

## Ferromagnetic Resonance in Polycrystalline Ferrites with Hexagonal Crystal Structure

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A theory is developed for the shape of the ferromagnetic resonance line of polycrystalline ferrites with hexagonal crystal structure. The theory is applicable if the anisotropy field is much larger than the saturation magnetization. It predicts the occurrence of several absorption peaks whose locations and intensities depend on the magnitudes of the various anisotropy constants. For intermediate values of the anisotropy constants two absorption peaks should occur on the low-field side of  $\omega/\gamma$  if  $K_1 < 0$ ; one peak should occur on each side of  $\omega/\gamma$  if  $K_1 > 0$ . Experimental results on various hexagonal compounds are in good qualitative agreement with the theory.

### I. INTRODUCTION

IN previous papers<sup>1,2</sup> a theory of ferromagnetic resonance in polycrystals has been described which is expected to be valid if the anisotropy field is much larger than the saturation magnetization. The basic approximation used in this theory is the neglect of dipolar interaction and demagnetizing effects. This approximation is well justified for nearly compensated ferrimagnetic materials and, to a lesser extent, for other materials with a comparatively large anisotropy field. Within the range of applicability of this theory, the motion of the magnetization vector of each single-crystal grain is independent of the motion of neighboring ones. Under these conditions the absorption as a function of magnetic field should be essentially proportional to the number of grains that go through resonance in a given range of applied field. This "distribution of resonance field strengths" can be calculated if the angular dependence of the anisotropy energy is known and if the orientations of the single-crystal grains are randomly distributed. Because of the finite line width of the single-crystal grains the observed absorption line should not be an exact but rather a smeared-out image of the calculated distribution. The neglected dipolar interaction may be expected to lead to an additional broadening and to a slight shift of the absorption maxima.

The theory previously developed for cubic materials has now been adapted to the case of hexagonal materials. In the present paper, some of the theoretical results will be described and compared with experimental data.

### II. THEORY

In hexagonal crystals the angular dependence of the anisotropy energy can be described by

$$E_{\text{anis}} = K_1 \sin^2\theta + K_2 \sin^4\theta + K_3 \sin^6\theta + K_4 \sin^6\theta \cos 6\varphi + \dots, \quad (1)$$

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<sup>1</sup> Ernst Schlömann, *J. Phys. Chem. Solids* 6, 257 (1958).

<sup>2</sup> E. Schlömann and J. R. Zeender, *J. Appl. Phys.* 29, 341 (1958).

where  $\theta$  and  $\varphi$  are polar coordinates of the magnetization vector in a coordinate system whose axis coincides with the hexagonal axis of the crystal. It may be expected on theoretical grounds that the magnitudes of the anisotropy constants  $K_n$  decrease rapidly with increasing  $n$ . An analysis of experimental resonance curves on the basis of the theory described in this paper supported this. The analysis also showed that the fourth term of Eq. (1) can be very important, even though it is small, if  $K_1$  is negative, i.e., if the plane perpendicular to the hexagonal axis is energetically preferred over the axis. The reason for this behavior is that the fourth term of Eq. (1) is the lowest one that leads to an anisotropy in the preferential plane. The third-order term on the other hand is not important and can be disregarded for practical purposes.

From Eq. (1) one can in principle obtain the resonance field strength as a function of the orientation of the dc field with respect to the crystal axes. In practice such a calculation is extremely involved, primarily because the direction of the magnetization does not necessarily coincide with the direction of the applied field. Fortunately, the distribution of resonance field strengths can be calculated in an approximate way without knowledge of the complete angular dependence. The essential information is a knowledge of the stationary points of the resonance field surface and of the behavior in the vicinity of these points. It was shown in reference 1 that the stationary points give rise to characteristic singularities of the distribution. If  $|K_2|$  is very small compared to  $|K_1|$  the only stationary points of the resonance field surface are those required by symmetry. They lie on the hexagonal axis or in the plane perpendicular to this axis. As the ratio of  $|K_2|$  and  $|K_1|$  increases, other stationary points develop. The distribution of resonance field strengths exhibits additional singularities in such a case. An example of this behavior is the "preferred cone" region of hexagonal materials.<sup>3</sup>

The width of the distribution is essentially determined by the first-order anisotropy constant since this

<sup>3</sup> H. B. Casimir, *J. phys. radium* (to be published).

is usually much larger than any other anisotropy constant. The distribution has a logarithmic singularity at a field strength corresponding to resonance in the intermediate direction. This singularity always produces a peak in the absorption curve. If the anisotropy is sufficiently large an additional peak occurs at a field strength corresponding to resonance in the easy direction. Under certain conditions a third peak may occur at a field strength corresponding to resonance in the hard direction. For  $K_1 > 0$  and  $|K_2| \ll K_1$  the theory predicts the occurrence of one or two absorption peaks associated with the easy and the intermediate directions. The two peaks lie on opposite sides of  $\omega/\gamma$  ( $\omega$  is the frequency and  $\gamma = ge/2mc$  is the gyromagnetic ratio) and the low-field peak becomes larger with increasing anisotropy. Their separation is essentially proportional to  $K_1$ . For  $K_1 < 0$  and  $|K_2| \ll |K_1|$  the theory predicts the occurrence of one, two, or three absorption maxima depending on the magnitudes of  $K_1$  and  $K_2$ . The two low-field peaks lie on the low-field side of  $\omega/\gamma$ . They correspond to resonance in the easy and intermediate directions, and their separation is essentially proportional to  $K_4$ . The high-field peak corresponds to resonance in the hard direction and lies on the high-field side of  $\omega/\gamma$ . It is usually quite weak and should be noticeable only if  $K_2$  is negative and of fairly large magnitude.

### III. MEASUREMENTS

Spherical samples of  $Mg_2Y$ ,  $Mg_2Z$ ,  $Zn_2Y$ ,  $Co_2Y$ ,  $Co_2Z$ , and  $MgZnY^4$  were prepared from carbonates and

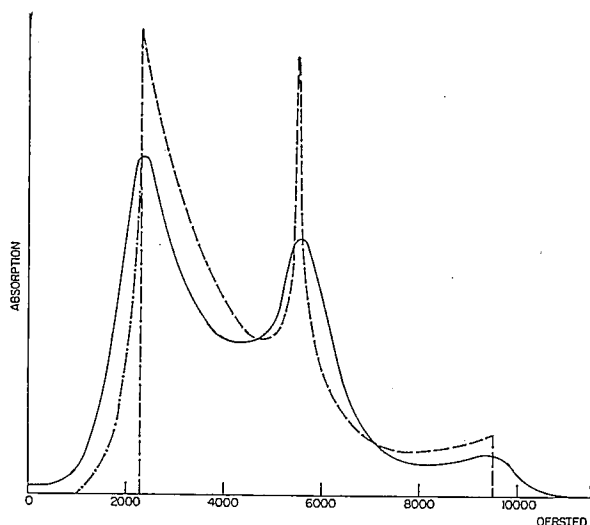


Fig. 1. Measured and calculated absorption lines for  $Ba_2Mg_2-Fe_{13}O_{22}(Mg_2Y)$  measured at 15967 Mc. The theoretical curve is valid for  $g=2$ ,  $2K_1/M = -3800$  oe,  $2K_2/M = -420$  oe,  $2K_4/M = 120$  oe,  $K_3=0$ .

<sup>4</sup>The notation is that used by Jonker, Wijn, and Braun, Philips Tech. Rev. 18, 145 (1956).

oxides by standard ceramic techniques. Ferromagnetic resonance was observed at room temperature at frequencies in the  $X$ -band and  $KU$ -band regions. The usual precautions were taken to avoid size effects. No significant line structure was observed in  $Co_2Y$ ,  $Co_2Z$ , and  $Zn_2Y$ ; and the  $Zn_2Y$  samples showed a comparatively narrow line ( $\Delta H \approx 500$  oe). In the other cases the resonance line was very broad and showed a well-defined structure, indicating  $K_1 > 0$  for  $Mg_2Z$  and  $K_1 < 0$  for  $Mg_2Y$  and  $MgZnY$ .

All of the  $Mg_2Y$  samples exhibited two well-resolved peaks at field strengths below  $\omega/\gamma$  (assuming  $g=2$ ). Some of the samples showed an additional very small peak at high fields. These samples were prepared using  $BaO$  rather than  $BaCO_3$  as a starting material and were prepared in a slightly different way.

### IV. DISCUSSION

Figure 1 shows a resonance curve measured at  $KU$  band that has been analyzed in detail. A similar curve was obtained with the same sample at  $X$  band. As expected on the basis of the theory, the  $X$ -band curve differed from the  $KU$ -band curve in its location and also in the relative intensity of the various peaks. It was found that a fairly good fit to the observed data could be obtained with a  $g$  value of 2. The anisotropy fields  $2K_1/M$ ,  $2K_2/M$ , and  $2K_4/M$  were then inferred from the observed locations of the absorption peaks. The theoretical curve calculated with these values is also shown in Fig. 1. It reflects the general structure of the observed resonance line quite well.

The third absorption peak that was observed in some of the  $Mg_2Y$  samples is attributed to a fairly large negative value of  $K_2$ . The difference in the anisotropy constants is probably due to a small impurity content in the starting material.

Similar agreement between theory and experiment has been obtained for  $Mg_2Z$ . In this case, only two peaks were observed, and their location indicated that  $K_1 > 0$ . Numerical values for  $2K_1/M$  and  $2K_2/M$  were inferred from the location of the two peaks ( $2K_1/M \approx 4000$  oe) but  $K_4$  could not be determined in this case.

### V. ACKNOWLEDGMENTS

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