# INVESTIGATION OF ANGULAR AND TEMPERATURE DEPENDENCE OF SPIN-WAVE RESONANCE SPECTRA IN MULTILAYER MAGNETIC FILMS

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**Abstract**. In this letter we study the dependences of the resonance field $H_n$ and the linewidth $2\Delta H_n$ of the spin-wave resonance (SWR) modes in two-layer ferrite-garnet films with dissipative and mixed spin-pinning mechanisms. It is established that for films with a dissipative mechanism of spin pinning, the increase in the linewidth at $\theta_H = 35^0$ is associated with the maximum misorientation between the external magnetic field and the direction of the equilibrium magnetization of the sample. For films with a mixed spin-pinning mechanism, an increase in the linewidth $2\Delta H_n$ with increasing angle $\theta_H$ is associated with an increase in the depth of penetration of the spin wave into the pinning layer for such films. On the temperature dependence of the linewidth $2\Delta H_n$ for samples with a mixed fixation mechanism at a perpendicular orientation, an increase in the width of the absorption peak lines is observed. And with an increase in the peak number, the maximum of the linewidth shifts to the low-temperature region. With parallel orientation, the linewidth $2\Delta H_n$ in a wide temperature range from $20^0$C to $200^0$C remains practically unchanged.

## 1 INTRODUCTION

The essence of ferromagnetic resonance is the selective absorption of the energy of a high-frequency electromagnetic field by a ferromagnet. The presence of an exchange interaction in magnetically ordered substances leads to a strong correlation between the orientations of the spins of neighboring atoms and the existence of exchange spin waves in such systems. Under certain boundary conditions, a uniform variable field can excite spin waves with a discrete set of wave numbers. This appearance was called the spin-wave resonance (SWR).

Despite the large number of papers devoted to spin-wave resonance (SWR) in thin films, the angular and temperature dependences of the SWR spectra remain far from being studied. Almost in all works, analysis and experimental studies of the SWR spectra are carried out for perpendicular or parallel orientations of a constant magnetic field relative to the plane of the film. At the same time, an analysis of the angular and temperature dependences of the resonance field $H_n$ and the linewidth $2\Delta H_n$ makes it possible to better understand the properties and features of the excitation of spin waves in magnetic films. For example, a change in the angle between $\vec{H}$ and the film as well as an increase in temperature can be used for certain values of the layer parameters as one of the ways of smoothly changing the degree of pinning of the spins.

Therefore, the purpose of this paper was to study the angular and temperature dependences of the SWR spectra in multilayer magnetic films.

## 2 EXPERIMENT

The investigations were carried out on double-layer single-crystal films of ferrit-garnets. The first type of samples had the following parameters: the first layer close to the substrate (the excitation layer of harmonic standing spin-wave (SW) modes) of the composition $Y_{2.98}Sm_{0.02}Fe_5O_{12}$ had thickness $h = 1.0$ µm, saturation magnetization $4\pi M_1 = 1740$ Gs, Gilbert damping parameter $\alpha_1 = (\Delta H\gamma/\omega) = 0.0009$, gyromagnetic ratio $\gamma_1 = 1.76 \cdot 10^7$ Oe$^{-1}$s$^{-1}$, exchange interaction constant $A = 3.7 \cdot 10^{-7}$ erg/cm, effective uniaxial anisotropy field $H_k^{eff} = (2K_u/M) - 4\pi M_s = -1715$ Oe, the second layer of the composition $(LaEr)_3(FeGa)_5O_{12}$ had $h = 1.2$ µm, $4\pi M_2 = 450$ Gs, $\alpha_2 = (\Delta H\gamma/\omega) = 0.84$, $\gamma_2 = 1.76 \cdot 10^7$ Oe$^{-1}$s$^{-1}$, $A = 3.7 \cdot 10^{-7}$ erg/cm, $H_k^{eff} = (2K_u/M) - 4\pi M_s = -78$ Oe. Here $\Delta H$ - the half-width of the absorption line, $\omega$ is the circular frequency

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of the microwave field. In this sample, the dominant mechanism for the spin pinning was the dissipative mechanism. Such a pinning mechanism arises in multilayer films with widely differing values of the Gilbert damping parameter in the layers. The presence of an exchange coupling between the layers leads to the appearance of a node of a standing spin wave at the interface of the layers or near it. One of the qualitative differences between the dissipative mechanism for the spin pinning from the dynamic one lies in the fact that it does not depend on the orientation of the external magnetic field relative to the film, which is related to the isotropy of the damping parameter. For any orientation, the excitation region of standing harmonic spin waves is localized in the layer with a small one.

The second sample had the following parameters: the first layer had a composition $Y_{2.98}Sm_{0.02}Fe_5O_{12}$, $h = 0.46$ μm, $4\pi M_s = 1740$ Gs, $\gamma = 1.76 \times 10^7$ Oe$^{-1}$s$^{-1}$, $H_k^{eff} = -1715$ Oe, $\alpha = (\Delta H\gamma/\omega) = 0.003$, $A = 3.7 \cdot 10^{-7}$ erg / cm. The second layer (the spin-pinning layer) had composition $(SmEr)_3Fe_5O_{12}$ and material parameters: $h = 1.2$ mkm, $4\pi M_s = 1330$ Gs, $\gamma = 1.38 \cdot 10^7$ Oe$^{-1}$s$^{-1}$, $H_k^{eff} = 96$ Oe, $\alpha = 0.2$, $A = 3.7 \cdot 10^{-7}$ erg/cm.

The third sample the first layer close to the substrate had the composition $Y_3Fe_{4.97}Ge_{0.03}O_{12}$, $h = 0.343$ mkm, $4\pi M_s = 1680$ Gs, $\gamma = 1.76 \times 10^7$ Oe$^{-1}$s$^{-1}$, $H_k^{eff} = (2K_u/M) - 4\pi M_s = -1620$ Oe, $\alpha = (\Delta H\gamma/\omega) = 0.0009$, $A = 3.7 \cdot 10^{-7}$ erg/cm. The second layer (the spin-pinning layer) had composition $(YSmLuCa)_3(FeGe)_5O_{12}$ and material parameters: $h = 2.0$ mkm, $4\pi M_s = 560$ Gs, $\gamma = 1.74 \cdot 10^7$ Oe$^{-1}$s$^{-1}$, $H_k^{eff} = 980$ Oe, $\alpha = 0.12$, $A = 3.7 \cdot 10^{-7}$ erg/cm. In the second and third samples the dominant mechanism for pinning the spins was the mixed mechanism of spin pinning (dissipative and dynamic).

In films with different fields of homogeneous resonance, the dynamic mechanism of spin pinning is realized in the layers. With a dynamic mechanism, a microwave field excites localized modes that are harmonic in one layer (a layer with a large value of the field of a homogeneous resonance $\vec{H}_{01}$) and exponentially fall off in another layer, which in external fields larger than its homogeneous resonance field $\vec{H}_{02}$ is for spin waves by a reactive (elastic) medium and thereby ensures the pinning of the spins. The interval of fields in which spin waves are intensively excited, with dynamic pinning mechanism is limited by the values $\vec{H}_{01}$, $\vec{H}_{02}$. In our films different fields of homogeneous resonance are realized and the damping parameters in the layers vary greatly; therefore, both the dissipative and the dynamic mechanism of spin pinning are appear, i.e. a mixed mechanism for the spin pinning is realized.

The registration of the SWR spectra was carried out on a RE-1301 radio spectrometer at the frequency of

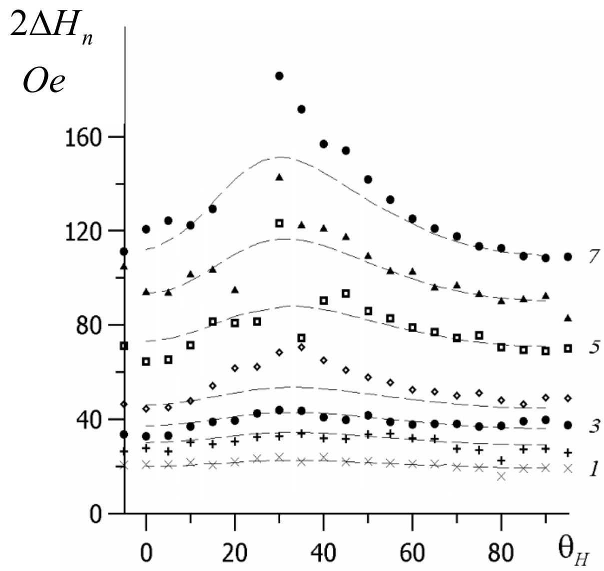


Fig.1. Dependence of the linewidth in the film with the dissipative mechanism of spin pinning on the angle between the external magnetic field and the film plane (the points - the experiment, the dashed line - the calculation). Figures for curves - numbers of spin-wave modes.

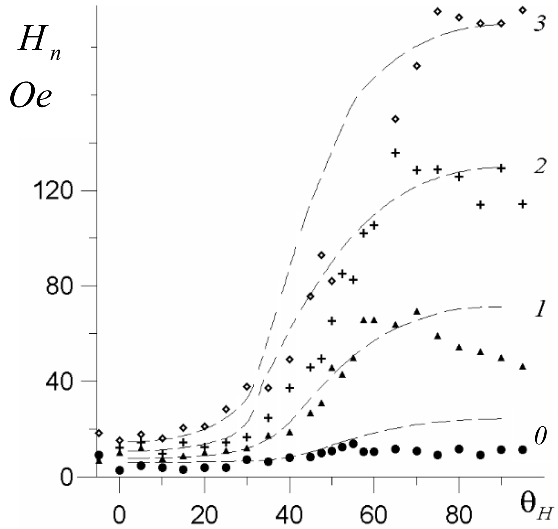


Fig.2. Dependence of the linewidth in a film with a mixed mechanism of spin pinning on the angle between the external magnetic field and the film plane (the points - the experiment, the dashed line - the calculation). Figures for curves - numbers of spin-wave modes.

the microwave field $9.34 \cdot 10^9$ Hz, and the magnetic field was measured with the help of the Hall's magnetic induction meter RSh1-10. The SWR spectra were recorded at different angles $\theta_H$ of the external magnetic field relative to the film plane. For carrying out the temperature studies, a special thermostat attachment was used, which allows setting the sample temperature in the range from -100$^0$C to 300$^0$C.

## 3 RESULTS AND DISCUSSION

As a result of experimental studies the following was established. In a sample with a dissipative mechanism of spin pinning on the anguar dependences of the linewidth a maximum of the linewidth $2\Delta H_n$ is observed for $\theta_H = 35^0$ (Fig. 1).

In a sample with a mixed mechanism of spin pinning with an increase in the angle between the external magnetic field and the film plane $\theta_H$ the fields of uniform resonance in the layers gradually approach each other. The number of spin-wave modes in the excitation layer decreases. On the angular dependences of the linewidth, a monotonous increase in the width of the line is observed. In this case, the maximum width of the lines is achieved with a parallel orientation of the external field relative to the film plane $\theta_H = 90^0$ (Fig. 2).

On the temperature dependences of the resonance fields $H_p$ in films with a mixed spin-pinning mechanism for a perpendicular orientation of the external magnetic field relative to the film plane a monotonic decrease in the resonance fields is observed. In this case, the width of the line $2\Delta H_n$ of the zero- and first- modes with increasing temperature remains practically unchanged. However, the linewidth of the second mode increases monotonically at a temperature T = 100 ° C reaches a maximum at T = 150 ° C and decreases monotonically to the previous values with a further increase in temperature. An analogous behavior of the linewidth is also observed for subsequent lines of spin-wave modes. In this case, the maxima on the dependences $2\Delta H_n$ shift towards smaller temperatures with increasing absorption peak number (Fig. 3, 4).

The linewidth was calculated as follows. According to [1-4], the width of the absorption line of each SW-mode $2\Delta H_n$ can be expressed in terms of the effective damping parameter of the n-th spin-wave mode:

$$2\Delta H_n = 2\alpha_n^{eff}\frac{\omega}{\gamma_i}, \quad (1)$$

$$\alpha_n^{eff} = \frac{\dfrac{\alpha_1}{\gamma_1 M_1}\displaystyle\int_0^{h_1} m_{1n}^2\,dz + \dfrac{\alpha_2}{\gamma_2 M_2}\displaystyle\int_{h_1}^{h_1+h_2} m_{2n}^2\,dz}{\dfrac{1}{\gamma_1 M_1}\displaystyle\int_0^{h_1} m_{1n}^2\,dz + \dfrac{1}{\gamma_2 M_2}\displaystyle\int_{h_1}^{h_1+h_2} m_{2n}^2\,dz}, \quad (2)$$

The distributions of the variable magnetization in the excitation layer $m_1(z)$ and in the pinning layer $m_2(z)$ were found as a result of solving the equations of the equilibrium orientation of the magnetization and the dispersion relations written for each of the layers of a two-layer magnetic film and also taking into account the boundary conditions at the outer boundaries of the film and at the interlayer boundary.

The calculation carried out showed that in films with a dissipative mechanism of spin pinnng an increase in the linewidth $2\Delta H_n$ at $\theta_H = 35^0$ is observed [3-4]. It is established that this increase is associated with an increase in the misorientation angle between the external magnetic field and the direction of the equilibrium orientation of the magnetization of the sample $\theta_H - \theta_M$.

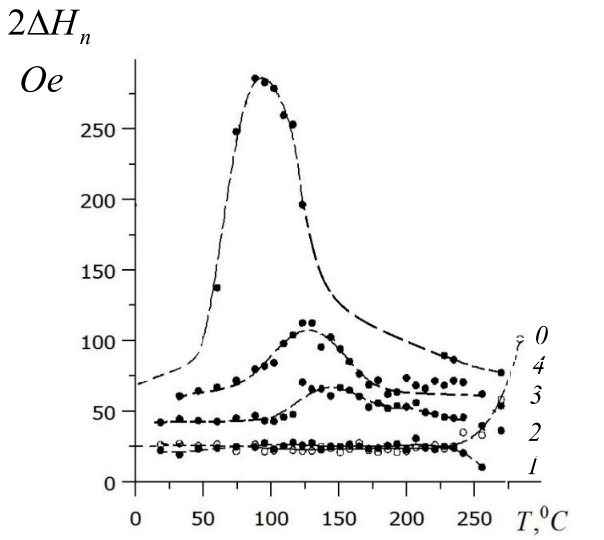


Fig.3. Dependence of the linewidth in a film with a mixed mechanism of spin pinning on temperature at a perpendicular orientation (points - experiment, dashed line - calculation). Figures for curves - numbers of spin-wave modes.

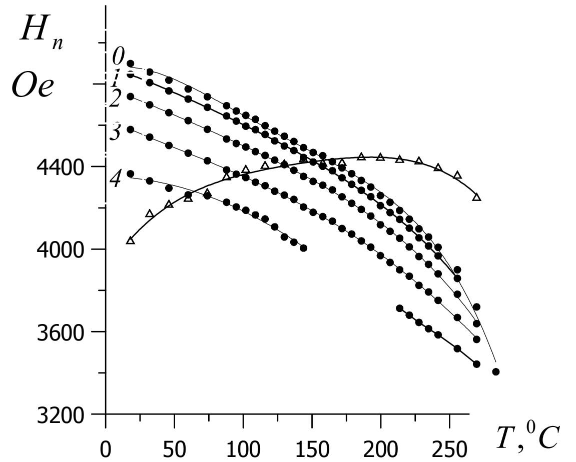


Fig.4. Dependence of the resonance field in a film with a mixed mechanism of spin pinning on temperature at a perpendicular orientation (points - experiment, solid line - calculation). Figures for curves - numbers of spin-wave modes.

Approximately equal values $2\Delta H_n$ for the perpendicular and parallel orientations are related to the same values of the depth of penetration of the spin wave into the pinning layers for both orientations.

In films with a mixed spin-pinning mechanism for a perpendicular orientation of the external field relative to the film plane ($\theta_H = 0^0$), the linewidth of all modes have values from 0 to 20 Oe. With an increase in the angle $\theta_H$, the linewidth for all modes monotonically increases. The maximum width of the lines is achieved with a parallel orientation of the external field relative to the film plane ($\theta_H = 90^0$), which is due to an increase in the depth of penetration of the spin wave into the pinning layer for this orientation.

To explain the dependences of the linewidth on temperature, the additional calculation was carried out. The decrease in the magnetization of the excitation layer of spin waves with increasing temperature is described by the Bloch law:

$$M(T)=M(0)\left(1-\left(\frac{T}{T_k}\right)^{3/2}\right), \quad (3)$$

where $M(0)$ is the saturation magnetization at 0 K, $M(T)$ is the saturation magnetization at a given temperature, $T_k$ is the Curie temperature of the given layer.

It can be seen from expression (3) that as the temperature increases, the magnetization of the substance decreases monotonically, as a result the resonance fields decrease with perpendicular orientation of the external field relative to the film, and increase with parallel.

The calculation showed that at a perpendicular orientation there is an intersection of the resonance field of the zero mode of the pinning layer $H_{02}$ and the resonance field of the corresponding SW-mode of the excitation layer $H_n$ (fig. 4). As a result, the depth of penetration of this SW-mode into the pinning layer increases, and accordingly, in the same temperature range, the linewidth of this SW-mode increases. For example, the intersection of the resonance fields $H_{02}$ and $H_3$ for the third SW-mode occurs in the interval $T \approx 100 \div 120^0 C$, in the same interval the linewidth increases, for the second SW-mode - $T \approx 125 \div 150^0 C$, etc. And with an increase in the number of the SW-modes, the maximum of the linewidth shifts to the low temperature region, which is associated with an increase in the penetration depth of the spin wave into the anchoring layers at these temperatures (fig.3, 4).

For a parallel orientation, the intersection of resonance fields of peaks corresponding to different layers does not occur (figs 5, 6). There is also no increase in the linewidth of the corresponding peaks.

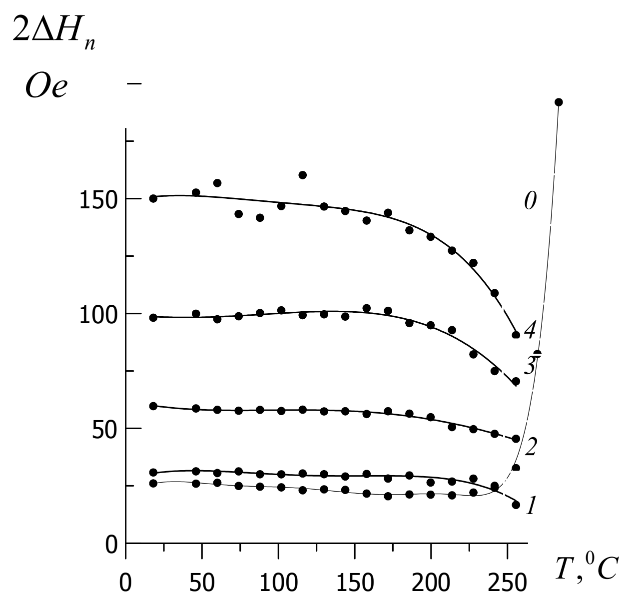


Fig.5. Dependence of the linewidth in a film with a mixed mechanism of spin pinning on temperature at a parallel orientation (points - experiment, solid line - calculation). curves - numbers of spin-wave modes.

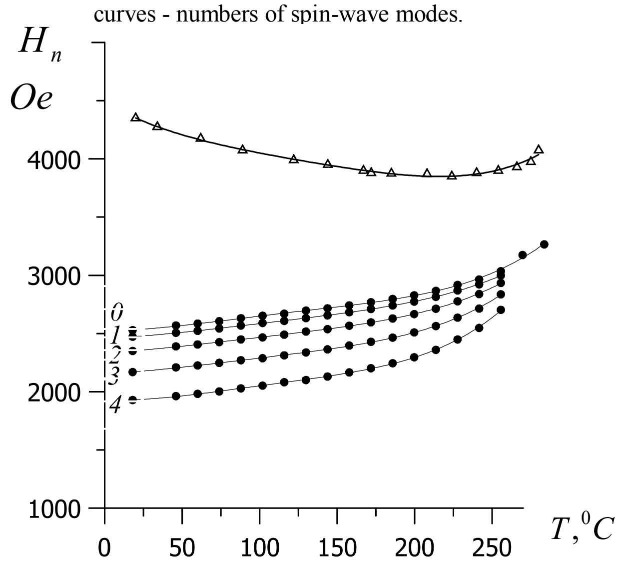


Fig.6. Dependence of the resonance field in a film with a mixed mechanism of spin pinning on temperature at a parallel orientation (points - experiment, solid line - calculation). Figures for curves - numbers of spin-wave modes.

## 4 CONCLUSION

Thus, we can draw the following conclusions:

1. It is established that for films with a dissipative mechanism of spin pinning, the increase in the linewidth $2\Delta H_n$ at $\theta_H = 35^0$ is associated with the maximum misorientation between the external magnetic field and the direction of the equilibrium magnetization of the sample $\theta_H - \theta_M$. Approximately equal values $2\Delta H_n$ for the perpendicular and parallel orientations are related to the same values of the depth of penetration of the spin wave into the pinning layer for both orientations.

2. It is established that for films with a mixed spin-pinning mechanism, an increase in the linewidth $2\Delta H_n$ with increasing angle $\theta_H$ is associated with an increase in the depth of penetration of the spin wave into the pinning layer for such films.

3. On the temperature dependence of the linewidth for samples with a mixed pinning mechanism at a perpendicular orientation, an increase in the linewidth of the absorption peak lines is observed. And with an increase in the peak number, the maximum linewidth shifts to low temperatures.

4. With parallel orientation, the linewidth of the SW-modes in a wide temperature range from $20^0$C to $200^0$C remains practically unchanged.

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