Journal of Magnetism and Magnetic Materials 345 (2013) 36–40

Contents lists available at SciVerse ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

# Ferromagnetic resonance frequency increase and resonance line broadening of a ferromagnetic Fe–Co–Hf–N film with in-plane uniaxial anisotropy by high-frequency field perturbation

K. Seemann *, H. Leiste, K. Krüger

*Karlsruhe Institute of Technology KIT (Campus North), Institute for Applied Materials, Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany*

ARTICLE INFO

*Article history:*
Received 18 March 2013
Received in revised form
28 May 2013
Available online 11 June 2013

*Keywords:*
Ferromagnetic film
Ferromagnetic resonance
Line broadening
Magnon processes

ABSTRACT

Soft ferromagnetic Fe-Co-Hf-N films, produced by reactive r.f. magnetron sputtering, are useful to study the ferromagnetic resonance (FMR) by means of frequency domain permeability measurements up to the GHz range. Films with the composition $Fe_{33}Co_{43}Hf_{10}N_{14}$ exhibit a saturation polarisation $J_s$ of around 1.35 T. They are consequently considered as being uniformly magnetised due to an in-plane uniaxial anisotropy of approximately $\mu_0 H_u \approx 4.5$ m T after annealing them, e.g., at 400 °C in a static magnetic field for 1 h. Being exposed to a high-frequency field, the precession of magnetic moments leads to a marked frequency-dependent permeability with a sharp Lorentzian shaped imaginary part at around 2.33 GHz (natural resonance peak), which is in a very good agreement with the modified Landau–Lifschitz–Gilbert (LLG) differential equation. A slightly increased FMR frequency and a clear increase in the resonance line broadening due to an increase of the exciting high-frequency power (1–25.1 mW), considered as an additional perturbation of the precessing system of magnetic moments, could be discovered. By solving the homogenous LLG differential equation with respect to the in-plane uniaxial anisotropy, it was revealed that the high-frequency field perturbation impacts the resonance peak position $f_{FMR}$ and resonance line broadening $\Delta f_{FMR}$ characterised by a completed damping parameter $\alpha = \alpha_{eff} + \Delta\alpha$. Adapted from this result, the increase in $f_{FMR}$ and decrease in lifetime of the excited level of magnetic moments associated with $\Delta f_{FMR}$, similar to a spin-½ particle in a static magnetic field, was theoretically elaborated as well as compared with experimental data.



## 1. Introduction

An ensemble of ferromagnetic transition metal atoms in a solid state whose magnetic spin moments are impelled by a magnetic high-frequency field to precess about their preferred direction generated by an external or anisotropy field, is of special interest in terms of resonance, permeability and damping behaviour. The Landau–Lifschitz–Gilbert differential equation [1] in combination to the Maxwell equation to describe eddy-currents [2], although quasi-classical in nature, perfectly describes the dynamics of these ferromagnetic moments in a wide frequency range. Dependent on the shape of the material the equation can be adapted in terms of demagnetisation effects, in order to illustrate the spatial dynamics of the magnetic moments [3]. Especially, ferromagnetic films, for which applications like magnetic storage devices, micro-inductors and electromagnetic noise absorbers exist, need a deep insight into their microscopic, dynamic material properties. A lot of work was made on damping, i.e., broadening processes in magnetic bulk materials dependent on the high-frequency power in the past [4–8]. But the question, what impact is generated by the intensity of a high-frequency excitation field in ferromagnetic films, has not been entirely treated in a pragmatic way. In the following explanation, a theoretic approach for the width of the permeability resonance curve (spectral linewidth) dependent on the high-frequency field intensity and its influence on the ferromagnetic resonance frequency and damping as well as its comparison with experimental data ought to be discussed.

## 2. Theory of FMR increase and resonance line broadening due to High-frequency field perturbation

In order to theoretically describe the impact of the high-frequency field on the frequency behaviour of a ferromagnetic film, we try to make an approach by means of the well-established Landau–Lifschitz–Gilbert (LLG) linear differential equation

$$\frac{\partial \vec{M}}{\partial t} = -\gamma \cdot \vec{M} \times \vec{H}_{eff} + \frac{\alpha}{M_s} \cdot \left( \vec{M} \times \frac{\partial \vec{M}}{\partial t} \right) \tag{1}$$

* Corresponding author. Tel.: +49 721 608 24255; fax: +49 721 608 24567.
*E-mail address:* klaus.seemann@kit.edu (K. Seemann).

0304-8853/$ - see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jmmm.2013.06.003

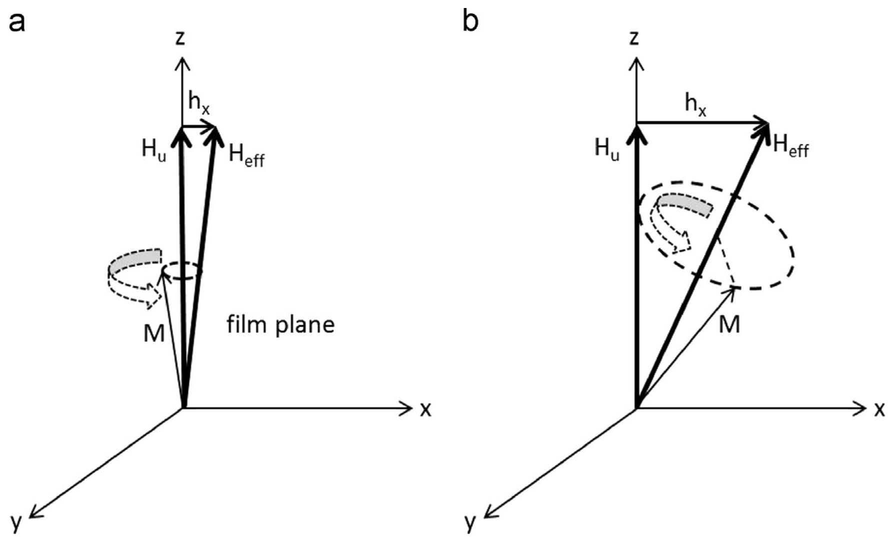


**Fig. 1.** Simple illustration of a magnetic moment which precesses about its effective field generated by the uniaxial anisotropy field $H_u$, the high frequency field $h_x$ and demagnetisation field $H_d$ (not indicated here). If $h_x$ is very small it can be neglected (a). If $h_x$ is higher it influences $H_{eff}$ and cannot be neglected (b).

For convenience, eddy-currents are neglected, i.e., the film must be thin enough and has to possess a sufficiently high resistivity. The ferromagnetic resonance frequency (FMR)

$$f_{FMR} = \frac{\gamma}{2\pi}\mu_0 \mathrm{H}_{eff} \tag{2}$$

results from the first term on the right hand side of (1) if the general phenomenological damping parameter $\alpha$ is hypothetically considered to be zero (or at least $\alpha \ll 1$). $\mu_0$ is the magnetic constant, and $\gamma$ is the gyromagnetic constant whose value is set to around 190 GHz/T. Expression (2) is also equal to a resonance transition of a quantum mechanical spin-½ system. If a non-negligible high-frequency field exists, which makes the system to precess, the resonance line, among other things, broadens due to perturbation or coupling. In order to feel out this behaviour for a film with a system of ferromagnetic moments, the following approach for the effective magnetic field vector $\mathbf{H_{eff}}$ is used [3], (Fig. 1(a)).

$$\vec{H}_{eff} = \vec{H}_u + \vec{\mathrm{h}} + \vec{H}_d = \begin{pmatrix} 0 \\ 0 \\ H_u \end{pmatrix} + \begin{pmatrix} h_x \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} -N_x \cdot m_x \\ -N_y \cdot m_y \\ -N_z \cdot M_s \end{pmatrix} = \begin{pmatrix} h_x - N_x \cdot m_x \\ -N_y \cdot m_y \\ \mathrm{H_u} - N_z \cdot M_s \end{pmatrix} \tag{3}$$

here, we consider a thin ferromagnetic film with an in-plane uniaxial anisotropy $\mathbf{H_u}$ and a saturation magnetisation $M_s$. The magnitudes are attributed to the *z*-direction. The demagnetisation field vector $\mathbf{H_d}$ with the demagnetisation factors $N$, set to $N_x = N_z = 0$ and $N_y = 1$, is sufficient for a film with a thickness much smaller than its lateral dimensions. The mean perturbation field $\mathbf{h}$ is defined to be in the *x*-direction and cannot be neglected if it is not small enough (Fig. 1(b)). The absolute value of the effective field vector in conclusion results in $|\mathrm{H_{eff}}|^2 = \mathrm{h_x}^2 + m_y^2 + \mathrm{H_u}^2$. After calculation the unknown magnetisation in y-direction can be obtained by the expression $m_y^2 = M_s \mathrm{H_u}$ assuming that $m_x$ is very close to $M_s$ at the undamped resonance state. Consequently, $\mathrm{H_{eff}}$ results in

$$\mathrm{H_{eff}} = \sqrt{\mathrm{h_x^2} + M_s \mathrm{H_u} + \mathrm{H_u^2}} \tag{4}$$

and therefore, expression (2) changes to the following form:

$$f_{FMR} = \frac{\gamma}{2\pi}\mu_0 \sqrt{\mathrm{h_x^2} + M_s \mathrm{H_u} + \mathrm{H_u^2}} \tag{5}$$

which is similar to the Kittel resonance formula. In order to determine the exact resonance peak with respect to damping and external perturbation, the detailed "anisotropic" LLG for all magnetisation directions can now be established according to the film dimensions.

$$\begin{pmatrix} \frac{\partial m_x}{\partial t} \\ \frac{\partial m_y}{\partial t} \\ \frac{\partial m_z}{\partial t} \end{pmatrix} = -\gamma \cdot \begin{pmatrix} m_x \\ m_y \\ m_z \end{pmatrix} \times \begin{pmatrix} \mathrm{h_x} \\ -m_y \\ \mathrm{H_u} \end{pmatrix} + \frac{\alpha}{M_s} \cdot \begin{pmatrix} m_x \\ m_y \\ m_z \end{pmatrix} \times \begin{pmatrix} \frac{\partial m_x}{\partial t} \\ \frac{\partial m_y}{\partial t} \\ \frac{\partial m_z}{\partial t} \end{pmatrix} \tag{6}$$

By calculating (6), the following system of two coupled homogeneous differential equations for $m_x$ and $m_y$ can be arranged.

$$\begin{aligned} \frac{\partial m_x}{\partial t} + \frac{\gamma \alpha \mathrm{H_u}}{1+\alpha^2} m_x + \frac{\gamma(\mathrm{H_u} + M_s)}{1+\alpha^2} m_y = 0 \\ \frac{\partial m_y}{\partial t} - \frac{\gamma \mathrm{H_u}}{1+\alpha^2} m_x + \frac{\gamma \alpha (\mathrm{H_u} + M_s)}{1+\alpha^2} m_y = 0 \end{aligned} \tag{7}$$

The "anisotropic" solutions for the boundary condition $m_x(t) = m_{0x}$ at time $t=0$ ($m_y(t)=0$) are formulated by the next expressions

$$m_x(t) = m_{0x} e^{t/\tau} \cos(2\pi f_{FMR} t) \tag{8}$$

$$m_y(t) = m_{0x} e^{t/\tau} \frac{\mathrm{H_u}}{\sqrt{\mathrm{H_u^2} + \mathrm{H_u} M_s}} \sin(2\pi f_{FMR} t) \tag{9}$$

where

$$\frac{1}{\tau} = -\frac{1}{2}\gamma\alpha \frac{(2\mathrm{H_u} + M_s)}{(1+\alpha^2)} \tag{10}$$

is the relaxation rate with the lifetime $\tau$ of the uniformly precessing system of magnetic moments.

The magnetisation in the *z*-direction can be decoupled from the system (6) because $\|\mathbf{M}\| = \mathrm{const.}$ ($\|\mathbf{M}\|/M_s = 1$), that is, $M_s$ is preserved, and then can finally be written as follows:

$$m_z = \sqrt{M_s^2 - (m_x^2 + m_y^2)} \tag{11}$$

We are now interested in the ferromagnetic resonance frequency $f_{FMR}$ which results from (7) and obtains the exact damping parameter-dependent form.

$$f_{FMR} = \frac{\gamma}{2\pi(1+\alpha^2)^2} \mu_0 \sqrt{\mathrm{H_u^2} + \mathrm{H_u} M_s - \frac{M_s^2 \alpha^2}{4}} \tag{12}$$

By applying $\alpha \ll 1$ or zero, one attains the Kittel resonance formula again which is frequently used in literature. But for an increasing damping parameter $\alpha$, it can now easily be observed by