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Magnetic Resonance in FeNi/Bi/FeNi Films

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Abstract—The magnetic resonance in FeNi/Bi/FeNi trilayer films with nonmagnetic semimetal spacer has been experimentally studied. It is found that the microwave absorption spectrum of samples has a complicated shape dependent on the nonmagnetic spacer thickness. In the interval of Bi layer thicknesses within 3–15 nm, the interlayer coupling has an antiferromagnetic character.

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Multilayer magnetic films with nonmagnetic spacers (in particular, in the ferromagnetic metal/semiconductor system [1]) and with semimetal spacers have received much attention of researchers due to a large variety of phenomena observed in these structures. When the spacer is a semiconductor, it is possible to control its properties and, hence, interlayer coupling by external factors (doping, various radiations, temperature, magnetic field, etc.).

It is an interesting task to create film structures that would combine the sensitivity to external factors with strong coupling between magnetic layers. One possible way to do this is related to using a semimetal bismuth (Bi) spacer instead of a semiconductor. According to the phase diagram [2], most elements do not form compounds in 3*d* metal–bismuth systems and, hence, the boundaries between layers will not smear. In addition, bismuth and its compounds exhibit some unusual properties and have important applications in the form of both bulk materials [3] and films [4]. Previous investigations have been devoted mostly to studying Bi-containing semiconductor alloys as materials for infrared detectors [5] and multilayer 3*d* metal–bismuth films as materials for MEMS structures [6].

It is important to note that the mean free path of electrons in Bi single crystals can reach a macroscopic scale. In Bi films, this parameter (as well as the concentration and mobility of charge carriers) depends on the layer thickness, temperature, and external magnetic fields.

Previously, we have originally synthesized and studied FeNi/Bi/FeNi trilayer films [7]. Permalloy was selected for magnetic layers due to its low magnetic crystallographic anisotropy, so as not to mask the interlayer coupling. Films were synthesized with various Fe/Ni atomic ratios in order to trace the interplay of intrinsic magnetic energy and interlayer coupling energy in the formation of a magnetic state of the system.

In the present work, we have synthesized permalloy films containing 18 at % iron and 82 at % nickel. In one technological cycle, two films were deposited with different thicknesses of bismuth spacer; in two sequential cycles, the film with greater bismuth spacer thickness (t_{Bi}) was repeatedly prepared. In all samples, the thicknesses of magnetic layers were the same, $t_{FeNi} \approx 10$ nm, while thicknesses of the bismuth spacer varied within $t_{Bi} = 3$–15 nm. The value of t_{FeNi} was selected to so as to effect a compromise between being small and, at the same time, ensuring that the saturation magnetization would not significantly depend on thickness fluctuations. The thicknesses of layers were determined using an X-ray spectroscopy technique. Electron-microscopic examination showed that deposited layers were continuous and possessed nominal composition. These observations revealed no any evidence of the formation of 3*d* metal–Bi compounds. The magnetization was measured using an MPMS-XL SQUID magnetometer. The electron magnetic resonance (EMR) spectra were measured on a spectrometer with microwave frequency $f_{UHF} = 36.7$ GHz at various temperatures in a range of $T = 90$–300 K. The magnetic field was oriented in the film plane. No anisotropy of the resonance field in this plane was observed.

Measurements of the field and temperature dependences of magnetization showed that the interlayer coupling depends on the Bi spacer thickness. It was previously established [8] that the shape of the $M(H)$

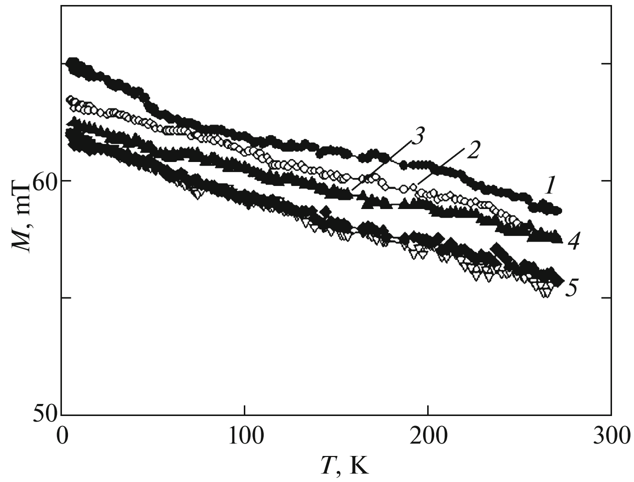

Fig. 1. Temperature dependences of the saturation magnetization of FeNi/Bi/FeNi trilayer films with t_{Bi} = 0, 4, 6, 11, and 15 nm (curves *1–5*, respectively).

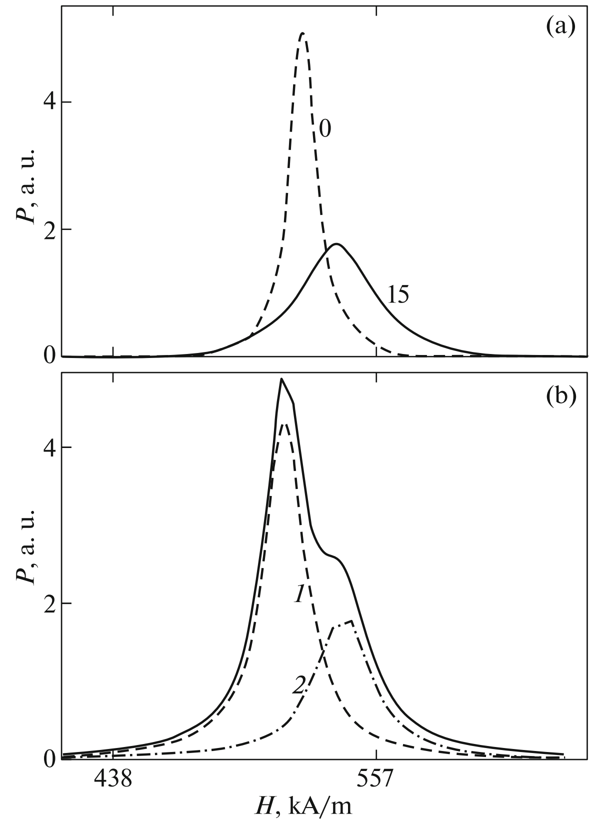

Fig. 2. EMR spectra of FeNi/Bi/FeNi trilayer films with (a) t_{Bi} = 0 and 15 nm (indicated at the curves) and (b) t_{Bi} = 4 nm measured at T = 228 K.

curve varies with increasing t_{Bi}. For a control film without a spacer ($t_{Bi} = 0$), the hysteresis loop is narrow and the magnetization curve exhibits a ferromagnetic character. For films with $t_{Bi} \neq 0$, the hysteresis width nonmonotonically varies with the spacer thickness, which is related to switching on of the interlayer coupling. The coercivity (H_c) exhibits an almost threefold growth with increasing bismuth spacer thickness, reaches a maximum at about t_{Bi} ~ 13 nm, and then decreases. This behavior is consistent with that reported in [9], where it was established that the period of oscillations in the interlayer coupling in CoFe/Bi/CoFe is greater than 10 nm.

The character of variation of the interlayer coupling depending on the temperature and nonmagnetic spacer thickness was studied using the EMR method. Figure 1 shows the temperature dependences of the saturation magnetization for a series of FeNi/Bi/FeNi films. Note that the magnetization saturation field for these films at liquid helium temperatures does not exceed 40 kA/m. The experimental plots in Fig. 1 are well described by dependences of the $M \sim T^{3/2}$ type. As the nonmagnetic spacer thickness increases, the saturation magnetization of the film exhibits a small (~5%) decrease (see curves *2–4*) and ceases to change for t_{Bi} > 11 mn (cf. curves *4* and *5*). This behavior can be related to the formation of either a nonmagnetic or "dead" layer in the ferromagnet at the metal–semimetal interface as a result of the mutual diffusion of elements. Another possible mechanism is related to the redistribution of polarized conduction electrons from the ferromagnet to semimetal by the mechanism of spin accumulation [10].

It is established that the microwave absorption curves of the control film with t_{Bi} = 0 and films with $t_{Bi} \geqslant 15$ nm have a Lorentz shape (Fig. 2a). In the interval of bismuth layer thicknesses within t_{Bi} = 3–12 nm, the EMR spectrum consists of two components (Fig. 2b, curves *1* and *2*), which can be related to an antiferromagnetic character of interlayer coupling between ferromagnetic layers. In order to elucidate this question, we have studied temperature dependences of the EMR spectra. As can be seen from Fig. 3a, the position of a low-field peak in the EMR spectrum weakly depends on the nonmagnetic spacer thickness and temperature (Fig. 3a), whereas the high-field peak depends much more strongly on these parameters (Fig. 3b).

The temperature dependence of the resonance field for the control film with t_{Bi} = 0 was calculated by the formula

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

where all notations are traditional, $H_M = 4\pi M$, and M values are taken from Fig. 1 (curve *1*). Good agreement of the experiment and calculation (Fig. 3, curve *5*) indicates that the anisotropy of the ferromagnetic layer at these temperatures is extremely small. A change in magnetization upon the introduction of a Bi spacer cannot give H_r values plotted in Fig. 3a. Therefore, the presence of a Bi spacer leads to additional

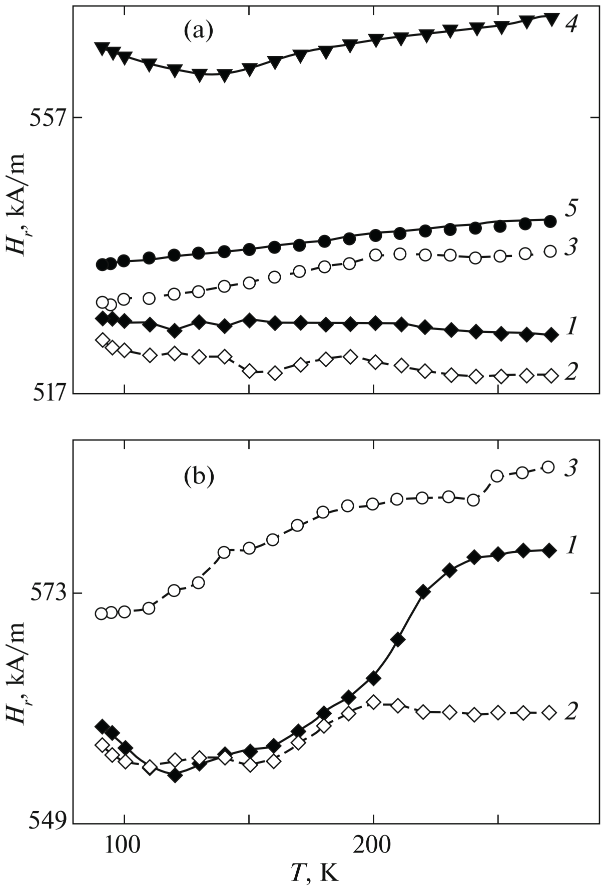

Fig. 3. Temperature dependences of resonance field H_r for (a) the low-field peak in Fig. 2b (curve *1*) and (b) the high-field peak in Fig. 2b (curve *2*) in FeNi/Bi/FeNi trilayer films with t_{Bi} = 4, 6, 11, 15, and 0 nm (curves *1–5*, respectively); for curve *5*, points present experimental data and solid curve shows the results of calculations by formula (1).

interactions that change magnetic dynamics of the trilayer film structure. At large thicknesses of the Bi spacer, the resonance spectrum again transforms into a single Lorentz curve, which is indicative of a ferromagnetic character of interlayer coupling, but with different parameters of the magnetic resonance. This behavior can be explained by assuming that, in addition to interlayer coupling, there appears an interfacial anisotropy.

Thus, the main experimental results consist in discovery of the influence of a semimetal Bi spacer on the magnitude and sign of the interlayer coupling in the FeNi/Bi/FeNi trilayer structure. this effect depends on the nonmagnetic spacer thickness and is manifested by changes in the EMR spectrum. A more detailed investigation of mechanisms responsible for the magnetic state formation and spin dynamics in FeNi/Bi/FeNi trilayer films will be reported in subsequent publications.

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