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Interlayer Interactions in FeNi/Bi/FeNi Trilayers

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Abstract—Interlayer interactions in FeNi/Bi/FeNi films are studied experimentally. It is established by SQUID magnetometry and magnetic resonance investigations that the interlayer interaction in these films is determined by the bismuth spacer thickness and temperature. A giant magnetoresistance effect is observed in the investigated trilayers.

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INTRODUCTION

Magnetic multilayer films with a nonmagnetic spacer, particularly those belonging to a ferromagnetic metal/semiconductor system [1] or containing a semimetal spacer, attract the attention of researches due to the variety of effects observed in these materials. The use of a semiconductor spacer makes it possible to control the characteristics of the spacer and interlayer interaction (J) by external factors (impurities, radiation, temperature, magnetic fields, and so on). It is therefore of interest to develop film structures with pronounced effects of the interaction between magnetic layers that remain sensitive to external factors. One way to solve this problem is to use a semi-metal Bi spacer instead of semiconductor material. First of all, according to the phase diagram of 3*d* metal–bismuth systems [2], most of their elements do not form compounds. Second, bismuth itself exhibits extraordinary physical properties in both bulk and film form. The electron mean free path in bismuth can take macroscopic values, as it is dependent on layer thickness, temperature, and the magnetic field. The density and mobility of carriers also vary.

EXPERIMENTAL

We synthesized and studied NiFe/Bi/NiFe trilayer films for the first time in [3]. We used permalloy as our magnetic layer because of its low magnetic crystallographic anisotropy in order to prevent shading of the interlayer interaction. To follow the effect of the competition between the intrinsic magnetic energy and the interlayer interaction energy on the formation of the magnetic state, films with different ratios of iron and nickel contents were synthesized. For all our samples, the magnetic layer thickness was $t_{NiFe} \approx 10$ nm and the bismuth layer thickness varied within $t_{Bi} = 3–15$ nm. The value of t_{NiFe} was chosen to be quite low yet sufficient for magnetization of the magnetic layer not to change with its thickness.

RESULTS AND DISCUSSION

The thicknesses of the layers were determined by X-ray spectroscopy. Electron microscopic studies showed that the layers were continuous over their squares and of nominal composition. No traces of 3*d* Bi compounds were found. The measured magnetic and temperature dependences of magnetization demonstrated the correlation between interlayer interaction and the thickness of the bismuth spacer. It was established that the shape of the $\sigma(H)$ curve changes with an increase in the bismuth layer thickness (Fig. 1). For the reference film with $t_{Bi} = 0$ in particular, the hysteresis loop is narrow and the magnetization curve is of the ferromagnetic type. For the films with $t_{Bi} \neq 0$, the width of the hysteresis of the magnetization curves nonmonotonically depends on thickness t_{Bi}, which is attributed to actuation of the interlayer interaction. With increasing bismuth spacer thickness, coercivity H_C grows by a factor of almost three and attains its maximum value $t_{Bi} \sim 13$ nm; the coercivity then falls again (Fig. 2). This is consistent with the data reported in [4], where it was established that the oscillation period of the interlayer interaction in CoFe/Bi/CoFe films exceeds 10 nm. The shape of the magnetization curves suggests that at room temperature the interlayer coupling weakens to an extent that the contributions of different layers can be clearly followed [5]. The coercivity at room temperature drops by more than an order of magnitude.

We also performed spectral investigations of the polar Kerr effect within the wavelength range λ = 400–800 nm at room temperature. No simple dependences on the bismuth spacer thickness that would be similar to one another were observed.

The obtained magnetostatic data, however, give no clear answer to the question of the value and behavior of the interlayer interaction. For this reason, we investigated the variation in interlayer interaction with temperature by means of electron magnetic resonance.

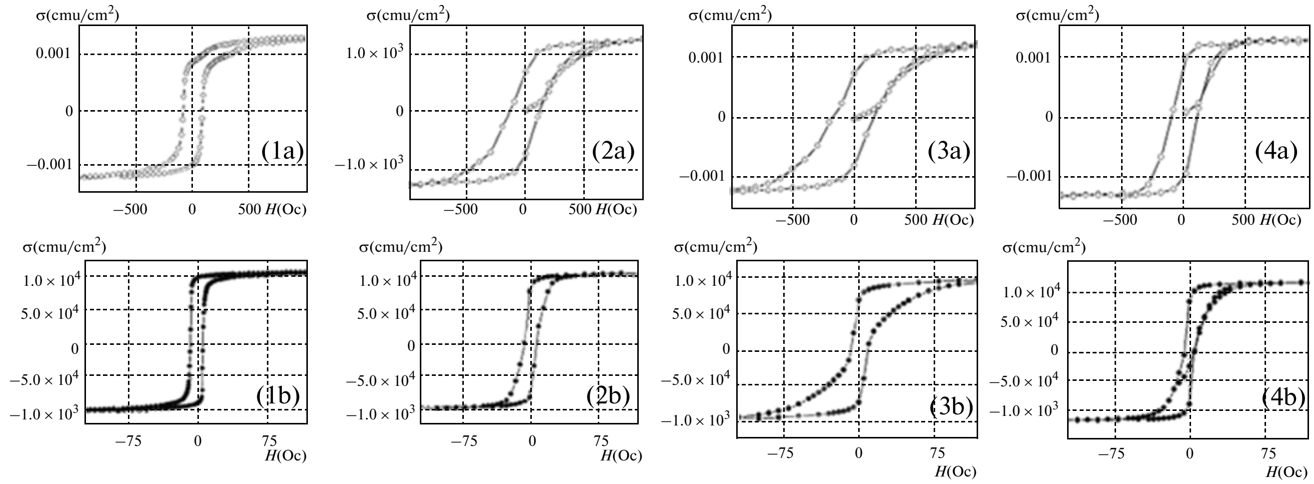

Fig. 1. Field dependences of magnetization for the NiFe/Bi/NiFe films at (a) $T = 4.2$ and (b) 300 K. $t_{NiFe} = 10$ nm (*1*, *2*, *3*, and *4*); $t_{Bi} = 0$, 8, 13, and 15 nm, respectively.

It was found that in the thickness range $t_{Bi} = 3$–12 nm, the magnetic resonance spectrum consists of two lines, indicating the antiferromagnetic character of the interaction between ferromagnetic layers. A single magnetic resonance line was observed for the reference film with $t_{Bi} = 0$ nm and films with $t_{Bi} \geq 15$ nm. The temperature dependences of the magnetic resonance parameters were measured to establish the temperature dependences of interlayer interaction J (see the inserts in Fig. 2).

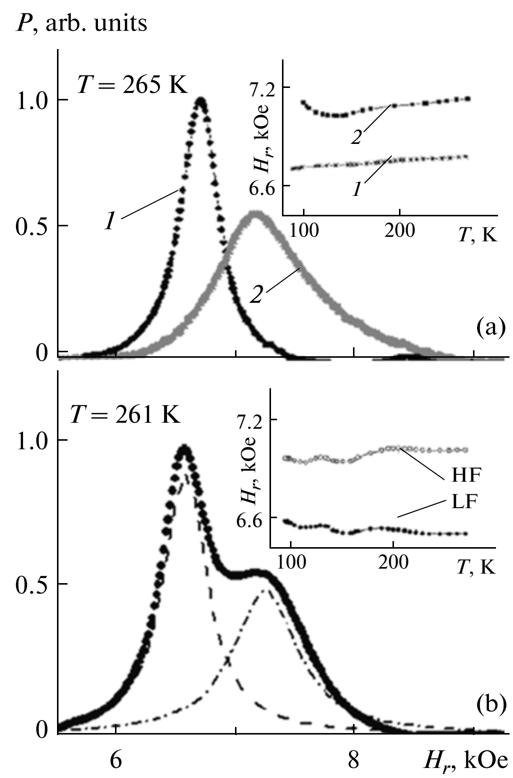

Fig. 2. Magnetic resonance spectra of the NiFe/Bi/NiFe films with $t_{NiFe} = 10$ nm and different bismuth thicknesses: (a) $t_{Bi} = 0$ (curve *1*) and 15 (curve *2*) nm and (b) $t_{Bi} = 6$ nm. The inserts show temperature dependences of the resonance field for the corresponding films. LF and HF are the low- and high-frequency branches of the oscillations.

The experimental results were processed by theoretical fitting of the magnetic resonance spectra for a magnetic trilayer. In our case, the free energy per unit square is

$$E = -J\cos(\varphi_1 - \varphi_2) - t_{FM}\left[\vec{H}\left(\vec{M}_1 + \vec{M}_2\right) - 4\pi\left(M_{1Z}^2 + M_{2Z}^2\right)\right], \quad (1)$$

where J is the interlayer exchange interaction constant, $\vec{H}$ is the external magnetic field; $\vec{M}_i$ is the magnetization of the ith ferromagnetic layer; φ_i is the angle of magnetization in the film plane counted from the direction of the external magnetic field; $i = 1, 2$ is the number of a ferromagnetic layer; and t_{FM} is the thickness of the magnetic layer. The Z axis is perpendicular to the film plane. In our calculations, we assume that $(t_{FM}HM) \gg J$ and the ferromagnetic layers are saturated, so $\varphi_i \approx \varphi_H = 0$. It is also assumed that the ferromagnetic layers are identical. Under these conditions, the resonance frequencies are expressed as

$$(\omega_1/\gamma)^2 = H(H + H_M), \quad (2)$$

$$(\omega_2/\gamma)^2 = H(H + H_M) + 2(2H + H_M)H_J + 4H_J^2, \quad (3)$$

where

$$H_M = 4\pi M \text{ и } H_J = J/(t_{FM}M). \quad (4)$$

Since quantities ω, H, and M are known from the experiment, it is easy to find H_J using expression (3), and to determine interlayer interaction constant J from expression (4).

Processing the temperature dependences of the resonance field allowed us to establish the temperature

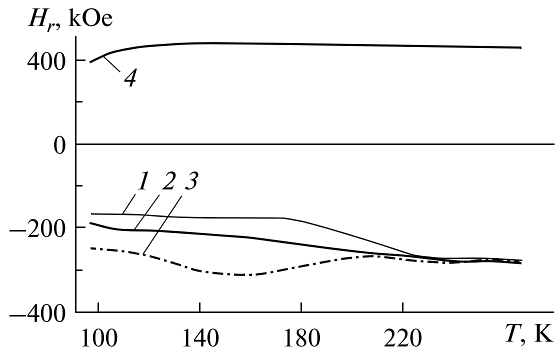

Fig. 3. Calculated temperature dependences of the exchange field for NiFe/Bi/NiFe films *1*, *2*, *3*, and *4* with t_{Bi} = 4, 6, 12, and 15 nm, respectively.

dependences of interlayer interaction (Fig. 3). It can be seen from the figure that the interlayer interaction constant grows weakly with a rise intemperature: at T = 100 K, exchange field $H_J = J/(t_{NiFe}\sigma)$ is approximately –150, –200, –250, and 400 Oe for the films with t_{Bi} = 4, 6, 12, and 15 nm, respectively. At temperatures $T \geq 225$ K, the dependences of the constants are identical. At greater bismuth thicknesses, however, the interaction between the ferromagnetic layers still exists, as follows from the shift of the magnetic absorption line for the film with t_{Bi} = 15 nm relative to the reference film with t_{Bi} = 0 nm, and from the greater width of its line.

A magnetoresistance of about 1% dependent on the bismuth layer thickness was found in the investigated films. This will be the subject of further investigation.

CONCLUSIONS

The effect of the semimetal Bi spacer on the value and sign of the interlayer interaction in the NiFe/Bi/NiFe structure, depending on thickness of the nonmagnetic layer, has been determined. The temperature dependence of the interlayer interaction was found by means of magnetic resonance.

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REFERENCES

1. Patrin, G.S. and Vas'kovskii, V.O., *Fiz. Met. Metall*, 2006, vol. 101, suppl. 1, p. 63.
2. Denisov, V.M., Belousova, N.V., Moiseev, G.S., et al., *Vismutsoderzhashchie materialy: Struktura i fiziko–khimicheskie svoistva* (Bismuth Containing Materials: Structure and Physicochemical Properties), Yekaterinburg: Izd. UrO RAN, 2000.
3. Patrin, G.S., Yakovchuk, V.Yu., and Velikanov, D.A., *Phys. Lett. A*, 2007, vol. 363, p. 164–167.
4. Harada, Y., Nakanishi, Y., Daibo, M., et al., *Physica B*, 2003, vols. 329–333, p. 1109.
5. Skomski, R., *J. Phys.: Condens. Matter*, 2003, vol. 15, no. 7, p. R841.