TEMPERATURE DEPENDENCE OF THE EFFECTIVE LINEWIDTH IN POROUS AND FINE GRAIN POLYCRYSTALLINE YTTRIUM IRON GARNET*

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Summary

Data on the temperature dependence of the off-resonance effective linewidth ΔH_{eff} have been obtained at 9.94 GHz for porous and fine grained samples of polycrystalline YIG. The high field ΔH_{eff} increases with decreasing temperature from 300K to 250K. From 250K to 100K, ΔH_{eff} is constant. ΔH_{eff} is linearly proportional to porosity, with about 0.4 Oe/%, which is superimposed on a porosity independent contribution which increases from a few tenths Oe at 300K to about 2.2 Oe below 250K. For samples with an average grain size a_o of 3μ to 30μ, ΔH_{eff} is proportional to $a_o^{-\frac{1}{2}}$ at 300K and to a_o^{-1} below 250K. These results are discussed in terms of a magnetostriction model and a spin-wave transit time model.

Introduction

The investigation of microwave losses in polycrystalline materials has led to interest in the origin of the off-resonance losses. The effective linewidth concept was introduced[1] to provide a meaningful loss parameter for ferrite materials biased at any applied magnetic field. Near resonance the losses are generally understood in terms of inhomogeneous broadening or degenerate spin wave scattering.[2] However, far from resonance, such scattering should not contribute. Particularly at high applied magnetic fields, the uniform precession mode excited by the microwave field is not degenerate with low wave vector spin waves, and two-magnon relaxation processes should not occur. Consequently, the effective linewidth ΔH_{eff} measured at high fields is generally taken as a measure of the microwave loss of the material in the absence of two-magnon relaxation or inhomogeneous broadening.

The high field ΔH_{eff} at 300K has been found to be independent of field, a linear function of porosity and proportional to $a_o^{-\frac{1}{2}}$, where a_o is the average grain size.[3,4,5] The values are generally greater than intrinsic single crystal linewidths by an order of magnitude or more. In the absence of two-magnon scattering or inhomogeneous broadening, these linewidths should,in theory, be comparable. No satisfactory explanation of this discrepancy has been discovered.

Two models have been suggested to be relevant to the off-resonance ΔH_{eff} in polycrystals. A process in which the anisotropic magnetostriction leads to phonon excitation was proposed by Schlömann.[6] He calculated a linewidth which varies as $(\lambda_{100}-\lambda_{111})^2/M_o$, where λ_{100} and λ_{111} are the magnetostriction coefficients measured along the [100] and [111] directions, respectively, and M_o is the saturation magnetization. He obtained a numerical value of less than 0.1 Oe for strain free YIG at 10 GHz, which is much too small to explain the data. It was proposed that the mechanism could yield larger linewidths in polycrystals which are not strain free.

A transit time model, first proposed to explain the grain-size dependence of the spin-wave linewidth,[7] has also been suggested as a possible explanation for ΔH_{eff}. The chief argument in favor of this mechanism is the success of the model for both the wave-number dependence and grain-size dependence of ΔH_k, combined with the fact that ΔH_k and ΔH_{eff} appear to track each other in porous YIG. The major drawbacks are: (1) the theoretical linewidths for the near zero wavenumber mode involved in the ΔH_{eff} experiment are much too small, on the order of 0.01 Oe. (2) The observed grain size dependence of ΔH_{eff} is $a_o^{-\frac{1}{2}}$, rather than the a_o^{-1} variation observed for ΔH_k and predicted by the model.[2,4]

In an attempt to evaluate candidate mechanisms, the temperature dependence of the off-resonance ΔH_{eff} has been investigated. The effective linewidths were measured for temperatures from 100K to 300K at 9.94 GHz for two series of polycrystalline YIG samples: (1) a porous series with porosity from 1.9% to 16.3%, and (2) a fine grained series with average grain size from 2.4μ to 9.7μ. A dense, large grain size polycrystalline YIG sample, with a porosity of less than 0.5% and an average grain size of 30μ, was also measured for comparison with the samples in each series. The samples are the same as those used for the earlier studies of Refs. 4 and 5.

Experiment and Data

The effective linewidths were determined from susceptibility data obtained with a high Q cavity feedback technique.[8] A cylindrical cavity with a Q of about 24,000 was operated in a TE_{011} mode. Improved sensitivity was obtained by using a high stability counter[9] to directly measure the klystron frequency to within 200 Hz at 10 GHz. A temperature regulated water jacket around the cavity was used to stabliize the cavity temperature. Short term temperature fluctuations were reduced to less than ± 0.002°C at 20°C. With this temperature stabilized cavity arrangement, changes as small as one percent in the cavity Q could be measured. The spherical samples were positioned in the center of a low dielectric tube[10] passing through the cavity. The tube was aligned along the axis of the transmission cavity. Sample temperature was controlled by varying the temperature of helium gas flowing through the tube. The microwave cavity was evaluated to reduce the effect of the sample tube on the temperature of the cavity.

The effective linewidth for a given sample was measured as a function of the applied magnetic field. For fields greater than about 6 kOe, the effective linewidth is relatively constant. Using the values of ΔH_{eff} for fields from 6 kOe to 9 kOe, an average value of the high field ΔH_{eff} was determined. The temperature of the sample was varied to obtain values of the high field ΔH_{eff} from about 100K to 300K. The ΔH_{eff} for three porous samples (1.9%, 6.5%, 16.3%) are shown as a function of temperature in Fig. 1. Data for the dense sample which has a porosity of less than 0.5% are also included. The results show that the high field ΔH_{eff} increases with decreasing temperature from 300K down to about 250K. Below 250K, the effective linewidth levels off at a constant value independent of temperature. The dense material shows no significant change in ΔH_{eff} over the entire tempreature range.

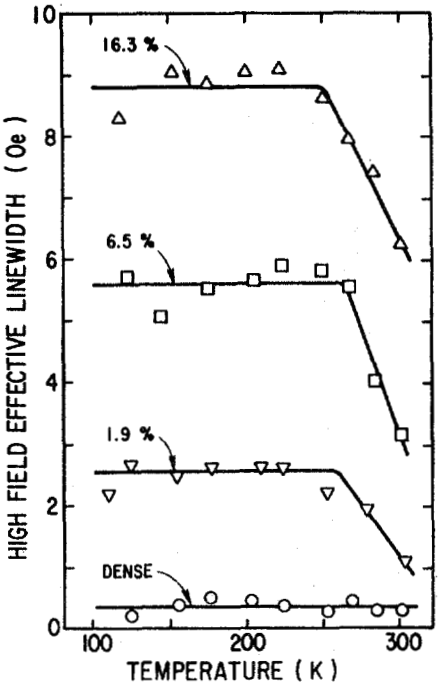

Fig. 1. High field effective linewidth versus temperature for porous YIG at 9.94 GHz.

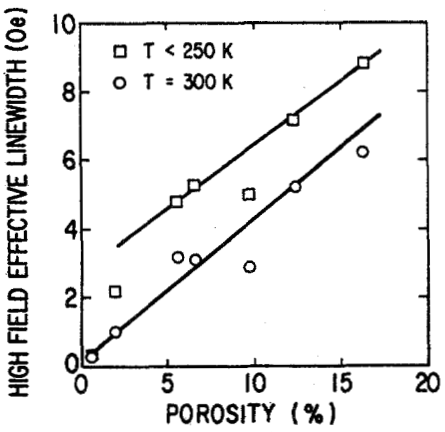

Fig. 2. Low temperature and room temperature high field effective linewidth versus porosity for porous series including points from Fig. 1.

Figure 1 also indicates that ΔH_{eff} increases with porosity both at 300K and at lower temperatures. The values of ΔH_{eff} for temperatures from 100K to 250K were used to compute a low temperature average. The average low temperature values and the room temperature values are plotted versus porosity in Fig. 2. In addition to points from the data in Fig. 1, data on samples with porosities of 5.5%, 9.7%, and 12.4%, based on measurements of ΔH_{eff} at 300K, 200K, and 120K, are also included. Figure 2 shows that at 300K the high field ΔH_{eff} is linearly proportional to porosity for porosities from 1% to 20%, with a slope of 0.4 Oe/%. This is in agreement with previous results. Below 250K, the results show that ΔH_{eff} is also linearly proportional to porosity for porosities above 5%. Below 5%, the low temperature value approaches the room temperature value. The slope of the linear portions at both temperatures is about the same. This result indicates that the temperature effect is porosity independent.

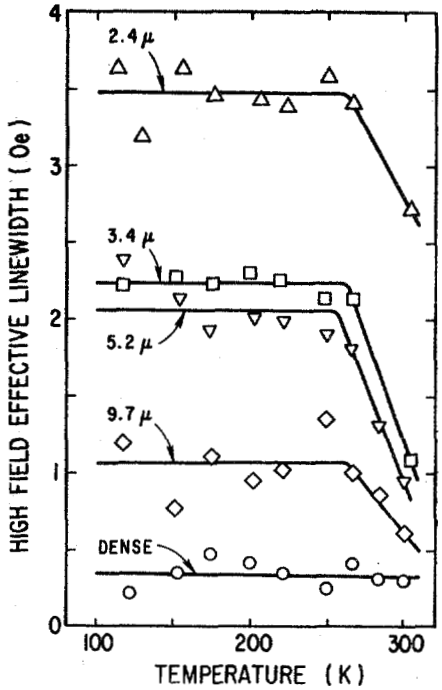

Fig. 3. High field effective linewidth versus temperature for fine grain YIG at 9.94 GHz. Average grain sizes are indicated.

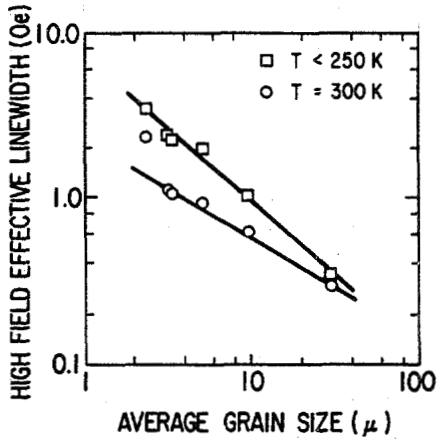

Fig. 4. Low temperature and room temperature high field effective linewidth versus average grain size.

The high field average of ΔH_{eff} for each sample of the fine grain series is plotted as a function of temperature in Fig. 3. Data for samples with average grain sizes of 2.4, 3.4, 5.2, and 9.7μ are included along with the dense 30μ grain size sample data. Each sample in the fine grain series shows the same qualitative temperature behavior as evidenced by the porous samples. An increase in ΔH_{eff} with decreasing temperature is observed down to 250K. The effective linewidth is constant below 250K. At any temperature, ΔH_{eff} increases with decreasing grain size.

A plot of the room temperature and the average low temperature ΔH_{eff} as a function of average grain size a_o is shown in Fig. 4. Included are points for the five samples of Fig. 3, and an additional 3.2μ sample for which measurements were made at 300K, 200K, and 120K. The data show that ΔH_{eff} varies as a_o to a negative exponent. At 300K, the variation is close to an $a_o^{-\frac{1}{2}}$ dependence, in agreement with previous work.[3,4] Below 250K, the variation is more like an a_o^{-1} dependence.

Discussion

Possible contributions to the effective linewidth include single crystal mechanisms, as well as those which derive from microstructure considerations. The usual contributions to the resonance linewidth in polycrystals, related to inhomogeneous broadening and two-magnon scattering, should not be important.

Impurity processes, including valence exchange, slowly relaxing impurity and rapidly relaxing impurity processes, may contribute to part of single crystal linewidths.[11] These temperature-peak processes usually produce a significant linewidth peak in the 50K - 200K temperature range. A low temperature peak is not observed in any of the data reported here. Impurity processes appear to contribute little to the measured effective linewidths of these samples.

The systematic variations in the effective linewidth vs. temperature, with porosity and grain size, imply that microstructural considerations are involved. Unfortunately, the two processes which have been proposed do not appear to explain the data in any systematic manner. Several features of the data are consistent with the magnetostriction or the transit-time mechanisms. On the other hand, several features are inconsistent. The remainder of this section will deal with these features.

Consider first the magnetostriction process. The variation of $(\lambda_{100} - \lambda_{111})^2/M_o$ with temperature can be determined from the known dependences of λ_{100}, λ_{111}, and M_o. Compared to the room temperature value for YIG, this factor doubles at 250K and increases sevenfold at 100K. The data for the fine grain series in Fig. 3 do show an increase by a factor of two in ΔH_{eff} in going from 300K to 250K for the 3.4μ, 5.2μ, and the 9.7μ grain size samples. This could be a manifestation of the magnetostriction process. Below 250K, however, the data do not show the continuous increase predicted by the model. Similar remarks apply to the 1.9% and 6.5% porous samples in Fig. 1.

If the increase in ΔH_{eff} from 300K to 250K is magnetostriction related, it should be quite sensitive to strains in the polycrystals. Hence, the increase should be much smaller in annealed samples. This experiment has yet to be done. If the magnetostriction process is operative, the leveling off below 250K would necessarily require that the crystallites become mechanically decoupled below this temperature. It is hard to imagine how such a decoupling could occur. Such behavior should be observable from measurements of the resonance linewidth or near-resonance effective linewidth as a function of temperature.

Finally, consider the transit time process. It is tempting to assign the low temperature ΔH_{eff} to this process because of the inverse grain size dependence. This does not appear to be reasonable, however, since the transit time contribution should not disappear at high temperature. Moreover, the values are much too large to be quantitatively explained by the model, as applied to the near-zero wavenumber mode involved in the effective linewidth experiment.

On the basis of magnetostriction and trainsit time processes, one would expect a relatively small temperature independent ΔH_{eff} with an inverse grain size dependence at high temperature and an increase in ΔH_{eff} according to $(\lambda_{100} - \lambda_{111})^2/M_o$ at low temperature. The data show a completely different behavior.

Conclusion

On the basis of the present data on effective linewidth versus temperature for fine grain and porous YIG, it is clear that there are major problems in the application of either the magnetostriction mechanism or the transit time model to explain off-resonance relaxation in polycrystalline ferrite.

The inverse grain size dependence below 250K is qualitatively consistent with the transit time process, but the numerical values are much too large and the a_o^{-1} dependence is in the wrong temperature range. Further data on the wave number dependence of the spin-wave linewidth as a function of temperature should clarify the role of a transit time process.

The two-fold increase in ΔH_{eff} from 300K to 250K is also qualitatively consistent with the magnetostriction process, but the abrupt cutoff below 250K and the temperature independent ΔH_{eff} below 250K is not consistent with the mechanism. If the crystallites become mechanically decoupled below 250K, this could resolve the problem. Such a decoupling should be evident in the temperature dependence of the resonance linewidth or the near-resonance effective linewidth. It would be evident as well from the k-dependence of ΔH_k at low temperature. If the magnetostriction process is indeed operative in this temperature region, strain relief by annealing should reduce the ΔH_{eff} substantially.

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