Ferromagnetic resonance frequency increase and line broadening of a $Fe_{33}Co_{43}Hf_{10}N_{14}$ film by high-frequency field perturbation

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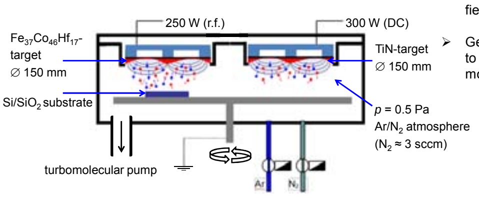
Abstract:
Soft ferromagnetic $Fe_{33}Co_{43}Hf_{10}N_{14}$ films, produced by reactive r.f. magnetron sputtering, are used to study the ferromagnetic resonance (FMR) by means of permeability measurements up to the GHz range. While being exposed to a high-frequency field, the precession of magnetic moments 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) [1]- Maxwell theory [2]. A slightly increased FMR frequency and a clear increase in the resonance line broadening due to the variation of the high-frequency amplitude, considered as an additional perturbation to the precessing system of magnetic moments, was observed. By calculating the homogenous LLG, it can be shown that the high-frequency field perturbation impacts the resonance peak location f_{FMR} and line broadening Δf_{FMR} characterised by a completed damping parameter $\alpha = \alpha_{eff} + \Delta\alpha$.

Experimental

Sample preparation

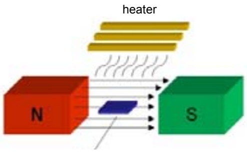
- Two-step process: Deposition and subsequent high-temperature activation

1. Reactive rf & dc magnetron sputter deposition



2. Heat treatment

- Annealing for 1h at 400°C in a static magnetic field (50 mT) in vacuum after deposition
- Generation of an in-plane uniaxial anisotropy H_u to ensure a homogenous precession of magnetic moments in an external high-frequency field



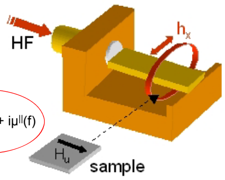
Measurement technique

5 GHz strip-line permeameter (Z_0= 50 Ω) connected to a networkanalysor:

$$S_{11} = S_0 \cdot e^{-\frac{i4\pi f \cdot \sqrt{\mu_{eff} \cdot \varepsilon_{eff}}}{c_0} \cdot l}$$

Reflection parameter S:

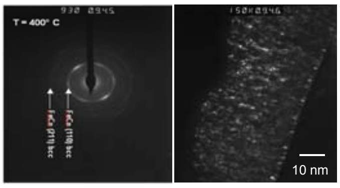
$\mu_r(f) = \mu^{I}(f) + i\mu^{II}(f)$



TEM images

Diffraction image

Dark field image



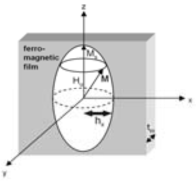
Theoretical approach

General LLG differential equation (DE):

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

FMR for damping parameter α = 0: $f_{FMR} = \frac{\gamma}{2\pi} \cdot \mu_0 \cdot \sqrt{h_x^2 + M_s \cdot H_u + H_u^2}$ with $H_{eff} = \sqrt{h_x^2 + M_s \cdot H_u + H_u^2}$

Calculation of the exact FMR by 2 coupled homogenous DE according to the in-plane uniaxial anisotropy:



$$\frac{\partial m_x}{\partial t} + \frac{\gamma \cdot \alpha \cdot H_u}{1+\alpha^2} \cdot m_x + \frac{\gamma \cdot (H_u + M_s)}{1+\alpha^2} \cdot m_y = 0$$

$$\frac{\partial m_y}{\partial t} - \frac{\gamma \cdot H_u}{1+\alpha^2} \cdot m_x + \frac{\gamma \cdot \alpha \cdot (H_u + M_s)}{1+\alpha^2} \cdot m_y = 0$$

Solution of the FMR for damping parameter α > 0:

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

By setting the electromagnetic wave power $P = K \cdot h_x^2$ and $\alpha = \alpha_{eff} + \Delta\alpha$, FMR results in:

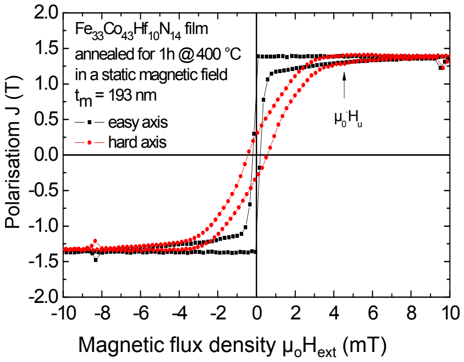
$$f_{FMR} = \frac{\gamma}{2 \cdot \pi \cdot \left(1 + (\alpha_{eff} + \Delta\alpha)^2\right)^2} \cdot \mu_0 \cdot \sqrt{\frac{P}{K} + H_u^2 + H_u \cdot M_s - \frac{M_s^2 \cdot (\alpha_{eff} + \Delta\alpha)^2}{4}}$$

According to [3], the ferromagnetic resonance linewidth results in:

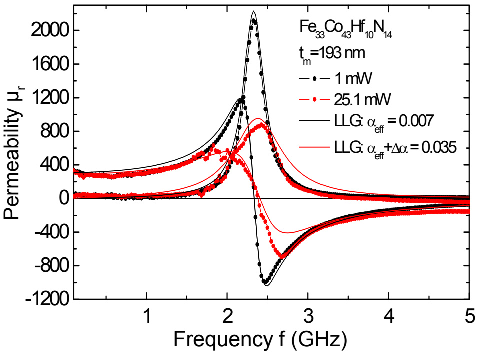
$$\Delta f_{FMR} = \sqrt{\frac{J_s}{\mu_0 H_u} + 1} \cdot f_{FMR} \cdot (\alpha_{eff} + \Delta\alpha)$$

Results and comparison with theory

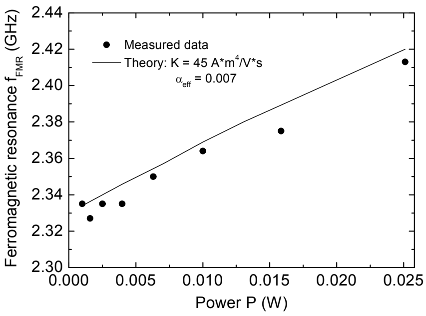
VSM measurement

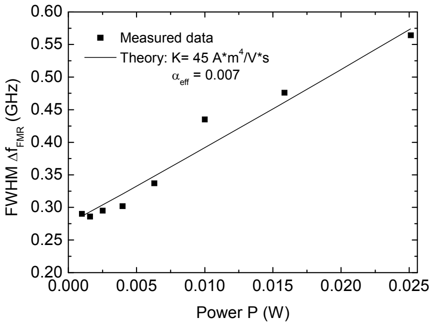


Frequency-dependent permeability and comparison with LLG



FMR frequency shift and line broadening





Summary:
- High frequency field perturbation influences FMR frequency and line broadening
- Theoretic model for the ferromagnetic resonance frequency increase and line broadening dependent on the electromagnetic wave power (1 mW to 25.1 mW)
- Good agreement of the measured data with the theoretical approach

[1] T.L. Gilbert, IEEE Trans. Mag. 40, 3443 (2004)
[2] K. Seemann, H. Leiste, V. Bekker, J. Magn. Magn. Mater. 278, 200 (2004)
[3] K. Seemann, H. Leiste, Ch. Klever, J. Magn. Magn. Mater. 321, 3149 (2009)