Microwave effective linewidth in thin metal films

H. Moosmüller, K. D. McKinstry, and C. E. Patton
Physics Department, Colorado State University, Fort Collins, Colorado 80523

An effective linewidth technique for characterizing microwave losses in thin ferromagnetic metal films, similar to the technique for ferrites, has been developed. The extension to metal films is nontrivial. A numerical solution of the electromagnetic boundary value problem for the fields inside the film must be used to evaluate the on- and off-resonance losses, and these calculated losses must be directly related to changes in the microwave cavity Q on an absolute scale. Specific measurements and analyses were done for polycrystalline permalloy on glass. Measurements at 10 GHz yield a change in $1/Q$ with field which is in accord with theory and can be modeled off resonance to obtain intrinsic losses. The analysis yielded an intrinsic Landau–Lifshitz damping parameter of 5.5×10^7 rad/s for permalloy. This corresponds to a half-power effective linewidth of 27 Oe, which is comparable to the best published 10 GHz linewidth for single-crystal iron films.

INTRODUCTION

Microwave losses in magnetic materials can be attributed to intrinsic processes which are typically described by the Landau–Lifshitz model[1] and to inhomogeneity and two-magnon scattering effects which occur near ferromagnetic resonance (FMR). While the FMR linewidth provides a measure of the combined losses, an off-resonance effective linewidth technique can be used to determine the field dependence of the losses.[2–4] In order to apply this technique to insulating magnetic materials, cavity Q and resonance frequency are measured versus applied static field for a microwave cavity containing the material of interest. Then, in conjunction with cavity perturbation theory and an analysis of the dynamic magnetic response of the material, these data are used to determine the complex microwave susceptibility as a function of static field. A field-dependent loss parameter or an effective linewidth can then be extracted from the susceptibility data using an appropriate model for the microwave response. Off resonance, this loss parameter (or effective linewidth) becomes independent of the magnetic field. This off-resonance effective linewidth provides a measure of the intrinsic microwave losses of the material.

The effective linewidth concept can also be applied to ferromagnetic metals, typically in the form of thin metal films. The determination of the field-dependent effective linewidth in permalloy was first reported some years ago,[5] based on cavity reflection coefficient and frequency shift data. The analysis followed the usual approach for insulators,[2,3] with no consideration for metallic properties. The results provided qualitative support for a field-dependent effective linewidth in permalloy and demonstrated the role of two magnon scattering in increasing the losses in the vicinity of FMR.

The work reported here was undertaken to (1) apply more precision and up-to-date measurement techniques to the metal film problem and (2) include the effects of conductivity and exchange in the theoretical analysis for ferromagnetic metals. The experimental procedure is basically the same as for insulators, in that one measures cavity Q versus applied static field. The solid points in Fig. 1 show some typical experimental results for the measured $1/Q$ versus static field for a cylindrical TE_{011} transmission cavity containing an in-plane magnetized 620-Å permalloy film, with the microwave field also in plane. The figure shows the usual FMR peak for the uniform mode.

The theoretical analysis for ferromagnetic metals, however, is more complicated than for insulators. It is necessary to set up the electromagnetic boundary value problem for the thin film under microwave excitation, based on Maxwell's equations and the Landau–Lifshitz equation of motion.[6] One then evaluates the power dissipation of the sample on an absolute scale as a function of static field and relates this power loss to the changes in cavity Q obtained experimentally. The Landau–Lifshitz damping λ (or other loss parameter) is used as a field-dependent fitting parameter.

THEORY

The theoretical evaluation of Q is based on a numerical solution of the electromagnetic boundary value problem, including damping, exchange, conductivity, and all reflected and transmitted fields.[6] The analysis yields the relative microwave power per unit area absorbed by the sample, $P_{\rm rel}$, as a function of static field, for specific sample parameters. This $P_{\rm rel}$ may be written in terms of the Poynting vectors into the sample and out of the sample, $S_{\rm in}$ and $S_{\rm out}$, as

$$P_{\rm rel} = (S_{\rm in} - S_{\rm out})/S_{\rm in}. \tag{1}$$

The net power P absorbed by the sample can then be written as

$$P = S_{\rm in} A P_{\rm rel} = 0.5\mu_0 c h_0^2 A P_{\rm rel}, \tag{2}$$

where μ_0 is the permeability of free space, c is the speed of light, A is the sample surface area (one side), and $S_{\rm in}$ is expressed in terms of the amplitude h_0 of the linearly polarized standing-wave microwave magnetic field at the sample position.

The energy E stored in the cavity may also be written in terms of h_0. For a cavity with the sample located at the maxi-

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mum microwave magnetic field, this energy can be written as

$$E = \mu_0 v_{\rm cav} g_{\rm cav} h_0^2, \tag{3a}$$

where $v_{\rm cav}$ and $g_{\rm cav}$ are the cavity volume and a cavity mode factor, respectively. The mode factor $g_{\rm cav}$ for a cylindrical TE_{011} cavity as used here, with radius r and length l, is given by

$$g_{\rm cav} = 0.25 J_0^2(X'_{01})\left[1 + (\pi r/lX'_{01})^2\right], \tag{3b}$$

where J_0 is the zeroth-order Bessel function of the first kind, and X'_{01} is the first root of $J'_0(x) = 0$. The cavity quality factor Q is defined by

$$Q = \omega E/P, \tag{4}$$

where ω is the angular frequency. The change in inverse Q due to the sample losses can be written as

$$\frac{1}{Q_S} = \frac{cAP_{\rm rel}}{2\omega v_{\rm cav} g_{\rm cav}}. \tag{5}$$

In order to obtain the total cavity Q, the high-field cavity inverse Q factor $1/Q_\infty$ must be added to the sample inverse Q factor $1/Q_S$:

$$\frac{1}{Q} = \frac{1}{Q_S} + \frac{1}{Q_\infty}, \tag{6}$$

where Q_∞ is obtained from a high-field extrapolation of the experimental data.[4]

EXPERIMENT

The measurements were made on 76% Ni vacuum-evaporated thin permalloy films on glass which have been used for several previous FMR investigations.[7] Film thicknesses were measured with a surface profilometer. The half-power FMR linewidth for parallel resonance at 10 GHz was 42 Oe.

The $1/Q$ measurements were carried out using a TE_{011} cylindrical cavity transmission spectrometer. The basic technique has been described previously.[4] The actual Q determination utilized the more modern, high-precision technique described in Ref. 8. The high-Q TE_{011} cavity had an extrapolated Q_∞ of about 22 000. Figure 1 shows measured values of $1/Q$ and changes in the inverse Q factor of the cavity due to the microwave losses in the sample as a function of static field H. The resulting resonance peak at $H \approx 950$ Oe corresponds to FMR. As noted above, the half-power linewidth is approximately 42 Oe. At fields well above and well below the FMR peak, the field dependence of $1/Q$ levels off as Q approaches Q_∞, the characteristic cavity Q without magnetic losses.

ANALYSIS AND DISCUSSION

The analysis and data fitting was applied to the experimental results shown in Fig. 1 for the 620-Å film. The solid line in Fig. 1 shows the calculated $1/Q$ result for a Landau–Lifshitz damping parameter $\lambda_{\rm FMR}$ of 1.45×10^8 rad/s. This value of λ was chosen to match up the $1/Q$ value at the FMR peak. It corresponds to an equivalent FMR linewidth of 80 Oe, which is about a factor of 2 larger than the actual half-width of the experimental resonance. This discrepancy may

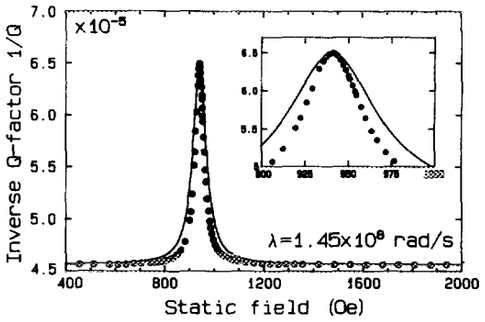

FIG. 1. Data (solid points) and theory (solid line) for the inverse Q factor vs in-plane static field for a 620-Å permalloy film at 10 GHz. The theory is for a value of the Landau–Lifshitz damping λ of 1.45×10^8 rad/s. The inset shows results for the resonance region on an expanded scale.

be due, in part, to the effect of dispersion and cavity frequency shift on the resonance line shape, as well as field-dependent two magnon scattering contributions to the loss. These points will be discussed at the end of this section. It is to be emphasized that the theoretical $1/Q$ change is based on an absolute loss calculation.

It is important to note that the theory and the data in Fig. 1 do not agree off resonance. The experimental $1/Q$ falls off much more rapidly than does the theory as one moves away from the FMR peak in field. In line with the expectation that the losses off resonance are smaller than those connected with FMR, the tails of the absorption profile can be fitted by a *smaller* value of λ than $\lambda_{\rm FMR}$. This result is shown in Fig. 2, for which the vertical scale has been expanded and the theoretical $1/Q$ versus field has been calculated for $\lambda_{\rm OFF} = 0.5\times10^8$ rad/s. Note that $\lambda_{\rm OFF}$ is a factor of 3 smaller than $\lambda_{\rm FMR}$. The fits for both the low- and high-field tail regions of the absorption profile are quite good.

The logical extension of the above results would be to fit the theory to the data point-by-point and obtain a field-dependent damping parameter $\lambda_{\rm eff}(H)$. The results of such a procedure are shown in Fig. 3. The fitted λ value of about 1.45×10^8 rad/s at FMR and tail values around 0.55×10^8 rad/s are evident. These fits corroborate the basic results in Figs. 1 and 2. The microwave losses are indeed field depen-

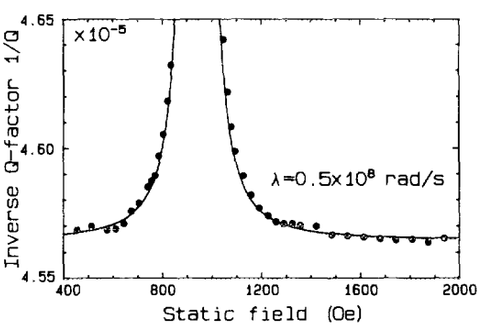

FIG. 2. Data (solid points) and theory (solid line) for the inverse Q factor vs in-plane static field for a 620-Å permalloy film at 10 GHz. The theory is for a value of the Landau–Lifshitz damping λ of 0.5×10^8 rad/s.

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dent and the off-resonance losses are substantially smaller than the losses at FMR. The fitted values of λ_{OFF} correspond to a half-power linewidth of 27 Oe, which is comparable to the best published values for single-crystal transition metal or alloy films.[9]

The results of the fitting procedure in Fig. 3 do reveal some significant problems for (1) the shoulder portions of the FMR just above and below the FMR peak and (2) the far-field tail regions. First consider the problem with the FMR shoulders. Figure 4 shows λ_{eff} versus field for the FMR region on an expanded scale. These results show that the fitted λ_{eff} is *double valued* in the shoulder region. One can fit the $1/Q$ data just to either side of the FMR point by either decreasing λ, corresponding to a very sharp and narrow resonance, or increasing λ, corresponding to a very broad resonance. Neither fit corresponds to the physical reality of some intermediate λ between λ_{FMR} and λ_{OFF}.

The problem here is related to the effect of dispersion on the line shape. In the case of insulators, one must use both the real and imaginary components of the microwave susceptibility, along with the data on *both* cavity Q and cavity frequency shift, in order to extract meaningful field-dependent loss in the vicinity of FMR.[2] In the case of metals, the theoretical analysis outlined above deals only with loss in the thin film and the effect of that loss on cavity Q. Dispersion is not included in the analysis. The importance of dispersion is underscored by the fact that the fitted λ_{eff} values make sense in two field regions only, one right at FMR where the dispersion is zero and the second far from resonance where dispersion has no effect. In order to resolve this problem, it will be necessary to solve not only the electromagnetic boundary value problem for the magnetic film, but also the total problem for the film cavity combination. On the basis of such solutions, fits could include both loss and dispersion and, in principle, yield meaningful, continuous fits for $\lambda_{eff}(H)$.

Return now to the problem with the fits in the far-field tail regions in Fig. 3. The λ_{eff} values below $H = 700$ Oe and above $H = 1300$ Oe show large scatter. The problem here is that in these far-field tail regions the difference between measured values of $1/Q$ and $1/Q_{\infty}$ becomes comparable to the error of the measurement. Forced fits of the theory to these tails lead therefore to large errors in λ_{eff}. This is also evident from Fig. 2. The theoretical curve in Fig. 2 is for λ_{OFF}

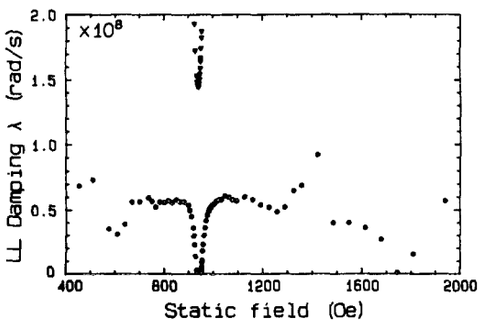

FIG. 3. Fitted values of the Landau–Lifshitz (LL) damping λ vs static field, based on the data in Fig. 1.

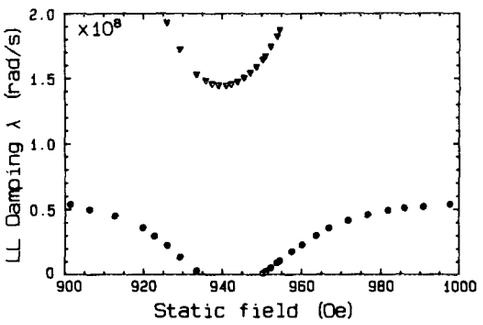

FIG. 4. Fitted values of the Landau–Lifshitz (LL) damping λ vs static field from Fig. 3 on an expanded scale.

$= 0.45 \times 10^8$ rad/s. In order to force the theory to match up with the data at any particular point, a relatively large change in λ_{eff} would be needed. The deviations of the data points from the curve in the high-field tail region of Fig. 2 are reflected in the scatter for the forced fits in Fig. 4. The problem is one of relative error in the far-field tail regions.

While the above fits yield a field-dependent λ_{eff} which satisfies the condition $\lambda_{OFF} < \lambda_{FMR}$ and is in qualitative accord with physical considerations, it is important to note one quantitative discrepancy in this result. Thin-film FMR for in-plane static fields occurs at a static field such that the top of the spin-wave band for low wave numbers matches the FMR frequency. In principle, because of two magnon scattering, this implies that fitted values of λ_{eff} should be large and comparable to λ_{FMR} for fields below FMR and should decrease to values smaller than λ_{FMR} only for fields above the FMR point. The good fits in both of the near-field tail regions for the *same value* of λ_{OFF} are inconsistent with this expectation. In line with the comments on the near-resonance fits, dispersion appears to be an essential ingredient for the quantitative determination of $\lambda_{eff}(H)$. The results of Ref. 5 do show a peak in effective linewidth just on the high-field side of FMR.

ACKNOWLEDGMENTS

This work was supported in part by the United States Office of Naval Research, Contract N00014-87-K-0325 P00001. The authors are grateful to T. E. Crumbaker for assistance with the surface profilometer measurements.

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