JETP Letters, Vol. 76, No. 3, 2002, pp. 175–179. Translated from Pis'ma v Zhurnal Éksperimental'noĭ i Teoreticheskoĭ Fiziki, Vol. 76, No. 3, 2002, pp. 209–213.


# Ferromagnetic Resonance Features in Anisotropic Magnetic Films with a Metastable State of Magnetic Moment

**B. A. Belyaev and A. V. Izotov**

*Kirenskiĭ Institute of Physics, Siberian Division, Russian Academy of Sciences, Krasnoyarsk, 660036 Russia*

*e-mail: belyaev@iph.krasn.ru*

Received July 2, 2002

In experiments on single-domain magnetic films with uniaxial in-plane anisotropy, a new homogeneous ferromagnetic resonance peak was observed in a planar magnetic field oriented at an angle to the easy magnetization axis and directed opposite to the magnetization projection onto the field direction. The peak was observed in fields smaller than the magnetization reversal field of the film, and the origin of the peak was found to be related to the metastable state of the magnetic moment. A good agreement was obtained between phenomenological calculations and experimental data. © *2002 MAIK "Nauka/Interperiodica".*

PACS numbers: 75.70.Ak; 76.50.+g

Previous studies [1] of thin magnetic films possessing induced uniaxial in-plane anisotropy by a scanning ferromagnetic-resonance spectrometer [2] revealed a narrow peak of microwave absorption that was accompanied by an abrupt increase in the magnetic susceptibility. The peak was observed in a constant magnetic field $H$ oriented normally to the easy magnetization axis (EMA). Its position corresponding to the uniaxial magnetic anisotropy field $H_k$ was independent of the pumping frequency $f$. The peak was shown to be caused by the nonlinear static magnetic susceptibility; however, it was clearly distinguished at high and microwave frequencies. This paper describes experiments performed on permalloy films with a uniaxial magnetic anisotropy, in which an additional absorption peak was revealed in the ferromagnetic resonance spectrum. Unlike the peak of the static susceptibility, the new peak was observed in a wide range of angles between the direction of the scanning constant magnetic field and the EMA. The new peak exists in the fields $H < H_k$, and its position strongly depends on both the pumping frequency and the angle between the scanning field and the EMA.

The film samples of thickness 500 Å were fabricated by the thermal vacuum deposition of permalloy with the composition $Ni_{75}$–$Fe_{25}$ characterized by a relatively small positive magnetostriction constant. The films were deposited on glass substrates 0.5 mm thick with dimensions 25 × 10 mm. The substrates were heated to 200°C, and the rate of deposition was 10 Å/s. The uniaxial magnetic anisotropy in the plane of a magnetic film was induced along the short side of the substrate by a constant magnetic field of 30 Oe applied during the deposition in the corresponding direction. To increase the anisotropy field, a uniaxial compression was applied to the films through a slight bending deformation of the substrate during the deposition [3]. Owing to the elastic stress, the anisotropy field in the middle of the film increased by a factor of more than 3, as compared to a stress-free sample, and reached the values $H_k > 15$ Oe. Simultaneously, the coercive force, which was measured by the magnetization reversal along the EMA, increased by almost an order of magnitude and reached the values $H_c > 4$ Oe [4]. The presence of a large anisotropy field in the samples was necessary to reduce the angular dispersion of the magnetic moment, while the increase in the coercive force (as will be shown below) was necessary to "hold" the magnetic moment of the film in the metastable state.

The experiment was performed with an automated scanning ferromagnetic resonance spectrometer [2] whose locality of measurement $S \approx 1$ mm$^2$ was determined by the diameter of the measuring aperture in the microwave head. The vectors of the external magnetic field $H$ and the orthogonally oriented microwave pumping field $h$ of frequency $f = 1.034$ GHz lay in the film plane (Fig. 1). The ferromagnetic resonance spectra were recorded within a local area of a thin magnetic film under investigation for different angles of the EMA orientation $\theta_n$. Before each measurement run, the sample was magnetized along the EMA by the field $H = 300$ Oe. Then, the field was reduced to zero, the required angle $\theta_n$ was set, the magnetic field direction was switched to the opposite, and, finally, two ferromagnetic resonance spectra were recorded in a given range of the scanning field. The first spectrum was recorded during the direct run of the scanning field $H$ (the dashed lines in Fig. 2), and the second spectrum (the solid lines) was recorded after the sample magne-

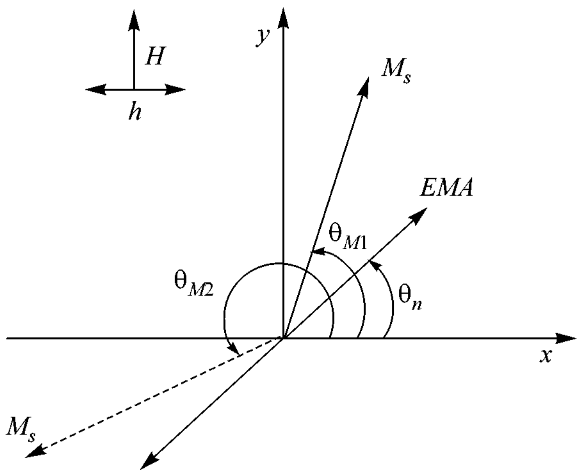


**Fig. 1.** Model of a magnetic film with a uniaxial anisotropy.

tization by the field $H$ = 300 Oe without changing the angle $\theta_n$ during the reverse run.

Evidently, at the beginning of the direct run of the scanning field $H$, the projection of the saturation magnetization vector $M_s$ onto the field axis (see Fig. 1) is directed opposite to the field, and, hence, the magnetic moment of the film area under investigation is in some metastable state until the magnetization reversal field of the film area under study is reached. Note that, owing to the presence of a low-frequency modulating magnetic field in the ferromagnetic resonance spectrometer [2] and the relatively small size of the film area under study, the magnetization reversal of this area occurs in a single Barkhausen jump. Therefore, the magnetization reversal field is the coercive force $H_c$ of the given area of a thin magnetic film [4]. From Fig. 2, one can see that, at "small" angles $\theta_n$, the amplitude of the ferromagnetic resonance signal in the stable state (i.e., ground state) is higher than in the metastable state, while at "large" angles, the situation is reversed. Note that the signal amplification factor achieved in recording the spectra for the angle $\theta_n$ = 25° was an order of magnitude greater than in the case of $\theta_n$ = 10°.

Figure 3 shows the angular dependences of the measured fields of the homogeneous ferromagnetic resonance $H_R(\theta_n)$ in the ground state of the magnetic moment (the full circles) and in the metastable state (the empty circles) for the central part of a film sample with the anisotropy field $H_k$ = 16.6 Oe and the effective saturation magnetization $M_s$ = 980 G. In the same figure, the empty triangles show the angular dependence of the magnetization reversal field $H_c(\theta_n)$ of the film area under study. In the case of film magnetization normal to the EMA, the magnetization reversal field almost coincides with the anisotropy field, but it rapidly decreases with an increase in $\theta_n$. The full triangles in Fig. 3 show the measured resonance fields for the inter-

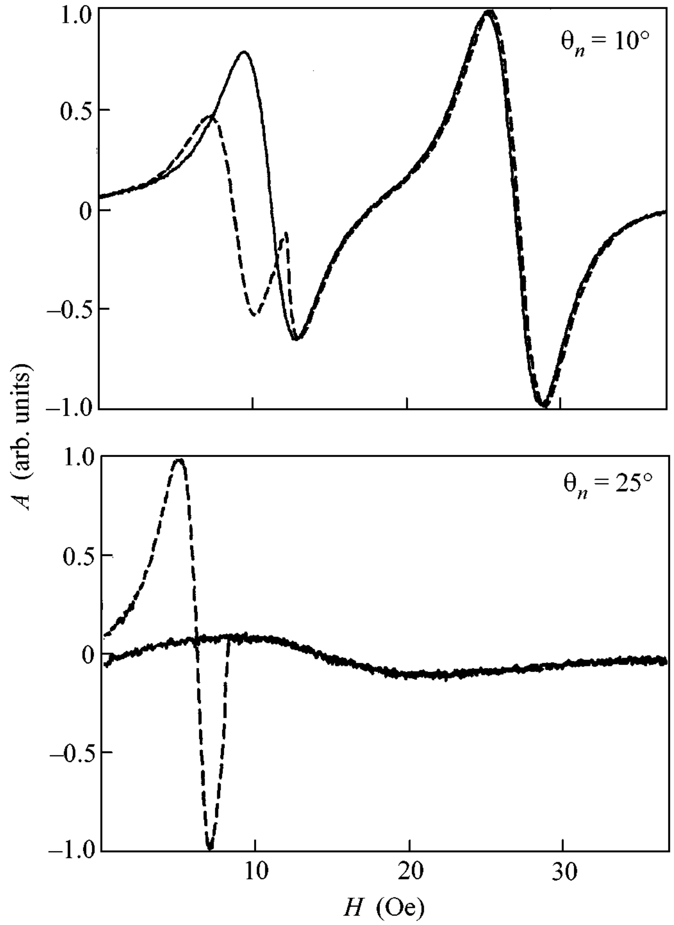


**Fig. 2.** Derivatives of the absorption lines for the ground state (the solid lines) and the metastable state (the dashed lines) of the magnetic moment of a thin magnetic film.

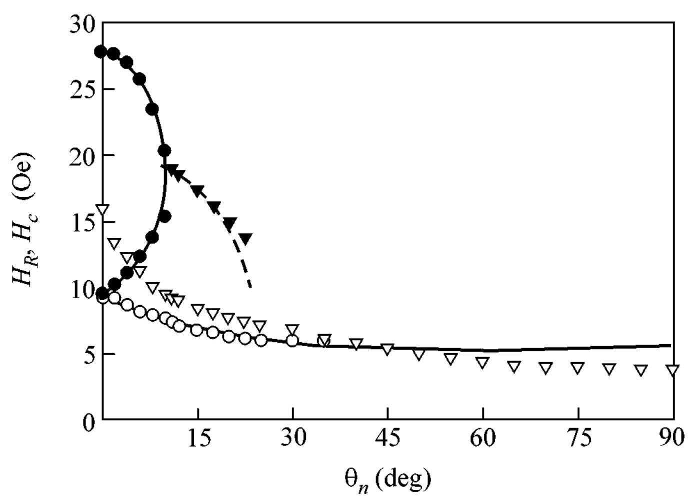


**Fig. 3.** Angular dependences of the resonance fields and the magnetization reversal field of a magnetic film. The dots represent the experimental data and the lines show the results of calculations (details are in the main body of the paper).

val of angles $\theta_n$ where the amplitude of the ferromagnetic resonance signal observed in the ground state of the magnetic moment is smaller than the amplitude observed in the metastable state. In this interval, an increase in $\theta_n$ is accompanied by a decrease in the resonance field and a monotone decrease in the amplitude of the ferromagnetic resonance signal, which gradually vanishes in noise. Figure 3 shows that the resonance field observed for the magnetic moment in the metastable state also monotonically decreases with increasing $\theta_n$, but this field can be measured only when $H_c > H_R$.

To reveal the origin of the resonances observed in the experiment, we consider the model of a boundless single-domain magnetic film possessing a uniaxial in-plane magnetic anisotropy with the EMA directed at an angle $\theta_n$ to the $x$ axis (Fig. 1). As is known, in a planar magnetic field $H$ applied at an arbitrary angle to the EMA, when the strength of this field is lower than that of the anisotropy field $H_k$, two thermodynamically stable positions of the magnetic moment vector exist in the film [5]. These two states are separated by a barrier whose height is determined by the value of $H_k$, and the region of existence of the two states is bounded by the curve described by the cycloid equation

$$H_x^{2/3} + H_y^{2/3} = H_k^{2/3}. \quad (1)$$

Thus, in addition to the ground state of magnetization with the equilibrium angle $\theta_{M1}$ (see Fig. 1) corresponding to the absolute energy minimum, the second, metastable, position is present with the equilibrium angle $\theta_{M2}$ corresponding to the local energy minimum. This fact, in particular, gives rise to a hysteresis and makes it possible to observe a ferromagnetic resonance for the two aforementioned states.

For the thin magnetic film model shown in Fig. 1, by solving the Landau–Lifshits equation in the absence of damping, it is easy to obtain (e.g., following [6]) the expression for the eigenfrequency of the magnetization precession $\omega_0$;

$$\omega_0^2 = \Omega_1\Omega_2, \quad (2)$$

where

$$\Omega_1 = \gamma[H\sin(\theta_M) + H_k\cos^2(\theta_n - \theta_M) + 4\pi M_S];$$

$$\Omega_2 = \gamma[H\sin(\theta_M) + H_k\cos 2(\theta_n - \theta_M)];$$

$\gamma$ is the gyromagnetic ratio; and the equilibrium angle $\theta_M$ for the magnetization vector $M_s$ is determined from the equation

$$H\cos(\theta_M) + \frac{1}{2}H_k\sin 2(\theta_n - \theta_M) = 0, \quad (3)$$

which is obtained from the condition of the minimal free energy density of the film, including the Zeeman energy, the anisotropy energy, and the energy of demagnetizing fields. Equation (3), depending on the magnetic field strength and the orientation of the EMA, yields either one value of the equilibrium angle $\theta_M$ or two different values corresponding to the ground and metastable states of the magnetization vector.

In Fig. 3, the solid lines show the angular dependences of the resonance field that were obtained from Eqs. (2) and (3) for both states of the magnetic moment of the film under study. One can see a good agreement between theory and experiment for both ground state and metastable states. However, the formulas obtained above do not describe the angular dependence of the peak position observed in the experiment for $\theta_n > 10°$ (the full triangles in Fig. 3). The origin of this peak can be explained by the field dependence of the component $\chi_{xx}$ of the dynamic magnetic susceptibility tensor. For the film model under consideration (see Fig. 1), this component is easily calculated by solving the Landau–Lifshits equation with the damping parameter $\alpha$ involved in the dissipative term in the Hilbert form:

$$\chi_{xx} = \frac{\gamma M_s(\Omega_1 + i\alpha\omega)\sin^2\theta_M}{\omega_0^2 - (1+\alpha^2)\omega^2 + i\alpha\omega(\Omega_1 + \Omega_2)}. \quad (4)$$

Separating this component into the real and imaginary parts and setting $\alpha^2 \ll 1$, we obtain

$$\chi_{xx} = \chi'_{xx} + i\chi''_{xx}, \quad (5)$$

$$\chi'_{xx} = \frac{\gamma M_s[\Omega_1(\omega_0^2 - \omega^2) + \alpha^2\omega^2(\Omega_1 + \Omega_2)]\sin^2\theta_M}{[(\omega_0^2 - \omega^2)^2 + \alpha^2\omega^2(\Omega_1 + \Omega_2)^2]}, \quad (6)$$

$$\chi''_{xx} = \frac{\gamma M_s\alpha\omega(\Omega_1^2 + \omega^2)\sin^2\theta_M}{[(\omega_0^2 - \omega^2)^2 + \alpha^2\omega^2(\Omega_1 + \Omega_2)^2]}. \quad (7)$$

Evidently, the change in the electromagnetic energy absorption in the magnetic film during the magnetic field scan is determined by the field dependence of the quantity $\chi''_{xx}$ with the absorption maxima corresponding to the conditions $d\chi''_{xx}/dH = 0$ and $d^2\chi''_{xx}/dH^2 < 0$. It can be easily shown that, in addition to the main absorption maxima observed at the ferromagnetic resonance in the fields $H_R$ when the pumping frequency is $\omega = \omega_0$, one more maximum is observed in the field where the condition

$$\frac{d}{dH}(\Omega_1\Omega_2) = 0 \quad (8)$$

is satisfied. The angular dependence of the position of this maximum was calculated from Eq. (7) for the pumping frequency used in the measurements ($f$ = 1.034 GHz). This dependence is shown in Fig. 3 by the dashed line and, as one can see, it also agrees well with the experiment.

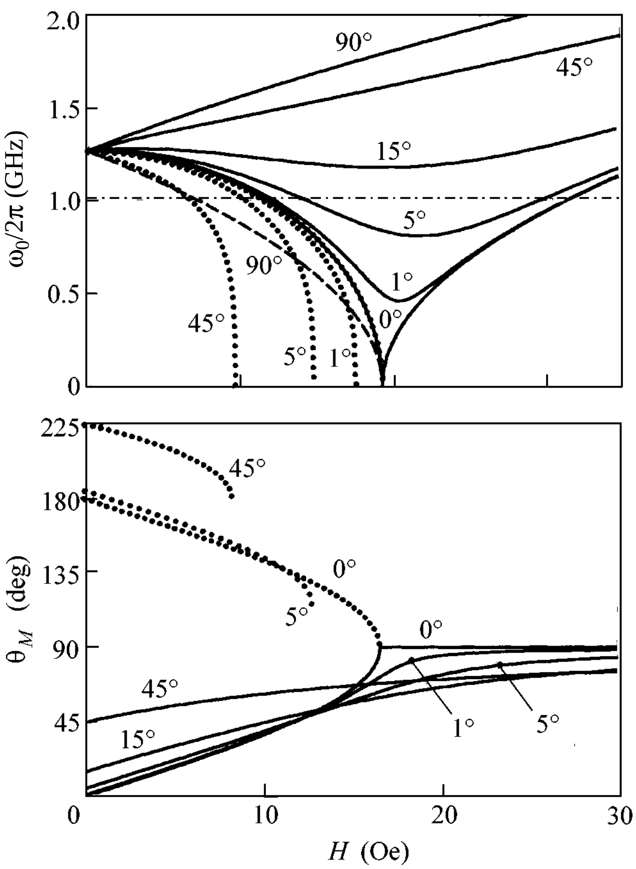


**Fig. 4.** Field dependences of the ferromagnetic resonance frequency and the equilibrium angle of magnetization for several directions of the easy magnetization axis. The solid lines correspond to the ground state of the magnetic moment and the dotted and dashed lines correspond to the metastable state.

The additional susceptibility maximum can be observed only in a limited range of variation of the angle $\theta_n$, and calculations show that the lower bound of this range is determined by the pumping frequency and tends to zero when $\omega \longrightarrow 0$. It should be noted that the susceptibility peak revealed in our experiment exists only when the pumping frequency satisfies the condition $\omega < \omega_0$. Therefore, this peak cannot be considered as a ferromagnetic resonance. In fact, this peak characterizes the microwave absorption that occurs in the magnetic film when the ferromagnetic resonance frequency approaches the pumping frequency in the course of the field scan and then moves away from it.

These conclusions are supported by the computational results shown in Fig. 4. The upper part of this figure presents the eigenfrequencies of homogeneous oscillations of magnetization in the magnetic film model under study as functions of the constant magnetic field. These dependences were calculated by Eq. (2) for different directions of the EMA. The solid lines show the ferromagnetic resonance frequencies for the ground state, and the dotted and dashed lines, for the metastable state. In the calculations, we used the parameters presented above for the magnetic film area under investigation. The horizontal dot-and-dash line indicates the pumping frequency used in the measurements. One can see that, owing to the nonmonotonic dependence $\omega_0(H)$ observed at certain angles, e.g., at $\theta_n = 15°$, the resonance frequency first approaches the pumping frequency and then moves away from it during the field scan. Therefore, the position of the maximum in the field dependence of the microwave absorption by the film coincides with the position of the minimum in the dependence $\omega_0(H)$ [see Eqs. (2) and (8)].

It was found that, for the frequency $\theta_n = 0$, as the angle $\theta_n$ increases, the ferromagnetic resonance field $H_R$ for the metastable state of the magnetic moment of the film first decreases reaching its minimal value $H_R = H_k/2$ at $\theta_n = 45°$ (see Fig. 4) and then increases to the maximal value $H_R = H_k$. Note that, when $\theta_n = 0$, the ferromagnetic resonance frequencies for the metastable and ground states observed in the fields $H < H_k$ fully coincide. The lower part of Fig. 4 shows the field dependences of the equilibrium orientation angles of the saturation magnetization. The curves were obtained by Eq. (3) for several values of $\theta_n$. As one would expect, these dependences prove to be noticeably different for the ground state (the solid lines) and for the metastable state (the dotted lines).

Thus, on specially prepared samples of thin magnetic films, we observed a ferromagnetic resonance in a specific metastable state of the magnetic moment. We studied the dispersion dependences of the ferromagnetic resonance field in the phenomenological approximation and obtained a good agreement between theory and experiment. We showed that, in the metastable state, the ferromagnetic resonance field can be measured only in conditions when this field is smaller than the field of magnetization reversal of the magnetic film sample under study. In other words, the effect revealed in our experiments can be observed in films with a sufficiently high coercive force.

In addition, we have found that the microwave absorption peaks observed in the experiment for the ground state of the film in a certain interval of angles of the EMA orientation result from the nonmonotonic dispersion dependence of the ferromagnetic resonance field. Despite the fact that, in the spectrum records, these peaks manifest themselves as ferromagnetic resonances, they are observed at frequencies below the ferromagnetic resonance frequencies and, hence, are of different origin. Namely, in this case, the change in the microwave absorption observed during the magnetic field scan is caused by the approach of the resonance frequency to the pumping frequency and its subsequent change in the opposite direction. The width of these absorption peaks is much greater than the width of the ferromagnetic resonance line. In principle, such peaks can be observed in any materials, including massive ones, in which a nonmonotonic behavior of the frequency dispersion of the resonance field takes place.

## REFERENCES


1. B. A. Belyaev, A. V. Izotov, and S. Ya. Kiparisov, Pis'ma Zh. Éksp. Teor. Fiz. **74**, 248 (2001) [JETP Lett. **74**, 226 (2001)].
2. B. A. Belyaev, A. A. Leksikov, I. Ya. Makievskiĭ, and V. V. Tyurnev, Prib. Tekh. Éksp., No. 3, 106 (1997).
3. B. A. Belyaev, A. G. Vladimirov, and V. V. Polyakov, in *Proceedings of the XVI International School-Workshop "Novel Magnetic Materials for Microelectronics," Moscow, 1998*, Part 1, p. 329.
4. B. A. Belyaev, A. V. Izotov, and A. A. Leksikov, Zavod. Lab. **67** (9), 23 (2001).
5. L. D. Landau and E. M. Lifshitz, *Course of Theoretical Physics*, Vol. 8: *Electrodynamics of Continuous Media* (Nauka, Moscow, 1982; Pergamon, New York, 1984).
6. A. G. Gurevich, *Magnetic Resonance in Ferrites and Antiferromagnets* (Nauka, Moscow, 1973), pp. 79–89.


*Translated by E. Golyamina*