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SURFACE MODES IN THIN FILMS OF PERMALLOY (NiFe)

Surface modes in spin wave resonance in as prepared thin films of $Ni_{80}Fe_{20}$ were studied. From 4 samples with 25, 50 75 and 100 nm of thickness only two (50 and 75 nm) have one surface mode. Using the surface inhomogeneity (SI) model with antisymmetric boundary conditions, the surface anisotropy constant K_s and variation of magnetization near the surface on the film $\partial_n M_s$ were determined. Also the critical angles θ_H^{cr} between the external magnetic field and the normal to the film's surface were defined. At this critical angle the surface mode coincide with the mode of uniform precession.

Key words: spin-wave resonance, Permalloy, thin film, surface mode, surface anisotropy

Introduction. Improving the technology of thin magnetic films allows their use in spintronic devices and microwave technology. Therefore there is an interest in their studies. As a powerful technique, the low energy excitations of spin waves and ferromagnetic resonance (FMR) play an important role in the study of thin films. Microwave technique can be used to investigate magnetic anisotropy, interlayer coupling, magnetic relaxation, film quality, and so on [3]. The spin wave resonance technique is the only way to study the surface modes. This sort of excitation is due to the surface anisotropy energy being different from the bulk value. The contribution of the surface energy is significant in thin films. Possibility of surface mode excitations are controlled by the state of the surface and close-to-surface inhomogeneities of the magnetization. Therefore the information about magnetic properties of the surface is available from the spin wave resonance experiment.

Experimental results and discussion. The samples were prepared by Electron Beam Evaporation (EBE) and have 75 and 50 nm of thickness. Measurements were carried out at room temperature using a Bruker E580 EPR spectrometer, with a fixed microwave frequency of 9.45 GHz. The goniometer was used to vary the angle. Samples were placed into the cylindrical mode resonator.

Figure 1 shows the sample oriented relative to some right-handed *X-Y-Z* frame such that the sample normal is parallel to the *Z* axis. External magnetic field H_{ext} and magnetization M lies in ZY plane. θ_H is the angle between H_{ext} and the sample normal Z, θ is an angle between M and Z.

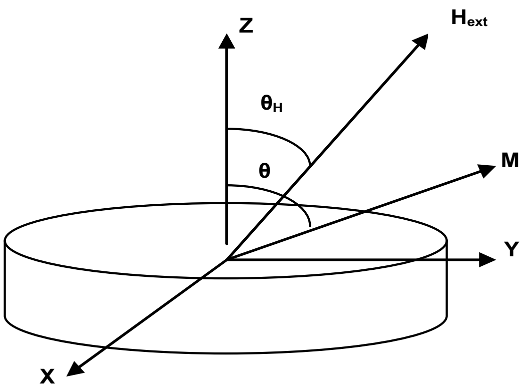

Fig. 1. Disk, field, and static magnetization geometry for the static equilibrium and FMR analysis

The spectra obtained for different angles θ_H presented in Fig. 2 and Fig. 3.

At the critical angle all modes except one vanish. We observe it as a transition of the surface mode into an uniform mode at the $\theta_H = \theta_H^{cr}$. At $\theta_H = 0^\circ$ the distance between the surface mode H_S and the uniform one H_u is maximum and with increasing of θ_H this distance decreases (Fig. 4). As we can see, H_S decreases faster than H_u.

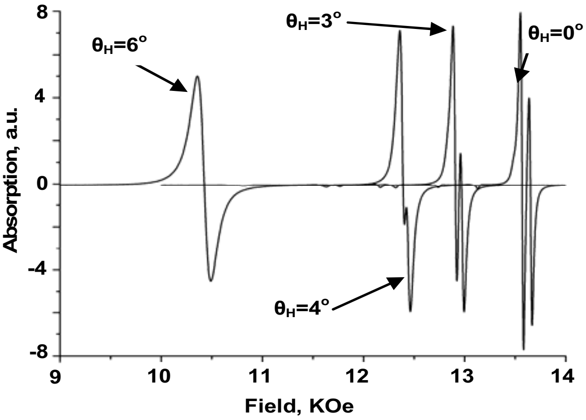

Fig. 2. Spin wave resonance spectra for different orientations of the applied magnetic field for 75 nm film

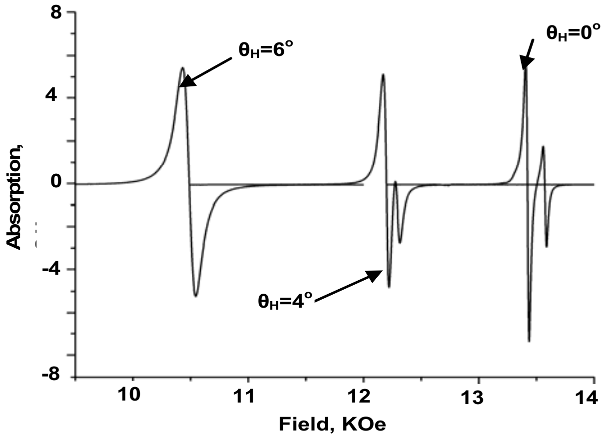

Fig. 3. Spin wave resonance spectra for different orientations of the applied magnetic field for 50 nm film

To use the SI model, we should decide which boundary conditions must be used first. This information could be extracted from perpendicular ($\theta_H = 0^o$) magnetization data. The surface mode exists in two cases [1,8]: symmetric (if anisotropy is easy-plane, $K_S < 0$) and anti-symmetric boundary conditions. For symmetric boundary conditions the spin pinning parameter is the same at each film's surface ($\xi_1 = \xi_2 < 0$). For the case $\xi_1 = -\xi_2$, one surface has easy axis anisotropy, and the second one – easy-plane.

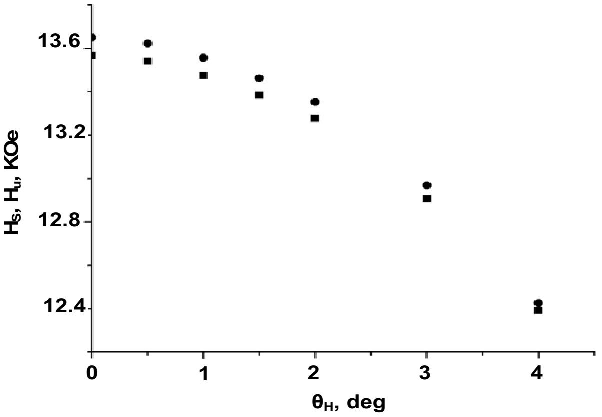

Fig. 4. Angular dependence of resonances fields H_S and H_u for 75 nm film. H_u are circles and H_S – squares

The resonance condition for normal magnetization is given by [1]:

$$H = \frac{\omega}{\gamma} + 4\pi M_S - {}^{2A}\!/\!_{M_S}\, k_z^2 \qquad (1)$$

$$ctgk_z d = \frac{k_z^2 - \xi_1\xi_2}{k_z(\xi_1 + \xi_2)} \qquad (2)$$

1. $\xi_1 = \xi_2 < 0$. Solving numerical the equation (2) we can get $k_n = {}^{\pi n}\!/\!_L$, L - the film's thickness and $k = ik_s$. Real wave number give ordinary standing volume spin waves, and imaginary k – surface mode. From experimental data of surface mode's position H_S and Eq. (1) we can calculate k_s, using (2) – spin pinning parameter ξ and then the position of the next resonance line H_U. For the 75 nm film we get $k_s \approx 2.3\times10^5\text{cm}^{-1}$, $|\xi| \approx 2.9\times10^5\text{cm}^{-1}$, $H_U = 12{,}7$ KOe.

2. $\xi_1 = -\xi_2$. There are also real $k_n = {}^{\pi n}\!/\!_L$ and imaginary $k = i\xi$. Similarly we get $k = |\xi| \approx 2.3\times10^5\text{cm}^{-1}$ and $H_U = 13.5$ KOe.

Fig. 5 represents the comparison of calculated H_U with experiment for 75 nm film. Namely, for anti-symmetric conditions calculated value of H_U agrees well with the experiment, while for symmetric conditions this value is less on 500 Oe. The same procedure was applied to 50 nm film and similar results were obtained. Now it's clear that both samples have anti-symmetric boundary conditions.

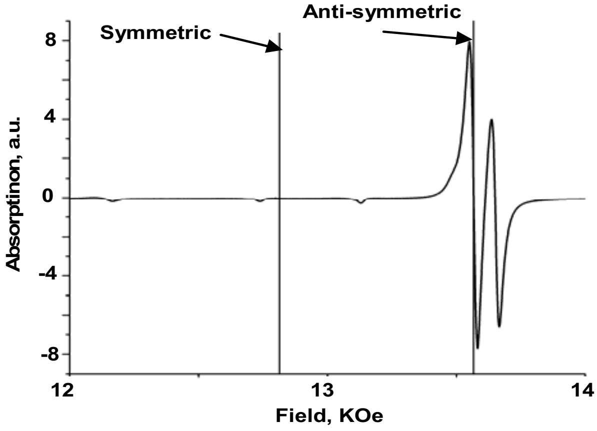

Fig. 5. Comparison of calculated H_u with experiment for 75 nm film

The SI model [4] was used to fit the experimental data. In this model boundary conditions include surface anisotropy energy and magnetization inhomogeneities close to the surface [7]. A simple form of the surface anisotropy $E_S \approx -K_S\cos^2(\theta)$ is taken, where K_S is the surface anisotropy constant. Using the equation of motion of magnetization the dispersion relation is written follow [5]:

$$\left(\frac{\omega}{\gamma}\right)^2 = \left[H\cos(\theta-\theta_H) + 4\pi M_{eff}\cos(2\theta) + \frac{2A}{M_S}k^2\right]\times$$
$$\times\left[H\cos(\theta-\theta_H) + 4\pi M_{eff}\cos^2(\theta) + \frac{2A}{M_S}k^2\right] \qquad (3)$$

$4\pi M_{eff} = 4\pi M_S - \frac{2K}{M_S}$. And the equilibrium condition is

$$2H_{res}\sin(\theta-\theta_H) = 4\pi M_S\sin(2\theta) \qquad (4)$$

The case $k^2 < 0$ provides purely imaginary $k = ik_s$, which describes damping of the microwave component of ***M*** with decreasing distance from the surface, so this case corresponds to the surface modes. The resonance field H_S for the surface mode is larger than field H_u for an uniform. Since the shift $H_S - H_U$ is small, we can get from (3) in the first approximation [2]:

$$H_S = H_U + \frac{2A}{M_S}\frac{k_s^2}{\cos(\theta-\theta_H)} \qquad (5)$$

According to [6, 7] the boundary conditions lead to the equation for the allowed wave vectors k_s:

$$\tanh(k_s L) = \frac{(p_1+p_2)k_s}{k_s^2 + p_1p_2} \qquad (6)$$

$$p = -(K_S/A)\cos(2\theta) + (\partial_n M_S)/M_S \qquad (7)$$

where p_1 and p_2 are values of p at the two surfaces of a film. As we already discussed our samples have anti-symmetric pinning parameters, $p_1 = -p_2$. ∂_n denotes the directional derivative along normal to the surface, so the term $(\partial_n M_S)/M_S$ accounts for possible variation of the magnetization close to the surface.

Equation (6) for allowed wave numbers is to be solved numerically. However, for typical parameters one can evaluate that $k_s L \gg 1$ unless we are very close to the critical angle and two approximate solutions are:

$$k_1 = p_1, k_2 = p_2. \qquad (8)$$

Therefore we expect two surface modes if $|p_1| \neq |p_2|$. For anti-symmetric boundary conditions $p_1 = -p_2$ only one surface mode is seen.

With the approximate solution (8) we can rewrite (5) in the form:

$$\sqrt{(H_s - H_u)\cos(\theta-\theta_H)} = \left(\frac{2}{AM_S}\right)^{1/2}|K_S|\times$$
$$\times\left[\cos 2\theta - \frac{A}{K_S}\frac{\partial_n M_S}{M_S}\right] \qquad (9)$$

where the exchange constant $A = 10^{-6}\,\text{erg / cm}$.

Table 1

Summary information

L, nm	θ_H^{cr} **SI model**	θ_H^{cr} **experiment**	**K_S, erg/cm^2**	**K_S, erg/cm^2 SI model**	$\partial_n M_S$ **Oe/nm**
75	6°	5°	0,18	0,32	15
50	6,7°	5°	0,19	0,31	10

Now we can plot the left hand side of equation (9) (defined as X) against $\cos(2\theta)$. If model is correct we expect a straight line, with deviations perhaps in the very vicinity of the critical angle. We can get the surface anisotropy $|K_S|$ from the slope of this line and the interception with the x-axis gives the magnetization variation $(\partial_n M_S)/M_S$.

Fig. 6 represents the comparison of the SI model with experimental data. It is seen that we have straight line within the experimental error which confirms the proposed model. The fitted values of surface anisotropy constant K_S are reasonable, and are collected in Table 1. We want to mention that the critical angles determined from the extrapolation of the straight lines agree well with the same angles observed directly in the experiment.

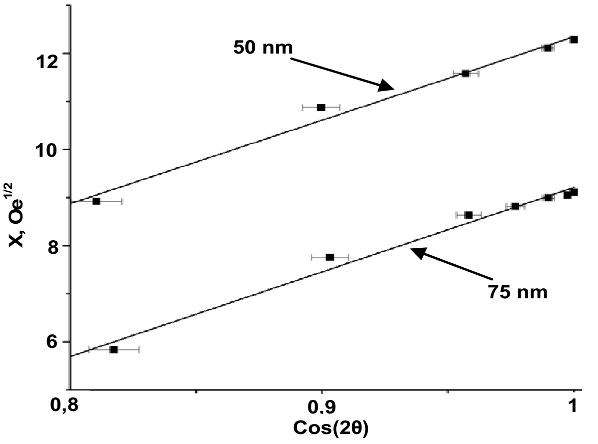

Fig. 6. Dependence of X against cos (2θ)

Conclusions. Angular dependence of surface modes in Permalloy thin films was studied. The surface anisotropy constant K_S and magnetization variation $(\partial_n M_S)/M_S$ were determined using the SI model. The values of K_S are in a good agreement with ones from the standing spin wave resonance experiments. Also this model provides the information about critical angles of surface modes' existence, which are in the agreement with experimental results. The SI model works well unless we are very close to the critical angle. So, the difference between fitted and experimental θ_H^{cr} may be caused by limitations of the surface inhomogeneities model.

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ПОВЕРХНЕВІ МОДИ В ТОНКИХ ПЛІВКАХ ПЕРМАЛОЮ (NiFe)

Досліджено поверхневі моди в тонких плівках $Ni_{80}Fe_{20}$ методом спін-хвильового резонансу. Із 4 зразків товщиною 25, 50, 75 та 100 нм лише два (50 та 75 нм) мають по одній поверхневій моді. Використовуючи модель неоднорідності поверхні з антисиметричними граничними умовами, було визначено константу поверхневої анізотропії K_s і варіацію намагніченності $\partial_n M_s$ поблизу поверхні плівки. Також були визначені критичні кути θ_H^{cr} між зовнішнім магнітним полем та нормаллю до поверхні плівки. При досягнені критичного кута поверхнева мода зливається із модою однорідної прецесії.

Ключові слова: спін-хвильовий резонанс, пермалой, тонкі плівки, поверхнева мода, поверхнева анізотропія

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ПОВЕРХНОСТНЫЕ МОДЫ В ТОНКИХ ПЛЕНКАХ ПЕРМАЛЛОЯ (NiFe)

Исследованы поверхностные моды в тонких пленках пермаллоя $Ni_{80}Fe_{20}$ методом спин-волнового резонанса. Из четырех образцов толщиной 25, 50, 75 и 100 нм два (50нм и 75 нм) имеют по одной поверхностной моде. Используя модель неоднородности поверхности с антисимметричными граничными условиями, определили постоянную поверхностной анизотропии K_s и вариацию намагниченности $\partial_n M_s$ вблизи поверхности пленки. Также были определены критические углы θ_H^{cr} между между внешним магнитным полем и нормалью к поверхности пленки. При достижении критического угла поверхностная мода сливается с модой однородной прецессии.

Ключевые слова: спин-волновой резонанс, пермаллой, тонкие пленки, поверхностная мода, поверхностная анизотропия.