Frequency dependence of the parallel and perpendicular ferromagnetic resonance linewidth in Permalloy films, 2-36 GHz

Carl E. Patton*

Colorado State University, Fort Collins, Colorado 80523

Z. Frait

Physics Institute Czechoslovakia Academy of Science, Prague, Czechoslovakia

C. H. Wilts

California Institute of Technology, Pasadena, California 91101
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Ferromagnetic resonance linewidth data for 75% Ni-25% Fe evaporated thin films at 2–36 GHz for both parallel and perpendicular orientations show that the two linewidths are the same and increase linearly with frequency above 10 GHz. At lower frequencies the parallel linewidth is in accord with the high-frequency behavior, but the perpendicular linewidth levels off at 10–30 Oe. These data suggest that the high-frequency relaxation is characteristic of a Landau-Lifshitz λ-type process but that the low-frequency losses are characteristic of a process intermediate between λ-type and $1/\tau$-type relaxation.

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The ferromagnetic resonance linewidth in 75% Ni-25% Fe evaporated thin films has been measured for both parallel and perpendicular FMR at frequencies from 2 to 36 GHz. This represents the first reported study of linewidth for both orientations over such a wide frequency range. The data were obtained at room temperature, for films ranging in thickness from 190 to 3100 Å. The films were prepared as described previously,[1] except that 1-cm-diam and 1.88-mm-diam films were simultaneously evaporated on 150–260 °C substrates for the low- (< 8 GHz) and high- (> 9 GHz) frequency measurements, respectively.

Data for films thinner than 500 Å are shown in Fig. 1. For an understanding of "intrinsic" relaxation processes in the ferromagnetic transition metal alloys, this thin-film limit is of particular importance because neither exchange conductivity eddy current losses nor two-magnon processes should contribute appreciably to the linewidth.[2–4] The results show that the parallel FMR linewidth increases linearly with frequency, and extrapolates to near zero at zero frequency. This linear dependence is consistent with a Landau-Lifshitz-type phenomenological description of the relaxation with a damping parameter α of 0.005 or $\lambda \approx 7\times10^{7}$ sec^{-1}.

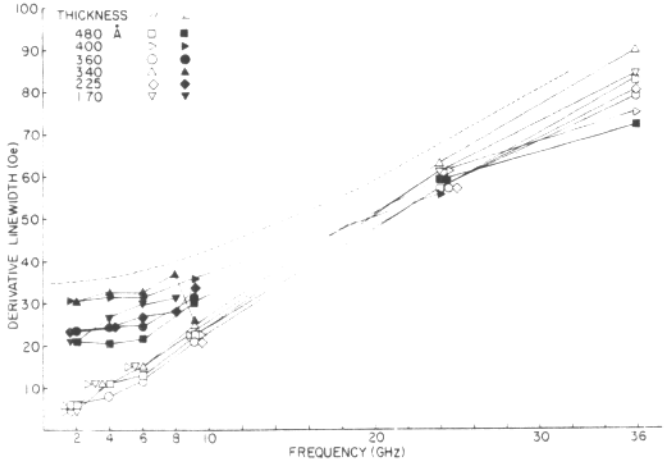

FIG. 1. Ferromagnetic resonance linewidth versus frequency for parallel and perpendicular FMR in films 170–480 Å thick.

The perpendicular linewidth data overlap the parallel results at 25 and 36 GHz, in that the linewidths are about the same. At lower frequencies, the perpendicular linewidths are larger than for parallel. In general, the perpendicular linewidth tends to level off at some value between 10 and 30 Oe at the low-frequency end of the plot. The perpendicular data show much more film-to-film variation than do the parallel linewidths.

Previous work has focused separately on frequencies of 9 GHz and above, or 7 GHz and below, and has arrived at seemingly contradictory conclusions. (i) For $f > 9$ GHz, $\Delta H_{\parallel}$ increased linearly with frequency.[5] In cases where *both* $\Delta H_{\parallel}$ and $\Delta H_{\perp}$ were measured, they were about the same.[3,6] These results supported the conclusion that the relaxation was of the Landau-Lifshitz type, which may be called a λ process. (ii) A linear frequency dependence for $\Delta H_{\parallel}$ was also observed for $f = 1-7$ GHz which was consistent with (i),[7] in that the increase gave the same α or λ. However, the $\Delta H_{\perp}$ was found constant at about 30 Oe for $f = 1-4$ GHz and the $\Delta H_{\parallel}$ when converted to frequency-swept linewidths yielded $\Delta\omega/\gamma \approx 30$ Oe, independent of frequency.[4] These results supported the conclusion that the relaxation was adequately de-

TABLE I. Comparison of the parallel and perpendicular linewidths at 9.2 GHz for films 170–480 Å thick.

Parallel	Perpendicular
20.4	34.0
21.0	31.0
21.5	31.0
22.5	30.0
23.0	32.5 (exception)
25.0	26.0

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scribed by a constant relaxation time, insofar as $\Delta(\omega/\gamma)_\perp = \Delta(\omega/\gamma)_\parallel$ is satisfied. [For $\perp$ FMR, $\Delta(\omega/\gamma)_\perp = \Delta H_\perp$.] Such relaxation may be termed a $1/\tau$ process.

The present results suggest that both of these conclusions are qualitatively correct in that the high-frequency coincidence of $\Delta H_\parallel$ and $\Delta H_\perp$ and the over-all linear frequency dependence of $\Delta H_\parallel$ are characteristic of a λ process, and the leveling off of the low-frequency $\Delta H_\perp$ to values approaching $\Delta(\omega/\gamma)_\parallel$ is characteristic of a $1/\tau$ process.

Clearly, the low-frequency relaxation is really intermediate between the λ and $1/\tau$ limits, since $\Delta H_\perp$ is greater than $\Delta H_\parallel$ (for a λ process they would be the same) but is smaller than the $\Delta(\omega/\gamma)_\parallel$ indicated by the dotted line (for a $1/\tau$ process, these would be the same).[7] It is comforting that the $\Delta H_\perp$ do fall between the two limits, $\Delta H_\parallel < \Delta H_\perp < \Delta(\omega/\gamma)_\parallel$.

A definite correlation was noted between large $\Delta H_\perp$ [approaching the $\Delta(\omega/\gamma)$ limit] and small $\Delta H_\parallel$ at 9.2 GHz, where linewidth determinations of the highest accuracy were possible. This correlation is shown in Table I. With one exception, small $\Delta H_\parallel$ and large $\Delta H_\perp$ go hand in hand. This observation helps to explain why the previous low-frequency $\Delta H_\perp$ results were on the order of 30 Oe. The films used in that study were selected on the basis of their small $\Delta H_\parallel$ values.[4,8]

This correlation also helps to eliminate the possibility that the $\Delta H_\perp$ are larger at low frequencies due to nonsaturation of the films when perpendicularly magnetized by fields only 300—2000 Oe in excess of $4\pi M_s$. If this were the case, there should be no such correlation between $\Delta H_\parallel$ and $\Delta H_\perp$. Furthermore, it is found that the spin-wave resonance peaks (for thicker films) have exactly the same spacings at 2 and 4 GHz as they do for 9.2 GHz.

The present data indicate that the basic character of the FMR relaxation at low frequency (< 7 GHz) and high frequency (> 9 GHz) is quite different. The high-frequency linewidths for parallel and perpendicular FMR are the same, and are nicely described by a λ process (as is FMR at intermediate angles).[6] The low-frequency $\Delta H_\perp$ are generally larger than the $\Delta H_\parallel$, and the linewidths, considered together, are most consistent with a $1/\tau$ process. The linear frequency dependence of $\Delta H_\parallel$,[5] confirmed here for the entire 2—35-GHz range, implies some kind of connection between the relaxation character for these two frequency regions. The same slope yields a constant λ at high frequency and a constant $1/\tau$ at low frequency.

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