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Singularity in High-Frequency Susceptibility of Thin Magnetic Films with Uniaxial Anisotropy

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A sharp peak of magnetic susceptibility has been observed in the ferromagnetic resonance spectra of uniaxial magnetic films placed in a planar field directed orthogonal to the easy magnetization axis, along which a pumping high-frequency magnetic field has been oriented. The peak width is considerably narrower than the line width of the uniform ferromagnetic resonance, and its position in a field equal to the film anisotropy field does not depend on the pumping frequency. The nature of the peak is associated with a drastic increase in the static transverse susceptibility of the film in the vicinity of the anisotropy field. It is shown phenomenologically that the peak can be observed only for quality samples with small angular and amplitude dispersion of the uniaxial anisotropy. *© 2001 MAIK "Nauka/Interperiodica".*

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It is known that one or two resonance peaks, depending on the pumping frequency, are observed in the ferromagnetic resonance (FMR) spectrum of magnetic films in the single-domain state possessing uniaxial magnetic in-plane anisotropy when a planar magnetic field is swept perpendicular to the easy magnetization axis (EMA) [1].The magnitude of the resonance fields for these peaks can be determined from the equations

$$\left(\frac{\omega}{\gamma}\right)^2 = \left(\frac{H_k^2 - H^2}{H_k}\right)(4\pi M_s + H_k), \quad H \le H_k,$$
$$\left(\frac{\omega}{\gamma}\right)^2 = (H - H_k)(4\pi M_s + H_k), \quad H \ge H_k, \tag{1}$$

where ω is the circular frequency of the pumping magnetic field, γ is the gyromagnetic ratio, H_k is the uniaxial magnetic anisotropy field, H is the FMR field, and M_s is the saturation magnetization.

We found another sharp peak in the FMR spectra of magnetic Co–Ni–P films. Its line width was an order of magnitude smaller than the line width of the uniform ferromagnetic resonance. The spectra were measured from local areas of samples on an automated scanning FMR spectrometer [2]. The locality of measurements was determined by the diameter of the measuring hole in the microstrip resonator of the detector with an area of ≈1 mm².

Magnetic films 0.05–1.0 μm thick were obtained by chemical deposition from a solution [3] at a temperature of 96–97°C on substrates 10 × 10 mm² in size. Glasses, fused quartz, and single-crystal GaAs wafers were used as substrate materials, and the structure of the films was X-ray amorphous, regardless of the substrate material. Microstructural studies of films were performed on a PRÉM-200 electron transmission microscope. These studies showed that a film consisted of microcrystallites 20–60 Å in size. The film composition was measured in the range $Co_{65–70}$–$Ni_{32–27}P_{3–5}$ wt % and was controlled by X-ray fluorescence analysis [4]. A planar uniaxial magnetic anisotropy field H_k = 25–30 Oe was induced by a uniform magnetic field H = 3 kOe applied in the substrate plane during film deposition. Measurements of magnetic properties in local areas of samples [5] showed their high uniformity in the central part ~6 × 6 mm² in size. For example, the effective saturation magnetization for a sample 0.3 μm thick varied from point to point within the range as small as $M_s = 1100 \pm 20$. The deviation of the directions of the easy magnetization axes in local areas of the film did not exceed ±0.4°, and the deviation of the anisotropy field from the average H_k = 28 Oe was less than 0.5 Oe. Ferromagnetic resonance spectra measured for this sample at three pumping frequencies in its central area

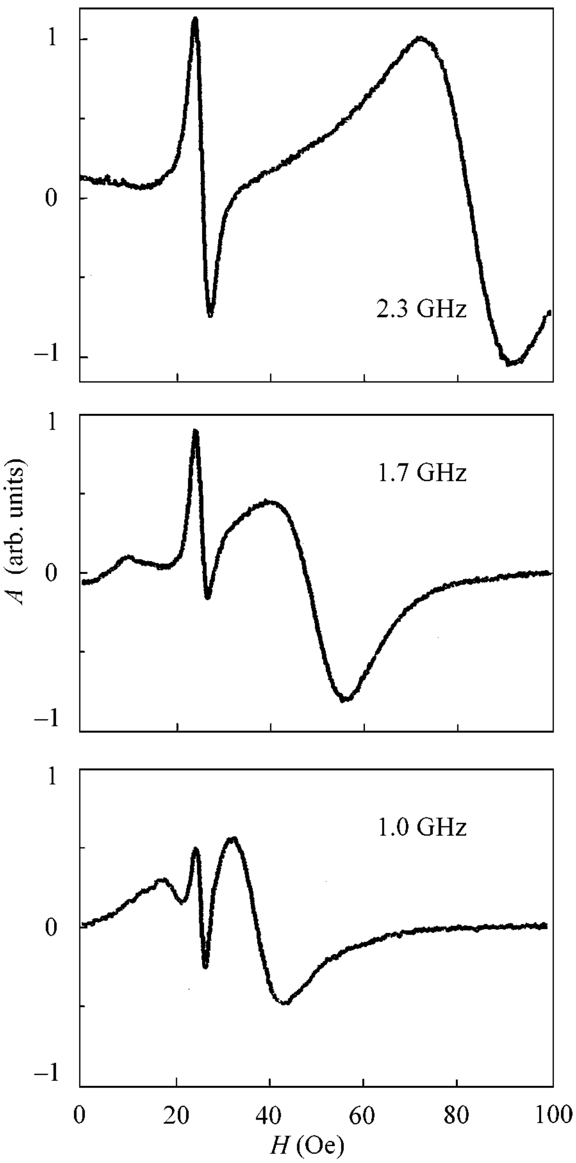

Fig. 1. Ferromagnetic resonance spectra at various pumping frequencies.

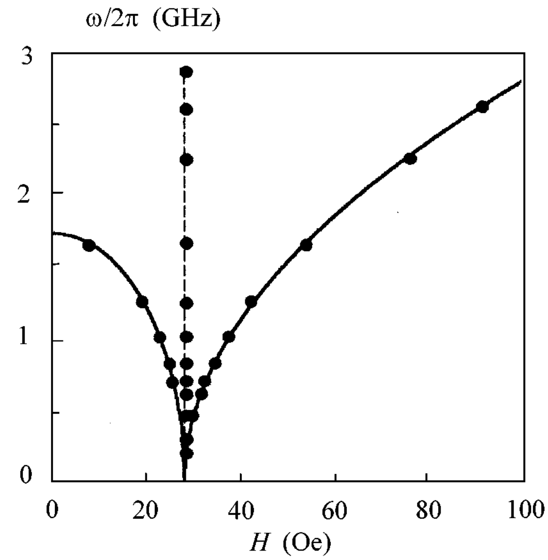

Fig. 2. Dependence of the resonance frequencies on the FMR field.

are presented in Fig. 1. The magnetic field in the experiment was oriented strictly perpendicular to the easy magnetization axis. Regardless of the pumping frequency, an intense sharp peak is observed in all spectra at the same magnetic field equal to the uniaxial magnetic anisotropy field H_k = 28 Oe. Its width is considerably smaller than the line width of the uniform magnetic resonance. The dependences of the resonance frequency of the uniform ferromagnetic resonance for the sample area under study calculated by the formulas in Eq. (1) are shown in Fig. 2. Points present the results of measurements. The vertical dashed line connects the points corresponding to the maximal susceptibility of the new peak found in the FMR spectrum. It should be noted that the amplitude of this peak drops rapidly with decreasing pumping frequency below 1 GHz because of its suppression by the uniform ferromagnetic resonance peaks moving closer together. As a result, this peak is hardly observed at a frequency of 0.2 GHz. With increasing pumping frequency above 2.6 GHz, the peak amplitude drops monotonically; this, evidently, can be explained by the manifestation of the skin effect. It is also important to note that the peak found in our work virtually disappears if the easy magnetization axis deviates from the orthogonality to the field H in one or another direction by only 1° (Fig. 3).

The revealed regularities in the behavior of the peak found in this work allow the suggestion that its nature is associated with the static susceptibility of the magnetic film. Actually, a kink is observed in the curve of film magnetization perpendicular to the EMA at a magnetic field equal to the anisotropy field of the sample [1]. This kink demonstrates instability of the magnetic moment at this point. Therefore, it is reasonable to expect here an increase in the transverse magnetic susceptibility.

Consider a model of an infinite magnetic film in the x–y plane, in which an external magnetic field H is directed at an angle θ_H to the x axis, and the easy magnetization axis of uniaxial magnetic anisotropy is directed at an angle θ_n to x. In this case, the equilibrium angle θ_M that characterizes the slope of the magnetization vector M_s to the x axis is determined from the equation

$$H\sin(\theta_H - \theta_M) + \frac{1}{2}H_k\sin 2(\theta_n - \theta_M) = 0. \qquad (2)$$

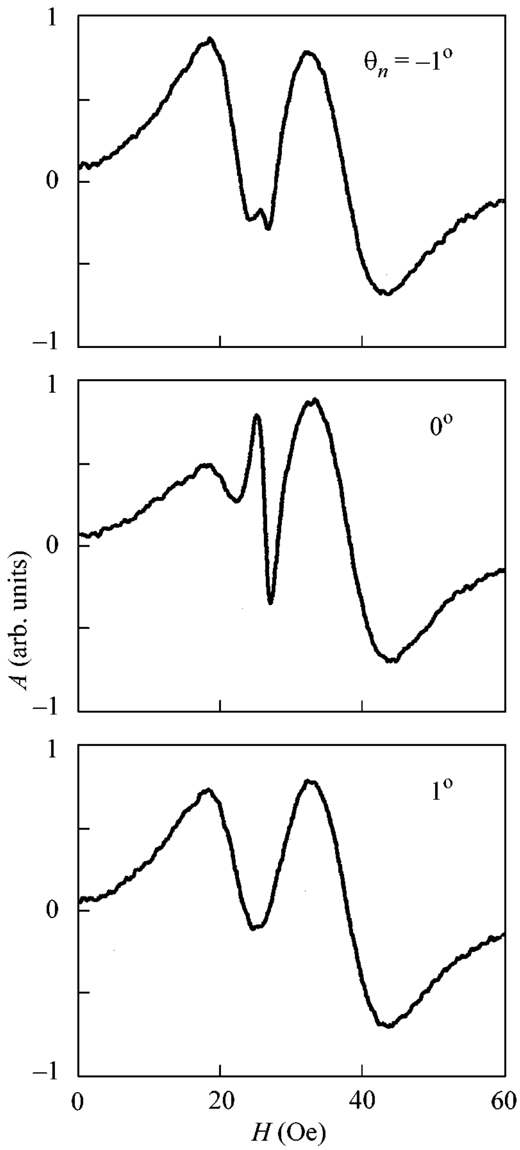

Fig. 3. FMR spectra for various orientation angles of the easy magnetization axis.

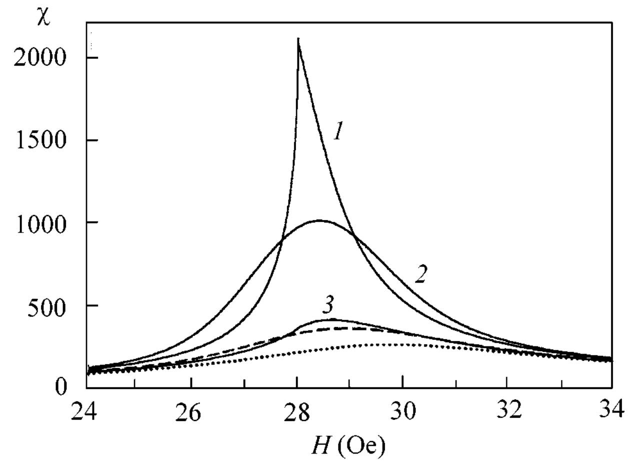

Fig. 4. Field dependences of magnetic susceptibility calculated numerically: (*1*) without anisotropy dispersion, (*2*) only amplitude dispersion of 1 Oe, and (*3*) only angular dispersion of 1°; dashed line designates that both angular and amplitude dispersions are present; and dots mean that dispersion is absent, but the EMA deviates by 1° from the initial direction.

Equation (2) is obtained from the minimum condition for the free energy density of the film

$$F = -(\mathbf{M}\cdot\mathbf{H}) + \frac{1}{2}(\mathbf{M}\cdot\overleftrightarrow{N}\cdot\mathbf{M}) - \frac{H_k}{2M}(\mathbf{M}\cdot\mathbf{n})^2. \quad (3)$$

Here, $\mathbf{M}$ is the magnetic moment vector, $\mathbf{n}$ is the unit vector that coincides with the EMA direction, and $\overleftrightarrow{N}$ is the tensor of demagnetization coefficients. This tensor is determined by the shape of the sample, and it has only one component $N_{zz} = 4\pi$ in the case of a magnetic film.

The static magnetic susceptibility of the film

$$\chi = m/h, \quad (4)$$

where m is the deviation of the magnetization vector from an equilibrium under the action of a test magnetic field h. It can be calculated from the solution of the equation

$$[\mathbf{M}\times\mathbf{H}_{\text{eff}}] = 0, \quad (5)$$

where $\mathbf{H}_{\text{eff}} = dF/d\mathbf{M}$. This equation is reduced to an equation of the third degree in the quantity $\psi = m/M_s$. In the general case, this equation takes the form

$$\psi^3 + \frac{h\cos(\theta_H-\theta_M) + H_k\sin 2(\theta_n-\theta_M)}{H_k\sin^2(\theta_n-\theta_M)}\psi^2$$
$$+ 2\frac{H\cos(\theta_H-\theta_M) + H_k\cos 2(\theta_n-\theta_M) - h\sin(\theta_H-\theta_M)}{H_k\sin^2(\theta_n-\theta_M)} \quad (6)$$
$$\times\psi = 2\frac{h\cos(\theta_H-\theta_M)}{H_k\sin^2(\theta_n-\theta_M)}.$$

The dependence of the transverse magnetic susceptibility of the film on the external magnetic field (curve *1*) obtained by numerically solving Eq. (6) is presented in Fig. 4 for the case $\theta_H = \pi/2$ and $\theta_n = 0$. The following parameters of the film area, the experimental results for which are presented in Figs. 1–3, were used in the calculations: saturation magnetization M_s = 1100 G, anisotropy field H_k = 28 Oe, test field h = 0.1 Oe. It is evident that the calculated curves, as well as the experimental data, exhibit a pronounced sharp peak of susceptibility at a magnetic field equal to the anisotropy field. Moreover, as well as in the experimental results, the calculation indicates that the peak of susceptibility almost disappears if the easy axis deviates by only one degree ($\theta_n = \pm 1°$) from the initial direction ($\theta_n = 0$) (see the dotted line in Fig. 4.) Our investigations also showed that the susceptibility monotonically grows as the anisotropy field decreases. It follows from these facts that both the angular and amplitude dispersions of uniaxial magnetic anisotropy must affect the susceptibility peak [6]. These dispersions may be significant in real samples because of imperfections in the technology of their preparation.

In order to estimate the anisotropy dispersion effect on the peak of magnetic susceptibility, we will use a Gaussian distribution for both the anisotropy field H_k and the direction of the easy magnetization angle θ_n [7]. The dependences of the transverse magnetic susceptibility on the external magnetic field also obtained by numerical calculations are shown in Fig. 4 for the cases when only the amplitude anisotropy dispersion Δ_k = 1 Oe (curve *2*), only the angular anisotropy dispersion $\Delta_\theta = 1°$ (curve *3*), and both the angular and amplitude dispersions of the same values (dashed line) are present in the film. It is evident that, if even a small angular dispersion of the uniaxial magnetic anisotropy occurs in the sample, the susceptibility peak under study almost disappears. This proves the fact that the effect found in this work can be observed only in high-quality samples. It should also be noted that a dispersion of anisotropy shifts the film susceptibility maximum toward the region of higher fields.

Note that, under the condition that $|H - H_k| \gg h$, the terms of the second order of smallness can be neglected when Eq. (5) is solved for the case when $\theta_H = \pi/2$ and $\theta_n = 0$ in the absence of the dispersion of uniaxial magnetic anisotropy.

Finally, we obtain

$$\chi \approx \frac{M_s H}{H_k^2 - H^2}, \quad H < H_k, \tag{7}$$

$$\chi \approx \frac{M_s}{H - H_k}, \quad H > H_k. \tag{8}$$

It is seen from Eqs. (7) and (8) that the dependence $\chi(H)$ in the region of "weak" fields is stronger than the same dependence in the region of "high" fields. This explains the asymmetry of the right and left slopes observed in the field dependence of the susceptibility numerically calculated without approximations (see Fig. 4). It is interesting that the occurrence of an amplitude dispersion in the magnetic anisotropy of the film decreases the asymmetry of the slopes of the $\chi(H)$ curve.

In the case when $H = H_k$, Eq. (6), under the condition that $\theta_H = \pi/2$ and $\theta_n = 0$, takes the simple form

$$\psi^3 + \frac{h}{H_k}\psi^2 = 2\frac{h}{H_k}. \tag{9}$$

Taking into account that $\psi = m/M_s$ and $h/H_k \ll 1$, we obtain the equation for the maximal susceptibility

$$\chi_{\max} \approx M_s \sqrt[3]{\frac{2}{H_k h^2}}. \tag{10}$$

Approximate Eq. (10) indicates that the maximal magnetic susceptibility decreases as $(h)^{-2/3}$ with increasing test field, and it decreases as $(H_k)^{-1/3}$ with increasing uniaxial magnetic anisotropy field. These regularities were confirmed sufficiently well by numerical calculations carried out without approximations.

Thus, a theoretical analysis showed that the narrow susceptibility peak found in the FMR spectrum is due to a drastic increase in the static transverse magnetic susceptibility of the film at the point of the instability of the magnetic moment observed in the field $H = H_k$. In this field, a kink is observed in the magnetization curve [1], which is leveled off with increasing angular and amplitude dispersion of anisotropy. The calculation also showed that the susceptibility peak almost disappears when the angular dispersion of the anisotropy field ≥1°. Therefore, in spite of the high quality of the obtained films, the effect is revealed only in the local areas of samples where the dispersion of anisotropy is sufficiently small. A signal due to static susceptibility is also seen in Permalloy films with uniaxial magnetic anisotropy that were obtained by vacuum sputtering in a magnetic field. However, its amplitude is almost two orders of magnitude smaller than the amplitude of the uniform ferromagnetic resonance signal. This is explained by the relatively high angular dispersion of anisotropy in these films.

It is important to note that the effect of an increase in static susceptibility in the field $H = H_k$ found in this work can be observed only at relatively high frequencies in the microwave range when the resonance fields of the uniform ferromagnetic resonance peaks are sufficiently distant from H_k (see Fig. 2). As the pumping frequency decreases, the uniform ferromagnetic resonance approaches the static susceptibility peak and suppresses it.

In our opinion, the static susceptibility peak studied in this work provides an explanation for the sharp increase in amplitude of the nuclear magnetic resonance signal observed in anisotropic cobalt films [8, 9]. This effect was also observed in the field equal to the anisotropy field when a film was magnetized perpendicular to the easy magnetization axis. In this case, the signal virtually disappeared when the magnetic field deviated from the orthogonal direction by only 1°.

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