MICROWAVE RELAXATION AND PHENOMENOLOGICAL DAMPING IN THIN FILMS

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The relation between relaxation time T, frequency swept resonance linewidth $\Delta\omega$, and phenomenological damping α is given by $\Delta\omega = 2/T = \alpha(\omega_x + \omega_y)$, where $\omega_{x,y} = \gamma(H_0 + (N_{x,y} - N_z)\,4\pi M_s)$. $N_{x,y,z}$ are sample demagnetizing factors, H_0 is the effective z-directed static field, $4\pi M_s$ is the saturation induction, and γ is the gyromagnetic ratio. This fairly simple but general relation shows that the numerical relation between damping and relaxation at a given frequency can be quite different for in-plane and normally magnetized thin films. For the *same* loss processes, so that $T_\parallel$ and $T_\perp$ are equal, $\alpha_\perp$ is larger than $\alpha_\parallel$. For permalloy films at 1 GHz, $\alpha_\perp = 15\alpha_\parallel$. In addition, the conventional field swept linewidth, $\Delta H = \alpha\omega/\gamma$, is simply related to $\Delta\omega$ only for $N_x = N_y$. Both α and ΔH are geometry dependent and do not provide an intrinsic measure of the relaxation. These results are confirmed by both resonance and transient response experiments. The large values of α for large angle switching may also be partially explained by this analysis because the relevant magnetization motion is due to a demagnetizing field normal to the film plane.

Past studies [1] have established the basic differences between field-swept and frequency-swept linewidths for ferromagnetic resonance in thin films, and the importance of using the frequency swept linewidth in any discussion of physical relaxation processes. In this report, the connection between phenomenological damping, relaxation, and linewidth is discussed in detail. From a rather simple equation-of-motion analysis, it is shown that both phenomenological damping parameters and field-swept linewidths are geometry dependent. Fundamental relaxation time determinations can come only from the frequency-swept linewidth or by measuring the decay time in a transient response experiment. The geometry dependence of damping also has some relevance to the interpretation of large angle switching data.

The basic relation between damping and relaxation time follows directly from an examination of the various phenomenological equations of motion for the magnetization. The Landau-Lifshitz form [2],

$$(1) \qquad \mathrm{d}\boldsymbol{M}/\mathrm{d}t = -\gamma(\boldsymbol{M} \times \boldsymbol{H}) - (\alpha/M_s)\,\boldsymbol{M} \times (\boldsymbol{M} \times \boldsymbol{H})\,,$$

expresses the relaxation in terms of a phenomenological damping parameter α (sometimes α is expressed in frequency units by $\lambda = \alpha\gamma\,.\,4\pi M_s$). The Bloch-Bloembergen form [3],

$$(2) \qquad (\mathrm{d}\boldsymbol{M}/\mathrm{d}t)_{x,y} = -\gamma(\boldsymbol{M} \times \boldsymbol{H})_{x,y} - M_{x,y}/T_2\,,$$

expresses the relaxation of the transverse, $x - y$ components of the magnetization

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in terms of a spin–spin relaxation time T_2, analogous with formulations for nuclear magnetic resonance. In the above equations, $\boldsymbol{M}$ denotes the magnetization vector, γ the gyromagnetic ratio (taken as positive for electrons), $4\pi M_s$ the saturation induction, and $\boldsymbol{H}$ the total internal magnetic field. Although more sophisticated formulations are also available, the above expressions are adequate for this discussion.

Consider an ellipsoidal sample with major axes aligned along x-, y-, and z-directions, respectively, with corresponding demagnetizing factors, $N_{x,y,z}$, in these directions, and magnetized to saturation along the z-axis by a static external field H_0. The steady state analysis based on Eqs. (1) and (2) yields the well-known resonance response with a frequency swept linewidth given by

$$\Delta\omega = \alpha(\omega_x + \omega_y) = 2/T_2 \,, \tag{3}$$

where

$$\omega_{x,y} = \gamma[H_0 + (N_{x,y} - N_z)\, 4\pi M_s] \tag{4}$$

are the two terms in the Kittel condition for uniform precession resonance, $\omega_{res} = \sqrt{(\omega_x \omega_y)}$. Note that $\Delta\omega$ is directly related to the relaxation time T_2 and that no other variables are involved. The relation between $\Delta\omega$ or T_2 and the damping α, however, involves a term $(\omega_x + \omega_y)$. For resonance at a given frequency, so that $\sqrt{(\omega_x \omega_y)} \approx \omega$ is constant, $(\omega_x + \omega_y)$ can change by an order of magnitude or more for different orientations. In 80 Ni-20 Fe thin films at 1 GHz, for example, the factor $(\omega_x + \omega_y)$ is about fifteen times smaller for perpendicular resonance (z-axis normal to film) than for parallel resonace (z-axis in-plane). This means that if we take the value of α inferred from parallel resonance and calculate the expected linewidth for the perpendicular configuration, the value of $\Delta\omega/\gamma$ which results should be fifteen times smaller. Previously published data show, however, that $\Delta\omega/\gamma$ is the same in the two cases. If we confine ourselves to the L–L formulation of Eq. (1), the data require an $\alpha_\perp$ which is fifteen times bigger than $\alpha_\parallel$.

Similar remarks apply to the interpretation of the field-swept linewidth ΔH which is measured in the usual FMR experiment. This linewidth is directly related to α by $\Delta H = 2\alpha\omega_{res}/\gamma$. The relation between ΔH and $1/T_2$ (or $\Delta\omega$) involves a term $\omega_{res} : (\omega_x + \omega_y)$, which is also geometry dependent. For FMR, ΔH and $\Delta\omega/\gamma$ cannot be regarded as equivalent ways to express the relaxation because of the nonlinear relation between ω_{res} and H_0 in the Kittel condition.

Now consider the free oscillation experiment [4, 5]. The decay varies as $m_{x,y} \sim \exp(t/T_2)$ with $1/T_2$ given by Eq. (4). This is simply a more general expression of the original Wolf result for films magnetized in-plane, $m_{x,y} \sim \exp(\lambda t)$. The general result, however, displays the geometry dependences of the decay. Note that, if the damping α were constant, the decay time for free oscillation in a normally magnetized film should be much shorter than for in-plane magnetized films. No such experiment has, in fact, been reported, but resonance data indicate that this is not the case [1]. Values of $\Delta\omega$ inferred from field-swept FMR data reveal that the relaxation times for FMR

at 1–4 GHz in very thin films are the same for the two configurations.[1]) Moreover, the T_2 from in-plane free oscillation data agree nicely with these FMR values. The present experimental situation is summarized in Table 1. The values are for FMR data (ref. [1]) and free oscillation data (ref. [5]) in 80 Ni-20 Fe evaporated films about 1000 Å thick. Even though the relaxation times (expressed in terms of a frequency-swept linewidth in field units) are all comparable, the damping for the perpendicular case is much larger than for the parallel case. This indicates that the free-oscillation waveform for transient decay in normally magnetized films should be about the same, with the same time constant, as for the in-plane data of Wolf [4] and Matsumoto et al. [5].

Table 1

Summary of experimental values for the damping and the frequency-swept linewidth (in field units) for perpendicular and in-plane magnetized films.

Response / Configuration	Resonance			Free-oscillation		
	$\omega/2\pi$ [GHz]	$\Delta\omega/\gamma$ [Oe]	α	$\omega/2\pi$ [GHz]	$\Delta\omega/\gamma$ [Oe]	α
Perpendicular	1·0	60	0·11	(Not reported)		
Parallel	1·0	55	0·008	0·85	51	0·006

Finally, these ideas may be relevant to the problem of large angle switching. Beginning with the early realization that the damping inferred from switching data and coherent rotation models was much larger than for in-plane FMR or free oscillation, more complicated modes of reversal have been considered. Even though some degree of success has been realized by these approaches, most notably from the recent experiments of Kryder and Humphrey [6], the above discussion of geometry effects on damping shows that the large values inferred from switching data are not really as disturbing as they initially appeared. Somewhat naively, coherent rotation may be viewed as precession about an internal demagnetizing field directed normal to the film plane. In this sense, switching more closely resembles the precession dynamics for a normally magnetized film than an in-plane magnetized film, and the damping should be interpreted accordingly. Even though the details of the analysis should certainly be different for large angle response, it is still reasonable to expect that the damping should be larger than for small amplitude, in-plane processes.

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[1]) For this film thickness and frequency range, the physical loss processes for the two configurations should be nearly the same, since two-magnon interactions are not important (ref. [1]).

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