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The Influence of the Interface on the Magnetic State in Two-Layer Films of the Fe–Bi System

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Abstract—Results of the experimental investigation of two-layer films in the Fe–Bi system are presented. It is found that the order of sequential deposition of the magnetic and nonmagnetic layers influences both the character of magnetization process and the magnetic resonance behavior. The obtained results are explained by the formation of a strongly anisotropic sublayer of nanogranular iron in the Bi/Fe film structure.

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The interest in nanodimensional film structures is related not only to solving fundamental problems of the physics of condensed matter, but also to developing applied research, in particular, of spintronic devices. In this context, tasks arise in the creation of new nanodimensional materials and the search for new effects applicable in practice. For example, the use of semiconductor and semimetal materials as nonmagnetic spacers in magnetic structures significantly expanded their functional possibilities (e.g., for the creation of spin masers [1]). These spacers allow both magnetic and semiconductor properties of initial materials to be integrated in combined structures [2] and can impart new properties to them that are not inherent in the initial state.

In the series of semiconductor and semimetal elements, bismuth is distinguished by that it almost does not form chemical compounds with 3*d* group metals [3]. This specific feature makes bismuth a convenient material for creating layered structures with sharp interfaces. Depending on the manufacturing technology, materials reported for the Fe–Bi system represented either solid solutions [4] synthesized at high speeds and temperatures of deposition (Fe_xBi_{1-x} films) or Fe/Bi multilayer structures [5] formed at low deposition rates. The former systems usually occurred in a magnetic state of the "spin glass" type, while the latter structures exhibited a much wider spectrum of magnetic states.

Most thorough investigations were devoted to film structures representing the Co–Bi system. In $[Co/Bi]_{19}/Co$ structures [6] with total thicknesses of <100 nm and various thicknesses of Co and Bi layers, it was found that a sequence of Bi layers with inclusions of Co granules was formed rather than clearly defined bilayers. This result was explained by the fact that Co atoms penetrated through Bi layers during deposition and produced mixing of the interface. An analogous result was obtained for MnBi films during layer-by-layer deposition of elements followed by annealing of the structure [7]. In three-layer Co/Bi/Co films [8] with interlayer thicknesses t_{Bi} = 1–30 nm, postgrowth annealing resulted in the formation of a cobalt-based structure with randomly distributed bismuth granules.

The present work was devoted to studying the magnetic properties of two-layer films in the Fe–Bi system as dependent on the order of deposition of the magnetic and nonmagnetic layers.

The films were prepared by the deposition of components upon thermal evaporation in vacuum at a residual gas pressure of $P \sim 10^{-6}$ Torr. Iron was selected as the magnetic component because it admitted easy determination of metastable modifications so as to avoid masking of the interlayer coupling. During deposition, the easy magnetization axis was aligned by applying a magnetic field of ~16 kA/m in the film plane. Two-layer films of various compositions (Fe/Fe, Fe/Bi, and Bi/Fe) were deposited onto glass substrates in a single technological cycle of the vacuum deposition system. In all samples, the magnetic layer thickness was t_{Fe} ~ 10 nm and the bismuth layer thickness was t_{Bi} = 15 nm. The value of t_{Fe} was selected so as to make it small enough but yet sufficient to ensure that the magnetization of magnetic layer would not change significantly with thickness fluctuations.

The thicknesses of deposited layers were determined by X-ray spectroscopy techniques. Electron

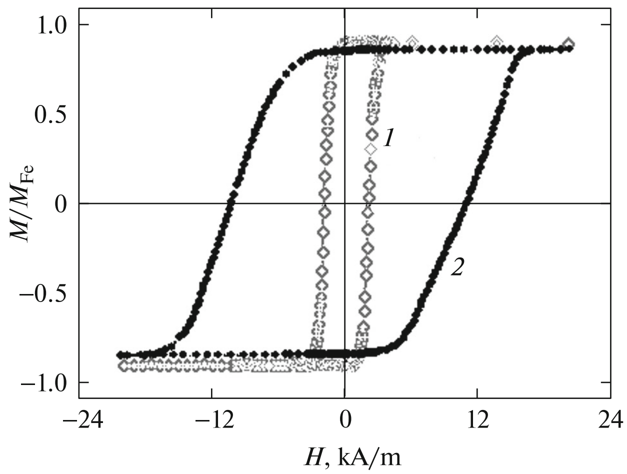

Fig. 1. Magnetic hysteresis loops of (*1*) Fe/Bi and (*2*) Bi/Fe two-layer films measured at $T = 300$ K.

microscopy measurements showed that deposited layers are continuous over the entire surface area and their compositions correspond to nominal. No traces of the presence of 3*d* metal–bismuth compounds were detected, and no iron oxides in deposited films were found. The surface structure of deposited films was studied on a Veeco MultiMode atomic force microscope at a 1-nm spatial resolution. It was established that the surface roughness height did not exceed 2.5 nm. The magnetization was measured on an MPMS-XL SQUID magnetometer. The magnetic field was oriented in the film plane and directed along the easy plane in all measurements. The resonance properties were studied on a Bruker E 500 CW EPR spectrometer operating frequency $f_{MWF} = 9.48$ GHz.

The results of magnetic measurements showed that the shape of the magnetization curve of a two-layer film depends on the order of depositing magnetic and nonmagnetic semimetal layers. Figure 1 shows the magnetization curves of (*1*) Fe/Bi and (*2*) Bi/Fe films, in which the maximum magnetization is normalized to the saturation magnetization of a reference film of pure iron. As can be seen, the saturation magnetization is almost the same in both films, but the coercivity of two-layer films with the top (structure *1*) and bottom (structure *2*) bismuth layer relative to iron is significantly (by about five times) different. In the given case, the magnetization is oriented in the film plane and directed along the easy axis, which implies that the demagnetizing field in both structures *1* and *2* is the same. As is known [9], the coercivity is proportional to the magnetic anisotropy, which allows us to assume that an additional interfacial anisotropy appears at the ferromagnet/semimetal interface.

Additional data were obtained from a study of magnetic resonance properties. Figure 2 presents the spectra of microwave absorption of the films studied. As can be seen in comparison to the spectrum of a reference film of pure iron (Fig. 2a), the deposition of second (bismuth) layer differently influences the spectrum of magnetic resonance, depending on the order of depositing the magnetic and nonmagnetic layers (cf. Figs. 2b, 2c). The most pronounced change was observed for the Bi/Fe film composition.

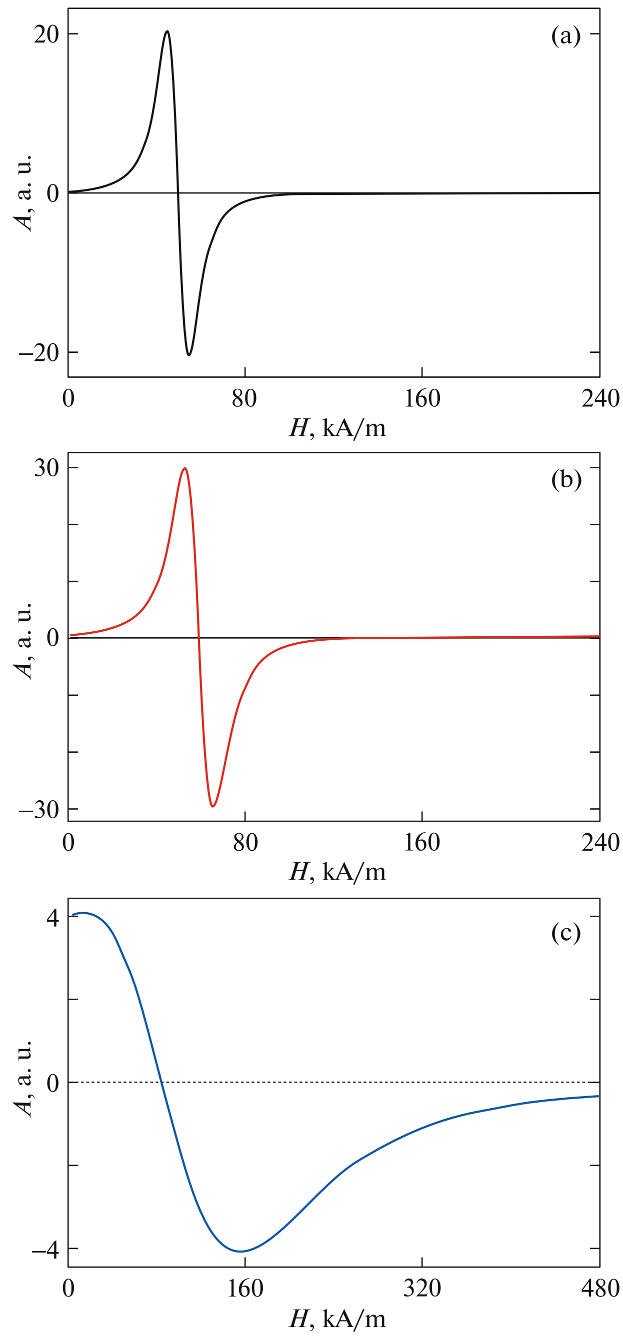

Fig. 2. Microwave absorption spectra of (a) Fe/Fe, (b) Fe/Bi, and (c) Bi/Fe two-layer films measured at $T = 300$ K for the external magnetic field directed along the easy axis in the film plane.

Figure 3a shows the temperature dependences of resonance fields. As is known [10], the dependence of resonance frequency (ω) on the magnetic field (with allowance for the shape anisotropy and magnetic anisotropy) can be expressed as follows:

$$(\omega/\gamma)^2 = H(H + H_M + H_A), \quad (1)$$

where $H_M = 4\pi M$ is the demagnetizing field, $H_A = 2K/(tM)$ is the anisotropy field, K is the anisotropy constant, t is the magnetic layer thickness, and γ is the gyromagnetic ratio. Since the saturation magnetization is the same for all films (Fig. 1), the H_M value is also the same and, hence, formula (1) indicates that the order of deposition of the magnetic and nonmagnetic layers influences the anisotropy field. This difference is still more strongly manifested in the temperature dependences of resonance line width ΔH_{PP} (Fig. 3b). Indeed, the line width for Bi/Fe film at liquid-nitrogen temperature is almost ten times greater than ΔH_{PP} for the reference iron (Fe/Fe) and Fe/Bi films.

A dependence of the magnetic properties of layered film structures on the state of interfaces was also observed previously, e.g., in the Ni–Ge system [11], where the atomic mixing at the interface led to the formation of nickel germanide that is stronger manifested for thinner nickel layers. The Si(100)/Cu(1000)/Ni(60)/Co/Cu(30) multilayer structure [12] exhibits orientational transition of the easy axis–easy plane type depending on the cobalt layer thickness, where the main role is played by the state of the Co/Ni interface in which the anisotropy of cobalt changes under the action of nearest environment.

However, in the case under consideration, no compounds are formed at the interface of magnetic and nonmagnetic layers [3]. Then, it can be suggested that a reconstruction of the iron layer takes place that leads to a change in its magnetic state. It should be recalled that the melting temperature of iron is ~1812 K, while that of bismuth is as low as ~545 K. In the case where iron is the bottom layer (Fe/Bi film), bismuth ions reaching the iron surface during deposition possess relatively low energies and cannot penetrate deep into the bulk of iron layer, so that a rather sharp interface is formed in which geometry of the nearest environment of iron is modified. This subset of iron atoms create a small additional magnetic anisotropy, which is confirmed by a small difference between the resonance fields and resonance line widths between Fe/Fe and Fe/Bi films (Fig. 3, curves *1*, *2*).

The situation changes drastically for the Bi/Fe structure, in which strongly heated, high-energy iron ions fall the surface of low-melting bismuth layer. Iron penetrates deep into the bulk of bismuth layer, which results in the formation of nanodimensional iron granules. As is known, nanogranular iron particles possess a much greater magnetic anisotropy. For example [13], iron particles with diameter $d \approx 5.5$ nm possess a much greater anisotropy constant of $K \approx 1.3 \times 10^5$ J/m^3 as compared to the value of $K \approx 4.8 \times 10^4$ J/m^3 for the bulk (bcc) phase. Thus, an additional subsystem of strongly anisotropic iron granules dissolved in bismuth is formed in the Bi/Fe film, which is exchange-coupled with the Fe layer. After deposition of the Bi/Fe film, its cooling in a magnetic field leads to an additional anisotropy that significantly influences both the magnetization process and dynamics of the magnetic system (Fig. 3, curve *3*).

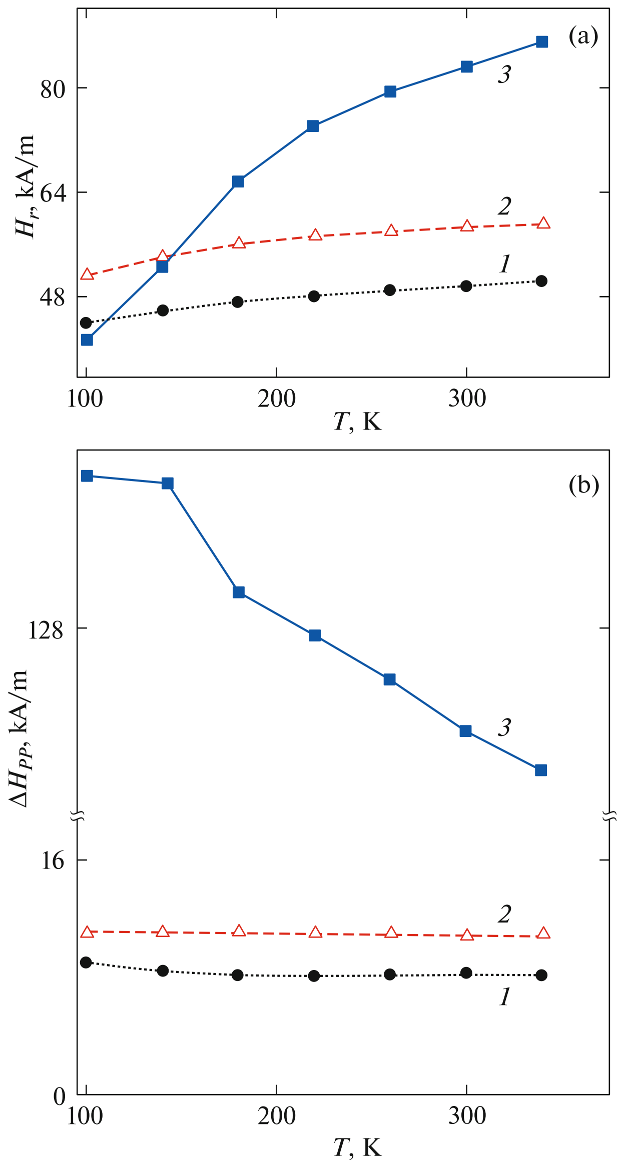

Fig. 3. Temperature dependences of the magnetic resonance parameters (a) resonance field H_r and (b) resonance line width ΔH_{PP} in (*1*) Fe/Fe, (*2*) Fe/Bi, and (*3*) Bi/Fe two-layer films.

The results obtained in the present work are important for the creation of multilayer structures with semimetal bismuth spacers between magnetic layers. In this system, it is important to take into account nonequivalence of the magnetic layers and the presence of an additional interfacial anisotropy. A more detailed investigation of peculiarities in the influence of granular iron subsystem on the magnetic properties of multilayer structures in the Fe–Bi system and related spin dynamics will be reported in a separate publication.

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REFERENCES

1. N. A. Viglin, V. V. Ustinov, and V. V. Osipov, JETP Lett. **86**, 193 (2007).
2. B. P. Zakharchenya and V. L. Korenev, Phys. Usp. **48**, 603 (2005).
3. V. M. Denisov, N. V. Belousova, G. S. Moiseev, S. G. Bakhvalov, S. A. Istomin, and E. A. Pastukhov, *Bismuth Containing Materials. Structure and Physico-Chemical Properties* (UrO RAN, Yekaterinburg, 2000) [in Russian].
4. Q. M. Chen, F. Z. Cui, Y. D. Fan, and H. D. Li, J. Appl. Phys. **63**, 2452 (1988).
5. F. Z. Cui, Y. D. Fan, Y. Wang, A. M. Vredenberg, H. J. G. Draaisma, and R. Xu, J. Appl. Phys. **68**, 701 (1990).
6. T. Hozumi, P. le Clair, G. Mankey, C. Mewes, H. Sepehri-Amin, K. Hono, and T. Suzuki, J. Appl. Phys. **115**, 17A737 (2014).
7. W. K. Unger and M. Stolz, J. Appl. Phys. **42**, 1085 (1971).
8. S. I. Vorobiova, O. V. Shutylieva, I. M. Pazukha, and A. M. Chornous, Eur. Phys. J. Plus **131**, 203 (2016).
9. S. Chikazumi, *Physics of Ferromagnetism*, 2nd ed. (Oxford Univ. Press, Oxford, 2009).
10. B. Heinrich, in *Ultrathin Magnetic Structures II. Measurement Techniques and Novel Magnetic Properties*, Ed. by B. Heinrich and J. A. C. Bland (Springer, Berlin, 2000), p. 195.
11. I. S. Edelman, G. S. Patrin, D. A. Velikanov, A. V. Chernichenko, I. A. Turpanov, and G. V. Bondarenko, JETP Lett. **87**, 262 (2008).
12. J. Lee, G. Lauhoff, and J. A. C. Bland, Phys. Rev. B **56**, R5728 (1997).
13. B. Mehdaoui, A. Meffre, L.-M. Lacroix, J. Carrey, S. Lachaize, M. Respaud, M. Gougeon, and B. Chaudret, J. Appl. Phys. **107**, A324 (2010).

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