Ferromagnetic Resonance in Various Ferrites

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The results of ferromagnetic resonance experiments at room temperature and at a frequency of 24,164 Mc/sec on spherical polycrystalline specimens of magnesium, nickel, cobalt, manganese, and manganese-zinc ferrites are summarized in Table I. Data showing the effect of sphere size ("size effect") on the apparent *g*-factor, line width, and magnetic energy absorption for a typical semiconducting ferrite are presented in the figures.

Table I. The *g*-factor and line width observed in various polycrystalline ferrite spheres.

Ferrite	Sphere diam. ~0.05 cm ΔH(*oe.*)[a]	Sphere diam. ~0.05 cm Apparent *g*	Sphere diam. →0 g^b
Mg	1030	2.01	2.03
Mg	870	2.04	2.06
Ni	520	2.18	2.21
Co	Extremely broad line	—	—
$Mn_{0.2}Zn_{0.8}$	520	2.005	2.02
$Mn_{0.3}Zn_{0.7}$	455	2.005	2.01
$Mn_{0.4}Zn_{0.6}$	465	2.01	2.03
$Mn_{0.46}Zn_{0.54}$	685	2.02	2.05
$Mn_{0.52}Zn_{0.48}$	550	2.01	2.02
$Mn_{0.8}Zn_{0.2}$	1675	2.07	2.05
$Mn_{0.9}Zn_{0.1}$	1263	2.07	2.06
Mn	618	2.02	2.05

[a] ΔH = Line width between half-power points.
[b] Estimated extrapolation to zero diameter.

The sphere diameter of each specimen was in most cases varied from 0.020 to 0.070 cm in order to take account of the "size effect" discussed below. The apparent line width and *g*-factor for a 0.050-cm sphere obtained by interpolation of the data are recorded in the second and third columns of Table I and the estimated extrapolation of the apparent *g*-factor to zero diameter is given in the last column. The precision of the measurements is in general about 0.5 percent.

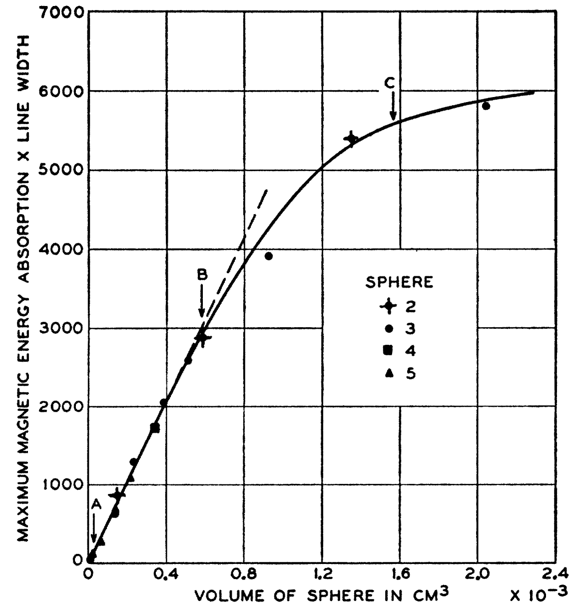

Fig. 1. (a) The effect of sphere size on the apparent *g*-factor of a specimen of polycrystalline manganese-zinc ferrite. (b) The effect of sphere size on the apparent line width of a specimen of polycrystalline manganese-zinc ferrite.

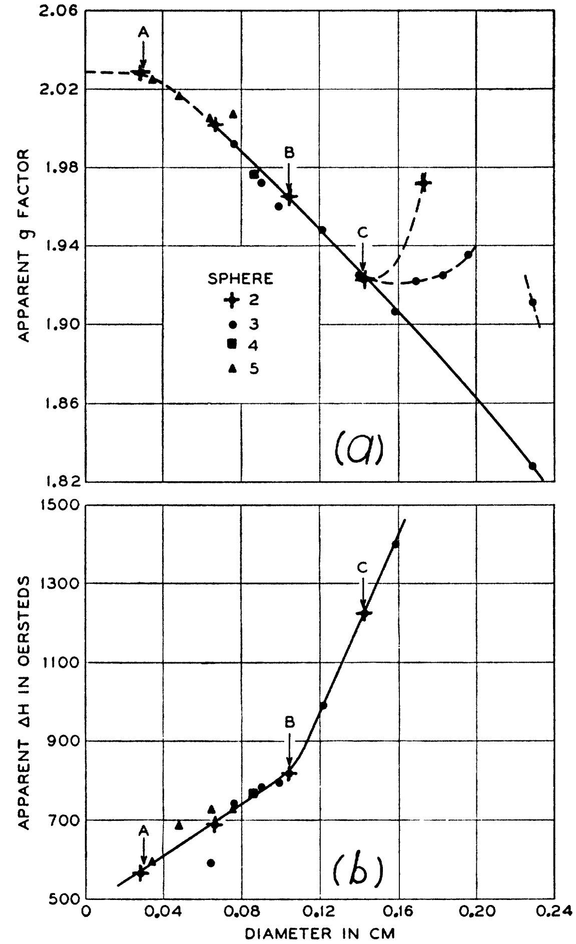

Fig. 2. The effect of sphere size on the magnetic energy absorption of a specimen of polycrystalline manganese-zinc ferrite.

The saturation magnetization (magnetic moment per gram at 0°K and infinite field) for the two specimens of Mg-ferrite in Table I having the same nominal composition but prepared at different temperatures is 41.1 and 29.3 respectively. One of us[1] has shown that they correspond to incompletely inversed ferrites. The magnitude of the *g*-factors obtained in these experiments indicates that the magnetic moment of Mg-ferrite and of the whole series of Mn-Zn ferrites is due almost entirely to the spin moments of the Fe^{+++} and Mn^{++} ions and that the contribution from the orbital moment is essentially zero in these materials. The fact that the *g*-factor and saturation moment[1] of Ni-ferrite are both considerably greater than the spin only values shows that the orbital moment contribution *is* important in Ni-ferrite. The *g*-factor of Co-ferrite could not be determined because of the extremely broad absorption line associated with its very high magnetic crystalline anisotropy.

The effect of sphere size on the apparent *g*-factor, line width, and magnetic energy absorption as determined from measurements on four spheres of a specimen of polycrystalline $Mn_{0.5}Zn_{0.5}Fe_2O_4$ is shown in Figs. 1 and 2. The observed behavior is at least qualitatively consistent with the hypothesis that the "size effect" is caused by one or more factors depending on the size of the test sphere relative to the wavelength and skin depth in the medium. The principal factors contributing to the "size effect" appear to be: (a) electromagnetic cavity-type resonance[2] above point *C*,

Fig. 1; (b) incomplete penetration of the r-f field into the sphere above B; and (c) inhomogeneity in the internal r-f field above A. Non-uniform r-f fields in the test sphere presumably give rise to a distribution of local r-f demagnetizing factors about an effective value whose deviation from the static value of $4\pi/3$ increases with diameter. At A and below, this deviation is very small but the line width still is much greater than that expected from the influence of magnetic crystalline anisotropy which should be very small in this material. The indications are that the skin depth becomes less than the radius of the sphere above point B since the break in the line width curve of Fig. 1b, the departure from a linear relationship in Fig. 2, and the onset of the "μ_R effect" all occur at this point. The "μ_R effect" refers to the minimum in the absorption curve previously observed in some ferromagnetic metals[3] and in magnetite.[4]

For the ideal case of uniform r-f fields in a sphere, the product of maximum energy absorption times line width should be directly proportional to the volume of the sphere. Figure 2 shows that the experimental data deviate from the linear relationship above point B thus indicating that the effective volume becomes smaller than the true volume for larger spheres.

The "size effect" is governed primarily by the wavelength and skin depth in the medium which may of course vary between wide limits in semiconducting ferrites depending upon such factors as composition, presence of impurities, heat treatment, etc. For example, the g-factor of polycrystalline spheres of one lot of manganese ferrite[5] was essentially independent of sphere size up to a diameter of 0.060 cm whereas that for another lot of the same ferrite disclosed a pronounced "size effect" in this region.

[1] C. Guillaud, J. Recherches C.N.R.S., No. 12, 1-10 (1950).
[2] Yager, Galt, Merritt, and Wood, Phys. Rev. **80**, 744 (1950).
[3] W. A. Yager, Phys. Rev. **75**, 316 (1949).
[4] L. R. Bickford, Jr., Phys. Rev. **78**, 449 (1950).
[5] Guillaud, Yager, Merritt, and Kittel, Phys. Rev. **79**, 181 (1950).

Precipitation and the Domain Structure of Alnico 5

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THE good magnetic properties of many permanent magnet materials originate in the precipitation from solid solution of a ferromagnetic phase. In the Alnico alloys during the precipitation heat treatment plate-like particles of an iron-rich phase form in a matrix which becomes rich in the intermetallic compound NiAl. The particles are parallel to {100} planes of the parent matrix. Thus, they present a maximum of three trace directions in any one crystal on a polished and etched surface of the polycrystalline alloy as shown by Fig. 1.

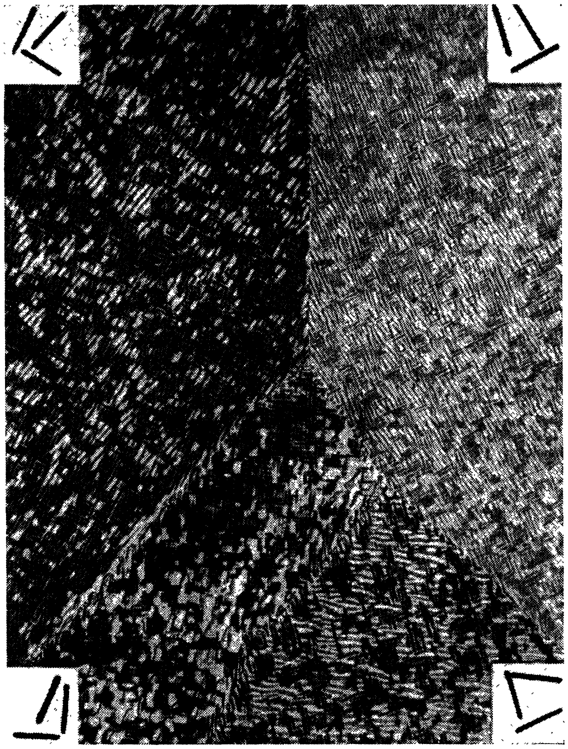

FIG. 1. Microstructure of Alnico 2 aged 300 hr at 800°C. ×500. Traces of the precipitate plates in the four crystals are indicated in the white squares at the corners.

Alnico 5 has the somewhat unique characteristic of exhibiting anisotropic properties when precipitation is initiated during cooling in a magnetic field. The residual induction is especially high in the direction of the field that is applied during cooling. Two years ago the author attributed this behavior to the preferential formation of precipitate particles on certain but not all of the three {100} planes.[1] Later Kittel, Nesbitt, and Shockley[2] showed that anisotropic properties are present immediately after the controlled cooling in the magnetic field and prior to the precipitation heat treatment. This indicates that the preferred orientation of nuclei is established during the cooling and that merely growth on these nuclei occurs during the subsequent aging treatment.

FIG. 2. Microstructure of Alnico 5 aged 300 hr at 800°C. ×500.

Kittel and his co-workers[2] attributed the preferred orientation to a minimum demagnetization energy for nuclei which have their surface closely parallel to the field direction. Recently, the author published further microscopic evidence that confirmed this expected preferred orientation: a single crystal which had been cooled with the field along the [001] direction and then reheated to 800°C and held for 16 hr to grow the precipitate