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Optical and Magnetic Properties of the Dy_xCo_{1-x}/Bi/Py Trilayers

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Abstract—We report on the results of investigations of the optical and magnetooptical properties of Dy_xCo_{1-x}/Bi/Py (Py is permalloy) trilayers. The temperature dependence of the magnetization has been examined using the magnetooptical Kerr effect and the optical refractive and absorption indices have been measured by spectral ellipsometry. It is shown that the thickness of the bismuth spacer affects the exchange coupling between the permalloy and DyCo layers, which manifests itself in the change in the magnetization compensation temperature and in the character of the exchange coupling.

Keywords: exchange coupling, magnetic springs, ellipsometry, magnetooptical Kerr effect.

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For many years, the rare-earth metal (Re)/transition metal (TM) alloys and compounds have been attracting close attention of researchers due to the prospect of using these materials in new-type magnetoresistive memory, recording media, high-sensitivity magnetic field sensors, etc., which exhibit the reliability and low power consumption [1, 2]. The extraordinary properties of such alloys follow from different degrees of thermal demagnetization in the Dy and Co sublattices [3]. At room temperature, the Dy_xCo_{1-x} alloy behaves like a hard-magnetic ferrimagnet with a fairly low coercivity and perpendicular magnetic anisotropy. On the other hand, such alloys included in multilayer heterostructures exhibit the intriguing magnetic properties. In particular, interest is presented by the effect of an exchange spring, which is observed in the magnetic multilayers consisting of exchange-coupled alternating soft- and hard-magnetic layers [4, 5]. To control the interlayer coupling as a decisive parameter when creating an exchange spring structure with specified characteristics, they attempt to introduce additional "control" nonmagnetic layers between magnetic layers. In addition, the use of semiconductor or semimetal materials as a nonmagnetic layer in a magnetic structure expands the functionality. This approach makes it possible to integrate the magnetic and semiconductor properties of initial materials in a single structure [6] and induce new properties that were not previously inherent in them. Bismuth holds a special place in the series of semiconductor and semimetal elements, since it has almost no chemical compounds with transition metals [7], which makes it a convenient material for creating layered structures with sharp interfaces.

In this work, we first synthesized trilayers consisting of the ferromagnetic permalloy (NiFe, hereinafter "Py") and Re ferrimagnetic alloy (Dy_xCo_{1-x}) films separated by a nonmagnetic semimetal Bi layer. In these structures, the Dy_xCo_{1-x} alloy plays the role of a hard-magnetic layer and Py is a soft-magnetic layer. The Dy_xCo_{1-x}/Bi/Py structures were synthesized by thermal evaporation in vacuum (a residual pressure of $\sim 10^{-6}$ mbar) onto a glass substrate. The DyCo layer was grown at a substrate temperature of about room temperature, and the permalloy layer was formed at a substrate temperature of 100°C. The thickness and chemical composition of the synthesized films were examined using X-ray fluorescence analysis. The thicknesses of the Py and DyCo layers remained invariable and amounted to $d_{\mathrm{Py}} = 15$ nm and $d_{\mathrm{DyCo}} = 30$ nm. The bismuth spacer thickness ranged from 0 to 4 nm. The magnetooptical study was carried out on a NanoMOKE2 setup in the meridional Kerr effect configuration at an angle of incidence of 45° with an Oxford Instruments optical cryostat in the temperature range of $T = 4.2$–300 K. A magnetic field was applied in the sample plane along the probe light

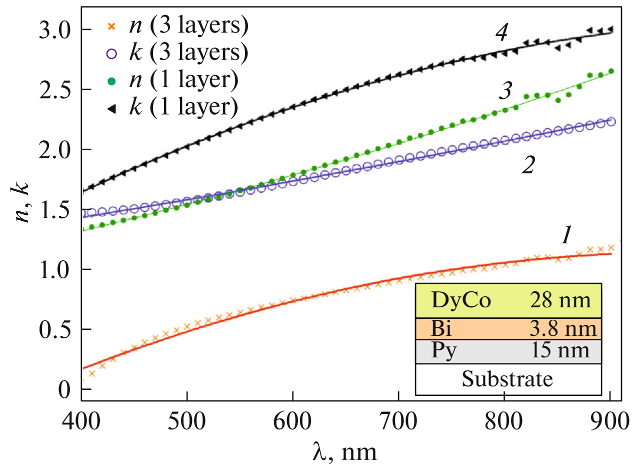

Fig. 1. Optical refractive indices n (curves *1*, *3*) and absorption indices k (curves *2*, *4*) for the Dy_xCo_{1-x}/Bi/Py structure (curves *1*, *2*) and the reference single-layer Dy_xCo_{1-x} film (curves *3*, *4*). Structural parameters used in the multilayer model in solving the inverse ellipsometry problem (lower right corner). Solid lines show the calculation results. Symbols show the experimental data.

beam. The optical refractive and absorption indices were measured with a Spectroscan spectral ellipsometer [8].

To control the composition of the Dy_xCo_{1-x} alloy, we synthesized single-layer films, which were also studied using the above-mentioned techniques. The spectral ellipsometry data are shown in Fig. 1. The spectra qualitatively resemble the dependences typical of 3d and 4f metals.

However, for the single-layer DyCo film, the refractive index was found to be lower than was expected for the $Dy_{21}Co_{79}$ alloy. The introduction of surface roughness into the model in solving the inverse ellipsometry problem made it possible to explain this discrepancy. In trilayers (curves *1*, *2* in Fig. 1), such geometric inhomogeneities most likely exist at each interface, which was also taken into account in the approximation of the ellipsometric spectra. In this case, the effective values of the optical indices of the trilayers are much lower than in the single-layer systems. In addition, having solved the inverse ellipsometry problem [9] using the effective medium model [10], we obtained the $DyCo_5$ alloy composition with 21% of Dy and 79% of Co, which is in good agreement with the data of X-ray spectral fluorescence analysis.

The temperature dependence of the magnetooptical Kerr effect measured in the reference single-layer Dy_xCo_{1-x} films (Fig. 2a) reveals the following features. At room temperature ($T = 300$ K), the magnetization curve corresponds to the signal from the ferromagnet; however, upon cooling (starting with a temperature of $T = 160$ K), the magnetization curve changes its shape. The hysteresis loop for a temperature of $T = 160$ K (Fig. 2a) keeps this shape upon further cooling up to $T = 120$ K (the magnetization curves in the range of $T = 120$–160 K are almost identical), which corresponds to the temperature of magnetization compensation in the $DyCo_5$ alloy [4]. However, in the trilayer films, the temperature of this transition can be different. Note that, at small thicknesses of the Bi spacer ($d \approx 1$ nm), the characteristic points in the temperature dependence of the magnetization almost coincide with the data for the Dy_xCo_{1-x}/Py ($d_{Bi} = 0$) bilayer (Fig. 2b). The magnetization curve then starts changing already at a temperature of $T \approx 224$ K. The situation significantly changes with an increase in the Bi spacer thickness (Fig. 2c). Starting already with helium temperatures, the magnetization curve becomes stepwise, which was the case in neither the single-layer DyCo reference film nor the Dy_xCo_{1-x}/Py bilayer. When passing through the compensation point for the $Dy_{21}Co_{79}$ composition, the hysteresis loop begins to transform and, at $T \geq 160$ K, acquires the shape characteristic of a ferromagnet.

With a decrease in the bismuth spacer thickness, the effect of the soft-magnetic layer on the hard-magnetic one increases. This means that the exchange coupling enhances. In addition, the coercivity decreases, which is attributed to the fact that the soft-magnetic layer stronger "magnetizes" the hard-magnetic one. Another reason for a decrease in the coercivity may be the formation of an interface. As was shown in [11], the bismuth/permalloy interface weakly affects the magnetic properties of the structure. In the DyCo/bismuth interface, the compounds pnictogenides (Dy_5Bi_3, Di_3Bi_2, or DyBi) can be formed, which can affect the general magnetic state. This assumption was confirmed by the ellipsometry data.

To study the temperature dependence of the magnetization, we plotted the curves by analyzing the temperature dependence of the magnetooptical Kerr effect signal using the following procedure. Since magnetization M_s is proportional to the angle of rotation of the polarization plane [12] caused by the Kerr effect upon reflection of a linearly polarized light beam, we assume $M_s \sim (I_{max} - I_{min})/2$, where I_{max} and I_{min} are the maximum and minimum intensities of the reflected polarized light in the opposite directions of the external magnetic field, respectively. It should be noted that, in this case, the absolute value of the sample magnetization cannot be obtained. However, we can detect its relative changes in a single experiment. This analysis revealed a nontrivial behavior of the magnetization of the Dy_xCo_{1-x}/Bi/Py system (Fig. 3), which is caused, first of all, by the presence of the Dy_xCo_{1-x} ferrimagnetic layer, in which the resulting magnetization is determined by the degree of dominance of the Dy–Co coupling over the Dy–Dy one [4].

In the low-temperature region, below the compensation point, the Dy magnetic sublattice parallel to the external magnetic field is dominant. As the tempera-

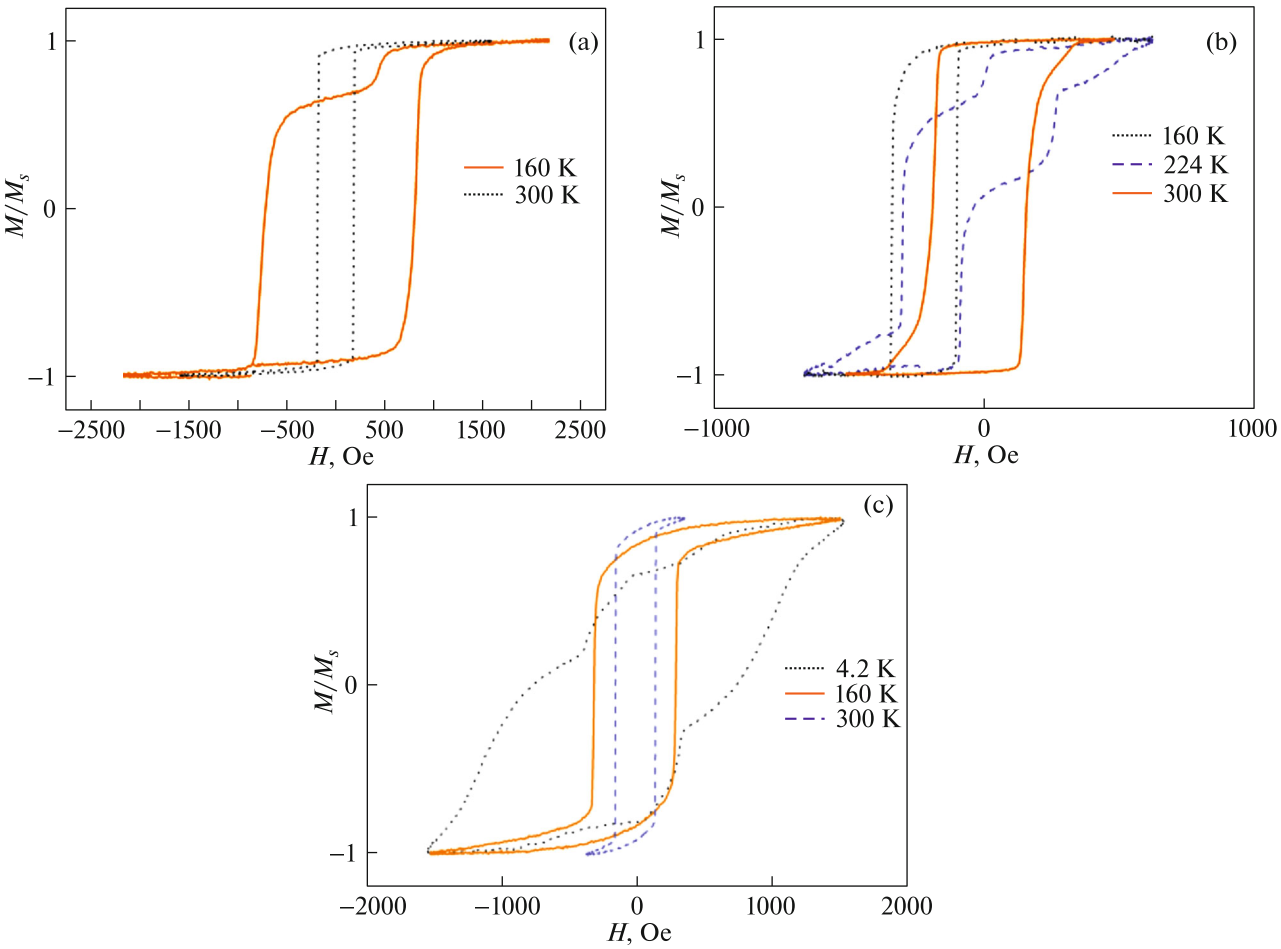

Fig. 2. Magnetization curves for the (a) reference Dy_xCo_{1-x} single-layer film, (b) Dy_xCo_{1-x}/Py bilayer, and (c) Dy_xCo_{1-x}/Bi/Py trilayer at a Bi spacer thickness of $d_{Bi} = 4$ nm.

ture increases, different degrees of demagnetization of the Dy and Co sublattices lead to the complete compensation of the magnetization. It is this situation can be observed when studying the magnetization of the reference single-layer Dy_xCo_{1-x} film (curve *1* in Fig. 3).

Concerning the behavior of the magnetization in the Dy_xCo_{1-x}/Bi/Py system, two fundamentally different situations can be distinguished. In the first case, the compensation point exists and its position can change (the family of curves *2*–*4* in Fig. 3 corresponding to different bismuth spacer thicknesses); i.e., we deal with the antiferromagnetic coupling between the DyCo and Py layers. In the second case, the compensation point vanishes (curve *5* in Fig. 3), while the magnetization decreases with increasing temperature. In this case, the interlayer coupling is ferromagnetic. To understand the origin of the change or disappearance of the compensation point, we refer to [13], where, using ab initio calculations, the temperatures of this transition were estimated by changing parameters J_{TM-TM} and J_{Re-TM} (the TM–TM and Re–TM exchange coupling constants, respectively). It was

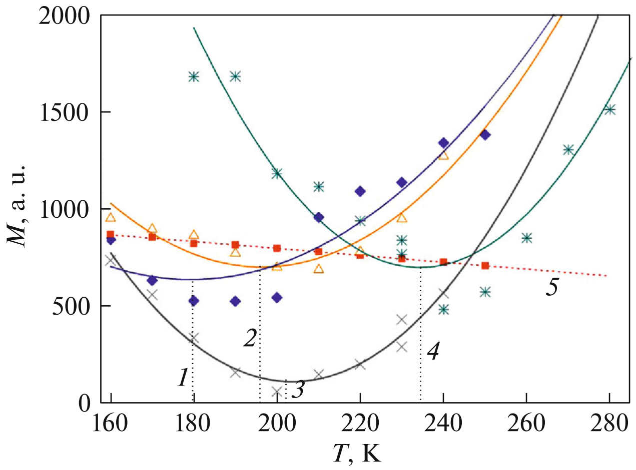

Fig. 3. Temperature dependence of magnetization for the Dy_xCo_{1-x} samples (rhombs and curve *1*), Dy_xCo_{1-x}/Bi/Py at Bi layer thicknesses of $d_{Bi} = 4$ nm (triangles and curve *2*), $d_{Bi} = 3$ nm (crosses and curve *3*), and $d_{Bi} = 2$ nm (asterisks and curve *4*) and the Dy_xCo_{1-x}/Py samples (squares and curve *5*). Vertical lines show the corresponding compensation temperatures for each sample.

found that the compensation point only appears at the low $J_{\mathrm{Re-TM}}$ values. With an increase in the $J_{\mathrm{TM-TM}}$ exchange, the range of $J_{\mathrm{Re-TM}}$ parameters for which a compensation point exists becomes wider. For example, it was shown for the case TM = Fe, Re = Tb that the compensation point can change in a wide temperature range from 220 to 950 K. Therefore, for the investigated $\mathrm{Dy}_x\mathrm{Co}_{1-x}$/Bi/Py systems, we can assume that the Bi spacer affects the magnetic state of the DyCo layer by changing the $J_{\mathrm{Dy-Dy}}$ and $J_{\mathrm{Dy-Co}}$ exchange constants. It should be noted here that even the pure DyCo_5/Bi interface (without the formation of any compounds) can significantly affect the anisotropy in the DyCo_5 film, since Bi is a heavy element, which has a fairly strong spin–orbit coupling. This fact will manifest itself in a significant anisotropy of the magnetic susceptibility even in the absence of *d* states in the conduction band. Therefore, even a minor exchange bias of the Bi *p* states from the DyCo_5 side can lead to a strong change in the magnetic anisotropy energy. The situation can be similar to that met in the functional ferromagnetic (FePt, MnBi) and antiferromagnetic (MnIr) alloys with a nonmagnetic heavy element [14].

Thus, it was established that the presence of a semimetal Bi layer in the $\mathrm{Dy}_x\mathrm{Co}_{1-x}$/Bi/Py trilayer leads to a change in the magnetic state, specifically,

—the change in the nature of the interlayer exchange coupling from antiferromagnetic to ferromagnetic; and

—the noticeable difference between the temperature dependences of the magnetization for the samples with different Bi thicknesses and the shift of the magnetic transition corresponding to the compensation temperature of the $\mathrm{Dy}_x\mathrm{Co}_{1-x}$ alloy along the temperature axis or the complete absence of this transition.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

REFERENCES

1. *Novel Magnetic Nanostructures: Unique Properties and Applications*, Ed. by N. Domracheva, M. Caporali, and E. Rentschler (Elsevier, Amsterdam, 2018).
2. A. A. Unal, S. Valencia, F. Radu, D. Marchenko, K. J. Merazzo, M. Vázquez, and J. Sánchez-Barriga, Phys. Rev. Appl. **5**, 064007 (2016).
3. A. Donges, S. Khmelevskyi, R.-M. Deak, D. Abrudan, I. Schmitz, F. Radu, L. Szunyogh, and U. Nowak, Phys. Rev. B **96**, 024412 (2017).
4. M. Labrune and M. Carbucicchio, J. Magn. Magn. Mater. **269**, 203 (2004).
5. D. Wang, C. G. Morrison, A. R. Buckingham, G. J. Bowden, R. C. C. Ward, and P. A. J. de Groot, J. Magn. Magn. Mater. **321**, 586 (2009).
6. B. P. Zakharchenya and V. L. Korenev, Phys. Usp. **48**, 603 (2005).
7. V. M. Denisov, N. V. Belousova, and G. K. Moiseev, *Bismuth-Containing Materials: Structure and Physical and Chemical Properties* (Inst. Metall. UrO RAN, Ekaterinburg, 2000) [in Russian].
8. V. A. Shvets, E. V. Spesivtsev, and S. V. Rykhlitskii, Opt. Spectrosc. **97**, 483 (2004).
9. H. Fujiwara, *Spectroscopic Ellipsometry: Principles and Application* (Wiley, Chichester, 2007).
10. D. E. Aspnes, J. B. Theeten, and F. Hottier, Phys. Rev. B **20**, 3292 (1979).
11. G. S. Patrin, V. Yu. Yakovchuk, S. A. Yarikov, Ya. G. Shiyan, and V. P. Furdyk, Tech. Phys. Lett. **45**, 507 (2019).
12. S. D. Bader, J. Magn. Magn. Mater. **100**, 440 (1991).
13. R. Moreno, S. Khmelevskyi, and O. Chubykalo-Fesenko, Phys. Rev. B **99**, 184401 (2019).
14. S. V. Grigoriev, E. V. Moskvin, V. A. Dyadkin, D. Lamago, T. Wolf, H. Eckerlebe, and S. V. Maleyev, Phys. Rev. B **83**, 224411 (2011).

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