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Magnetic and Resonant Properties of Fe–Bi Films

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Abstract—Film structures in the Fe–Bi system have been studied experimentally. The magnetic state of the two-layer structures is shown by electron magnetic resonance to be dependent on the order of depositing magnetic and nonmagnetic layers. The three-layer structures demonstrate the effect of the exchange bias, the value of which is dependent on the bismuth interlayer thickness.

Keywords: bismuth interlayer, exchange bias, granulated subsystem, and magnetic anisotropy

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1. INTRODUCTION

Magnetic nanodimensional layer structures with a semimetallic interlayer are scantily known and they are of significant interest for the physics of condensed state. Many investigations were devoted to studying Bi-containing semiconductor alloys as materials for infrared receivers [1] or multilayer 3*d* metal–bismuth films [2] for microelectromechanical devices (MEMS). In this direction, the studies are continued both in the development of the technologies and in the studies of the fundamental properties, in particular, the influence of the interface on the magnetic and transport properties.

Film structures with an intermediate nonmagnetic bismuth interlayer have been studied before. It was found [3] that the interlayer interaction in the CoFe/Bi/Co structure demonstrates two periods of oscillations 9 and 25 nm. The study of the Co/Bi/Co samples [4] also confirmed the existence of a bond between magnetic layers in a wide range of the interlayer thicknesses (from 0.2 to 50 nm). Here, the dependence of coercive force H_C and saturation magnetization H_S has an oscillating character with different vibration periods. It was found in film structures of the Fe–Bi system [5] that Fe/Bi films have a perpendicular magnetic anisotropy if the iron layer thickness was less than 1.5 nm, and the magnetization lay in the film plane at larger thicknesses of the iron layer. There are no anisotropic effects in three-layer FeNi/Bi/FeNi structures [6, 7] with the ferromagnetic layer thickness t_{FeNi} = 10 nm, and no anisotropy is also observed in the film plane. In this case, it was established that there are interlayer exchange oscillations with a period t_{Bi} ~ 8 nm and the anisotropy sign is changed near t_{Bi} ~ 15 nm.

Depending on the technology, either solid solutions [8] are obtained at high deposition rates and high deposition temperatures (Fe_xBi_{1-x}) or film structures (Fe/Bi) are obtained at low deposition rates [5]. In the first case, as a rule, the "spin glass"-type magnetic state is realized; in the second case, a much wider spectrum of states takes place.

The aim of this work is to elucidate the features of the influence of technological conditions on the formation of the magnetic properties.

2. EXPERIMENTAL

The films were obtained by thermal evaporation at a base pressure $P \sim 10^{-6}$ Torr. Iron was used as a magnetic material, since, in our case, it was easy to control the formation of metastable iron modifications lest the interlayer interaction be shaded. In addition, of semimetallic elements, bismuth stands out as a metal that almost does not form chemical compounds with 3*d* metals [9]. To induce the easy-magnetization axis during deposition, a magnetic field of ~200 Oe was applied in the film plane. For one deposition cycle, Fe/Fe, Fe/Bi, and Bi/Fe films were deposited on glass substrates. The Fe/Bi/Fe films were independently deposited during another cycle. The magnetic layer thickness of all the films was $t_{Fe} \approx 10$ nm, and the bismuth layer thicknesses were t_{Bi} = 15 nm for two-layer structures and t_{Bi} = 3.5, 4.5, 6, 8, 10, and 12 nm for three-layer films. The value of t_{Fe} was chosen for the reason that it would be fairly small but, at the same

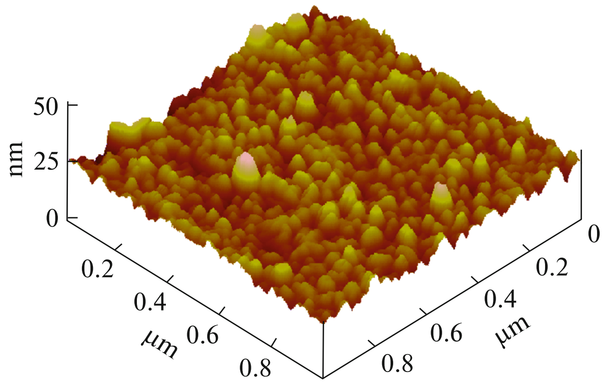

Fig. 1. Morphology of a Bi/Fe film obtained by AFM method.

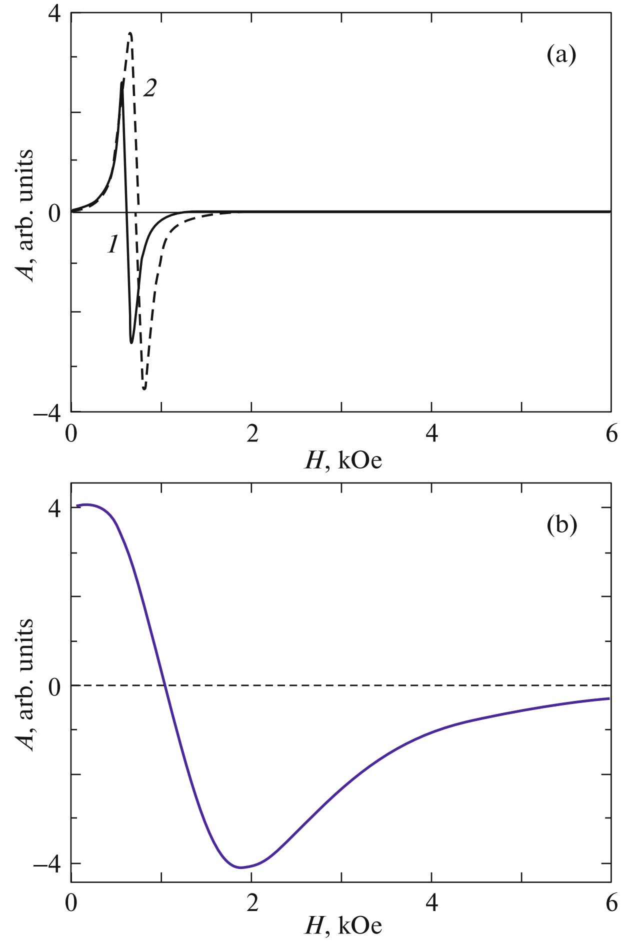

Fig. 2. Magnetic resonance spectrum of films: (a) (*1*) Fe and (*2*) Fe/Bi; (b) Bi/Fe. The magnetic field is directed along the easy-magnetization axis in the film plane. T = 300 K.

time, sufficient in order for the magnetic layer magnetization to be unchanged as its thickness fluctuates.

The layer thicknesses were determined by X-ray spectroscopy. The electron-microscopy measurements showed that the layers were continued in areas and their compositions correspond to the nominal composition. No traces of the presence of 3*d*-metal–bismuth compounds were observed. The existence of iron oxides was also not observed. The 100–200-nm-thick coatings of either Ag or Cu were deposited on the films from above. The film surface structure was studied using a Veeco Multi Mode atomic-force microscope (AFM) with resolution of 1 nm. It is found that the surface roughness height is not higher than 2.5 nm (Fig. 1), and this fact means that there is no direct contact between ferromagnetic iron layers. The magnetization was measured by an MPMS-XL SQUID setup. The magnetostatic measurements were carried out in a magnetic field lying in the film plane and directed along the induced easy axis. The resonant properties were measured using a "Bruker E 500 CW EPR" EPR spectrometer operating at frequency f_{MWF} = 9.48 GHz.

3. RESULTS AND DISCUSSION

The studies of the Fe–Bi film structures revealed that the magnetic behavior of the two-layer films is strongly dependent on the sequence of depositing the magnetic and nonmagnetic layers. This fact is demonstratively observed on the magnetoresonance parameters. As the magnetic field is in the film plane, a solo absorption line is observed, and its position is dependent on the sequence of depositing the layers (Fig. 2). In the case, as the external field is applied perpendicularly to the plane of a two-layer Bi/Fe film, two absorption lines (Fig. 3b) are observed, and two other compositions (Fe/Bi and Fe) have single absorption lines with close resonant fields (Fig. 3a). These data show that the deposition of the Bi/Fe structure is accompanied by the appearance of one more subsystem with a stronger anisotropy. So, it is established for Co–Bi films that the $[Co/Bi]_{19}/Co$ structure [10] with a summary thickness <100 nm and different thicknesses of the Co and Bi layers does not have a clear layered structure and there is a sequence of bismuth layers with inclusions of cobalt granules. Based on the fact that the iron melting temperature is ≈1812 K and the bismuth melting temperature is only ≈545 K, it can be assumed that, in the case of the Bi/Fe films, highly heated high-energy iron ions drop on the low-melting bismuth layer. The iron penetrates deep into the bismuth layer thickness. As a result, a layer of nanodimensional iron granules forms. These circumstances exactly influence the resonant properties of two-layer systems. In the case of Fe/Bi, no modified iron subsystem forms; moreover, as it is seen in Fig. 2a, the influence of the interface at the Fe–Bi boundary only slightly changes the iron layer properties (the resonant fields of lines *1* and *2* differ very insignificantly). The

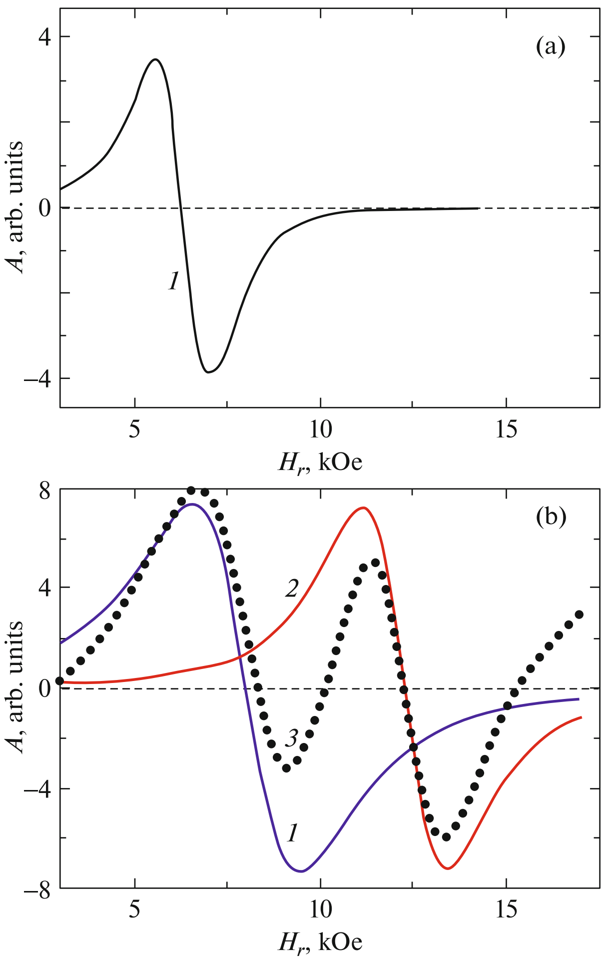

Fig. 3. Magnetic resonance spectrum of films: (a) (*1*) Fe; (b) Bi/Fe: (*1*) and (*2*) are the expansions into the component lines; (*3*) is the curve observed experimentally. The magnetic field is perpendicular to the film plane. $T = 300$ K.

existence of a granulated layer is clearly observed in the Bi/Fe films. These data are confirmed by magnetostatic measurements on two-layer films. The coercive force is dependent on the order of deposition of the layers (the difference by a factor of almost five), and the saturation magnetizations are the same within the experimental error. In particular, this is seen from the resonance spectrum measured in the geometry in which the external magnetic field is directed perpendicularly to the film plane (the perpendicular geometry). The magnetic resonance spectrum consists of two lines (Fig. 3b). Here, it is seen that one line (line *1* in Fig. 3b) is at the fields inherent in the magnetic resonance of the iron film (Fig. 3a) and another line (line *2* in Fig. 3b) is in the region of much higher fields. This behavior can be explained if we take into account that the deposition is carried out in a magnetic field and, as a result, strongly anisotropic iron granules [11] are oriented predominantly along the induced easy axis. In the perpendicular geometry, we observe a solo granular subsystem with additional anisotropy that arranges the granule magnetic moment into the film plane, which leads to a bias the resonance to higher magnetic fields.

It is clear that this feature must be observed in the magnetic properties of the multilayer structure. Figure 4 shows the magnetization curves of three-layer Fe/Bi/Fe films with different thicknesses of the semimetallic interlayer ($\sigma_{Fe} = M_{Fe}t_{Fe}$ is the magnetic moment of the unit film surface). At liquid-helium temperatures, the magnetization curves have a biasing shape. In this case, both the coercive force and the exchange bias are dependent on the bismuth interlayer thickness. At room temperature, the bias disappears.

The exchange bias field is usually determined as $H_E = (H_{C2} + H_{C1})/2$ [12] (Fig. 4, panel 1a), where H_{C1} and H_{C2} are the coercive fields of the magnetization curve. In our case, $H_E < 0$, and it implies that the exchange interaction between the pinning and remagnetized layers is antiferromagnetic. It is likely that the granulated iron sublayer formed on the Bi–Fe interface is the pinning layer. Figure 5 shows the dependence of the exchange bias field on the thickness of the nonmagnetic bismuth layer. It is seen that the curve has the maximum near $t_{Bi} = 4.5$ nm; further increase in the bismuth thickness leads to a decrease in H_E. Proposing a model for our situation, we can represent the system as Fe_1/Bi/FeGr/Fe_2 composition, where FeGr is the granulated iron subsystem. As the experiment shows, $M_{Fe1} \approx M_{Fe2} + M_{FeGr}$, providing that the M_{Fe2} and M_{FeGr} subsystems interact ferromagnetically. On the other hand, the interaction via the bismuth interlayer is antiferromagnetic. In this case, the anisotropy features will be determined by the granulated subsystem. This situation is, to some degree, analogous to that considered in [13] for the two-layer spin glass (SG)/ferromagnet (FM) system, where the spin glass layer plays the role of the pinning layer. In this case, the cooling field and temperature strongly influence the exchange bias value.

The modern state of the theory of exchange bias in nanostructures is given in [14], where an antiferromagnetic layer is considered the pinning layer. However, there is no theory for such exotic situations as in [13] or in our case. The dependence of the exchange bias on the bismuth interlayer thickness is understood qualitatively. It seems likely that, at low bismuth thicknesses, deposited iron penetrates deep to t_{max} = 4.5 nm. At bismuth thicknesses $t_{Bi} < t_{max}$ the thickness of the granulated iron subsystem increases and becomes maximum at t_{max}. Simultaneously with this, the volume and the anisotropy of the granulated subsystem increase. As t_{Bi} continues to increase, the effect of attenuation of the interlayer interaction begins to be dominant, which leads to a decrease in the exchange

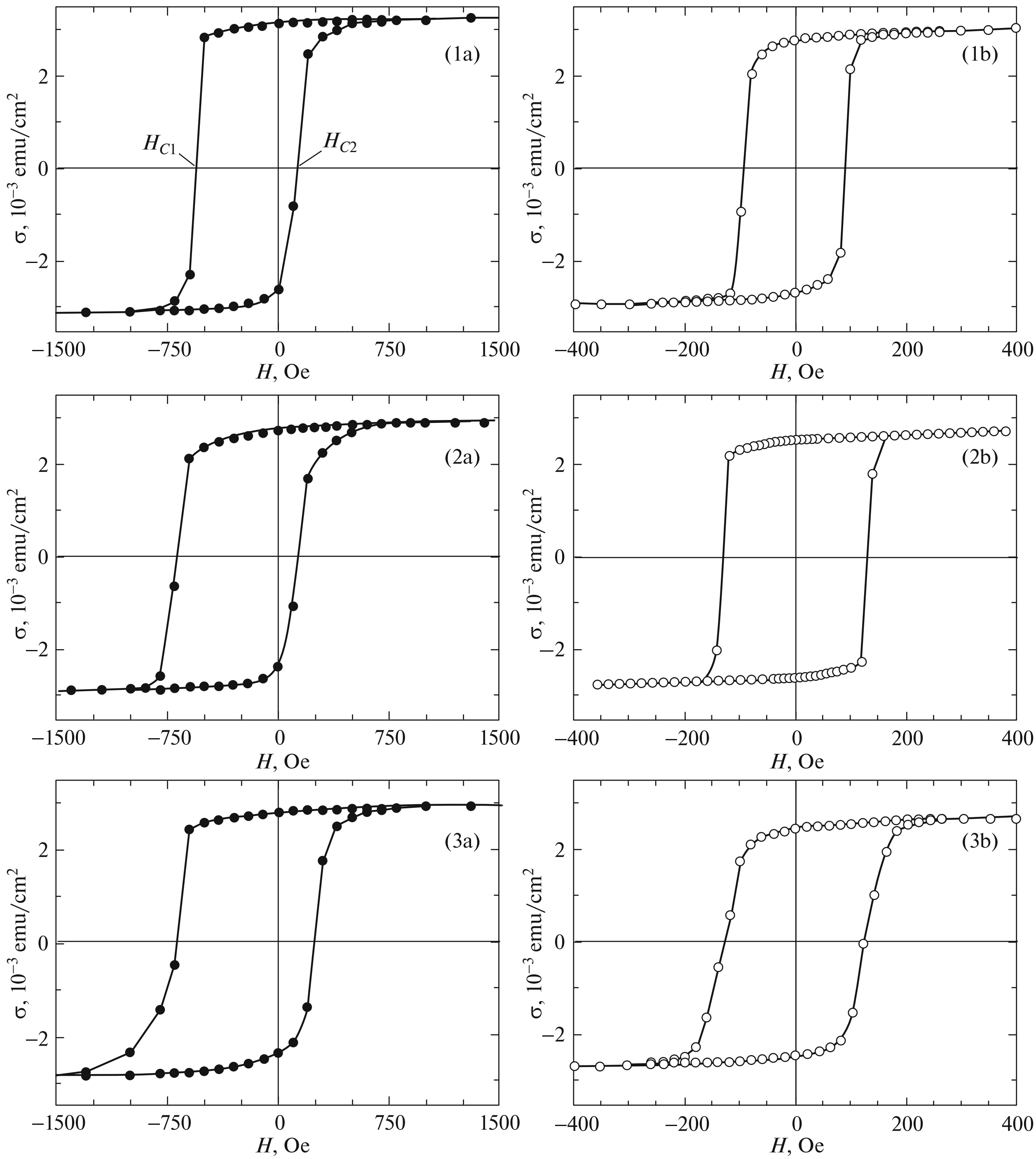

Fig. 4. Magnetization curves of films: T = (a) 4.2 K, (b) 300 K. (*1*–*3*): t_{Bi} = 3.5, 4.5, and 8.0 nm, respectively. The magnetic field is directed along the easy-magnetization axis in the film plane.

bias. The pinning layer does not manifest itself during magnetization as a step; since its fraction is quite low, it has a strong anisotropy (the anisotropy of a granule with diameter $d \sim 5.5$ nm is $L \approx 1.3 \times 10^6$ erg/cm^3 [15]); there is no clear flatten out in fields $H < 1.5$ kOe, and the "paraprocess" is observed (Fig. 4).

4. CONCLUSIONS

As a result of our studies, it is established that the magnetic state of the two-layer film structures is dependent on the order of depositions of the ferromagnetic iron layer and the nonmagnetic bismuth layer. In this case, in the Bi/Fe structures, a granulated

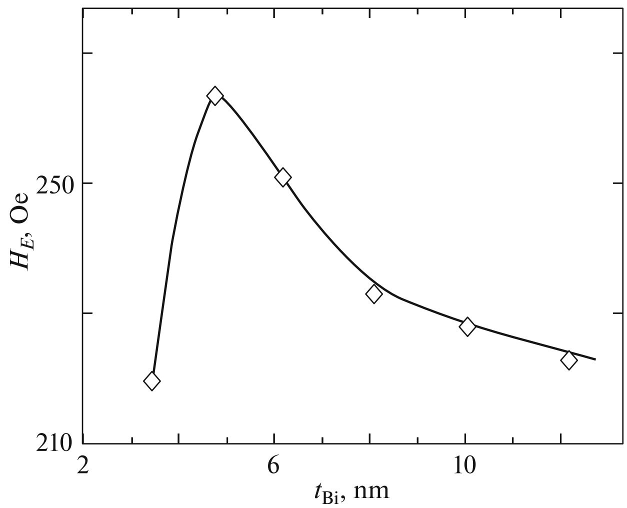

Fig. 5. Dependence of exchange bias H_E on the nonmagnetic interlayer thickness in Fe/Bi/Fe films at $T = 4.2$ K.

iron subsystem with strong magnetic anisotropy forms. The existence of this granulated subsystem leads to a nonequality of magnetic layers in the multilayer film structures. One of the manifestations of this effect is the appearance of the exchange bias depending on the thickness of the nonmagnetic semimetallic interlayer.

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CONFLICT OF INTEREST

The authors declare that they do not have conflicts of interest.

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