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# Extrinsic contribution to Gilbert damping in sputtered NiFe films by ferromagnetic resonance

Bijoy K. Kuanr*, R.E. Camley, Z. Celinski

*Physics Department, University of Colorado at Colorado Springs, 1420 Austin Bluffs Parkway, Colorado Springs, CO 80933-7150, USA*

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**Abstract**

We quantitatively determine the intrinsic and extrinsic contribution to frequency ($\Delta f_{res}$) and field ($\Delta H$) linewidths using Network Analyzer ferromagnetic resonance (NA-FMR) (using two different excitation cells) and conventional ferromagnetic resonance (FMR) techniques in sputtered thin permalloy (NiFe) films. There are some common features in these two FMR measurements, which allow us to get important information on damping mechanisms and structural magnetic qualities. The NA-FMR data show an increase in frequency linewidth ($\Delta f_{res}$) as magnetic field ($H$) increases. A distinct change in the slope of this increase is noted for a field above 200 Oe. To explain this result, we consider available theories including the "two-magnon" model, and the "local-resonance" model. From a fitting of $\Delta f_{res}$ versus $H$ data to the Arias-Mills' two-magnon model results, we obtain the Gilbert damping parameters. The frequency variation of conventional FMR linewidth ($\Delta H$) data also yields an effective value for the Gilbert damping ($\alpha_{eff} = 0.0128$), in good agreement with the data from the Network Analyzer data ($0.013 \pm 0.004$). In addition to the theoretical analysis presented in this paper, we compare our experimental results from RF-excitation cell to the commonly used co-planer waveguide technique.


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*Keywords:* Relaxation; Linewidth; Permalloy; Two-magnon

## 1. Introduction

Magnetic thin films and multilayers have been the subject of great interest due to their fundamental differences in magnetic and electronic properties from their bulk counterparts. The thin film properties are greatly influenced by the presence of interfaces. The recent spintronic and magnetoelectronic devices operating in the microwave frequency range are based on the unique properties of thin magnetic films. Therefore, it is important to understand the relaxation [1–4] of magnetization, which is governed by spin

*Corresponding author. Fax: +1 719 262 3013.
*E-mail address:* bkuanr@uccs.edu (B.K. Kuanr).

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interactions, and the quality and structure of the interfaces. One of the major issues in the magnetic-data-storage industry is the data-transfer rate. Frequencies for writing and reading are now almost in the microwave region, which raises the question, "How fast can magnetic materials switch?" The answer is determined in part by the relaxation mechanisms in the magnetic film.

The measurement of the resonance linewidth is one of the main techniques used to investigate relaxation mechanisms in a ferromagnetic film. The origin of ferromagnetic resonance (FMR) linewidth in ultrathin films is of considerable interest due to the fact that its relaxation time falls in the nanosecond time regime, which is useful for the high-density magnetic recording employing fast magnetization reversal processes. The recent experimental [2,3] and theoretical [5–8] studies show that FMR linewidth consists of intrinsic and extrinsic contributions. The extrinsic part to linewidth was explained by various theories including the defect-induced two-magnon model, the local resonance model [5–8], etc.

In this paper, we present results for the frequency dependence of the FMR field linewidth from conventional FMR and the magnetic field dependence of frequency linewidth from Network-Analyzer-based FMR techniques. Our studies allowed us to determine the Gilbert parameters from the linewidth data.

## 2. Experiment

Polycrystalline permalloy films of various thicknesses (20–50 nm) were grown on Si substrates by magnetron sputtering with a background pressure better than $10^{-7}$ mbar. First a 5 nm thick Ti seed layer was grown for good adhesion to the Si substrate. The permalloy deposition rate was maintained at 0.1 nm/s. The permalloy layer was covered by a 5 nm thick Cu layer to prevent oxidation. The samples were characterized by X-ray diffraction (XRD). From the full-width at half-maximum of the XRD peak, the average grain size ($X$) of the sample was found [9] to be ~80 Å. The grain size of the sample is important to determine the exact theory applicable to the model calculation for the relaxation processes. The coercivity ($H_C$) and uniaxial anisotropy of the permalloy film measured from magneto optic Kerr effect (MOKE) hysteresis loop measurements are 6 and 8 Oe, respectively.

The Network-Analyzer FMR (NA-FMR) measurements were done with a Vector Network Analyzer (HP model 8510C). We have used two different RF excitation systems to determine the complex **S**-parameters. In the first method, the film was placed across a coaxial receptacle to produce an electric short circuit between the center ($d_1 = 0.135$ cm) and outer ($d_2 = 0.4$ cm) conductors of the 50 Ω transmission line, as used earlier [10]. Calibration is accomplished through the open-short-load method. In the second method we used a Cascade microprobe station along with a silver (Ag; 1 μm) co-planer waveguide (CPW). The sample was mounted on top of the CPW structure (with center conductor $w = 50$ μm and length $L = 6.6$ mm) by employing the flip-chip technique. We characterized the Ag-CPW transmission lines at frequencies from 0.5 to 20 GHz using the NIST Multical software for through-short-line (TSL) calibration process.

The effects of the connections as well as the substrate were subtracted from the measured **S**-parameter data in both the techniques. A fixed magnetic field, $H$ ($> H_C$) was applied in the film plane parallel to the easy axis (EA), while the driving frequency $f$ ($= \omega/2\pi$) was swept. In this configuration the microwave magnetic field ($\mathbf{h}_{RF}$) component aligned perpendicular to the EA of the permalloy causes the magnetization to precess. Using the coaxial receptacle a simple transmission line approach [10] was used to extract the real ($\mu'$) and the imaginary ($\mu''$) components of permeability ($\mu$) from the measured **S**-parameters. However, it is not clear that the contribution from currents within the film is correctly accounted for in this method. The NA-FMR measurements for the CPW geometry are more complex [11,12]. For example due to the non-uniformity of RF magnetic field ($\mathbf{h}_{RF}$), there is a possibility of the excitation of spin-wave with finite wave-vector ($\mathbf{k}_{\parallel}$) due to the fact that the sample is large compared to the dimensions of the CPW [12]. We have also used 10 and 24 GHz FMR systems to study the resonance field modes ($H_{res}$) as a function of in-plane field angle. The peak-to-peak linewidth ($\Delta H$) was measured from the differential FMR signal.

## 3. Results and discussion

Fig. 1 shows the imaginary ($\mu''$) part of the experimental permeability spectra obtained from a coaxial-cell (lower panel) for a 30 nm thick permalloy film. The Lorentzian fit to $\mu''$ shows the resonance frequency ($f_{res}$) and frequency linewidth ($\Delta f_{res}$). At resonance $\mu''$ shows a peak value. The upper panel of this figure shows the transmitted amplitude ($S_{12}$) spectra obtained from the CPW geometry. The linewidth from the coaxial-cell broadens with the increase of applied field, as is normally expected. However, the increase is surprisingly large. In part, this is because we use the L only model [13] to find $\mu''$. This model overestimates the amplitude of $\mu''$, but generally gives peak positions and linewidths close to that of the better RLC model [14]. In contrast, the width of the peaks seen in the CPW measurements shows a decrease with the increase of field. It has been pointed out that the width of the peaks seen in $S_{12}$ is not necessarily directly related to the linewidth seen in the permeability. For example, it has been argued [12] that the generation of $k \neq 0$ spin waves can influence the absorption of energy substantially in CPW-like measurement.

Fig. 2 shows the in-plane NA-FMR linewidth ($\Delta f_{res}$) as a function of applied magnetic field ($H$) for a 30 nm thick permalloy film for the coaxial

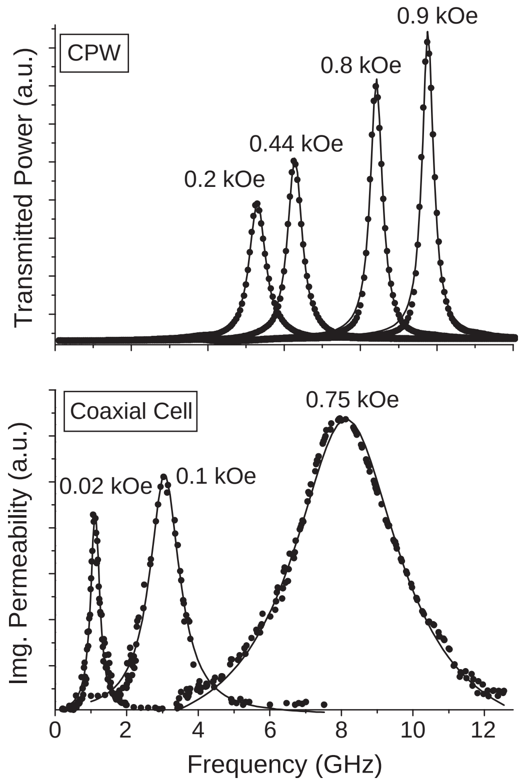


Fig. 1. Permeability spectra (imaginary part) obtained from NA-FMR S-parameters using coaxial cell (lower panel) and a fit to the Lorentzian function to determine the resonance frequency and frequency linewidth. The upper panel shows the CPW $S_{12}$ spectra. The values of the applied field in each case are shown in the figure.

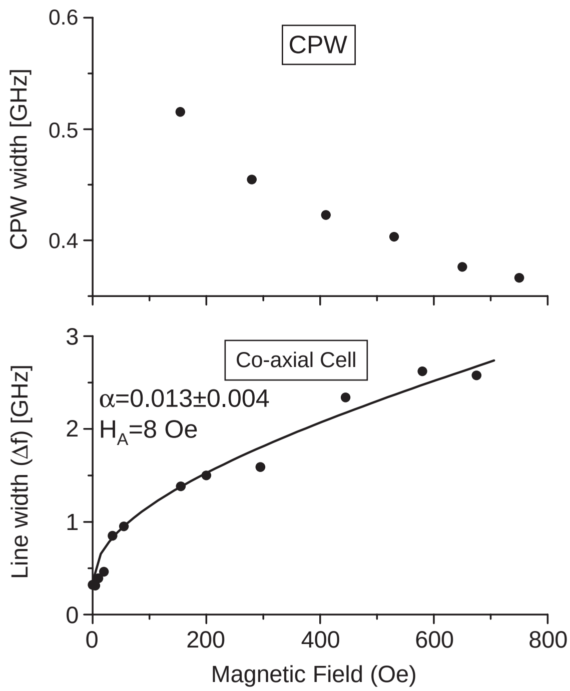


Fig. 2. NA-FMR frequency linewidth obtained from the coaxial-cell (lower panel) measurements as a function of applied magnetic field for $H$ in-plane configuration for a permalloy (30 nm) film. The solid line is a fit to Eq. (2) in conjunction with Eq. (3) as described in the text. The upper panel shows the width obtained from measurements in the CPW geometry.

receptacle (lower panel) and for the CPW peaks in $S_{12}$ (upper panel). The linewidth for the coaxial receptacle measurements increases with the increase of magnetic field and hence the resonance frequency. The $\Delta f_{res}(H)$ data of Fig. 2 show a marked slope change below 200 Oe. In contrast, the $\Delta f_{res}(H)$ data from CPW geometry show a decrease of linewidth with the increasing field. For our coaxial receptacle cell, the maximum $\mathbf{k}_{\|}$ possible is $(\pi/d_1)\sim 1\times 10^1\,\text{cm}^{-1}$. But for the second system with a CPW waveguide the maximum $\mathbf{k}_{\|}$ possible is $(\pi/w)\sim 1\times 10^3\,\text{cm}^{-1}$. Thus, the largest $k$ values in the CPW structure are two orders of magnitude larger than those in the coaxial receptacle cell. So the broadening of linewidth observed in CPW geometry at low field is partly due to the excitation of frequency over a continuous range from $f_{res}(\mathbf{k}=0)$ mode to $f_{res}(\mathbf{k}\sim 1\times 10^3\,\text{cm}^{-1})$ mode. The non-uniformity arising from the coaxial-cell exists, though it is very small in magnitude. Therefore, the observed linewidth pattern from coaxial cell is almost similar to a conventional FMR experiment [1–3]. The extrinsic contribution to linewidth arising from the CPW measurement procedure [11,12] is a CPW-geometrical effect, rather than arising from the intrinsic properties of a magnetic material. A detailed comparative study will be reported later.

The increase of $\Delta f_{res}$ with magnetic field in the coaxial receptacle measurements is basically attributed to both intrinsic and extrinsic contributions. The intrinsic contribution ($\Delta f^{int}$) comes from damping and is a fundamental property of a magnetic material, whereas the extrinsic linewidth ($\Delta f^{ext}$) [5,7,8] is associated with the magnetic inhomogeneities [1,3] within the material (e.g. due to surface and interface roughness) and the variations in anisotropy [4]. Recently, McMichael et al. [8] have pointed out the relation of sample inhomogeneity on the ferromagnetic resonance linewidth. They used a model that consists of the size of the grain ($X$) and an inhomogeneous effective field ($H_A$) that varies from grain to grain with a film thickness $d$ and magnetization $M_S$. According to them [8], the resulting linewidth agrees well with the ‘‘two-magnon’’ model if the films have small grain inhomogeneities, with $H_A X \ll \pi M_S d$. For large grain inhomogeneities, $H_A X \gg \pi M_S d$, the magnetization precession becomes localized and the spectrum approaches that of the local precession on independent grain.

The films under the present investigation, having a grain size ($X$) of about 80 Å, satisfy McMichael et al.s [8] first relation [$H_A X \ll \pi M_S d$] and, therefore, a two-magnon model is appropriate for the inhomogeneous broadening of the linewidth observed in this study. Using the Arias–Mills two-magnon model [5], the linewidth is modeled theoretically by using the spin wave propagator $\mathbf{S}_{xx}(\mathbf{k}_{\|}=0,\omega)$ (Eq. (54) of Ref. [5]). In this case the denominator of $\mathbf{S}_{xx}$ is given by

$$\omega_{res}^2 - \omega^2 - i\gamma\alpha\omega[2H + 4\pi M_S + H_A] - i\Gamma = 0. \tag{1}$$

The linewidth in that paper is obtained in terms of a small variance $\Delta H$. Here, instead of relating the damping parameter, $\Gamma$, to the FMR field linewidth ($\Delta H$), we relate $\Gamma$ to the frequency linewidth ($\Delta f_{res}$) as measured experimentally by NA-FMR in the coaxial receptacle. In this case, the response function is considered for the NA-FMR approach, where the frequency $\omega$ ($\omega = 2\pi f$) is swept through $\omega_{res}$ ($\omega_{res} = 2\pi f_{res}$) at a constant $H$. We consider $\omega$ to be a little away from $\omega_{res}$ and replace $\omega$ by $(\omega_{res} - \Delta\omega_{res})$ in the denominator (Eq. (54) of Ref. [5]). Neglecting terms of order $(\Delta\omega)^2$ we find

$$\Delta f_{res} = (\gamma\alpha/2\pi)(2H + 4\pi M_S + H_A) + (\Gamma/8\pi^2 f_{res}) = \Delta f^{int} + \Delta f^{ext}. \tag{2}$$

The first term of Eq. (2) is the intrinsic contribution to linewidth (in frequency) and the second term is the extrinsic contribution. Inserting the value of $\Gamma$ in Eq. (2) we finally obtain the extrinsic contribution arising from two-magnon scattering to linewidth as

$$\Delta f^{ext} = \frac{1}{2\pi}\left[\frac{4sH_A^2\gamma^2\left[H^2 + 2(2H + 4\pi M_S + H_A)^2\right]}{\pi D\omega_{res}[2H + 4\pi M_S + H_A]}\right] \times \sin^{-1}\sqrt{\left(\frac{H}{H + 4\pi M_S + H_A}\right)}, \tag{3}$$

where $D$ is exchange stiffness and $s = pb^2(\langle a/c\rangle - 1)$ is a defect parameter. The parameters $p$, $b$, $a$ and $c$ are dimensions of a rectangular defect (details described in Refs. [2–5]). The square bracket term is the field-dependent $\Gamma$. That means the extrinsic contribution to linewidth is also dependent on applied magnetic field, like the intrinsic contribution. The extrinsic linewidth is essentially due to the scattering of uniform precession ($k = 0$) mode to the non-zero ($k \neq 0$) wave-vector mode. Therefore, it was rightly pointed out earlier [5] that, if $f \to 0$, then $\Gamma \to 0$. This means the extrinsic contribution to linewidth is zero at zero frequency. The reason for this is that the phase space available to final state spin waves becomes vanishingly small [5]. We obtain effective Gilbert damping ($\alpha_{eff} = \alpha_{int} + \alpha_{ext}$) as $0.013 \pm 0.004$ from the fitting of $\Delta f_{res}$ data to Eq. (2) in conjunction with Eq. (3) (the solid line in Fig. 2, lower panel). In the field range greater than 200 Oe, $\Delta f^{ext}$ is fairly linear with field, whereas below 200 Oe it decreases sharply. This is an indication of strong two-magnon contribution to the extrinsic damping mechanism [5]. The values of $4\pi M_S$ and $D$ used for fitting are 10 kOe and $2 \times 10^{-9}$ Oe cm$^2$, respectively, for permalloy. The geometrical parameter $s$ was used as a fitting parameter. We found that the $s$ values (from the coaxial cell) were quite large because of the very large linewidths found experimentally.

The FMR field linewidth, $\Delta H$, is not only proportional to the microwave frequency ($f = \omega/2\pi$) but also possesses a zero-frequency offset [$\Delta H(0)$] as given in the following relation [1,3]:

$$\Delta H(f) = \Delta H(0) + 1.16\frac{2\pi f}{\gamma}\alpha. \tag{4}$$

Fig. 3 shows the FMR spectra (for $\Delta H$) of a 30 nm permalloy film along easy-magnetization axes as a function of sweeping field at 10 and 24 GHz. From the straight line fit of Eq. (4) to the measured frequency points [1,3] we obtain $\Delta H(0)$ as 8.6 Oe and $\alpha_{eff}$ as 0.0128 as shown in the inset of Fig. 3. These values are close to earlier data [2]. As reported earlier [3], Gilbert damping obtained from $\Delta H$ contains both intrinsic and extrinsic contributions. Thus, by fitting a few data points for $\Delta H(f)$ it is not possible to separate the bulk damping, which is surely linear with frequency from extrinsic contribution with origin in surface and interface defects.

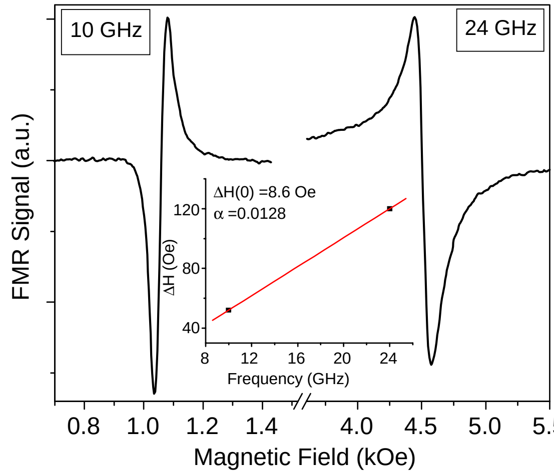


Fig. 3. FMR spectrum of 30 nm permalloy film measured at 10 and 24 GHz. The inset shows the $\Delta H$ versus $f$ data.

## 4. Conclusion

NA-FMR and conventional FMR measurements were carried out on a polycrystalline permalloy film. The Gilbert damping found from the fitting of the $\Delta f_{res}(H)$ data is $0.013 \pm 0.004$. The linear slope of $\Delta H$ to operating frequency data in conventional FMR also yields effective Gilbert damping as ($\alpha_{eff}$) 0.0128 close to NA-FMR result. This is in good qualitative agreement with the "two-magnon" model where magnetic inhomogeneities contribute to the extrinsic linewidth. The strength of two-magnon contribution to $\Delta f_{res}$ decreases with decreasing frequency and hence decreasing field.

## Acknowledgement

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