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Influence of semimetal spacer on magnetic properties in NiFe/Bi/NiFe trilayer films

G.S. Patrin [a,b,*], V.Yu. Yakovchuk [a], D.A. Velikanov [a]

[a] *L.V. Kirensky Institute of Physics, Siberian Branch of Russian Academy of Sciences, Krasnoyarsk 660036, Russia*
[b] *Krasnoyarsk State University, prospect Svobodny 79, Krasnoyarsk 660041, Russia*

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Abstract

The results of experimental study of magnetic properties in *permalloy/bismuth/permalloy* trilayer films synthesized for the first time are presented. Measurements of magnetic field and temperature dependences of magnetization have shown that the interlayer coupling depends on bismuth spacer thickness. The dependence of saturation magnetization of the system on semimetal thickness has been found. Possible mechanisms responsible for the observed features of behavior are discussed.

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Multilayer magnetic films with a nonmetal spacer, in particular, those belonging to the system *ferromagnetic metal/semiconductor* [1], or with a semimetal spacer attract close attention by virtue of a great variety of effects observed in these films. When a semiconducting spacer is used, the interest of researchers is caused by the possibility of changing the current carriers concentration in a nonmagnetic layer by means of influence of external factors, which allows controlling the interlayer interaction. However, in this case the interlayer exchange between ferromagnetic layers is fairly weak because of relatively low concentration of conductivity electrons in a semiconducting spacer (for example, in $(\mathrm{Gd/Si/Co/Si})_n$ films the interlayer exchange is about 10^{-4} erg/cm^2 order of magnitude at $T \approx 80$ K [2]). For this reason, currently the creation of film structures that would keep sensitivity to external conditions and effects along with far more effective interaction between ferromagnetic layers remains the urgent problem to solve. One of the ways to accept the challenge seems to use semimetal Bi instead of semiconducting material as a nonmagnetic interlayer. First, according to the phase diagram [3], in a 3*d-metal-Bi* system most of the elements do not form compounds, which means that different layers do not mix in a film structure and interfaces of materials are sharp. For multilayer films this corresponds, within certain limits, to the model situation. Second, bismuth by itself possesses of extraordinary set of physical properties both in bulk [4,5] and in film [6] state. In Bi the free path of electrons can reach macroscopic scales; besides, depending on bismuth film thickness, temperature and magnetic field, the concentration and current carrier mobility vary [7].

The pioneer works on study of film structures in the Bi–Co system [8] were aimed to investigation of electric properties of bismuth. The strong influence of magnetic field on transport properties of the films at low temperatures was discovered. It was shown that the effects of electron–electron interaction and current carrier localization determine the main contribution. The presence of cobalt magnetic layers leads to the decrease of spin–spin scattering of current carriers and reduction of resistivity. Study of magnetic properties of multilayer Fe/Bi films has shown that, depending on thickness of a magnetic layer (t_{Fe}), iron may be either in ordered or in paramagnetic state, and

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[*] Corresponding author.
E-mail address: patrin@iph.krasn.ru (G.S. Patrin).

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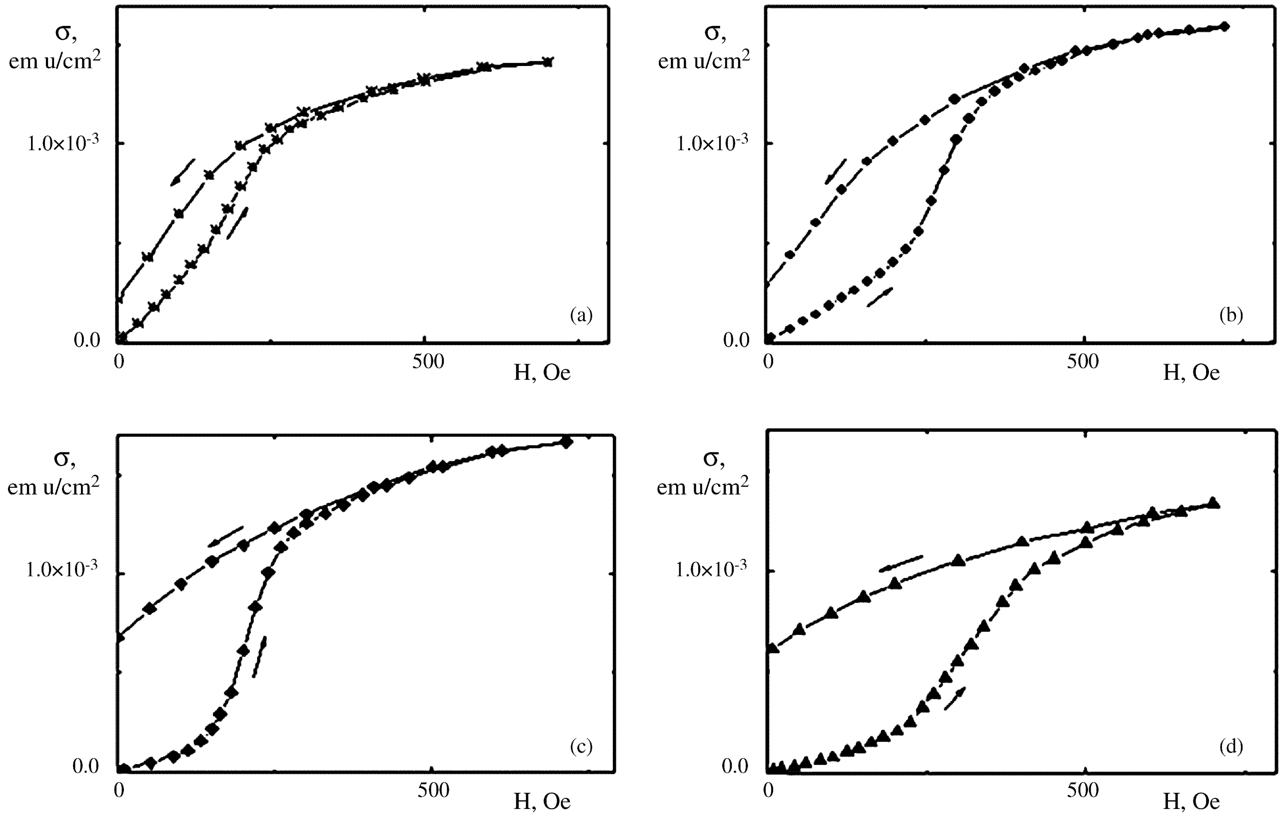

Fig. 1. Field dependences of magnetization in NiFe/Bi/NiFe films. (a) $t_{\mathrm{Bi}} = 0$ nm, (b) $t_{\mathrm{Bi}} = 4$ nm, (c) $t_{\mathrm{Bi}} = 6$ nm, (d) $t_{\mathrm{Bi}} = 12$ nm. $T = 4.2$ K. Arrows indicate the directions of magnetic field scanning.

at $t_{\mathrm{Fe}} > 1$ nm the change of magnetic anisotropy from perpendicular to intra-planar takes place [9]. Data taken from trilayer Fe/Bi/Fe films [10] allowed the authors to draw a conclusion about influence of bismuth layers on anisotropic properties of the structure as a whole. For CoFe/Bi/Co films [11] the oscillating character of the interlayer exchange interaction via the bismuth spacer was reported. It has been found that the oscillation period is much more than that in films with a nonmagnetic metal spacer, and the exchange value growth with temperature decreasing.

We carried out the research of magnetic properties of trilayer films in the *permalloy/bismuth* system. Permalloy has been selected as a magnetic layer because of its low magnetic crystallographic anisotropy, to prevent the interlayer interaction effects shading.

NiFe/Bi/NiFe films (Ni-82% at. and Fe-18% at.) were obtained in a single cycle by vacuum evaporation at working pressure $P \sim 10^{-5}$ Torr. As a substrate material, cover glass was used. For all films the permalloy layer thickness and bismuth spacer thickness were $t_{\mathrm{NiFe}} \cong 10$ nm and $t_{\mathrm{Bi}} = 0, 4, 6, 12(\pm 0.5)$ nm, respectively. The value t_{NiFe} was selected to be rather small, but at the same time, to keep a film continuous and magnetization of a magnetic layer independent of its thickness. Sickness of layers was determined by X-ray spectroscopy. Electron microscopic study showed that the layers were continuous on area and their composition corresponded to the nominal. No traces of known 3d-metal-Bi compounds were found. Magnetic measurements were made at temperatures $T = 4.2$–300 K with the SQUID-magnetometer operating at magnetic fields $H \leqslant 800$ Oe. During the measurements magnetic field was in the film plane. Magnetic anisotropy in the film plane does not reveal.

It was found that the bismuth spacer formation influences essentially the system magnetization. Field dependences of magnetization for the films under study are given in Fig. 1. One can see that the shape of $\sigma(H)$ curve changes with bismuth spacer thickness increasing. In particular, the test film with $t_{\mathrm{Bi}} = 0$ has the narrow hysteresis loop and magnetization curve of a ferromagnetic type (see also the temperature dependence in the insert, Fig. 2). For the films with $t_{\mathrm{Bi}} \neq 0$ the magnetization curves are typical for films possessing either by "strong" intra-layer anisotropy or by antiferromagnetic interlayer coupling. Since anisotropy is not experimentally observed, we attribute such a behavior to the presence of interlayer antiferromagnetic exchange. Also, it captures one's attention that at the same thickness of magnetic layers, saturation magnetization of films with different thickness t_{Bi} has different values. In our case, magnetization first increases, reaching the difference of about 15% for the film with $t_{\mathrm{Bi}} = 60$ nm as compared to the test film, then decreases again, with $\sigma_{\max}(t_{\mathrm{Bi}} = 0\ \mathrm{nm}) > \sigma_{\max}(t_{\mathrm{Bi}} = 120\ \mathrm{nm})$. When $t_{\mathrm{Bi}} \approx 15$ nm the magnetization is almost equal to magnetization of the test film without a bismuth spacer (at higher thickness t_{Bi} no research was carried out). This behavior of saturation magnetization of a film in dependence on t_{Bi} thickness is not typical. Fig. 2 illustrates the temperature behavior of saturation magnetization for the films with a bismuth spacer of

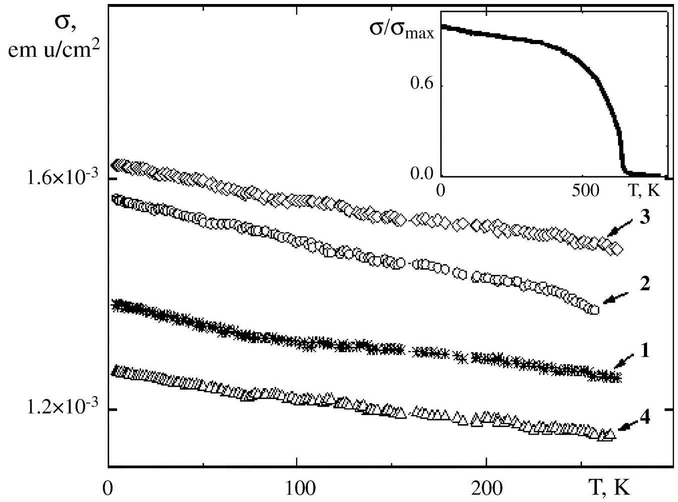

Fig. 2. Temperature dependences of saturation magnetization. (1) $t_{\text{Bi}} = 0$ nm, (2) $t_{\text{Bi}} = 4$ nm, (3) $t_{\text{Bi}} = 6$ nm, (4) $t_{\text{Bi}} = 12$ nm. $H = 600$ Oe. The dependence for the reference film is given in the insert.

different thicknesses. It must be noticed that in the figure all the curves are of the kind analogous to the reference film.

The experimental results obtained do not fit the ordinary scheme of the multilayer structure magnetism formation, when a nonmagnetic layer influences the interlayer interaction only, with no touching saturation magnetization of a system determined by the state of a magnetic layer. Since in our case no traces of NiBi compound have been found, and there are no stable compounds in the Fe–Bi system, the observed peculiarities may be attributed to the formation of areas with a different magnetic state induced by the presence of bismuth at the interface. It must be taken into account that the electron density distribution at the interface of different materials depends on the correlation of Fermi levels of mating materials. Depending on which material has an initially higher Fermi level, either enrichment or depletion of a near-surface layer by electrons from the direction of a material of interest will occur.

In 3d-metals and their alloys magnetization is mainly determined by localized ion moments, while collective electrons make lower contribution and serve as interaction carriers [12]. In the structures *semiconductor/magnetic metal* the polarization of electrons in a semiconducting layer by means of the proximity effects was observed [13] (also occurrence of electron polarization due to the spin-dependent reflection from the interface with a magnetic medium is possible [14]). The effect of spin accumulation in a nonmagnetic metal at the expense of diffusion of electrons from a magnetic layer was theoretically considered [15]. As was established there, in a nonmagnetic layer the spin density is determined as follows

$$S(x) = \left\{(D_N \cdot P \cdot e \cdot V/2)/\left(1 + L_S \cdot \coth(t_{\text{Bi}}/2 \cdot \lambda_S)\right)\right\} \cdot \left\{\sinh(x/\lambda_S)/\sinh(t_{\text{Bi}}/2 \cdot \lambda_S)\right\}, \tag{1}$$

where D_N is the density of states on the Fermi level in nonmagnetic metal, P is the degree of polarization of conductivity electrons in a magnetic layer, V is the potential difference on a contact, λ_S is the spin diffusion length, $L_S = R_T \cdot \sigma_N/\lambda_S$, R_T is the resistivity of an unit contact area, σ_N is the conductivity of a nonmagnetic material, e is the electron charge. In the absence of external voltage $V = [\varepsilon_{\text{F(FM)}} - \varepsilon_{\text{F(Bi)}}]/e$, where $\varepsilon_{\text{F}(j)}$ is the Fermi energy of the jth layer ($j = \text{FM, Bi}$). A coordinate x is counted from the center of a semimetal spacer. In the framework of this approach, the energetic diagram and magnetization distribution in a structure *ferromagnetic metal/semimetal/ferromagnetic metal* qualitatively have a form presented in Fig. 3(a) and (b), respectively.

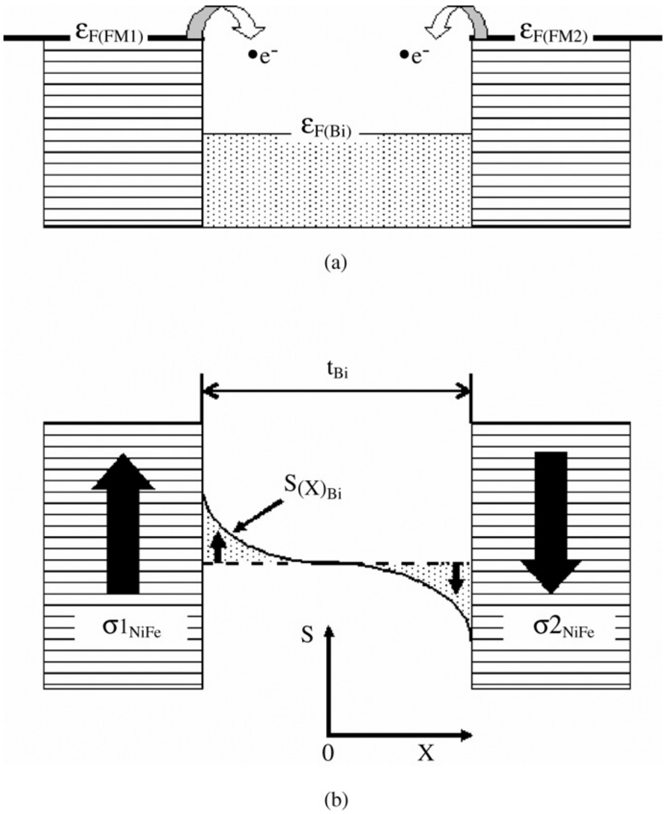

Fig. 3. (a) Scheme of the energetic structure of a trilayer film, ε_{F} is Fermi level. (b) Magnetic structure of a trilayer film and distribution of spin density in a semimetal spacer.

The proximity effect works when there is sufficient number of eigen free electrons in a nonmagnetic spacer, which are polarized due to interference between states of electrons of magnetic and nonmagnetic layers. On one hand, in case of a semimetal the increase of the concentration of free electrons takes place because of heterogeneity in sample volume [16]. Also, it was experimentally shown for bismuth films [7] that at the layer thickness decreasing to ~ 25 nm the concentration of current carriers increases almost in two orders of magnitude; the Fermi level enhances as compared to that of a bulk material [17], and at $t_{\text{Bi}} \leqslant 12$ nm even the transition *semimetal/semiconductor* is possible. On the other hand, it is known that the Fermi energy levels of both Fe and Ni [18] are considerably higher than that of Bi [4,5]. In this case, from the direction of a metal the “leakage” of electrons into the near-boundary area of a semimetal is possible, and, since the insulation constant in bismuth has a value ~ 30 nm [19], for given thicknesses the total bismuth film will be the area of the increased electron density. Besides, the degree of spin polarization of free electrons both in Fe and in Ni at the Fermi level is $\geqslant 0.6$ [18], therefore, the flow of electrons polarized by a spin will take place.

To create additional magnetization, for example, $\Delta\sigma = \sigma(t_{\mathrm{Bi}} = 6\ \mathrm{nm}) - \sigma(t_{\mathrm{Bi}} = 0\ \mathrm{nm})$, the number of polarized electrons $N \sim 10^{22}\ \mathrm{cm}^{-3}$ is required, which cannot be provided only for the expense of the bismuth transition to a film state. Apparently, both opportunities are possible, however, the experimentally observed magnetization enhancement in the structure NiFe/Bi/NiFe is connected with the formation of areas of the increased electron density with polarized spins in bismuth mainly due to the diffusion effect.

Thus, as a result of investigations carried out it was found:

- dependence of interlayer interaction on semimetal spacer thickness in the trilayer NiFe/Bi/NiFe film;
- dependence of saturation magnetization of the structure NiFe/Bi/NiFe on bismuth layer thickness that can be attributed to the effect of spin accumulation in a semimetal.

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