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Simulation of the FMR Line Shape

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Abstract

This paper proposes a method for determining the linewidth of Lorentz type for the case when the absorption line shape is described by the Lorentz-Gaussian function. As a result of the comparison between theory and experiment for the samples in series of Fe/Fe_3O_4 values of the line width of Lorentz type ΔH and S_H were extracted, that allowed to determine the damping parameter. Knowledge of this parameter is very important for diagnosis of the functional properties of thin films.

Keywords: FMR, damping constant, linewidth, homogeneous/ inhomogeneous broadening

1. Introduction

The ferromagnetic resonance (FMR) method is widely used to determine the magnetic anisotropy, the magnetic damping constant (Gilbert constant), to diagnose the thin-layer structures quality (W. Platow et al., 1998), because the spectral parameters such as the value of resonance fields, g-factor, the line width are sensitive to internal magnetic fields, anisotropy field and depend on the electronic structure of matter and the presence of local defects. The FMR data can be used to obtain important parameters to characterize the physical and functional properties of multilayer structures. It was shown that the line width depends on the details of the sample preparation, temperature, and a film thickness. The critical value of current for the magnetization reversal in magnetic multilayer structures designed for magnetic memory elements is proportional to the Gilbert damping constant associated with the width of the FMR line (J. Z. Sun, 2000, J. Grollier et al., 2003). Fast switching of the magnetization is achieved at the high Gilbert damping constant (R. H. Koch et al., 2004).

The phenomenological approach based on the Landau-Lifshitz-Gilbert equation is used to analyze the FMR data and to extract the Gilbert damping constant (L.D. Landau, E. M. Lifshitz, 1935).

$$\frac{d}{dt}\vec{M} = -\gamma\left[\vec{M}\times\vec{H}_{eff}\right] + \frac{G}{\gamma M^2}\left[\vec{M}\times\frac{\partial\vec{M}}{\partial t}\right] \qquad (1)$$

Here G is the Gilbert damping constant, γ is the gyromagnetic ratio, M is the saturation magnetization (H. Suhl, 1955):

$$\Delta H^{\mathrm{Gilb}} = \frac{dH}{d\omega}\Gamma \qquad (2)$$

Here Γ is the frequency linewidth, which defined as

$$\Gamma = \frac{\alpha\gamma}{\sqrt{3}M}\left(F_{\theta\theta} + \frac{F_{\phi\phi}}{\sin^2\theta}\right) \qquad (3)$$

for the case when attenuation of the magnetization precession is not too strong.

$F_{\theta\theta}$, $F_{\phi\phi}$ are the second partial derivatives of the free energy density on the angles (φ,θ) which define the direction of the magnetization **M** .

The analysis shows that, in accordance with the LLG equation, the resonance dependence has a Lorentzian shape, and in the special case when the equilibrium magnetization direction coincides with the direction of the constant magnetic field, the peak –to-peak linewidth due to the intrinsic damping is directly proportional the damping constant .

$$\Delta H^{\mathrm{Gilb}} = \frac{2\omega}{\sqrt{3}\gamma}\alpha \qquad (4)$$

Here $\alpha = G/\gamma M$ *is the* damping constant.

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However the line width of the thin-film structures depends not only on the internal processes of decay, but also on a number of external factors caused by magnetic inhomogeneities, surface roughness and defects in the thin films (S. Misukami et al., 2001, M.Oogane et al., 2007).

In recent years, polycrystalline structures on silicon substrates have excited a growing interest due to their prospects of implementation in production. Several studies demonstrate that the FMR line width depends on the method of a sample preparation. In particular, the issue of the influence of the annealing process to the line width of the FMR and Gilbert constant is discussed (D. Watanabe et al., 2009). In polycrystalline structures some additional factors appear which can lead to inhomogeneous broadening of the lines associated with the distribution of the directions of the individual magnetic moments of crystallites in a polycrystalline structure. The study of annealing polycrystalline structures by FMR shows that the shape of the resonance dependence cannot be described by the Lorentz function or the Gaussian function.

There are two main experimental approaches to separate homogeneous (induced by so-called "intrinsic" mechanism) and inhomogeneous (induced by so-called "extrinsic" mechanism) contributions. In the first approach, the determination of the different contributions caused by internal damping and obtaining the exact value of the Gilbert constant can be done on the basis of the frequency dependence of FMR linewidth (B.Heinrich et al. 1994), related to the presence of extrinsic mechanisms of the line broadening. The second approach is based on the study of angular dependencies of the field-swept linewidth at the constant microwave frequency.

In the majority of papers devoted to the definition of the Gilbert constant for the calculation of the resulting linewidth, which has homogeneous and inhomogeneous broadening, the total linewidth is calculated as the sum of the homogeneous and inhomogeneous contributions (T. Jundvirth et al., 2006).

However if the homogeneous and inhomogeneous mechanisms contribute to the line broadening, the resulting line shape is determined by the combination of these processes. The line shape is described by the mixing contour. In this case, the extraction of the homogeneous contribution becomes problematic.

The main aim of our work is to simulate the FMR line shape in the presence of homogeneous and inhomogeneous broadening line to extract Lorentz contribution. The statistical method is used for the description of the line shape. Our approach is used to study the shape of the FMR line of the polycrystalline structures with Fe/Fe_3O_4, exposed to the annealing process, and to determine a homogeneous contribution and the Gilbert constant.

2. The mathematical model of the line shape

In common case the various relaxation mechanisms that contribute to the linewidth, both internal and external, can be set using functions

$$\mathrm{F}(\lambda_j) = \exp(-\lambda_j^{k_j} t^{k_j}) \quad (5)$$

The line shape function can be found with the use of the Fourier transform:

$$f(h) = \frac{1}{2\pi}\int_{-\infty}^{\infty} \prod_j \exp(iht)\exp(-\lambda_j^{k_j} t^{k_j})\mathrm{d}t \quad (6)$$

There h is the varying parameter or frequency ω, or the magnetic field strength H.

If the relaxation mechanism refers to a uniform mechanism with $k_j = 1$, then the line shape is described by the Lorentz function and λ_j characterizes the line half-width at half maximum of the resonance line $\lambda_j = \Delta h_{1/2}$. According to the properties of the Fourier transformation the convolution of two Lorentz contour with a line width equal Δh_1 and Δh_2 gives again the Lorentz line with the width equal $\Delta h = \Delta h_1 + \Delta h_2$. If the relaxation mechanism refers to the non-uniform mechanism the line shape is described by the Gaussian function with $k_j=2$ and $\lambda = \Delta h_{1/2}/\sqrt{ln2}$ or by the Holzmark function with $k_j=3/2$ and $\lambda = 1.44 \cdot \Delta h_{1/2}$. The magnetic inhomogeneity may lead to the Gaussian function but the point defects may lead to the Holzmark function. In the common case in the presence of "internal" and "extrinsic" mechanisms the FMR line shape may be describe by the convolution of the Lorentzian, Gaussian and Holzmark functions with k=1, k=2 and k=3/2 correspondingly.

There are some methods, which allow us to analyze the line shape. Van Vleck proposed the method of moments. The moment of the n - order line is determined by the following formula:

$$M_n = \int_0^{\infty}(h-h_0)^n f(h)dh = 1 \quad (7)$$

Odd moments equal to zero because of the symmetry of the Lorentz and Gauss functions. The identification of the lines can be made based on the calculations of the second and fourth moments. For example, for the Gaussian line we have the following ratio:

$$\frac{M_4}{M_2^2} = 3 \quad (8)$$

And for the Lorentzian line $h >> h_0$:

$$\frac{M_4}{M_2^2} = \frac{x\pi}{3\Delta} \gg 1 \quad (9)$$

However, the exact identification of the line shape is problematic, since if $n >> 1$, the integrals of moments from the Lorentzian function diverge. Therefore, small changes in the form of lines caused by the inhomogeneous distribution of the parameter x, cannot be identified by this method. Several authors have studied the form of a mixed contour (integral Voigt)) depending on the ratio of the Gaussian and Lorentzian contributions $\frac{\Delta_G}{\Delta_L} = \eta$ (Charles P. Pole, 1996). Some works are devoted to the research of the Voigt integral and numerical methods of its calculation (S. R. Drayson, 1976, Joseph H., 1977, Alan H.