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PHYSICS OF MAGNETIC PHENOMENA

DOMAIN STRUCTURE AND MAGNETIZATION REVERSAL IN MULTILAYER STRUCTURES CONSISTING OF THIN PERMALLOY FILMS SEPARATED WITH NONMAGNETIC INTERLAYERS

B. A. Belyaev,[1,2] N. M. Boev,[1,2] A. V. Izotov,[1,2] and P. N. Solovev[1]

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Using numerical micromagnetic modeling, we have investigated the development of domain structure and magnetization reversal in multilayer thin-film structures. The permalloy ($Ni_{80}Fe_{20}$) *magnetic layers had the in-plane uniaxial and perpendicular magnetic anisotropy. We found that as the thickness of nonmagnetic interlayers decreases, the in-plane configuration of magnetic moments in the permalloy layers transforms from a single domain state to stripe domains, which is caused by the increase of magnetostatic interaction between layers. In structures with "thick" interlayers, even weak magnetostatic interaction enforces the neighboring single domain permalloy layers to have opposite orientations of magnetic moments. The saturation field of such samples increases linearly with the number of layers. By analyzing the dynamic characteristics of multilayers, we determined the optimum number of layers ensuring the maximum conversion efficiency of wideband microwave microstrip sensors of weak magnetic fields.*

Keywords: micromagnetic modeling, multilayer magnetic film, domain structure, hysteresis loop, microstrip resonator, magnetic field sensor

INTRODUCTION

For many years, nanocrystalline thin magnetic films (TMF) have attracted the attention of not only scientists who solve fundamental problems, but also researchers who create various microelectronic devices, including those with electrically controlled characteristics. In such devices, soft magnetic films serve as active media and usually possess a relatively small in-plane uniaxial magnetic anisotropy, as well as a low value of coercive force and high magnetic permeability [1]. Due to the pronounced anisotropy of the TMF shape, the magnetostatic energy does not allow the magnetic moments to leave the plane. Therefore, in the ground state, the film is single-domain with the orientation of magnetization along the easy magnetization axis (EMA). The behavior of such samples in magnetic fields approaches the behavior of an ideal uniaxial uniformly magnetized Stoner–Wohlfarth ferromagnetic particle [2]. Due to the above-mentioned properties of nanocrystalline thin magnetic films, they are widely used in a variety of devices [3–5].

In recent years, magnetic films have been especially actively used in the magnetic field sensors. To date, a number of designs of sensors with TMFs have been proposed, the operation of which is based on various physical principles [6]. Most of these sensors have in common the fact that their performance improves (all other things being equal) with an increase in the volume (thickness) of the magnetic film. For example, an increase in the TMF thickness

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[1] Kirensky Institute of Physics Federal Research Center KSC of the Siberian Branch of the Russian Academy of Sciences, Krasnoyarsk, Russia, e-mail: belyaev@iph.krasn.ru; boev@iph.krasn.ru; psolovev@iph.krasn.ru; [2] Siberian Federal University, Krasnoyarsk, Russia, e-mail: AIzotov@sfu-kras.ru. Translated from Izvestiya Vysshikh Uchebnykh Zavedenii, Fizika, No. 6, pp. 170–176, June, 2021. Original article submitted February 25, 2021.

leads to a decrease in the contribution to the useful signal from thermal magnetic noise in sensors based on giant magnetoresistance [7] or magnetic tunnel junction [8]. With increasing film thickness, the effect of giant magnetic impedance is enhanced, which increases the sensitivity of magnetic field sensors based on this effect [9]. With an increase in the film volume, the characteristics of the sensor of weak magnetic fields based on a microstrip resonator with TMFs, also improve [10, 11].

As is known, back in the 1960s, it was shown that when a certain critical value of the film thickness is exceeded, a periodic stripe domain structure (stripe structure) is formed in it [12, 13]. This structure is associated with a relatively small perpendicular magnetic anisotropy caused by the layer-by-layer growth of films. The transition to the stripe-domain state is accompanied by a sharp change in the film characteristics, in particular, an increase in the coercive force and saturation field, as well as a significant decrease in the magnetic permeability [14, 15]. Obviously, the appearance of stripe domains is a negative phenomenon that prevents the use of "thick" films in most TMF devices. It is known that the critical film thickness is inversely proportional to the value of the perpendicular magnetic anisotropy of the film [16]. Therefore, by selecting the technological conditions for the manufacture of thin-film samples, it is possible to achieve a certain increase in the critical thickness due to a decrease in the perpendicular anisotropy [17, 18]. However, in practice, the more valuable approach is the creation of multilayer thin-film structures consisting of magnetic layers separated by nonmagnetic dielectric interlayers [8, 19–21]. It can be expected that at a thickness of each magnetic layer less than the critical value and a sufficient thickness of the interlayers, such a sample will exhibit characteristics close to the properties of a single-domain film. In this case, it is obvious that the multilayer structure will have a larger volume of magnetic material, proportional to the number of magnetic layers. In this work, using micromagnetic modeling, we investigate the possibilities of implementing the above approach to improve the characteristics of multilayer TMFs and devices based on them.

1. MICROMAGNETIC MODELING

The equilibrium configuration of magnetic moments in multilayer thin-film structures, the processes of their magnetization reversal, and the dynamics of magnetization were calculated using numerical micromagnetic simulation. The structure under study consisted of successively alternating magnetic layers of thicknesses t_M separated by nonmagnetic interlayers of thicknesses t_{NM} (Fig. 1). The object under consideration was divided into identical discrete elements (cells), much smaller than the thickness of the layers. In this case, each cell of the magnetic layers was assumed to be uniformly magnetized and characterized by a certain averaged vector of the magnetic moment. For cells of nonmagnetic interlayers, the magnetic moment was assumed to be zero. In the calculations we took into account the energies of magnetostatic and exchange interactions between the discrete elements, as well as the energies of interaction of the magnetic moment of each cell with an external constant magnetic field H_0 and the fields of the in-plane H_U and perpendicular H_P magnetic anisotropies. The numerical micromagnetic model of a ferromagnet used in this work is considered in more detail in [22–24].

The ground (equilibrium) state of the multilayer structure magnetization was determined from the solution of a system of linear inhomogeneous equations with undetermined Lagrange multipliers [22]. The obtained equilibrium magnetization distribution was tested for stability, and if this condition was not met, a search was made for a new equilibrium magnetization distribution in the direction of the system relaxation [22]. To calculate high-frequency properties of the multilayer structure, we used the numerical implementation of the method of undetermined coefficients [24] when solving the linearized system of Landau – Lifshitz equations describing the motion of magnetization in each cell.

In the present study, we considered a model of a multilayer thin-film structure, whose parameters of the magnetic layers corresponded to the typical parameters of the permalloy $Ni_{80}Fe_{20}$ film: the saturation magnetization $M_S = 1000$ G, the exchange constant $A = 1\cdot10^{-6}$ erg/cm, the uniaxial in-plane magnetic anisotropy field $H_U = 6.5$ Oe, the field of perpendicular magnetic anisotropy $H_P = 517$ Oe, and the damping constant $\alpha = 0.005$. The easy magnetization axis (EMA) of the in-plane anisotropy was directed along the x axis, and the EMA of the perpendicular anisotropy was directed along the z axis, which is the normal to the film plane. The size of each discrete element was set to be $6.25\times6.25\times6.25$ nm. In this work, we considered the case of magnetization of a sample by an external field H_0 in the

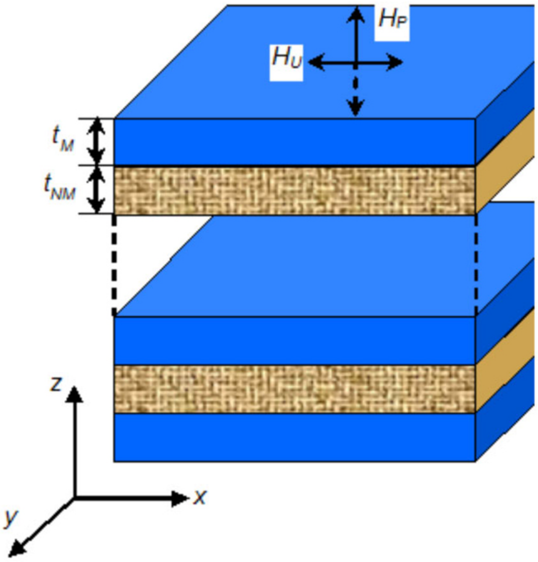

Fig. 1. Model of a multilayer thin-film structure consisting of magnetic layers of thicknesses t_M and non-magnetic layers of thicknesses t_{NM}. The magnetic layers have uniaxial in-plane H_U and perpendicular H_P magnetic anisotropy.

plane of the film along the hard magnetization axis (HMA), i.e. along the y-axis. Taking into account the symmetry of the problem, the following three-dimensional model of a multilayer sample was considered: along the x-axis, it was divided into 1024 discrete elements, along the y-axis - into 64 elements, and along the z-axis the number of elements varied depending on the total thickness of the sample. The number of magnetic layers was specified by the number n. The number of nonmagnetic interlayers was always $n-1$. Additionally, periodic two-dimensional boundary conditions in the xy plane of the film were used to calculate the exchange and magnetostatic interactions [25]. This made it possible to eliminate the effect of demagnetization fields at the edges of the films [26, 27] and to bring the characteristics of the simulated structure closer to the characteristics of real samples.

2. RESULTS OF STUDIES

Earlier, it was shown analytically and using micromagnetic modeling [28] that for a permalloy film with the magnetic parameters listed above, the critical thickness t_{crit} was 125 nm. At such a thickness, a domain stripe structure was formed in the film, and at a thickness less than this threshold value, the film passed into a single-domain state. Therefore, in this work, we began the study of multilayer structures by considering a two-layer TMF, in which the thickness of each magnetic layer was t_{M} = 118.75 nm, i.e. was slightly less than critical one. The micromagnetic calculation showed that, depending on the thickness of the nonmagnetic interlayer t_{NM}, either a stripe structure or a single-domain state of magnetization can be realized in the magnetic layers.

Figure 2*a* shows the magnetization distribution in a two-layer film with a nonmagnetic interlayer thickness t_{NM} = 12.5 nm calculated in the absence of an external magnetic field. The arrows in the figure show the directions of the magnetic moments, and the shade of the color corresponds to the magnitude of the projections of the moments on the x axis. It can be seen that a so-called “weak” stripe structure [29] has formed in both magnetic layers, which consists of alternating vortex distributions of magnetization with the opposite directions of twisting. In the upper and lower magnetic layers, “antiphase” directions of twisting are observed. However, already at a layer thickness of t_{NM} = 18.75 nm, a uniform magnetization distribution with magnetic moments lying in the film plane and directed along the EMA of the in-plane uniaxial magnetic anisotropy is formed in the magnetic layers.

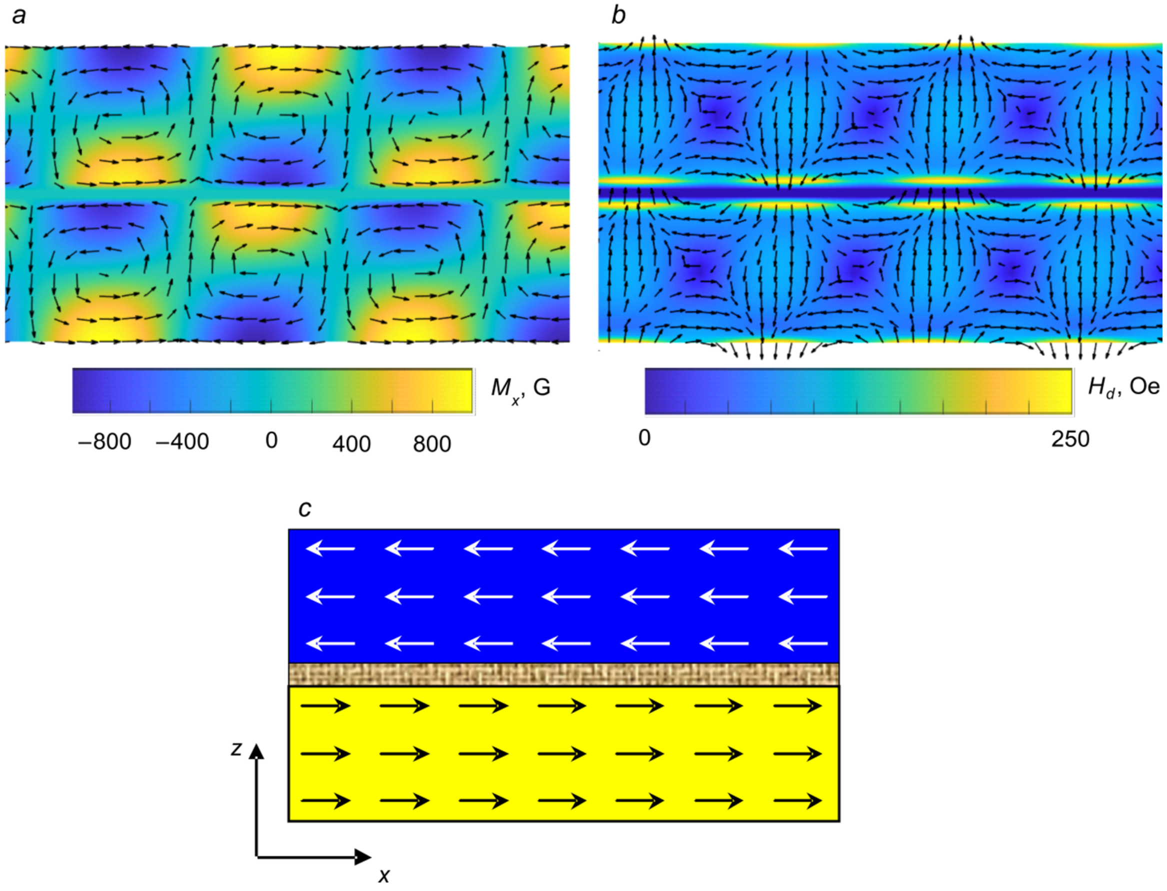

Fig. 2. Distribution of magnetic moments in a two-layer permalloy film (H_0 = 0) at a magnetic layer thickness t_M = 118.75 nm and nonmagnetic interlayer thicknesses t_{NM} = 12.5 (*a*) and t_{NM} = 18.75 nm (*c*). (Shades of color correspond to the projection of the magnetization vector on the *x* axis.) Distribution of the internal demagnetization field H_d in a two-layer film with t_{NM} = 12.5 nm (*b*). (The arrows show the direction of the field strength vector, and the color shades correspond to the field amplitude H_d).

The revealed dependence of the magnetic configuration of a two-layer thin permalloy film on the thickness of the non-magnetic interlayer was obtained by minimizing the magnetostatic energy of the entire system under study. Indeed, in the considered micromagnetic model, the exchange interaction is limited only by the neighboring discrete cells [22]. Therefore, the magnetic moments of even the nearest cells of the upper and lower magnetic layers can mutually influence only through magnetostatic (dipole-dipole) interaction. The appearance of a domain stripe structure in TMF is associated with a change in the balance between the energy of perpendicular magnetic anisotropy and magnetostatic energy [29], which is primarily determined by the anisotropy of the sample shape. At a relatively small film thickness ($<t_{\text{crit}}$), the increase in the magnetostatic energy associated with the escape of magnetic moments from the film plane is greater than the energy contribution from the perpendicular anisotropy.

However, in the presence of several magnetic layers, the magnetic flux from the magnetic "charges" created on the film surface by magnetic moments with a nonzero normal component M_z can be partially closed on magnetic "charges" of the opposite sign of the adjacent magnetic layer. This is clearly seen in Fig. 2*b*, which shows the distribution of the internal demagnetization field H_d calculated for a two-layer TMF with t_{NM} = 12.5 nm. As a result, the magnetostatic energy of the two-layer structure decreases somewhat, which makes the configuration of magnetic

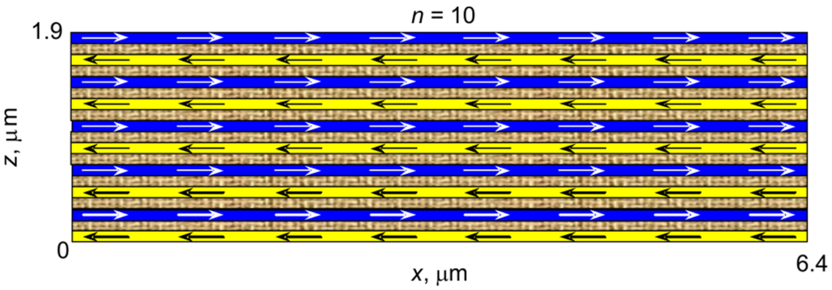

Fig. 3. Distribution of magnetic moments in a multilayer structure consisting of 10 permalloy layers with the thicknesses of magnetic and nonmagnetic layers $t_M = t_{NM} = 100$ nm.

moments in the form of a stripe structure energetically more favorable even at thicknesses of magnetic layers lower than t_{crit}. At the same time, as the thickness t_{NM} increases, the magnetostatic coupling between the layers rapidly weakens, and the single-domain configuration of magnetization becomes energetically favorable. In this case, the minimum free energy of the system will be achieved when the magnetic flux closes at the edges of the film (along the *x* axis), i.e. at the opposite directions of magnetization in different magnetic layers (Fig. 2*c*).

Thus, the performed calculation made it possible to establish the theoretical limiting thicknesses of magnetic and nonmagnetic layers, at which a uniform configuration of magnetic moments is realized in two-layer magnetic films, which, as already noted, improves the characteristics of many devices based on TMFs. However, the best characteristics of devices can be obtained only with the use of multilayer structures, which make it possible to significantly increase the volume of magnetic films. Therefore, it is of great interest to study the dependence of the integral magnetic characteristics of multilayer thin-film structures on the number of their layers. For this, the equilibrium configuration of magnetic moments was determined using micromagnetic modeling and the processes of magnetization reversal in multilayer films with the same thickness of magnetic and nonmagnetic layers $t_M = t_{NM} = 100$ nm were investigated. The number of magnetic layers n varied from 1 to 20. For example, Fig. 3 shows the distribution of magnetic moments in the absence of an external magnetic field in a structure consisting of 10 permalloy layers. As expected, each individual magnetic layer is in a single-domain state. However, the magnetizations in the neighboring layers have opposite signs. In other words, in a multilayer structure consisting of magnetic films with nonmagnetic interlayers, a periodic "layer-by-layer" stripe domain structure can be formed at certain layer thicknesses.

Figure 4*a* shows the hysteresis loops calculated for films with $n = 2$ and 20 layers when the external magnetic field H_0 was swept along the hard axis of the in-plane uniaxial magnetic anisotropy. It can be seen that the hysteresis loops of multilayer structures exhibit properties similar to the properties of single-layer TMFs in the single-domain state described by the Stoner–Wolfarth theoretical model [2]. In this case, according to the Stoner–Wolfarth model, the saturation field H_S of the film should coincide with the field of in-plane uniaxial magnetic anisotropy H_U. However, an increase in the number of magnetic layers in a multilayer structure leads to a linear increase in the field H_S (Fig. 4*b*), which is due to the need to overcome the impact of additional magnetostatic energy during magnetization reversal of samples associated with the layer-by-layer domain structure, and this energy increases in proportion to the number of layers.

It is obvious that an increase in the saturation field of thin-film structures with an increase in the number of layers can change the characteristics of devices based on such structures, for example, a sensor of weak magnetic fields [30], in which the sensitive element is a microstrip microwave resonator with magnetic films. The principle of operation of such a sensor is based on recording the change in the Q-factor of the resonator. The Q-factor depends on the imaginary part of the transverse component of the high-frequency magnetic susceptibility of the magnetic film structure, which changes under the influence of the measured alternating magnetic field. One of the main characteristics of the sensor is the conversion coefficient, which is proportional to the following expression:

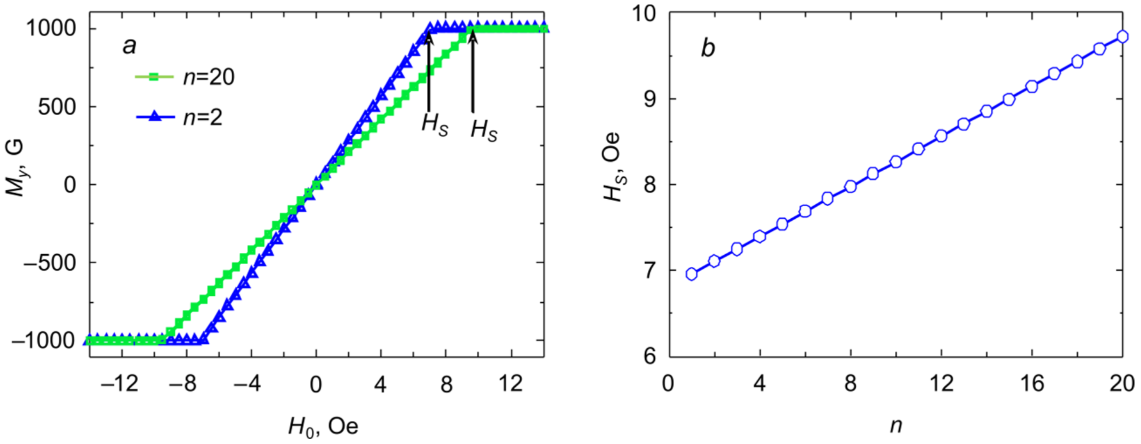

Fig. 4. Hysteresis loops upon magnetization reversal by an external field H_0 directed along the HMA of in-plane anisotropy for structures with the magnetic layers numbers $n = 2$ and 20 (*a*). Dependence of the saturation field H_S of a multilayer structure on the number of layers n (*b*).

$$K \sim V \frac{\chi''(+h_s) - \chi''(-h_s)}{2h_s}, \tag{1}$$

where V is the volume of magnetic layers in a multilayer magnetic structure, χ'' is the imaginary part of the high-frequency magnetic susceptibility of the film, and h_s is the amplitude of the measured magnetic field.

Using micromagnetic modeling, the dynamics of magnetization of multilayer thin-film structures with equal layer thicknesses $t_M = t_{NM} = 100$ nm was calculated and their high-frequency magnetic susceptibility was determined [24]. The calculation was carried out for a fixed frequency of 550 MHz of an alternating magnetic pumping field and for an amplitude of the measured field $h_s = 0.1$ Oe, which were applied in the film plane. It was assumed that the multilayer magnetic structure is in an external planar magnetic field $H_0 = H_S$ directed at an angle θ_H to the EMA of the in-plane magnetic anisotropy orthogonal to the polarization of the microwave pumping magnetic field. At the above parameters, for each value of the angle θ_H, the value of the imaginary part of the susceptibility χ'' [24] of multilayer structures with the number of magnetic layers from $n = 1$ to $n = 20$ was calculated. This made it possible to calculate the conversion coefficients K of the magnetic field sensor under consideration using formula (1).

Figure 5*a* shows the dependences of the normalized conversion coefficients $K/K_{\max}$ on the angle of the bias field direction θ_H (the angle θ_H was measured relative to the axis $x \parallel$ EMA), plotted for films with $n = 1$, 10, and 20 layers. It can be seen that K changes the sign at the point $\theta_H = 90°$, and the dependence $K(\theta_H)$ has two pronounced extrema for certain angles of the external field direction, which is in good agreement with experiment [30]. In addition, it can be seen from the graphs that the maximum modulus values of the conversion coefficients first increase with increasing the number of layers and then, they decrease. This fact is confirmed by the normalized dependence of the maximum value of the conversion coefficient on the number of layers $K_{\max}(n)$ shown in Fig. 5*b*. It is obvious that an increase in $K_{\max}(n)$ with the increase in the number of magnetic layers in the initial part of the dependence is due to an increase in the volume of the magnetic material in the structure. However, in this case, the saturation field H_S of multilayer structures also increases (see Fig. 4*b*), which, according to the condition of the problem noted earlier, is equal to the external bias field H_0. But with an increase in the bias field, the magnetic susceptibility of the film structure decreases. As a result, the dependence $K_{\max}(n)$ has a maximum at $n = 10$, after which, with further increase in the number of layers to $n = 20$, the conversion coefficient monotonically decreases by almost 2 times.

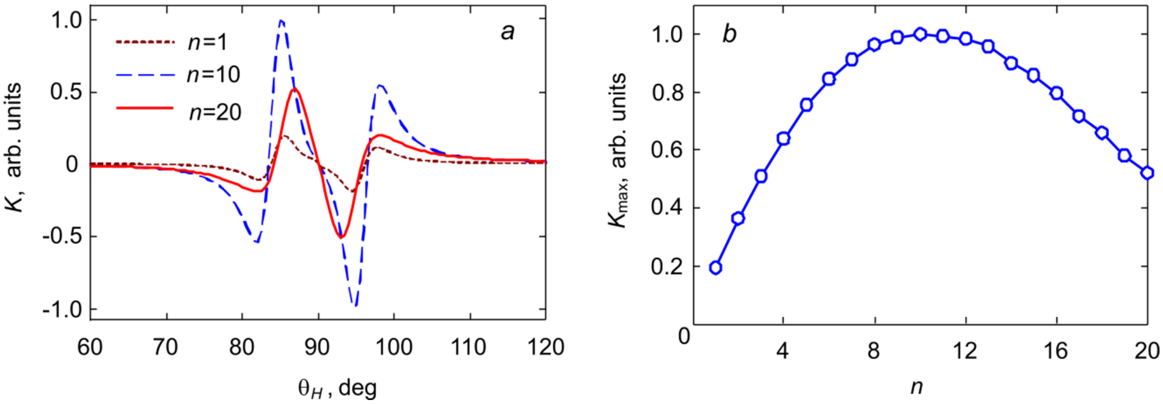

Fig. 5. Dependences of the normalized conversion coefficients of the magnetic field sensor on the direction angle of the external field θ_H plotted for structures with different numbers of magnetic layers (*a*) and the dependence of the normalized maximum conversion coefficient on the number of layers $K_{\max}(n)$ (*b*).

CONCLUSIONS

Thus, using numerical micromagnetic modeling, the processes of domain formation and the processes of magnetization reversal of magnetic multilayer thin-film systems are studied with varying the number of their layers from 1 to 20. The high-frequency magnetic susceptibility of multilayer thin-film structures consisting of alternating magnetic layers and non-magnetic interlayers has been calculated. It was found that, depending on the thickness of the nonmagnetic interlayer, either a single-domain state or an inhomogeneous domain stripe structure can be realized in the magnetic layers.

It is shown that the formation of a stripe structure in the multilayer films at interlayer thicknesses less than a certain critical value is associated with the dipole-dipole interaction of magnetic layers. When the thickness of the non-magnetic interlayer is greater than the critical value, the magnetic films in the multilayer structure are in a single-domain state, but the magnetizations in the adjacent layers have opposite directions, forming a periodic “layer-by-layer” stripe domain structure. This fact leads to a linear increase in the saturation field H_S with increasing number of magnetic layers in the multilayer structure. The nature of the H_S growth is explained by the fact that during magnetization reversal of multilayer samples, it is necessary to overcome the effect of magnetostatic energy associated with the “layer-by-layer” domain structure, which increases in proportion to the number of layers.

The calculation of the high-frequency magnetic susceptibility of multilayer thin-film structures made it possible to study the behavior of the conversion coefficient of a microwave-pumped weak magnetic field sensor, in which a microstrip resonator with thin magnetic films serves as a sensitive element. It was found that the conversion coefficient of the microstrip microwave sensor based on TMF depends nonmonotonically on the number of layers in the thin-film magnetic structure. This result of the conducted research is very important for practice, as it proves the existence of the optimal number of magnetic layers, at which the conversion coefficient of the sensor of weak magnetic fields reaches its maximum value.

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REFERENCES

1. G. Herzer, Acta Mater., **61**, 718–734 (2013).
2. E. C. Stoner and E. P. Wohlfarth, Phil. Trans. Roy. Soc., **A240**, 599–644 (1948).
3. J. P. Volkerts, Magnetic Thin Films: Properties, Performance and Applications, Nova Science Publishers (2011).
4. J. Petzold, J. Magn. Magn. Mater., **242–245**, 84–89 (2002).
5. I. Fergen, K. Seemann, A. V. D. Weth, and A. Schüppen, J. Magn. Magn. Mater., **242–245**, 146–151 (2002).
6. S. Tumanski, Handbook of Magnetic Measurements, CRC Press (2011).
7. N. Smith and P. Arnett, IEEE Trans. Magn., **38**, 32–37 (2002).
8. W. F. Egelhoff, J. Bonevich, P. Pong, *et al*., J. Appl. Phys., **105**, 013921 (2009).
9. C. Tannous and J. Gieraltowski, J. Mater. Sci. Mater. Electron., **15**, 125–133 (2004).
10. A. N. Babitskii, B. A. Belyaev, G. V. Skomorokhov, *et al*., Tech. Phys. Lett., **41**, 324–327 (2015).
11. A. N. Babitskii, B. A. Belyaev, N. M. Boev, and A. V. Izotov, IEEE Sensors 2017: Conf. Proc. 316–318 (2017).
12. N. Saito, H. Fujiwara, and Y. Sugita, J. Phys. Soc. Jpn., **19**, 1116–1125 (1964).
13. Y. Sugita, H. Fujiwara, and T. Sato, Appl. Phys. Lett., **10**, 229–231 (1967).
14. J. Wei, Z. Zhu, H. Feng, *et al*., J. Phys. D: Appl. Phys., **48**, 465001 (2015).
15. D. Cao, L. Pan, X. Cheng, *et al*., J. Phys. D: Appl. Phys., **51**, 025001 (2018).
16. Y. Murayama, J. Phys. Soc. Jpn., **21**, 2253–2266 (1966).
17. A. V. Svalov, I. R. Aseguinolaza, A. Garcia-Arribas, *et al*., IEEE Trans. Magn., **46**, 333–336 (2010).
18. P. N. Solovev, A. V. Izotov, and B. A. Belyaev, J. Magn. Magn. Mater., **429**, 45–51 (2017).
19. N. Kataoka, T. Shima, and H. Fujimori, J. Appl. Phys., **70**, 6238 (1991).
20. K. Ikeda, K. Kobayashi, and M. Fujimoto, J. Appl. Phys., **92**, 5395–5400 (2002).
21. H. Greve, C. Pochstein, H. Takele, *et al*., Appl. Phys. Lett., **89**, 242501 (2006).
22. B. A. Belyaev, A. V. Izotov, and An. A. Leksikov, Phys. Solid State, **52**, 1664–1672 (2010).
23. B. A. Belyaev and A. V. Izotov, Phys. Solid State, **55**, 2491–2500 (2013).
24. A. V. Izotov, B. A. Belyaev, P. N. Solovev, and N. M. Boev, Phys. B, **556**, 42–47 (2019).
25. K. M. Lebecki, M. J. Donahue, and M. W. Gutowski, J. Phys. D: Appl. Phys., **41**, 175005 (2008).
26. B. A. Belyaev, A. V. Izotov, G. V. Skomorokhov, and P. N. Solovev, Mater. Res. Express., **6**, 116105 (2019).
27. B. A. Belyaev, A. V. Izotov, G. V. Skomorokhov, and P. N. Solovev, Russ. Phys. J., **63**, No. 5, 837–843 (2020).
28. P. N. Solovev, A. V. Izotov, B. A. Belyaev, and N. M. Boev, Phys. B, **604**, 412699 (2021).
29. A. Hubert and R. Schäfer, Magnetic Domains, Springer, Berlin (1998).
30. A. N. Babitskii, B. A. Belyaev, N. M. Boev, *et al*., Instrum. Exp. Tech., **59**, 425–432 (2016).