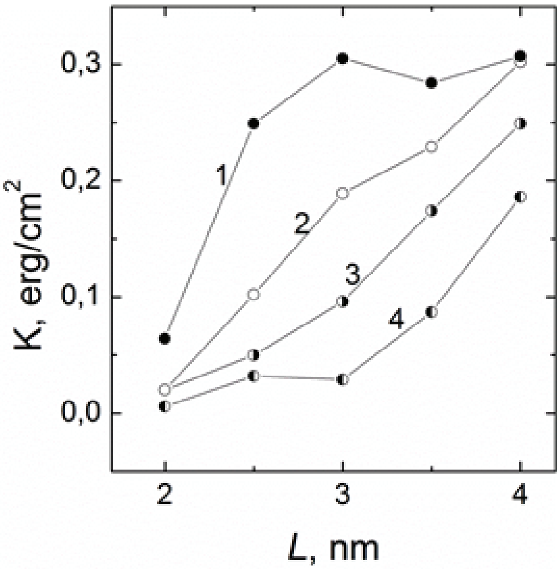

Figure 4: Dependence of the exchange coupling constant of FeMn layer thickness at different temperatures: 1 – 5 K; 2 – 50 K; 3 – 100 K; 4 – 150 K.

L_1 = 40 nm. Corresponding values of M_s for different temperatures were determined experimentally and showed a variation of 740 Gs at 5 K to 720 Gs at 150 K. As can be seen, K_s exhibits strong growth with an increase of the antiferromagnetic layer thickness. However, level of the coupling constant and nature curves $K_s(L)$ depend on the temperature. In particular, with decrease of temperature dependence $K_s(L)$ has a tendency to saturate. It is thought that the main contribution in K_s is determined by properties of the antiferromagnetic layer (constant anisotropy and the exchange interaction) [6]. This data can be viewed as a reference to essential role of the size factor in the formation of these constants.

As discussed above, the block temperature in the investigated films does not exceed room temperature. In this regard, steady magnetic structure of ferromagnetic layers formed at cooling should reflect the magnetic state of the samples, in which a lock arises. The data presented in Figures 3 and 4 was obtained at a certain magnetic prehistory of film, which was cooled in a superconducting solenoid without current. For the most samples this gave reproducible exchange bias characteristics, except the one with thickness L = 3 nm. For this sample, not only quantatitive parameters, but also the hysteresis loops changed with numerous measurements (Fig. 5). Based on these loops, the exchange bias in different layers could have the same sign (Fig. 5a).

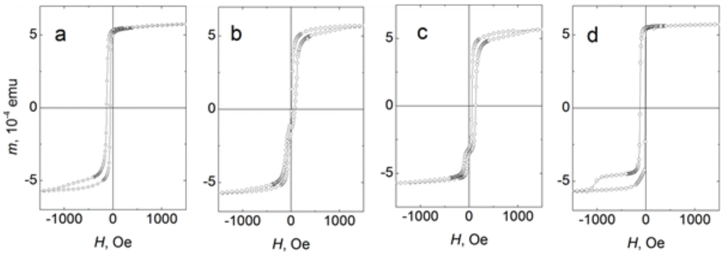

Figure 5: Hysteresis loops obtained after cooling in a residual field of superconducting solenoid (a, b, c) and field intensity of 500 Oe (d) for a sample with *L* = 3 nm and temperature of 5 K.

For this case, dependendences $H_{e1}(T)$ and $H_{e2}(T)$ in Figure 3 were determined. In other experiments, hysteresis loop had another form with different bipolar shift component parts (Fig. 5b,c). The reason for this ambiguity can be an uncontrolled variation in the residual field of the solenoid, and thus several different magnetic prehistory of the sample.

This multi-polarity shift in the volume of one sample can come from the presence of domains in ferromagnetic layers at the time of the magnetic lock. In this case, the formation of multi-domain state was possible at $L \sim 3$ nm, probably, because of a certain balance between the residual magnetic field of the solenoid, the field of positive connection between the two ferromagnetic layers, and the coercive force of the characteristic values. This version is confirmed by the results obtained after cooling of the sample in a strong magnetic field. On the corresponding hysteresis loop (Fig. 5d), reversal between layers and unipolar bias ferromagnetic layers are clearly seen. However, characteristics of the reversal magnetization of the samples with different thicknesses of FeMn layer do not change when varying their cooling process. In particular, Figure 6 shows the hysteresis loop of the sample with *L* = 2,5 nm at different conditions of magnetic prehistory. As can be seen, the form of hysteresis loop and its quantitative parameters varied slightly when sample was cooled in magnetic field close to zero (residual field solenoid) or an intensity of -500 Oe. It changed only a sign of the exchange bias, which was determined by the polarity of the magnetization at the temperature lock of ferromagnetic layers.

4. Conclusion

The exchange bias in $Fe_{20}Ni_{80}$/FeMn(*L*)/$Fe_{20}Ni_{80}$ films with different FeMn thicknesses is absent at room temperature for $L \leq 4$ nm. However, at lower temperatures it emerges and leads to the one-step or two-step magnetization reversal, depending on the *L* value. Magnetic history has a particularly strong influence on the magnetization reversal in the transitional thickness region ($L \sim 3$ nm).

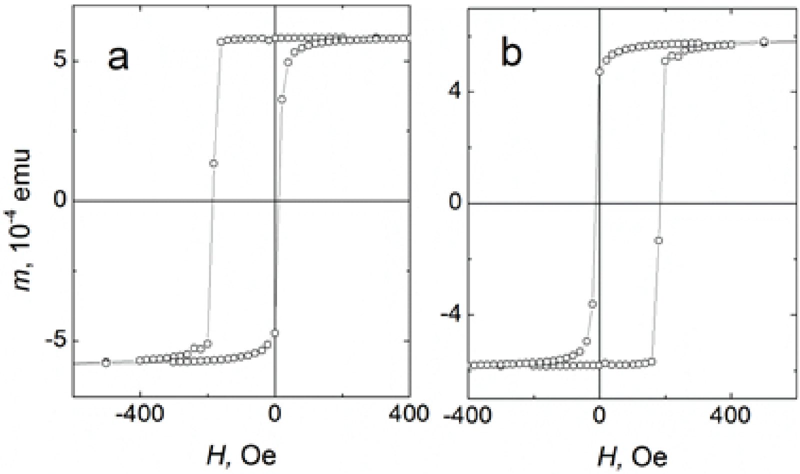

Figure 6: Hysteresis loops obtained after cooling in a residual field solenoid (a) and a negative magnetic field an intensity of 500 Oe (b) for a sample with L = 2,5 nm temperature of 5 K.

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