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PRECISE DETERMINATION OF THE FERROMAGNETIC RESONANCE POINT IN THIN FILMS*

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The resonance formula for the determination of the ferromagnetic resonance point in thin isotropic films are evaluated for the case of the Bloch-Bloembergen and the Landau–Lifshitz damping in the parallel and perpendicular configuration. It is shown that the resonance point determination depends on the method of measurements and that in the accurate evaluation of FMR experiments the influence of the magnetization motion damping cannot be neglected.

ТОЧНО ОПРЕДЕЛЕНИЕ ТОЧКИ ФЕРРОМАГНИТНОГО РЕЗОНАНЦА В ТОНКИХ ПЛЕНКАХ

В работе приведены резонансные формулы для определения точки ферромагнитного резонанса в тонких изотропных пленках для случая затухания Блоха–Бломбергена и Ландау–Лифшица при параллельной и перпендикулярной конфигурациях. Показано, что определение резонансной точки зависит от метода измерения и что при точных вычислениях результатов ФМР-экспериментов нельзя пренебречь влиянием, затухания, вызванного намагничиванием.

I. INTRODUCTION

The magnetic behaviour of a ferromagnetic thin film sample is characterized by means of several parameters, as e.g. by the static magnetization, the spectroscopic splitting ratio, the effective fields of various anisotropy mechanisms, the magnetization motion damping constant, etc. [1]. Some of these parameters can be measured by means of static methods (e.g. the saturation magnetization, the induced anisotropy constants), however, the ferromagnetic resonance experimental method (FMR) is a very useful tool for the determination of several important quantities as the effective magnetization M_0 (by means of which the influence of internal stresses can be described [2]), the spectroscopic splitting ratio γ (which can be otherwise

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measured only indirectly by the gyromagnetic measurements [3]), the damping parameters α or T and others (various effective fields caused by anisotropy [4]). These quantities can be evaluated from the measurements of the resonance absorption as dependent on the ratio or microwave frequency, on the external static magnetic field intensity and on the sample orientation towards the external field direction. The main task of the experimental procedure is first to determine the resonance point (the values of the static field intensity and the frequency at which the absorption is maximum). The main quantities describing the ferromagnetic sample are evaluated by comparing the experimental resonance point values with quantities obtained from the theoretical formulas [1].

We have shown in paper [5] that for the case of the magnetic resonance in a weakly interacting paramagnetic system (of electrons of nuclei) the exact experimental determination of the resonance point depends on the method of measurements, i.e. if the resonance point is approached either by the change of the external static magnetic field intensity (at a constant radio or microwave frequency) or by the change of the frequency (at a constant field intensity). This dependence has its origin in the damping of the magnetization vector motion in a real magnetic system. In the present paper we shall treat a similar situation for the case of a ferromagnetic material, i.e. we shall study the influence of the experimental method on the precise determination of the resonance point in thin film samples. We shall evaluate the expressions for the resonance point (so called resonance conditions) in a more exact form than it is usually presented and we shall discuss briefly their applications.

We shal assume that the thin film plane is oriented either parallel or perpendicular to the static magnetization vector (the so-called parallel or perpendicular orientation). The case of a magnetically saturated isotropic film with no surface magnetization pinning is considered (only the homogeneous FMR mode is excited), the thickness of the film is much smaller than the skin-depth value, therefore the exchange -conductivity effects [6] need not to be considered even for the case of metallic films [7]. The linear FMR is assumed (the radio or microwave magnetic field intensity is much smaller than the static field value) and the SI system of units is used. The magnetization motion damping mechanism, described by the term $\boldsymbol{R}$ in the equation of motion

$$\frac{\mathrm{d}\boldsymbol{M}}{\mathrm{d}t}=\gamma[\boldsymbol{M}\times\boldsymbol{H}]+\boldsymbol{R} \tag{1}$$

will be used either in the Bloch-Bloembergen (BB) form [8]:

$$R_{xy}=-\frac{M_{xy}}{T},$$

or in the Landau–Lifshitz (LL) form [9]:

$$\boldsymbol{R}=\frac{\alpha\gamma}{M}[\boldsymbol{M}\times[\boldsymbol{M}\times\boldsymbol{H}]].$$

In principle both of these or a similar term should be included in the equation of motion [10], for simplicity we shall assume that for a certain material only one of the damping mechanisms is dominant. In the formulas $\boldsymbol{M}$ represents the total magnetization vector measured in the relative magnetization units in teslas, $M=\mu_0 M'$, μ_0 ... the permeability of vacuum, M' the magnetization in Am^{-1} units, γ ... the spectroscopic splitting ratio in HzT^{-1} units, $\boldsymbol{H}$ ... the total magnetic field inside the sample (including various effective fields representing the influence of demagnetization, anisotropy, etc. [4]) measured in the relative field units in teslas, $H=\mu_0 H'$, H' ... the field intensity in Am^{-1} units, T ... the BB relaxation time, α ... the LL damping constant. The microwave or radiofrequency absorption for the most common case of the linearly polarized high frequency fields (if we use the nondegenerate cavities or wave guides [11]) is proportional to the imaginary part of the complex high frequency permeability $\mu=\mu_1-j\mu_2=\mu(m_{hf},\ h_{hf})$ [9], where $m_{hf}(h_{hf})$ are the amplitudes of the high frequency components of the magnetization vector (magnetic field intensity), respectively. In order to obtain the explicit theoretical expressions for μ_2 (which are compared with the data measured in the FMR experiment) the equation of motion (1) must be solved analytically.

II. RESONANCE CONDITIONS

The computations of μ_2 were performed by several authors (e.g. [8], [9], [12]); their results adjusted for the case of the isotropic thin film statistically magnetized in the film plane (the parallel configuration of the experiment) may be written in the form

$$\mu_2=\frac{\gamma^2 M_0(H+M_0)}{(\omega_0^2-\omega^2)^2+4\omega^2/T^2}\frac{2\omega}{T}, \tag{2a}$$

where

$$\omega_0^2=\gamma^2 H(H+M_0)+\frac{1}{T^2} \tag{2b}$$

and

$$\mu_2=\frac{\gamma M_0\alpha\omega[\gamma^2(H+M_0)^2(1+\alpha^2)+\omega^2]}{(\omega_0^2-\omega^2)^2+\omega^2\alpha^2\gamma^2(2H+M_0)^2}, \tag{3a}$$

where

$$\omega_0^2=\gamma^2 H(H+M_0)(1+\alpha^2) \tag{3b}$$

for the case of BB and LL damping, respectively.

For the perpendicular orientation (i.e the film is statically magnetized along the film normal) we get the following expressions:

$$\mu_2 = \frac{\gamma^2 M_0 (H - M_0)}{(\omega_0^2 - \omega^2)^2 + 4\omega^2/T^2} \frac{2\omega}{T}, \tag{4a}$$

where

$$\omega_0^2 = \gamma^2 (H - M_0)^2 + 1/T^2. \tag{4b}$$

(the BB case), and

$$\mu_2 = \frac{\gamma M_0 \alpha \omega (\omega_0^2 + \omega^2)}{(\omega_0^2 - \omega^2)^2 + 4\omega^2 \alpha^2 \gamma^2 (H - M_0)^2}, \tag{5a}$$

where

$$\omega_0^2 = \gamma^2 (H - M_0)^2 (1 + \alpha^2) \tag{5b}$$

(the LL case). In these formulas ω denotes the radio or microwave frequency value, M_0 the static magnetization (which may in some cases include also the effects of stresses or magnetic anisotropies, then M_0 is called „the effective magnetization" [2], [4], measured again in relative units, H is the external static magnetic field intensity in relative units.

The formulas for the resonance frequency ω_r and for the resonance field intensity H_r shall be obtained by solving the expressions for $d\mu_2/d\omega = 0$ and $d\mu_2/dH = 0$. In this process the terms including the damping parameters α and T in a cubic or higher power are omitted. For the case of approaching the resonance point by changing the frequency ω (the external static field H is kept constant) we obtain at the parallel cinfiguration the formulas

$$\omega_r^2 = \gamma^2 H (H + M_0) \tag{6}$$

and

$$\omega_r^2 = \gamma^2 H (H + M_0)(1 + \alpha^2) + \alpha^2 \gamma^2 H^2 \tag{7}$$

for the BB (the LL) type of damping, respectively (these cases were discussed by us already in [13]). For the same case we have at the perpandicular orientation

$$\omega_r = \gamma (H - M_0) \tag{8}$$

and

$$\omega_r = \gamma (H - M_0)(1 + \alpha^2)^{1/2} \tag{9}$$

for the BB (the LL) type of damping, respectively.

The expressions for the resonance field values (the resonance point is approached by changing the external static magnetic field intensity, the radio or the microwave frequency is kept constant) are:

$$H_r = -M_0/2 + \left[(M_0/2)^2 + \left(\frac{\omega}{\gamma}\right)^2 - \left(\frac{1}{\gamma T}\right)^2 \frac{M_0/2}{H + M_0/2}\right]^{1/2}, \tag{10}$$

$$H_r = -M_0/2 + \left[(M_0/2)^2 + \left(\frac{\omega}{\gamma}\right)^2 \left(\frac{1 - \alpha^2}{1 + \alpha^2}\right)\right]^{1/2} \tag{11}$$

for the BB (the LL) damping, respectively, and at the parallel configuration;

$$H_r = \frac{\omega}{\gamma} + M_0, \tag{12}$$

$$H_r = \frac{\omega}{\gamma}(1 - \alpha^2) + M_0 \tag{13}$$

for the BB (the LL) damping, respectively, and at the perpendicular orientation.

III. DISCUSSION

From the expressions (6—13) we may first observe that the resonance points (i.e. the pairs of quantities ω_r, H or ω, H_r) are generally different, depending on the method applied in the experiment, even for the same type of the damping description and for the same configuration, except in the case of the BB damping in the perpendicular configuration (see equations (8) and (12)). In the practice of FMR measurements, in some cases one of the quantities ω of H is being changed periodically with a small amplitude (the so-called frequency or field modulation) in order to increase the sensitivity of the apparatus by using the lock-in technique [14]. Then the resonance point, which is again approached either by a slow field or frequency change, is detected by observing the zero value of the derivative of the radio or microwave absorption. In this case the appropriate resonance formula must be chosen according to that quantity the chaange of which is faster (i.e. in most cases the modulated quantity).

In some FMR measurements both parameters ω and H are changed simultaneously, e.g. in the direct measurements of the microwave permeability by the cavity perturbation method [15], where the frequency ω of the microwave generator must be adjusted (manually or automatically) exactly to the resonance frequency of the microwave resonator. Here the microwave absorption is observed as dependent on the external static field intensity, however, the frequency ω also to be changed during this process, as the resonant frequency of the microwave cavity is detuned by the simultaneous change of the real part of the complex microwave permeability [11], [15]. In these cases a more detailed analysis of the experimental conditions (e.g. the quality and the filling factor of the cavity) is needed before we can make the final statements about the exact resonance point values.

We shall now compare the expressions (6—13) with the resonance formulas, which are commonly used for the evaluation of the FMR experiment in thin films. In most cases (see e.g. [16]—[25]) the measurements are performed at a constant frequency and are evaluated by simple Kittel's formulas (no damping effects considered, [26[) in the form

$$H_r = -M_0/2 + [(M_0/2)^2 + (\omega/\gamma)^2]^{1/2} \qquad (14)$$

and

$$H_r = M_0 + \omega/\gamma \qquad (15)$$

for the parallel and the perpendicular case, respectively. These formulas agree with the more precise expressions derived in Chapter II only for the perpendicular case with the BB damping, eq. (12). In many cases (e.g. [16—19] the quantities $(\omega T)^{-1}$ and α are small compared with unity and the use of the formulas (14) and (15) is substantiated. However, if the damping is large (e.g. at low frequencies [20—25]) and/or if a great accuracy is required, the excat formulas must be applied. We shall illustrate this statement with two examples.

1. Low frequency FMR measurements (around 1 GHz) in thin permalloy films (80 % Ni – 20 % Fe, $M_0 \doteq 1$ T) 500 nm thick were performed in the parallel configuration by Kingston and Tannenwald [22]. Besides the values for the induced anisotropy field (0.6 mT) and the relaxation time (5×10^{-10} s, obtained from the measured linewidths values) they evaluated by means of formula (14) the g-factor for these films ($g = \gamma \hbar \mu_B^{-1}$, $\hbar$ ... the Planck constant divided by 2π, μ_B ... the Bohr magneton) as $g = 2.2$. This is a too high value (5 %) compared with the real veluge $g = 2.1$ (e.g. [27], [28]). However, if we evaluate these measurements with the more accurate formula (10) (the use of the BB damping is substantiated by the fact that the measured linewidths are almost frequency independent), the right value for g is easily obtained (at the frequency 1200 MHz).

2. Amorphous GdAl thin films were studied by Jamet and Malozemoff [19] by means of FMR at 9 GHz in the parallel and perpendicular configurations in the temperature interval 4—300 K. In these measurements mainly the values for the field dependent magnetization and for the g-factor were evaluated by means of the formulas (14) and (15). At higher temperatures (200—300 K) the evaluated g values $g = 2.003$ are close to the free-ion value of Gd $g = 1.992$, however, as the authors point out, on the average there exists a small shift to higher g values, $\Delta g = 0.006 \pm 0.004$. In the following let us point out that by a proper introduction of the damping term into the resonance equations this g-factor shift may disappear.

By a more detailed observation of the pair of equations (11) and (13) we see that they can be rewritten into the form (14) and (15) if in (11) and (13) the substitution $\gamma_{ef}^{-1} = \gamma^{-1}(1-\alpha^2)$ is introduced. Therefore, the effective value g_{ef}, evaluated by menas of (14) and (15) is related to the real g value by the relation $g = g_{ef}(1-\alpha^2)$. By assuming $\alpha = 0.074$ we obtain from $g_{ef} = 2.003$ the correct value $g = 1.992$ in agreement with the free-ion value. This value of α agrees with the linewidth measurements of the sample in [19], which yield approx. 0.1 T. The LL damping mechanism with $\alpha = 0.074$ causes about one half of the observed value of linewidth, the rest of the line broadening is most probably due to the inhomogeneities in the sputtered thin film samples. The apparent increase of the g-factor can also be explained by using the equations (10) and (12) and a suitable T value (then we get a more complicated relation between g and g_{ef}).

IV CONCLUSION

We have evaluated the resonance formulas for the FMR of magnetic thin films for the case of the magnetization motion damping described by the Bloch-Bloembergen or the Landau–Lifshitz term; the isotropic film is statically magnetized either parallel or perpenducular to the film plane. It is shown that in general different formulas must be used depending on the method of the experiments, e.g. on the kind of approach of the resonance point (maximum of the radiofrequency or microwave absorption) either by changing the static magnetic field intensity (at a constant frequency) or the frequency (at a constant field intensity value). Finally, it is emphasized and shown on examples that in the process of precise evaluation of the FMR parameters the influence of the magnetization motion damping must be taken into account.

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REFERENCES

[1] Soohoo, R. F.: *Magnetic Thin Films*, Harper and Row, New York 1965.
[2] Frait, Z.: Phys. Stat. Sol. *2* (1962), 1417.
[3] Scott, G. G., Sturner, H. W.: Phys. Rew. *184* (1969), 490.
[4] Macdonald, J. R.: Proc. Phys. Soc. *64* (1951), 968.
[5] Frait, Z.: Fraitová, D.: Czech. J. Phys. B *27* (1977), 1292.
[2] Bhagat, S. M.: *in Technique of Metals Research* VI, 2, Edited by E. Passaglia. J. Willey, New York 1973.
[7] Wilts, C. H., Ramer, O. G.: J. appl. Phys. *47* (1976), 1151.
[8] Bloembergen, N.: Phys. Rev. *78* (1950), 572.
[9] Yager, W. A.: Galt, J. K., Merritt, F. R., Wood, E. A.: Phys. Rev. *80* (1950), 744.
[10] Jakovlev, Yu. M.: Fiz. Met. Metalov. *23* (1967), 420.
[11] Artman, J. O., Tannenwald, P. E.: J. appl. Phys. *26* (1955), 1124.
[12] Frait, Z.: *Ph. D. Thesis*, Prague 1957.
[13] Frait, Z., Fraitová, D.: *Proc. I. Natl. Conf. on Radiospectr.*, Košice 1969.
[14] Poole, C. P. Jr.: *Electron Spin Resonance*. Interscience Publ., New York 1967.
[15] von Aolock, W., Rowen, J. H.: Bell System Tech. J. *36* (1957), 427.
[16] Frait, Z., Nagy, I., Tarnoczi, T.: Phys. Letts. A *55* (1976), 429.
[17] Soohoo, R. F.: in *Amorphous Magnetism* II. Ed. by Levy R. A. and Hasegawa R. Plenum Press, New York 1978.

[18] Cronemeyer, D. C.: AIP Conf. Proc. *10* (1973), 85.
[19] Jamet, J. P., Malozemoff, A. P.: Phys. Rev. B *18* (1978), 75.
[20] Hasty, T. E.: J. appl. Phys. *34* (1963), 1079.
[21] Hasty, T. E.: J. appl. Phys. *35* (1964), 1486.
[22] Kingston, R. H., Tannenwald, P. E.: J. Appl. Phys. *29* (1959), 232.
[23] Ngo, T. D.: J. appl. Phys. *34* (1963), 3626.
[24] Hoper, J. H.: IEEE Trans. Mag. *MAG-5* (1969), 484.
[25] Kornyev, Yu. V.: Fiz. Met. Metalov. *36* (1973), 698.
[26] Kittel, C.: Phys. Rev. *73* (1948), 155.
[27] Wilts, C. H., Lai, S. K. C.: IEEE Trans. Mag. *MAG-8* (1972), 280.
[28] Frait, Z.: Phys. *86—88 B* (1977), 1241.

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