01,05,13

Features of remagnetization of the two-layer film structure of the YIG/FeNi

© *A.V. Svalov*[1], *V.E. Ivanov*[1], *V.N. Lepalovskij*[1], *A.A. Feshchenko*[1], *A.N. Gorkovenko*[1], *I.A. Makarochkin*[1], *V.O. Vas'kovskiy*[1,2], *G.V. Kurlyandskaya*[1]

[1] Institute of Natural Sciences and Mathematics,
Ural Federal University named after the First President of Russia B.N. Yeltsin,
Yekaterinburg, Russia
[2] M.N. Mikheev Institute of Metal Physics, Ural Branch, Russian Academy of Sciences,
Yekaterinburg, Russia

E-mail: andrey.svalov@urfu.ru

Received April 29, 2022
Revised April 29, 2022
Accepted May 12, 2022

The results of magneto-optical and magnetometric measurements carried out on two-layer film structures of YIG/FeNi are presented. YIG films were grown by liquid-phase epitaxy, and FeNi films were deposited by magnetron sputtering. It has been established that an interlayer magnetic coupling takes place in the YIG/FeNi system, which is mainly due to magnetostatic interaction.

Keywords: yttrium-iron-garnet, permalloy, interlayer coupling, magnetostatic and exchange interaction, magnetic domain structure.

DOI: 10.21883/PSS.2022.09.54141.04HH

1. Introduction

YIG films, the interest in which many years ago was due to their use in the technique of magnetic bubble domains (BD) [1], are now again the subject of active attention as part of structures used magnonics devices and other applications based on the features of magnetodynamics of materials [2,3]. Both in BD devices and in elements of UHF-electronics and spintronics, YIG films can be in contact with ferromagnetic metal films, which leads to the occurrence of a magnetic interaction between them [1,4–6]. However, there is no clear answer in the publications regarding the nature of this relationship. Some researchers speak about the presence of exchange interaction in such two-layer structures, without specifying the exchange mechanism [1,4,7,8], others suggest direct exchange [5,9] or superexchange [9], others explain the interlayer coupling by magnetostatic interaction [6].

If there is an exchange interaction in such a two-layer system, it may turn out to be an interesting model object, provided that there is a perpendicular magnetic anisotropy in the YIG film. The issue of the exchange mechanism in film systems with orthogonal orientation of magnetizations remains open up to now [10–12]. In this paper, we study the features of remagnetization of YIG/FeNi and YIG/Ta/FeNi two-layer film structures.

2. Study methodology

Films of doped yttrium iron garnet (YIG) 5 μm thick were grown by liquid-phase epitaxy on a substrate 500 μm thick of gadolinium-gallium garnet, whose surface orientation coincides with plane (111). $Fe_{20}Ni_{80}$ (FeNi) permalloy films 10−40 nm thick were deposited by magnetron sputtering onto glass substrates and onto the YIG film both directly and through an intermediate layer Ta up to 10 nm thick. The film sputtering process was carried out in the presence of a technological permanent magnetic field with a strength

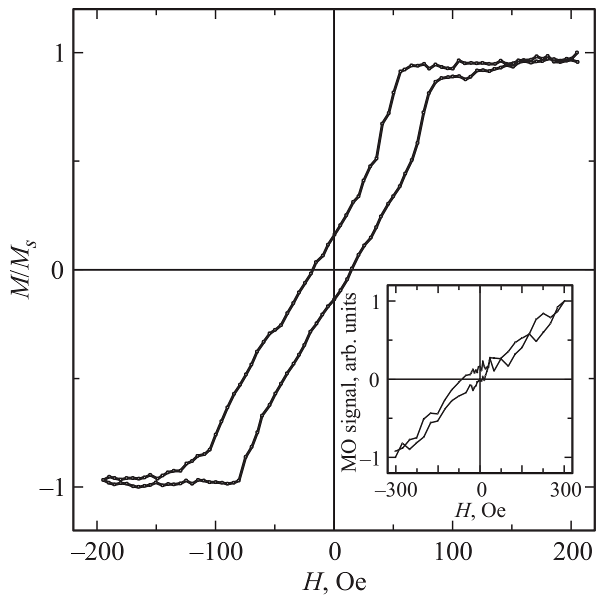

Figure 1. Magneto-optical hysteresis loops of the YIG film measured in the geometry of the polar Kerr effect when the magnetic field is oriented perpendicular to the sample plane and in the sample plane (inset).

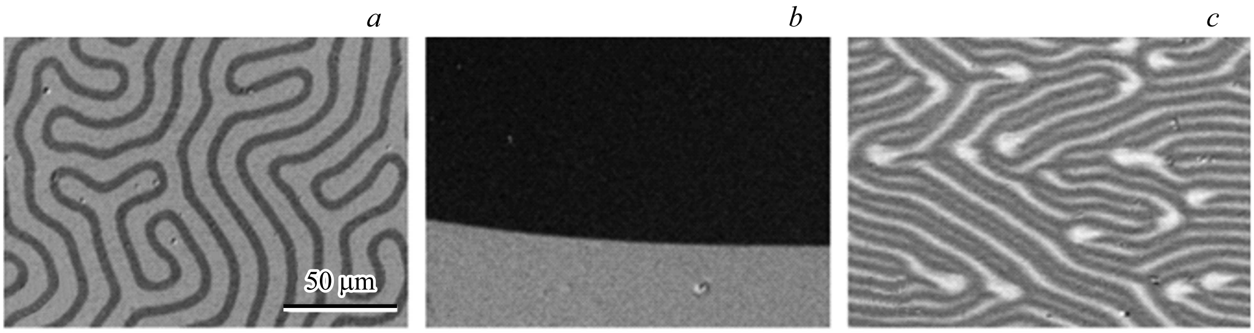

Figure 2. Images of the magnetic domain structure of the YIG (a), FeNi film on a glass substrate (b) and FeNi film deposited on YIG (c) obtained in the geometry of the polar (a) and longitudinal (b, c) Kerr effect.

of 250 Oe, oriented in the plane of the substrates. X-ray diffraction studies of the samples were performed on a D8-Advance diffractometer. The magnetic properties of the films were measured using a vibrating magnetometer and a Kerr-microscope Evico Magnetics at room temperature.

3. Results obtained

X-ray studies of the samples did not reveal any dependence of the structural features of the FeNi layers on the substrate material and the presence of the Ta sublayer. The average size of FeNi crystallites, determined using the Scherrer formula, for all samples was 15 nm.

The magnetization of the garnet films was 20 G. The YIG films, according to the characteristic hysteresis loops (Fig. 1), had a perpendicular magnetic anisotropy. In the plane, they were isotropic, this was confirmed by the presence of a typical labyrinth magnetic domain structure (DS) (Fig. 2, a). Besides, the external magnetic field applied in the plane of the YIG film with an amplitude of 300 Oe did not change the DS configuration. Thus, it can be assumed that during the FeNi layer deposition in the presence of the technological field of 250 Oe, a labyrinthine domain structure was present in the YIG film.

Permalloy films of various thicknesses deposited on glass substrates (Corning) in the presence of the technological permanent magnetic field of 250 Oe, had induced uniaxial magnetic anisotropy. The easy magnetization axis (EMA) was oriented in the film plane and coincided with the axis of application of the technological field (Fig. 3), which was reflected in the characteristic domain structure (Fig. 2, b). The nature and possible mechanisms of this so-called M-induced anisotropy in polycrystalline films of 3D--metals and their alloys are well studied [13]. The values of the coercive force and the anisotropy field of the FeNi films were 1.1 ± 0.1 Oe and 5 ± 1 Oe, respectively.

In FeNi films deposited on YIG, the labyrinth DS was also observed (Fig. 2, c). The period of this structure, measured in the absence of an external magnetic field, was $11 \pm 1\,\mu$m for all YIG/FeNi samples, regardless of the thickness of the permalloy layer and the presence or absence of the Ta interlayer, and coincided with the DS period of the YIG film within the measurement accuracy. Note that after the action of a pulse of a vertical magnetic field, the value of which exceeded the saturation field of the YIG film, in a zero external field the configuration of the labyrinthine DS in the permalloy film changes. This indicates that the deposition of the FeNi layer on the YIG does not result in the stabilization of the domain walls in the permalloy layer.

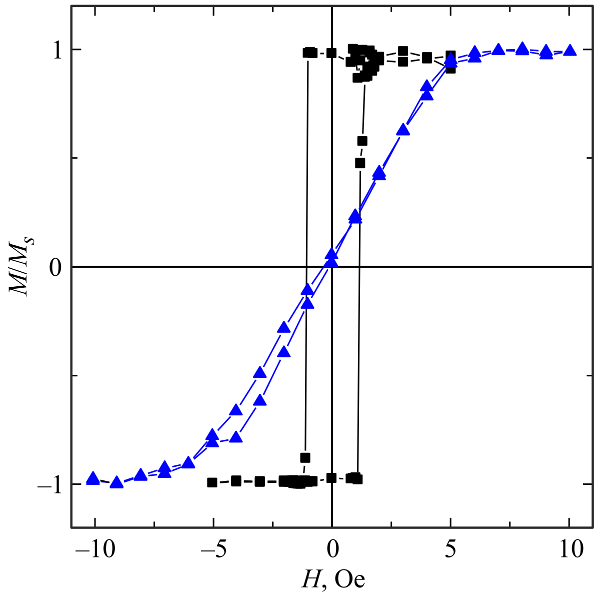

Figure 3. Magneto-optical hysteresis loops of the FeNi(10 nm) film, measured in the geometry of the longitudinal Kerr effect along (squares) and perpendicular (triangles) to the axis of the technological magnetic field.

The magneto-optical (MO) hysteresis loops of FeNi films deposited on YIG differ noticeably from the loops of permalloy films deposited on glass substrates both in shape and in the increased coercive force ($H_c = 9 \pm 2$ Oe). Fig. 4 shows the MO hysteresis loop of the YIG/FeNi(40 nm) sample, the remagnetization axis coincided with the axis of the technological field application, and the corresponding DS images.

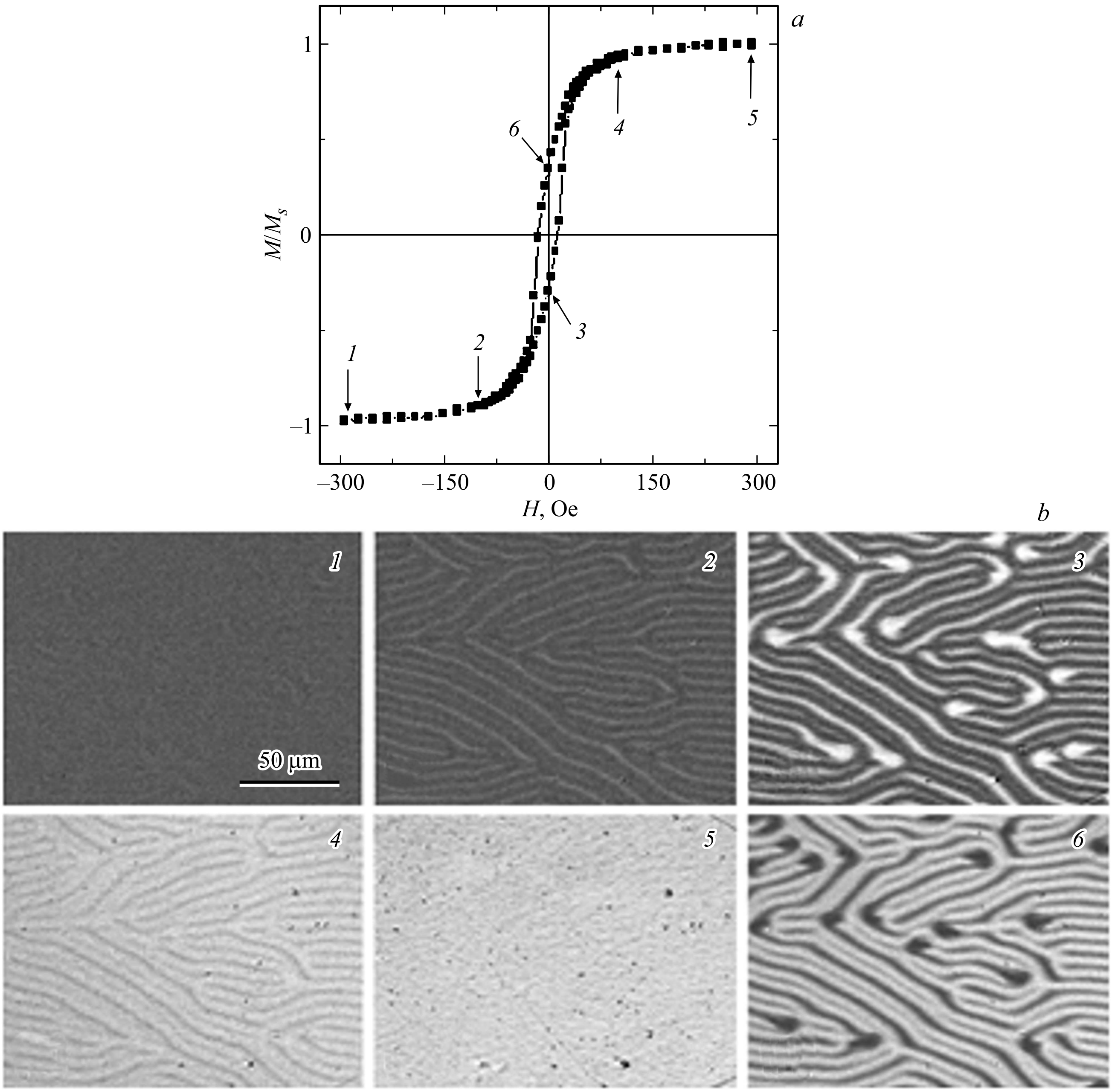

Figure 4. Magneto-optical hysteresis loop of the FeNi(40 nm) film deposited on YIG, measured in the geometry of the longitudinal Kerr effect along the axis of the technological magnetic field (a), and images of the magnetic domain structure corresponding to the sections of the loop hysteresis, indicated by numbers.

At absolute field strength of 300 Oe the FeNi film is magnetized to saturation. Reverse-phase domains appear in the field of view before the direction change of the external field and, under the conditions of observation used become distinguishable when the field is reduced to about 150 Oe. As noted above, the period of this DS coincides with the period of the YIG DS. In this case, the general form of the DS under the action of the external field is preserved, and only the number and width of domains of different phases change. All this indicates that the DS in the FeNi layer is formed primarily under the influence of the scattering fields of the YIG labyrinth DS. In other words, the permalloy layer acts as an indicator film [14,15] that reacts to the scattering fields of the magnetic system formed by YIG domains, in which magnetization is oriented perpendicular to the sample plane. The vertical component of scattering fields over domains in such a structure is about $2\pi M_s$, or about 120 Oe for the YIG type used in this work. It is known that the tangent component of the scattering field above the Bloch wall in an open-type stripe domain structure can noticeably exceed this value [16]. This may be the reason why, when the samples studied here are demagnetized DS in the permalloy

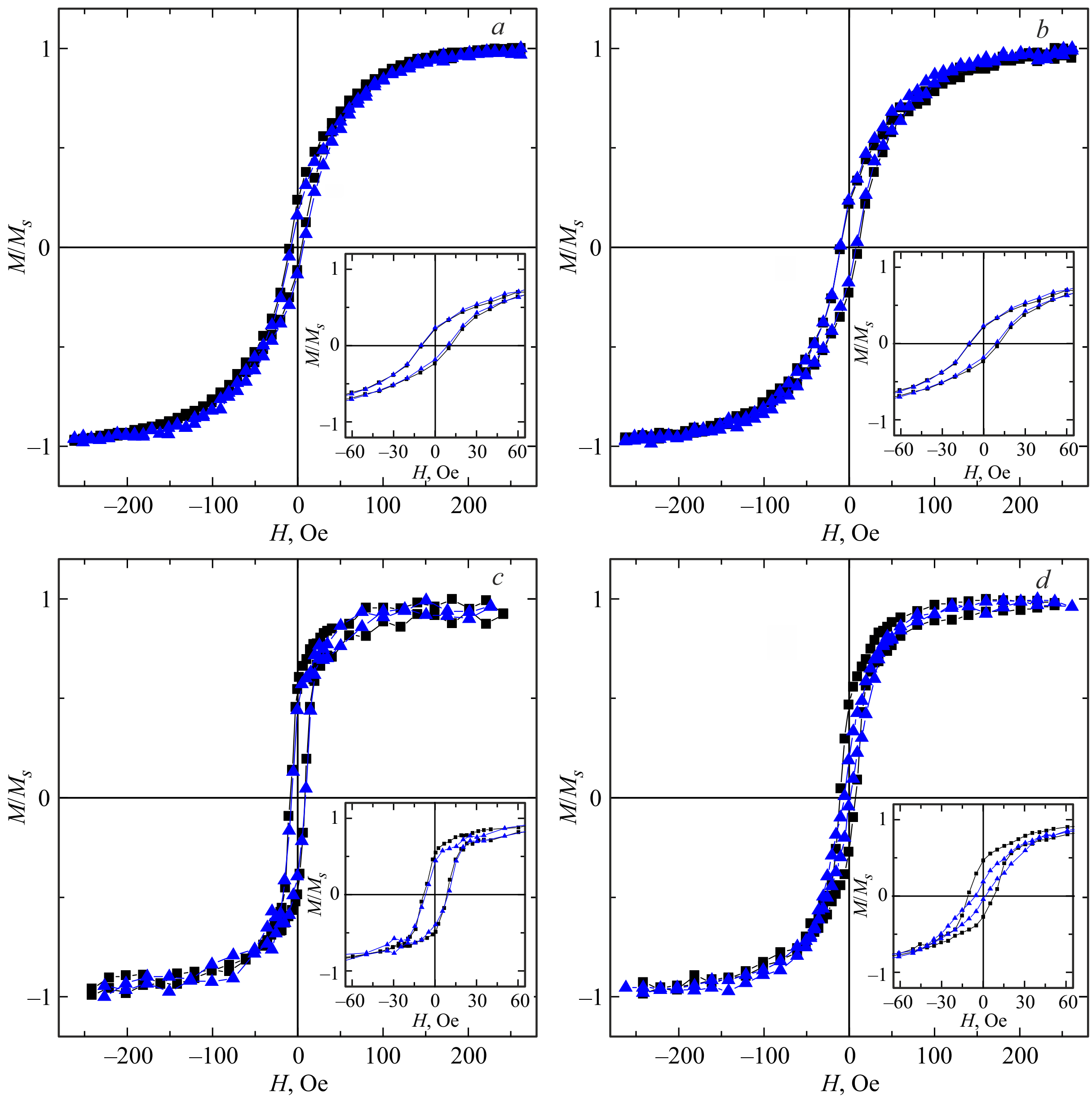

Figure 5. Magneto-optical hysteresis loops of 10 nm (a, b) and 40 nm (c, d) FeNi films deposited on YIG (a, c) and YIG/Ta(10 nm) (b, d) measured in the sample plane in the geometry of the longitudinal Kerr effect along (squares) and perpendicular (triangles) to the axis of the technological field. The insets show zoomed parts of the loops.

layer „appears“ even in the external field of about 150 Oe, i.e. much earlier than in a single-layer permalloy film.

In paper [7], Fe films also deposited on YIG, which has perpendicular magnetic anisotropy, were studied. On the basis of measurements carried out using magnetic force microscopy, the authors conclude that in Fe films with a thickness below 20 nm, magnetization has a perpendicular component, and at a greater thickness it is oriented in the film plane. The data of this study indicate that even for FeNi(10 nm) layers magnetization is oriented in the plane of the sample.

The shape and quantitative parameters of the hysteresis loops measured along and perpendicular to the axis of the technological field (Fig. 5, a, b) indicate that the permalloy layer leads itself as magnetoisotropic. This fact also finds a logical explanation under the assumption that the remagnetization of the FeNi layer occurs primarily under the influence of the scattering fields of the DS of the YIG film, which greatly exceed the characteristic value of the field of magnetic anisotropy induced in permalloy films during deposition in the presence of an external magnetic field. In this case, the directions of the scattering fields of the YIG DS are distributed with equal probability in the plane of the samples due to the specific configuration of the labyrinth YIG DS.

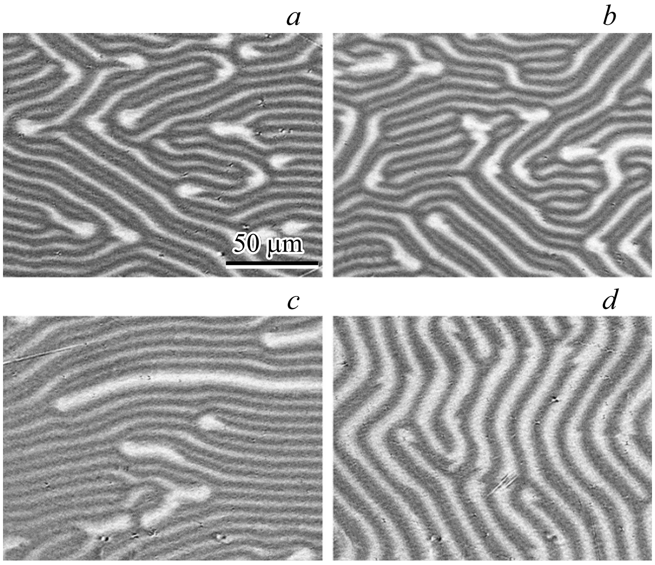

Figure 6. Images of the DS of the film FeNi(40 nm) as part of the YIG/FeNi (*a, b*) and YIG/Ta/FeNi (*c, d* systems) obtained in a zero field after magnetizing the samples to saturation along (*a, c*) and perpendicular to (*b, d*) the axis of the technological field. The measurement field application axis is parallel to the horizontal sides of the DS images.

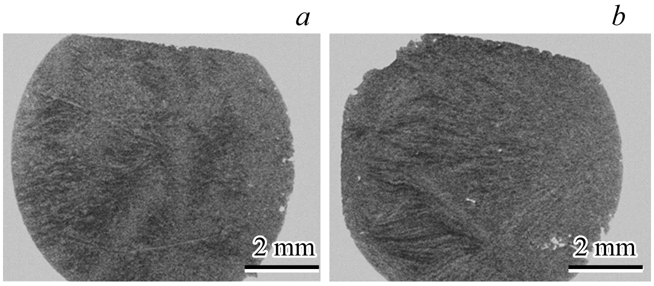

Figure 7. DS images of samples YIG/FeNi(40 nm) (*a*) and YIG/Ta(10 nm)/FeNi(40 nm) (*b*).

A series of samples, during the deposition of which Ta interlayer was introduced between YIG and FeNi, was prepared in order to determine the roles of possible exchange interaction and magnetostatic interlayer bond. It is known that the introduction of a non-magnetic interlayer several nanometers thick between magnetic layers leads to the disappearance of the interlayer exchange interaction between the layers [17]. In the YIG/(metal magnetic film) system, this occurs when the interlayer thickness is 5 nm maximum [9,18]. In our samples, the introduction of a Ta layer 10 nm thick between the garnet and the permalloy film had practically no effect on the properties of the sample with the FeNi(10 nm) film: the shape of the hysteresis loops, the value of H_c remained the same as for the sample without the Ta interlayer (Fig. 5, *a, b*). In this case, for the sample YIG/Ta(10 nm)—FeNi(40 nm) the introduction of the interlayer Ta(10 nm) partially restores the magnetic anisotropy in the plane of the permalloy film (Fig. 5, *c, d*).

The influence of the Ta interlayer on the magnetic anisotropy of the FeNi layer also manifests itself in the features of the DS observed in the absence of he field after samples magnetization to saturation in the direction of the technological field and perpendicular to it (Fig. 6).

The dependence of the magnetic anisotropy of the FeNi layer on its thickness may be due to the features of the deposited film formation under the simultaneous action of both the scattering fields of the garnet DS and the external technological field. The above estimate of the value of scattering fields shows their comparability with the value of the technological field. Taking into account the labyrinth shape of the garnet DS, it seems logical to assume the formation of local magnetic anisotropy axes, the dispersion angle of which is close to 180°, which should ultimately lead to a loss of the resulting anisotropy of the FeNi layer. However, the FeNi film growing on the garnet becomes a kind of magnetic shunt for the scattering fields of the garnet DS. The outer layers of the deposited permalloy film are less affected by the scattering fields of the garnet DS, as a result of which the relative role of the technological field increases. Thus, a heterogeneous induced magnetic anisotropy is formed through the thickness of the permalloy film.

An indirect confirmation of the proposed scenario can be the results of measuring MO-loops and observing the DS of the FeNi layers, carried out at a low optical magnification, which does not make it possible to distinguish the labyrinth DS. The hysteresis loops of the YIG/FeNi(10 nm) and YIG/Ta(10 nm)/FeNi(10 nm) samples measured in the sample plane turned out to be similar to those shown in Fig. 5, *a, b*, while the MO-image smoothly changed contrast when the external field changed. For YIG/FeNi(40 nm) and YIG/Ta(10 nm)/FeNi(40 nm) samples the hysteresis loops are also similar to those measured at higher magnification (Fig. 5, *c, d*). However, MO-images show large domains near the coercive force field (Fig. 7). The configuration of these DSs indicates a large dispersion of local EMAs both in the case of the sample without the Ta interlayer and in its presence.

4. Conclusion

It was demonstrated in this paper that in two-layer YIG/FeNi film structures, in which the YIG film has a perpendicular magnetic anisotropy, there is a magnetic coupling between the layers. Its consequence is, in particular, the labyrinth magnetic domain structure observed in permalloy films, the coercive force increasing, and the absence of the occurrence of induced magnetic anisotropy in the plane of FeNi films deposited on YIG in the presence of the technological magnetic field oriented in the film plane. The presented results, as well as the absence of a shift of the hysteresis loops of permalloy films, indicate that the magnetostatic interaction makes the main contribution to the interlayer magnetic interaction of YIG and FeNi films.

Funding

The results were obtained as part of implementation of the state assignment of the Ministry of Education and Science of Russia FEUZ-2020-0051.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] R. Suzuki, M. Takahashi, T. Kobayashit, Y. Sugita. Appl. Phys. Lett. **26**, 342 (1975).
[2] S.A. Nikitov, D.V. Kalyabin, I.V. Lisenkov, A.N. Slavin, Yu.N. Barabanenkov, S.A. Osokin, A.V. Sadovnikov, E.N. Beginin, M.A. Morozova, Yu.P. Sharaevskiy, Yu.A. Filimonov, Yu.V. Khivintsev, S.L. Vysotsky, V.K. Sakharov, E.S. Pavlov. UFN, **185**, 1099 (2015) (in Russian).
[3] A.R.L. Sousa, M. Gamino, A. Ferreira, A.B. de Oliveira, F. Vaz, F. Bohn, M.A. Correa. Sensors **21**, 6145 (2021).
[4] T.A. Shaikhulov, G.A. Ovsyannikov, K.I. Konstantinyan, A.A. Klimov, V.V. Demidov, K.L. Stankevich, N. Tiercelin, P. Pernod, S.A. Nikitov. FTT **62**, 1488 (2020) (in Russian).
[5] N. Vukadinovic, J. Ben Youssef, V. Castel, M. Labrune. Phys. Rev. B **79**, 184405 (2009).
[6] M. Pashkevich, A. Stupakiewicz, A. Kirilyuk, A. Maziewski, A. Stognij, N. Novitskii, A. Kimel, Th. Rasing. J. Appl. Phys. **111**, 023913 (2012).
[7] Y.S. Chun, K.M. Krishnan. J. Appl. Phys. **95**, 6858 (2004).
[8] S. Klingler, V. Amin, S. Geprägs, K. Ganzhorn, H. Maier-Flaig, M. Althammer, H. Huebl, R. Gross, R.D. McMichael, M.D. Stiles, S.T.B. Goennenwein, M. Weiler. Phys. Rev. Lett. **120**, 127201 (2018).
[9] B.B. Krichevtsov, A.M. Korovin, S.V. Gastev, S.M. Suturin, K.V. Mashkov, M. Sawada, N.S. Sokolov. J. Magn. Magn. Mater. **502**, 166542 (2020).
[10] G.I. Frolov, V.Yu. Yakovchuk, V.A. Seredkin, R.S. Iskhakov, S.V. Stolyar, V.V. Polyakov. ZhTF, **75** (69), 2005 (in Russian).
[11] K. Chen, A. Philippi-Kobs, V. Lauter, A. Vorobiev, E. Dyadkina, V.Yu. Yakovchuk, S. Stolyar, D. Lott. Phys. Rev. Appl. **12**, 024047 (2019).
[12] A.V. Svalov, V.N. Lepalovskij, A.N. Gorkovenko, I.A. Makarochkin, E.A. Stepanova, A. Larrañaga, G.V. Kurlyandskaya, V.O. Vas’kovskiy. IEEE Trans. Magn. **58**, 2100605 (2022).
[13] A.G. Lesnik. Navedennaya magnitnaya anizotropiya v polikristallicheskikh plenkakh. Nauk. dumka, Kiev (1976). 163 s. (in Russian).
[14] V.E. Ivanov. J. Magn. Magn. Mater. **324**, 2572 (2012).
[15] V.E. Ivanov, A.V. Koveshnikov, S.V. Andreev. FMM **118**, 772 (2017) (in Russian).
[16] V.N. Samofalov, V.D. Belozorov, A.G. Ravlik. UFN, **183**, 287 (2013) (in Russian).
[17] E. Shalygina, A. Kharlamova, S. Efremova, A. Makarov, G. Kurlyandskaya, A. Svalov. J. Phys. Conf. Ser. **1389**, 012021 (2019).
[18] Y.S. Chun, H. Ohldag, K.M. Krishnan. IEEE Trans. Magn. **43**, 3004 (2007).

Editor D.V. Zhumanov