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Spin-wave resonances in a diffusion-sensitive epitaxial film YIG

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

It is shown that in a tangentially magnetized film of iron yttrium garnet exist two types of resonances — a homogeneous ferrimagnetic resonance in the region of the film's homogeneous magnetization (outside the diffusion layer), and inhomogeneous spin-wave resonance within the thickness of the diffusion layer. A method of calculating the magnetization distribution over the film thickness using measured frequencies of the spin-wave and ferrimagnetic resonances.

The method of mathematical modeling has established that the magnetic inhomogeneity of the transition layer layer introduces significant distortions of the oscillation epure at the frequency of the spin-wave resonance, and the nature of the distortions significantly depends on the magnitude of the magnetizing field. The results of the conducted can be useful for nondestructive control of the layered structure of YIG epitaxial films.

Keywords: yttrium iron garnet epitaxial films, exchange spin waves, spinwave electronics, magnonics.

DOI: 10.21883/PSS.2022.09.54156.03HH

1. Introduction

The current stage in the development of micro- and nanoelectronics is characterized by the widespread use of quantum phenomena in solids. This served as the basis for the rapid development of fundamental and applied studies in the field of micro- and nanomagnetism. In terms of practical application, the greatest interest is the study of spin-wave excitations in magnetically ordered ferrite media. Based on these studies, new scientific directions were formed, such as spin-wave electronics [1], spintronics [2] and magnonics [3–5]. Further development of these areas was associated with the practical development of ultrashort exchanged spin waves (ESW) with wavelengths of about 100 nm and less [6].

The existence of exchange spin waves was predicted as early as 1930 in Bloch's famous paper [7]. These waves resulted in particular interest due to their exceptionally small lengths, about the radius of the exchange interaction. However, this advantage created significant difficulties in their detection. For the excitation of exchange waves, an unattainably high localization of UHF magnetic fields, about 10 nm, was required. The first observation of ESW was reported only in 1957, in Sulla's paper [8]. Waves were observed in the form of parametric decay products. Shortly thereafter, spin-wave resonances (SWR) were identified, which were initially observed in thin permaloy films [9,10], and then in epitaxial films of yttrium iron garnet (YIG) [11,12]. The excitation of SWR did not require high localization of magnetic fields. They could be excited even in a uniform UHF magnetic field, but this required the spins pinning on the surface film [13].

In papers [14,15] another mechanism of ESW excitation was proposed, based on the transformation of electromagnetic and exchange spin waves in heterogeneous magnetic fields. The field heterogeneity was created by demagnetization fields in bulk samples of single-crystal YIG. Later, the effects of SWR excitation were discovered in implanted YIG films [16,17]. The waves were excited in the implanted layer, propagated deep into the YIG film, and reflected from its opposite surface. In the pulse mode, they could be observed in the form of a series of equidistant echo pulses of the ESW. Similar results were obtained in specially made YIG films with a smoothly varying magnetization over the entire thickness of the film [18,19].

Note that in all the papers cited, an artificially created magnetic heterogeneity of the film was used, although it was known that YIG epitaxial films themselves are heterogeneous. Structural heterogeneities of YIG films were studied in a number of papers [20–23]. It was shown that a thin diffusion (transition) layer with reduced magnetization always forms on the inner surface of YIG film adjoining a nonmagnetic gadolinium-gallium garnet (GGG) substrate. The transition layer was formed during epitaxial growth due to the diffusion of nonmagnetic ions Gd^{3+}, Ga^{3+} into the YIG film ($Y_3Fe_5O_{12}$) and magnetic ions Y^{3+}, Fe^{3+} into the GGG substrate ($Gd_3Ga_5O_{12}$). This equally applied to YIG films grown by liquid-phase epitaxy [21], ion-beam epitaxy [22], and magnetron sputtering [23]. Depending on the type of epitaxy and substrate temperature during growth, the thickness of the transition layer could vary from ~ 5 nm [22] to ~ 500 nm [23]. The greatest thickness of the transition layer was achieved with liquid-phase epitaxy.

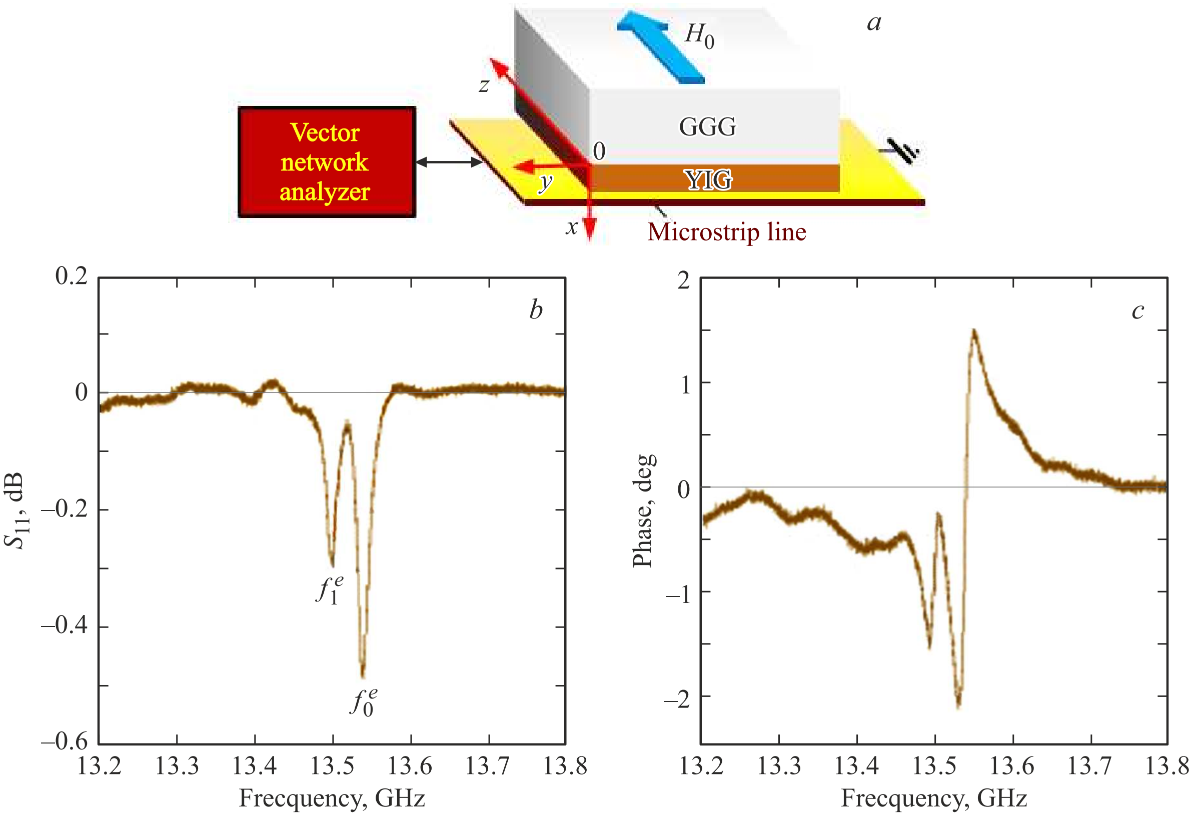

Figure 1. Measurement scheme of S-parameters of the experimental prototype (a) and the results of measurements of amplitude-frequency (b) and phase-frequency characteristics (c) of the reflected signal. Magnetizing field $H_0 = 3972$ Oe, resonance frequencies $f_0^e = 13.536$ GHz, $f_1^e = 13.498$ GHz.

In recent papers [24,25] it was shown that in the transition layer of the YIG film, the effects of transformation of electromagnetic and exchange spin waves also arise. The excitation of exchange waves was observed as a series of echo pulses radiated deep into the YIG film and reflected from its opposite surface. However, ESW echo pulses could be observed only in the case of normal film magnetization.

In this paper we discuss the features of the excitation of exchange spin waves, which arise during the tangential magnetization of the epitaxial YIG film.

2. Research structures and mathematical modelling

To observe the effects of ESW excitation, we used YIG film $d = 2.4\,\mu$m thick grown by liquid-phase epitaxy on a nonmagnetic GGG substrate with orientation (111). The film sample had dimensions of 2×2 mm. The sample was installed near the shorted end of the microstrip transducer. The transducer width was comparable to the dimensions of the film sample. The sample, together with the transducer, was placed in a constant magnetic field $\mathbf{H}_0 \parallel \mathbf{z}$, oriented in the film plane, as shown in Fig. 1, a. A continuous UHF signal was applied to the transducer input. The S11-parameters of the reflected signal were measured. The measurements were carried out at fixed values of the magnetizing field. Typical measurement results are shown in Fig. 1, b, c.

A pair of resonant absorption peaks was observed on the amplitude-frequency characteristic of the reflected signal (Fig. 1, b). The resonant nature of the peaks was confirmed by characteristic distortions of the phase-frequency characteristic in Fig. 1, c. Peak frequencies f_0^e and f_1^e were measured using vector analyzer markers. As the field H_0 increases, the peak frequencies $f_0^e(H_0)$ and $f_1^e(H_0)$ monotonically shifted to higher frequencies region. At the same time, it was visually observed that the intervals between them $\Delta f^e(H_0) = f_0^e(H_0) = f_1^e(H_0)$ also increased. Within the measurement accuracy, the field dependences of $f_0^e(H_0)$ and $f_1^e(H_0)$ almost coincided. Difference frequency $\Delta f^e(H_0) \ll f_1^e(H_0)$, $f_0^e(H_0)$ turned out to be within the confidence interval, which made it difficult to quantify it.

To identify the reasons for the peaks appearance, we solved the problem of ESWs excitation in a tangentially magnetized YIG film. It was taken into account that within the thickness of the transition layer the film was doped with nonmagnetic ions Gd^{3+} and Ga^{3+}. According to the theory of diffusion in solids [26], the concentration of doping ions was described by the Gaussian function $N(\sigma, x) \sim \exp[-(x/\sigma)^2]$. Taking this into account, the

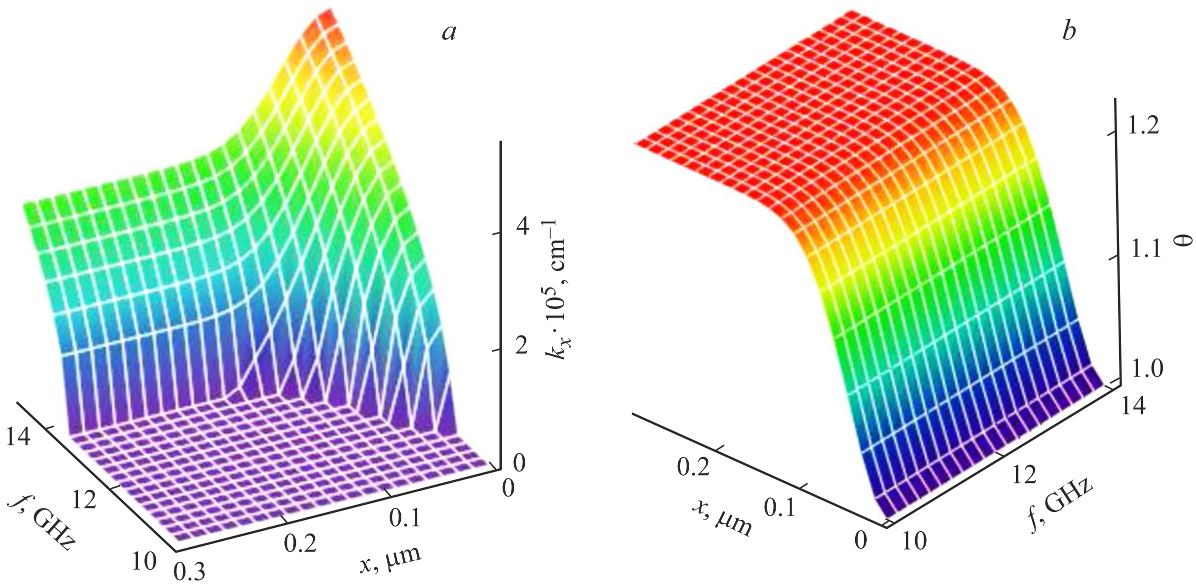

Figure 2. The results of calculating the dispersion law $k_x(f, x)$ (a) and the ellipticity parameter of the precession wave $\theta(f, x)$ (b) near the film-substrate interface. $H_0 = 3972$ Oe, $M_s = 151$ G, $\sigma = 6.48 \cdot 10^{-6}$ cm.

magnetization distribution in the transition layer could be represented as $M(M_s, \sigma, x) - M_s\{1 - \exp[-(x/\sigma)^2]\}$, where σ is phenomenological distribution parameter, M_s is uniform magnetization of the film outside the transition layer. The crystallographic anisotropy of the YIG film and dissipative processes were not considered.

The linearized Landau–Lifshitz equation, written with an allowance for heterogeneous exchange, and the Maxwell equations system were jointly solved. The solution was sought in the form of plane monochromatic magnetization precession waves $\mathbf{m} \sim \exp[i(\omega t - k_x x)]$ propagating in the transverse direction of the YIG film, where k_x is wave number, $\omega = 2\pi f$ is cyclic frequency, f is excitation frequency. As a result of the solution, an analytical expression for the dispersion law of ESW $k_x(f, H_0, M_s, \sigma, x)$ and the precession wave ellipticity ratio $\theta(f, H_0, M_s, \sigma, x)$ were obtained. The ellipticity relation reduced the problem to finding one component of the precession vector, for example, $m_x \sim \exp[i(\omega t - k_x x)]$.

To calculate the parameters M_s and σ we used the expression for the dispersion law of the ESW with the substitution of the experimental values of the resonant frequencies $f_0^e \simeq 13.536$ GHz, $f_1^e \simeq 13.498$ GHz and magnetizing field $H_0 = 3972$ Oe (see Fig. 1, b). As a result, the values of the parameters $M_s = 151$ G and $\sigma \simeq 6.48 \cdot 10^{-6}$ cm were obtained, which were used to simulate the processes of excitation of the precession wave in the selected sample of the YIG film.

Fig. 2 shows 3D plots of the dispersion law $k_x(f, x)$ (Fig. 2, a) and the ellipticity parameter of the precession wave $\theta(f, x)$ (Fig. 2, b). It can be seen that the coordinate dependence of the dispersion law and the ellipticity parameter is most pronounced near the film-substrate interface. The dispersion of the precession wave shifted to the low-frequency region, the precession of the magnetization vector gradually approached circular polarization $\theta(f, x) \to 1$.

It is clearly seen in Fig. 2, a that the origin of the precession wave occurred at the line of intersection between the dispersion surface $k_x(f, x)$ and the plane $k_x = 0$. Using the dispersion law of ESW, it was not difficult to calculate the coordinate dependence of the excitation frequencies $f(x)$ (Fig. 3, a) and the frequency dependence of the coordinates of the precession wave excitation plane $x(f)$ (Fig. 3, b). For comparison, Fig. 3, a shows magnetization distribution through the film thickness $M(x)$. It can be seen from the comparison of $f(x)$ and $M(x)$ curves that the maximum calculated excitation frequency of the precession wave $f_{\max} \simeq f_0$ was reached in the region of uniform magnetization of the YIG film. This means that at the frequency of the high-frequency peak $f_0^e \simeq 13.536$ GHz we observed a uniform ferrimagnetic resonance (FMR) that was excited outside the transition layer of the YIG film. Consequently, at a lower frequency $f_1^e \simeq 13.498$ GHz we observed the heterogeneous spin-wave resonance, which was excited within the thickness of the transition layer. This is illustrated in the inset in Fig. 3, b, which shows a fragment of the curve $x(f)$ with marked frequencies f_0^e, f_1^e and the coordinate of the plane of origin of the precession wave x_1.

Fig. 4, a shows the calculated plots of the field dependence of the resonant frequencies $f_1(H_0) \approx f_0(H_0)$ and $\Delta f(H_0) = f_0(H_0) - f_1(H_0)$. The dots on the plot $f_1(H_0)$ mark the SWR frequencies $f_1^e(H_0)$ measured at fixed values of the field H_0. The plot of the field dependence of the difference frequency $\Delta f(H_0)$ is plotted in reduced scale. It can be seen that, within the measurement error the experimental and calculated dependences of the

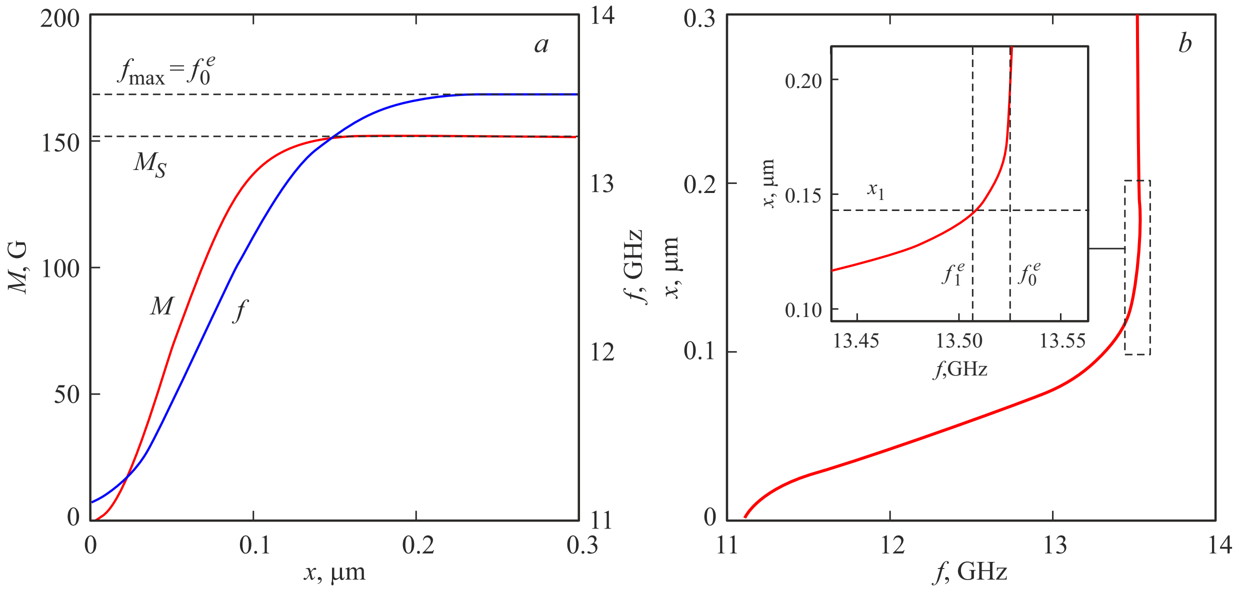

Figure 3. Coordinate dependence of the precession wave excitation frequencies and YIG film magnetization (a) and frequency dependence of the precession wave excitation point coordinates (b). $H_0 = 3972$ Oe, $M_s = 151$ G, $\sigma = 6.48 \cdot 10^{-6}$ cm, $f_0^e = 13.536$ GHz, $f_1^e = 13.498$ GHz, $x_1 = 0.136\,\mu$.

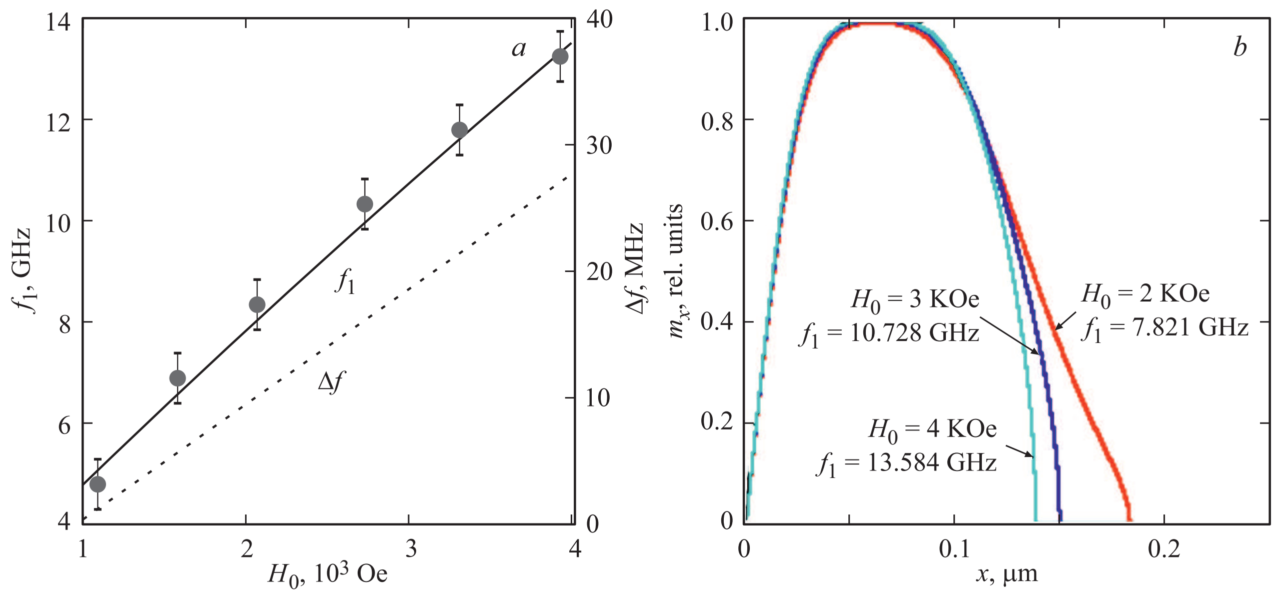

Figure 4. Field dependence of the excitation frequencies of the spin-wave resonance (a) and the diagram of oscillations of the precession wave (b) in the diffusion layer of the epitaxial YIG film. The dots in Fig. 4, a mark the measured SWR frequencies.

SWR frequencies practically coincided, which confirmed the reliability of the mathematical model.

Fig. 4, b shows diagrams of oscillations of the magnetization precession vector $m_x(x) \sim \sin[k_x(x)x]$, calculated at the frequency of the first mode of spin-wave resonance for given values of the magnetizing field $H_0 = 2, 3, 4$ KOe. It can be seen that the heterogeneity of the transition layer magnetization introduces distortions into the oscillation diagrams. When the field H_0 increases, the region of spin-wave resonance excitation narrows. In this case, the difference frequency $\Delta f(H_0)$ monotonously increases, as shown in the graph in Fig. 4, a.

3. Conclusion

Based on the studies it was found that two types of resonances are excited in a tangentially magnetized epitaxial YIG film, i.e., an uniform ferrimagnetic resonance, which was excited in the region of uniform magnetization of the YIG film (outside the transition layer), and a heterogeneous spin-wave resonance, which was excited within the thickness of the transition layer. It was found that the resonance frequencies depend significantly on the magnetization distribution through the film thickness. A method was proposed for calculating the parameters of the magnetization distribution through the film thickness. The found values of the parameters were used to simulate the processes of SWR excitation. It was found that the reduced magnetization in the transition layer causes the excitation spectrum shift of the precession wave to the low-frequency region. In this case, a sufficiently wide frequency band occurs, in which the condition of matching with external homogeneous microwave field was satisfied. At the matching points the precession wave was generated, which was radiated deep into the transition layer and reflected from the inner film'substrate interface, where the magnetization of the YIG film reached zero. Due to the small thickness of the transition layer, the excitation of the precession wave could only be observed in the form of spin-wave resonance at the peak absorption frequency of the microwave signal. Another feature was that the diagrams of oscillations at the frequency of the spin-wave resonance had a distorted non-sinusoidal character. When the field increases, the thickness of the resonating layer narrows. At the same time, the difference between SWR and FMR frequencies increased. For this reason, separate observation of peaks in the amplitude-frequency response characteristic was possible at sufficiently strong fields, when the difference between the SWR and FMR frequencies exceeded the width of the resonant peaks.

Thus, it was shown that the transition layer of the YIG epitaxial film, despite its strong magnetic heterogeneity, has its own resonant properties. The results of the studies performed can be useful for nondestructive testing of the layered structure of YIG epitaxial films.

Funding

The study was performed with the support of the Ministry of Education and Science of Russia under the Government Task (project No. FSRR-2020-0005).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] Y. Kajiwara, K. Harii, S. Takahashi, J. Ohe, K. Uchida, M. Mizuguchi, H. Umezawa, H. Kawai, K. Ando, K. Takanashi, S. Maekawa, E. Saitoh. Nature **464**, 262 (2010).

[2] A. Hirohata, K. Yamada, Y. Nakatani, L. Prejbeanu, B. Diény, P.h. Pirro, B. Hillebrands. J. Magn. Magn. Mater. **509**, 166711 (2020).

[3] 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**, *10*, 1099 (2015) (in Russian).

[4] A. Barman, G. Gubbiotti, S. Ladak, A.O. Adeyeye, M. Krawczyk, J. Gräfe, C. Adelmann, S. Cotofana, A. Naeemi, V.I. Vasyuchka, B. Hillebrands, S.A. Nikitov, H. Yu, D. Grundler, A.V. Sadovnikov, A.A. Grachev, S.E. Sheshukova, J.-Y. Duquesne, M. Marangolo, G. Csaba, W. Porod, V.E. Demidov, S. Urazhdin, S.O. Demokritov, E. Albisetti, D. Petti, R. Bertacco, H. Schultheiss, V.V. Kruglyak, V.D. Poimanov, S. Sahoo, J. Sinha, H. Yang, M. Münzenberg, T. Moriyama, S. Mizukami, P. Landeros, R.A. Gallardo, G. Carlotti, J.-V. Kim, R.L. Stamps, R.E. Camley, B. Rana, Y. Otani, W. Yu, T. Yu, G.E.W. Bauer, C. Back, G.S. Uhrig, O.V. Dobrovolskiy, B. Budinska, H. Qin, S. van Dijken, A.V. Chumak, A. Khitun, D.E. Nikonov, I.A. Young, B.W. Zingsem, M. Winklhofer. J. Phys.: Condens. Matter **33**, 413001 (2021)

[5] Ph. Pirro, V.I. Vasyuchka, A.A. Serga, B. Hillebrands. Nature Rev. Mater. **6**, 1114 (2021)

[6] A.I. Akhiezer, V.G. Baryakhtar, S.V. Peletminskiy. Spinovye volny. Nauka, M. (1967). 368 s. (in Russian).

[7] F. Bloch. Z. Physik **61**, 206 (1930).

[8] H. Suhl. J. Phys. Chem. Solids **1**, 209 (1957).

[9] M.H. Seavey, P.E. Tannenwald. Phys. Rev. Lett. **1**, 168 (1958).

[10] G.T. Rado, J.R. Weertman. J. Phys. Chem. Solids **11**, 315 (1959).

[11] R.E. De Wames, T. Wolfram. J. Appl. Phys. **41**, 987 (1970).

[12] J.D. Adam, T.W. O'Keeffe, R.W. Patterson. J. Appl. Phys. **50**, 2446 (1979).

[13] C. Kittel. Phys. Rev. **110**, 1295 (1958).

[14] E. Schlömann. J. Appl. Phys. **35**, 160 (1964).

[15] E. Schlömann, R.I. Joseph, T. Kohane. Proc. IEEE **53**, 1495 (1965).

[16] Yu.V. Gulyaev, P.E. Zilberman, E.S. Sannikov, V.V. Tikhonov, A.V. Tolkachev. Pis'ma v ZhTF **14**, *10*, 884 (1988) (in Russian).

[17] V.V. Tikhonov, A.V. Tolkachev. FTT **36**, *1*, 185 (1994) (in Russian).

[18] P.E. Zil'berman, A.G. Temiryazev, M.P. Tikhomirova. UFN **165**, *10*, 1219 (1995) (in Russian).

[19] A.G. Temiryazev, M.P. Tikhomirova, P.E. Zilberman, A.V. Maryakhin. J. Phys. IV France **7**, *1*, 395 (1997).

[20] V.V. Tikhonov, A.N. Litvinenko. Izv. RAN. Ser. fiz. **78**, *2*, 192 (2014) (in Russian).

[21] 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).

[22] J. Chen, C. Liu, T. Liu, Y. Xiao, K. Xia, G.E.W. Bauer, Mi. Wu, H. Yu. Phys. Rev. Lett. **120**, 217202 (2018).

[23] M. Shone. Circuits Systems Signal Proc. **4**, 89 (1985).