Journal of Magnetism and Magnetic Materials 440 (2017) 136–139

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Exchange interaction in Co/Bi/Co thin-film systems with Bi interlayer

E.E. Shalygina[a,*], A.M. Kharlamova[a], G.V. Kurlyandskaya[b], A.V. Svalov[b]

[a] Faculty of Physics, Moscow State University, 119991 Moscow, Russia
[b] Ural Federal University, 620002 Ekaterinburg, Russia

ARTICLE INFO

Keywords:
Interlayer coupling
Magnetic properties
Magneto-optical effect

ABSTRACT

The magneto-optical and magnetic properties of Co(5 nm)/Bi/Co(5 nm) samples and the peculiarities of exchange coupling between Co layers through the Bi spacer layer are studied. The magneto-optical investigations indicate that the shapes of Transverse Kerr effect (TKE) spectra are similar for all studied samples but the TKE values decrease at $t_{Bi} > 4$ nm as compared with TKE values of the single-layer Co thin film. The decrease in the volume ratio of the magnetic to nonmagnetic phases causes the reduction of the contribution of the magnetic phase to magnetooptical signals. Magnetic investigations show that the coercivity force, H_C, and saturation field, H_S, of the Co/Bi/Co samples increase with increasing t_{Bi}. The oscillatory behavior of H_C and H_S with various periods (short and long) is observed in a wide range of t_{Bi} values (from 0.2 to 50 nm). These data are explained by the dependence of Fermi energy on t_{Bi} and the changes in the Bi band structure with decreasing t_{Bi}.

1. Introduction

Physical properties of thin magnetic films of 3d-transition metals and magnetic multilayers are the most important area of the physics of magnetic phenomena and applied magnetism. It's connected with the rapid development of the fundamental knowledge related to phenomena such as quantum size effects [1,2], giant magnetoresistance [3,4] and oscillating exchange coupling between ferromagnetic layers (Fe, Co) through nonmagnetic (e.g., Cu, Cr, Ag and Au) spacers [4,5] and wide practical applications of these materials in devices of spintronics and micro- and nanoelectronics. Despite the huge amount of publications devoted to the study of aforementioned materials, the peculiarities of exchange interaction in thin-film magnetic nanostructures with a diamagnetic semimetallic Bi interlayer are far from complete understanding. Some aspects of the exchange interaction in thin-film systems with the Bi interlayer have been discussed in [6–8]. It was found, that there are the oscillatory exchange interactions in the NiFe(10 nm)/Bi(3–15 nm)/NiFe(10 nm) [6,7] and CoFe(15 nm)/Bi(1–60 nm)/Co(15 nm) samples [8]. The periods of oscillations, Λ, were 18–20 nm, which were significantly higher than those found for other thin-film systems with a metallic spacer, in particular, for the trilayer structures, consisting of two identical magnetic layers (Fe, Co) and different interlayers such as diamagnetic (Ag, Au), paramagnetic (Mo, Pt, Pd, Ta, Zr) and semiconducting Si [9–11]. Considering the above the study of thin film systems with bismuth deserves attention. The diamagnetic semimetallic bismuth has unusual physical properties [12]. In particular, it does not form compounds near interfaces in multilayer thin-film systems. The Fermi wavelength, λ_F, of semimetallic Bi is of the order of 40 nm. The value of the mean free path of bismuth electrons depends on layer thickness, temperature and applied magnetic field.

The aim of this work is the investigation of influence of Bi on the magneto-optical and magnetic properties of the Co/Bi/Co thin-film systems and also examination of the peculiarities of exchange coupling between Co layers through the Bi spacer layer.

2. Materials and methods

Co/Bi/Co samples were grown by magnetron sputtering at room temperature using Co and Bi targets. The surface roughness of the substrates was about 0.5 nm. The Ta seed layers of 5 nm thick were deposited on the glass substrates. The background pressure in the vacuum chamber was 4×10^{-7} mbar and the argon pressure during the film deposition was as high as 3.8×10^{-3} mbar. A constant magnetic field of 250 Oe was applied parallel to the substrate, H_{SUB}, in order to form an in-plane easy magnetization axis (EMA). The thickness of the Co layers, t_{Co}, in all samples was equal to 5 nm. The thickness of the Bi layer, t_{Bi}, varied from 0.2 to 50 nm.

The microstructure of the thin-film systems was studied by X-ray diffraction (XRD) using CuKα radiation. The deposition rate was 2.6 nm/min for Co and 2.0 nm/min for Bi. The surface morphology of samples was investigated by AFM. The domain structure (DS) was investigated by the High-Resolution Kerr microscope (HRM). The

* Corresponding author.
E-mail address: shal@magn.ru (E.E. Shalygina).

http://dx.doi.org/10.1016/j.jmmm.2016.12.144
Received 25 October 2016; Accepted 18 December 2016
Available online 25 March 2017
0304-8853/

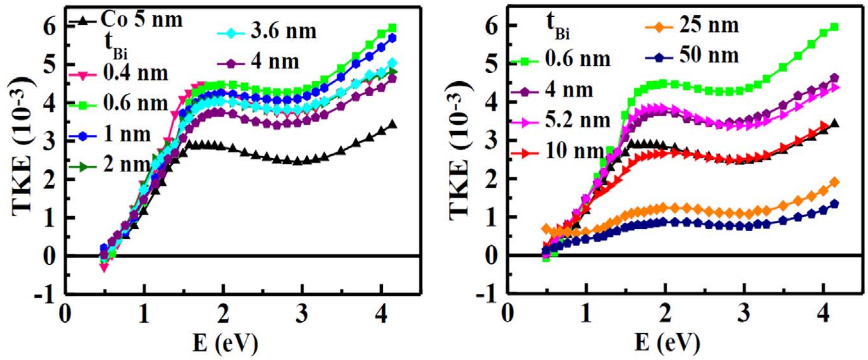

Fig. 1. Spectral dependences of TKE observed for the single-layer Co film of 5 nm thickness and Co/Bi/Co samples with the different thicknesses of Bi layer.

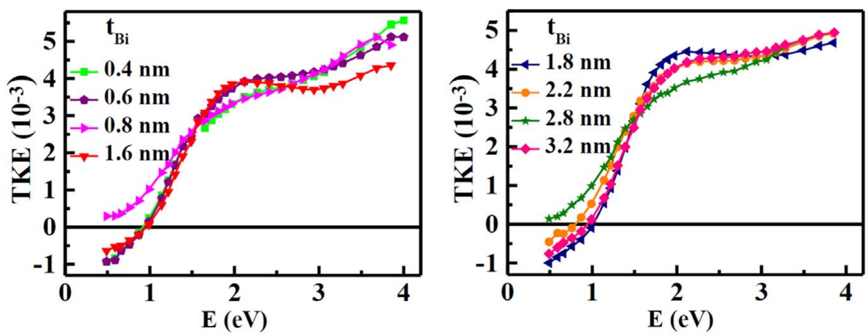

Fig. 2. Spectral dependences of TKE observed for the Co/Si/Co samples with the different thicknesses of Si layer.

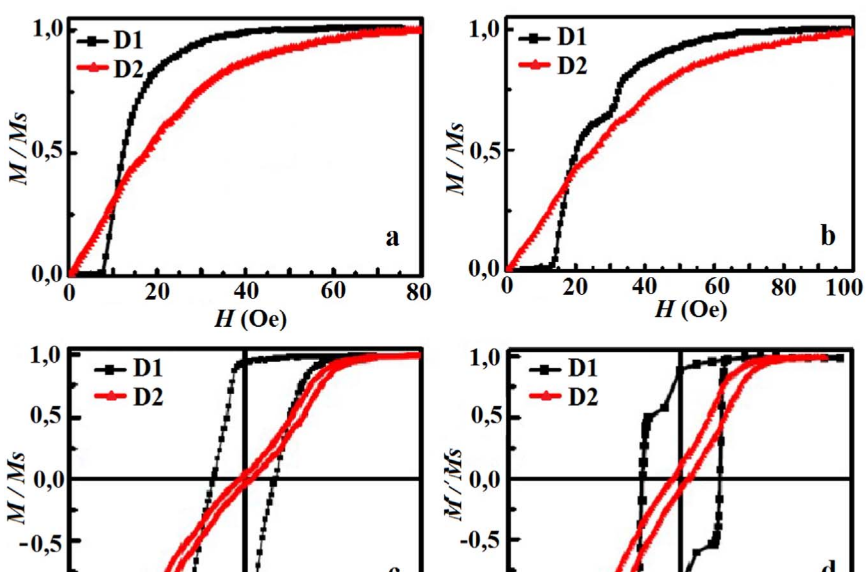

Fig. 3. Typical magnetization and hysteresis loops observed for the Co/Bi/Co samples with t_{Bi} =0.4 nm (a, c) and t_{Bi} =2.0 nm (b, d) in the magnetic field applied parallel to D1 and D2 directions.

magnetic characteristics and magneto-optical spectra of the Co/Bi/Co thin-film systems were measured employing a magneto-optical magnetometer and spectral magneto-optical equipment [described in 13,14] using the transverse Kerr effect (TKE).

The hysteresis loops of the studied samples were measured in two different directions of the external magnetic field. In one case *H* was parallel to the EMA direction (direction D1) and in the other–perpendicular to D1 (direction D2). The next dependences were measured: $\delta(H)/\delta_S \propto M(H)/M_S$, where δ_S is the value of TKE for $M = M_S$, M_S is the saturation magnetization of the sample. The value of *H* was changed from −*H* to +*H* and from +*H* to −*H*.

3. Results and discussion

The results of XRD measurements showed that Co layers in the Co/Bi/Co samples have a nanocrystalline structure and no Bi–Co compounds are formed on the interfaces. The relative intensity of the diffraction peaks of Bi increases with increasing the Bi layer thickness.

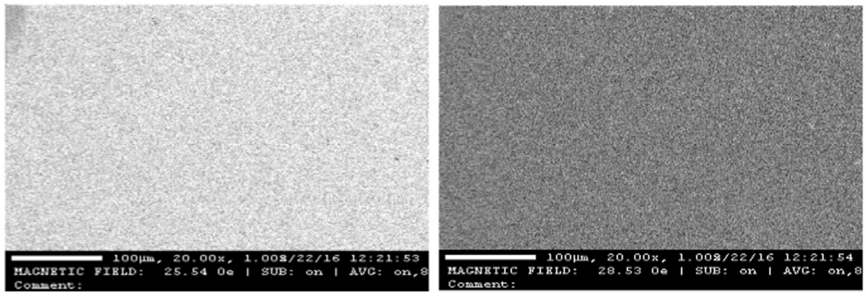

Fig. 4. : Typical images of DS obtained for Co/Bi/Co samples by the HRM during remagnetization process from −H to +H.

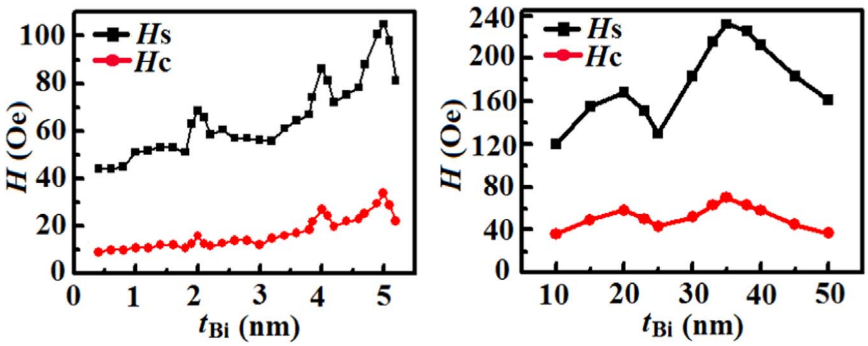

Fig. 5. Dependences of HC and HS on the tBi of the Co/Bi/Co samples measured at the magnetic field applied parallel to D1 direction.

According to AFM investigations, the average surface roughness R_a of the studied samples is about 0.5 nm, and the magnitude of R_a does not depend on Bi layer thickness. This experimental finding indicates that the variation of Bi layer thickness does not influence the magneto-optical and magnetic properties of the studied samples.

The spectral dependences of TKE of the Co/Bi/Co thin-film samples are presented in Fig. 1.

Fig. 1 shows that the shapes of TKE spectra are similar for all samples in contrast to the spectra, observed for the Co/Si/Co samples in [11] (Fig. 2).

The found oscillatory behavior of TKE at the fixed *E* for the Co/Si/Co samples was explained by the appearance of Co-Si compounds near the interfaces that was confirmed by data of the XRD investigations. This fact shows that the identity of TKE spectra in Fig. 1 reaffirms the absence of Bi-Co compounds near interfaces in the Co/Bi/Co samples.

The change of TKE values of the Co/Bi/Co samples with increasing t_{Bi} > 4 nm can be explained as follows. It was experimentally proven [15] that the value of t_M^{crit} (an information depth of magneto-optical signals) of cobalt in the range of photon energies, *E*, from 1.5 to 4.5 eV is of the order of 20–15 nm, which exceeds t_{Co} in the Co/Bi/Co samples. In the case of the trilayer samples the values of t_M^{crit} are determined by the multiple reflections of the incident light from the sample interfaces and can depend on the optical properties of Bi layers. Our measurements of the absorption spectra of the single-layer Bi films showed that the Bi layer is characterized by the relatively high transparency. So the existence of the second Co layer and Bi interlayer causes the increase of TKE values at t_{Bi} ≤4 nm about 1.5 times as compared with the single-layer Co film. The TKE values decrease at t_{Bi} > 4 nm. The increase of t_{Bi} causes a decrease of the volume ratio of the magnetic (Co) to nonmagnetic (Bi) phases. As a result, the contribution of the magnetic phase to the value of magneto-optical signal decreases.

The magnetic characteristics of the Co/Bi/Co samples were measured employing a magneto-optical magnetometer. Fig. 3 shows the typical magnetization curves and hysteresis loops of studied samples. One can see in Fig. 3 that the hysteresis loops, measured in the magnetic field, applied along the D1 and D2 directions differ from each other. This fact indicates the formation of induced magnetic anisotropy with EMA parallel to the direction of magnetic field, applied during the deposition process. According to the commonly accepted notions, the main mechanism underlying the appearance of induced magnetic anisotropy is the pair ordering of atoms [16].

The shape of hysteresis loops measured along the D1 direction depends on the t_{Bi}. In particular, some samples exhibit almost rectangular hysteresis loops (Fig. 3c), while others are characterized by the double-stage hysteresis loops and rather large values of the H_S (Fig. 3d). According to the previously reported experimental and calculated data [9–11,17], almost rectangular and double-stage hysteresis loops are observed for parallel and antiparallel orientations of magnetization components in cobalt layers. The samples with the rectangular hysteresis loops have parallel orientation of magnetization in adjacent Co layers. The magnetization reversal in these systems proceeds via irreversible growth of the remagnetization nuclei. Abrupt change in optical contrast during the remagnetization process, observed by using HRM, confirms this fact (Fig. 4).

The measurements of hysteresis loops allowed to receive the dependences $H_C(t_{Bi})$ and $H_S(t_{Bi})$, presented in Fig. 5. One can see that the dependences $H_C(t_{Bi})$ and $H_S(t_{Bi})$ have oscillatory behavior. The peaks of H_C and H_S are observed at t_{Bi}=2, 4, 5, 20, 35 nm. The distances between peaks, Λ, are equal to 2, 1 and 15 nm, i.e. the oscillations are observed with various periods in a wide range of t_{Bi} values (0.2–50 nm). The oscillatory behavior of $H_S(t_{Bi})$ can be explained by the mechanism of the exchange coupling via the RKKY interaction [18,19]. In this case the Λ must be of the order of λ_F. The Fermi wavelength of bismuth is of the order of 40 nm, which is more than the experimentally determined. The oscillation period in this system may be inconstant. The reasons of variation in Λ are the dependence of Fermi energy on t_{Bi} [20], which arises from the nonparabolic band structure of bismuth and also the changes in the band structure of the thin Bi layer as compared with a bulk sample [21–23].

4. Conclusions

The results of investigations of magneto-optical and magnetic properties of the Co/Bi/Co samples allowed to make the following conclusions.

The shapes of TKE spectra are similar for the all studied samples. The TKE values of the Co/Bi/Co samples change insignificantly with t_{Bi} ≤4 nm and decrease with t_{Bi} > 4 nm as compared with TKE values of the single-layer Co thin film. The increase of t_{Bi} results in a decrease in the volume ratio of the magnetic (Co) to nonmagnetic (Bi) phases and the contribution of the magnetic phase to the value of magneto-optical signal decreases. The values of H_C and H_S increase for the all samples and show oscillatory behavior (existence antiparallel and parallel orientations of magnetization components in Co layers) with the increase in $t_{Bi.}$ The oscillatory behavior of H_S has been observed with various periods in a wide range of t_{Bi} values (from 0.2 to 50 nm).

The obtained experimental data can be taken into account for the development of nanostructured layered magnetic materials for modern devices of spintronics and micro- and nanoelectronics.

Acknowledgements

This work was supported by the Russian Foundation of Basic Research, Grants 15-02-02077 and 16-32-50028.

References

[1] G. Bayreuther, F. Bensch, V. Kottler, J. Appl. Phys. 79 (1996) 4509.
[2] Z. Qin, N.V. Smith, J. Phys.: Condens. Matter 14 (2002) R169.
[3] M.N. Babich, J.M. Broto, A. Fert, F. Nguyen VenDau, F. Petgroff, Phys. Rev. Lett. 61 (1988) 2472.
[4] P. Grunberg, R. Schreiber, Y. Pang, M.B. Brodsky, H. Sowers, Phys. Rev. Lett. 57 (1986) 2442.
[5] S. Parkin, N. More, K. Roche, Phys. Rev. Lett. 64 (1990) 2304.
[6] G. Patrin, V. Yakovchuk, E. Eremin, A. Zaitsev, Proc. Int. Symp. Ordering in Mineral and Alloys, 2008, p. 105.
[7] G. Patrin, V. Yakovchuk, D. Velikanov, Phys. Lett. A 363 (2007) 164.
[8] Jen-Hwa Hsua, D. Sahu, Appl. Phys. Lett. 86 (2005) 192501.
[9] E. Shalygina, G. Maximova, M. Komarova, A. Shalygin, L. Kozlovskii, Solid State Phenom. 162–163 (2009) 253.
[10] E. Shalygina, A. Rojnovskaya, A. Shalygin, Solid State Phenom. 190 (2012) 514.
[11] E. Shalygina, E. Gan'shina, A. Kharlamova, A. Mukhin, G. Kurlyandskaya, A. Svalov, Solid State Phenom. 233–234 (2015) 653.
[12] N. Garcia, Y.H. Kao, M. Strongin, Phys. Rev. B 5 (1972) 2029.
[13] E. Shalyguina, M. Komarova, V. Molokanov, Sov. Phys. JETP 95 (2002) 511.
[14] E. Balykina, E. Gan'shina, G. Krinchik, Sov. Phys. JETP 66 (1987) 1073.
[15] E. Shalyguina, K.-Ho Shin, J. Magn. Magn. Mater. 220 (2000) 167.
[16] S. Chikazumi, Physics of Magnetism, Willey, New York, 2001, p. 554.
[17] K Zvezdin, Phys. Solid State 42 (2000) 120.
[18] Z. Qiu, J. Pearson, A. Berger, S. Bader, Phys. Rev. Lett. 68 (1992) 1398.
[19] P. Bruno, C. Chappert, Phys. Rev. Lett. 67 (1991) 1602.
[20] D.M. Edwards, J. Mathon, J. Magn. Magn. Mater. 93 (1991) 85.
[21] Y. Yafet, Phys. Rev. B 36 (1987) 3948.
[22] M.D. Stiles, Phys. Rev. B 48 (1993) 7238.
[23] P. Bruno, Phys. Rev. B 52 (1995) 411.