SOVIET PHYSICS JETP VOLUME 30, NUMBER 6 JUNE, 1970

INVESTIGATION OF THE DOMAIN STRUCTURE OF A NICKEL FERRTIE SINGLE CRYSTAL BY THE FMR METHOD

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Submitted June 23, 1969

Zh. Eksp. Teor. Fiz. 57, 1940–1946 (December, 1969)

FMR and resonance of the boundary shift in a spherical Ni ferrite single crystal sample are studied experimentally for fields oriented along the [011] and [100] axes. Resonance absorption peaks are obtained for transverse and longitudinal oscillation modes. For the [100] axis absorption peaks are obtained, which correspond to resonance of the shift of the domain boundaries. The good agreement between the experimental data and the theoretical relations suggests that in these cases the domain structure in the sample is predominantly perpendicular. Possible explanations of variation of the shape intensity and absorption peak width due to variation of the stationary field with change of the conditions of approach to the point of domain structure instability are discussed.

THEORETICAL and experimental investigations[1,2] of magnetic resonances in single-crystal ferrites in weak magnetizing fields have made it possible to determine the connection between the resonance conditions and the type of domain structure. It has been demonstrated in these investigations that it is possible to determine the type of the domain structure from the dependence of the resonant frequencies of different types of oscillations on the external constant field. The most definite information concerning the type of the domain structure is given by the dependences of the resonant frequencies for the longitudinal modes[1,2], since they are not connected with the displacements of the domain boundaries. An investigation[1,2] carried out on single crystals of yttrium garnet and MgMn and Li ferrites along the crystallographic axes [100] and [011] has led to conclusions concerning the type of the domain structures in these samples. It turned out that for yttrium garnet, with the field oriented along the [011] axis, the most probable is a perpendicular plate-like domain structure (with boundaries perpendicular to the [011] axis); for all the remaining samples, both for field orientation along the [011] axis and along the [100] axis, the most probable is an almost parallel domain structure. For yttrium garnets, the type of domain structure was determined in these investigations only from the dependence of the resonant frequency for the transverse oscillation mode. However, in[3], using cylindrical samples of yttrium garnet, they obtained the dependences of the resonant frequencies on the field in the case of longitudinal excitation, for field orientations along the [011] and [100] axes. These data show that in this case, too, the most probable domain structure in yttrium garnet is the perpendicular structure.

So far, however, in none of the samples were transverse and longitudinal resonant modes excited for a perpendicular domain structure. In this connection, interest attaches to the results obtained in the present investigation of single-crystal Ni ferrite, since longitudinal and transverse modes were excited in it in the case of orientations along the [100] and [011] axes. The dependences of the resonant frequencies of these modes on the constant field gives grounds for assuming that perpendicular domain structures are the most probable for both orientations. The measurements were performed on a spherical sample of single-crystal $NiFe_2O_4$ ($4\pi M = 3270$ G, $\Delta H = 6.7$ Oe) of 1.30 mm diameter in the frequency range from 400 to 5500 MHz. The measurement method and apparatus are described in[1,2,4]. As a preliminary, the values of the resonant FMR fields with the field oriented along the axis [100] and [011] and [111], measured in the 9000 MHz band, were used to determine the anisotropy fields and the gyromagnetic ratio (γ):

$$K_1/M = -260\ \text{Oe},\ K_2/M \approx 0, \quad \gamma = 3.05\ \text{MHz/Oe}$$

where K_1 and K_2 are the first and second anisotropy constants. These data were used to calculate the theoretical dependences of the relative frequencies ($\omega' = \omega(\gamma\,|K_1|/M)^{-1}$) on the reduced field ($H' = H(|K_1|/M)^{-1}$). The experimental results, in the form of plots of the relative resonant frequencies against the relative resonant field are shown in Fig. 1 ([011] axis) and in Fig. 2 ([100] axis). The solid lines in the same figures show the theoretical fields calculated for perpendicular domain structures without allowance for the connection with the boundary displacement. The calculation for the field oriented along the [011] axis was made in accordance with formulas (7) of[1], and for the [100] axis in accordance with formulas (14) of[4]. Figures 3 and 4 show plots of the absorption curves for the same field orientations at different excitation conditions.

For the case of the [011] axis, with transverse excitation, absorption peaks were observed, corresponding to the branches AB, AC, AD, and EF. The branch AB corresponds to FMR in a sample magnetized to saturation. For the branch AC there is very good agreement between the experimental points and the theoretical curve for the transverse mode. Just as in the preceding investigations, a branch AD appears, corresponding to the saturation field of the sample. The variation of the intensities of the resonant peaks for these branches is the same as for the samples investigated in[1,2,4]. The branch EF apparently corresponds to the resonance of the boundary displacement, since relatively distinctly pronounced peaks are observed against the background of the broad absorption band in the case of asymmetrical excitation. In the case of symmetrical excitation, an absorption band appears in this region of fields and frequencies. The most interesting are the results obtained with longitudinal excitation (the branch KLM). It is seen from Fig. 1 that there is very good agreement between the experimental point and the theoretical curve of the resonant frequencies of the longitudinal mode, calculated for a perpendicular domain structure. The intensity, form, and width of the peaks corresponding to the KLM branch change very strongly when the field changes. On the strong-field side (branch LM), the peaks have a symmetrical form and a relatively small width, so that even at relatively small intensities they are clearly pronounced ($\omega' = 0.65$, Fig. 3b). The width of these peaks is the same as for the FMR peaks of the branch AB. The peaks reach maximum intensity in fields corresponding to the central part of the branch KLM. With further decrease of the field, the intensity of the peaks decreases sharply, and they become very asymmetrical and broad, while on the weak-field side an absorption band appears. In fields $H' \approx 1.65$, there remains a sufficiently weak peak against the background of a broad absorption band, which vanishes with further decrease of the frequency. For the frequencies $\omega' < 1.5$ in the field region $H' < 1.5$, a broad absorption band is observed, with a smooth decrease towards the strongfield side.

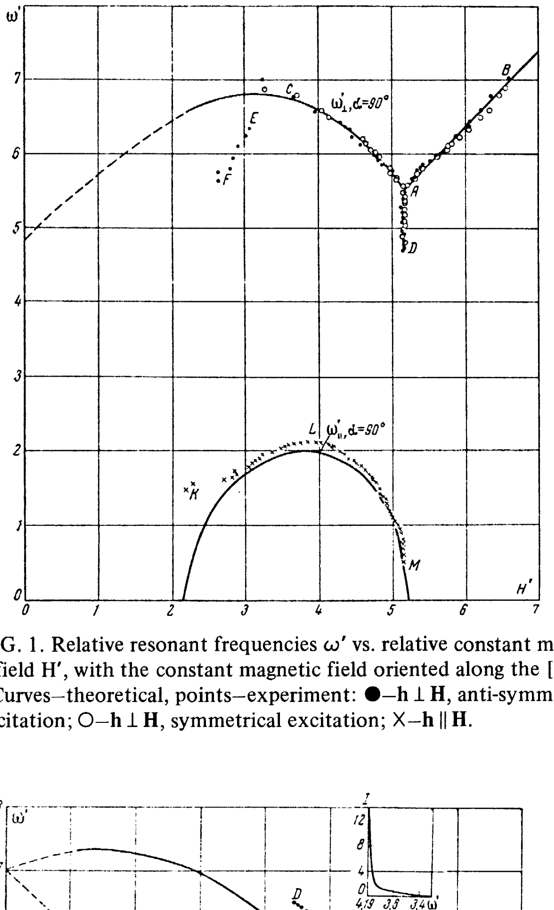

FIG. 1. Relative resonant frequencies ω' vs. relative constant magnetic field H', with the constant magnetic field oriented along the [011] axis. Curves—theoretical, points—experiment: ●—$\mathbf{h} \perp \mathbf{H}$, anti-symmetrical excitation; ○—$\mathbf{h} \perp \mathbf{H}$, symmetrical excitation; X—$\mathbf{h} \parallel \mathbf{H}$.

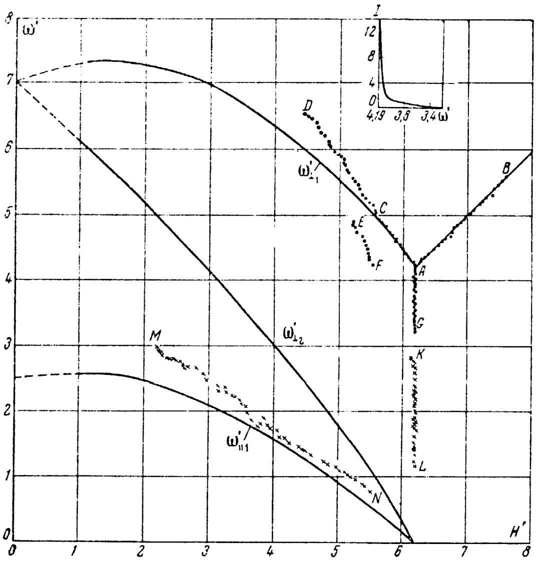

FIG. 2. Relative resonant frequencies ω' vs. the relative constant magnetic field H', with the constant magnetic field oriented along the [100] axis. Curves—theoretical, points—experiment; ●—$\mathbf{h} \perp \mathbf{H}$, X—$\mathbf{h} \parallel \mathbf{H}$. The insert shows the frequency dependence of the intensity I of the peaks of the branch AG.

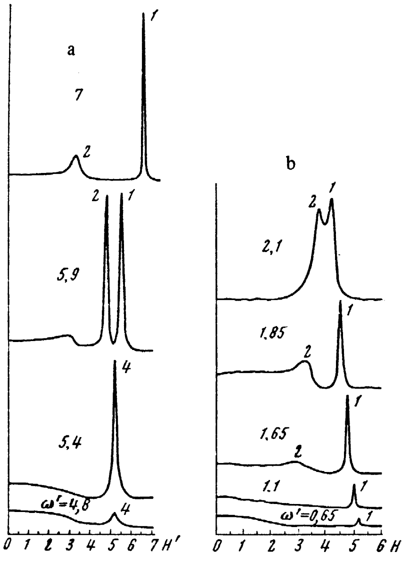

FIG. 3. Absorption curve with the constant magnetic field oriented along the [011] axis. a) Transverse excitation: 1—resonant peak of branch AB, c—of branch AC; peak at H' = 3 and $\omega' = 5.9$—branch EF; 4—of branch AD. b) Longitudinal excitation; 1—resonant peak of section KL of the branch KLM.

It is interesting to note that a similar picture is observed also for transverse modes of the branch AC. In the region of the point A, the peaks have a regular symmetrical form and a relatively small width; with increasing frequency, and consequently with decreasing field, the intensity of the peaks decreases, their width increases, and they become less symmetrical. One can assume that these changes of the width, intensity, and shape of the absorption peaks, corresponding to longitudinal and transverse oscillation modes, are connected with the singularities in the changes of the domain structure with changing field. Apparently, in relatively strong fields (but weaker than the saturation field), the domain structure is sufficiently uniform in type, and therefore in the entire volume of the sample the resonant conditions are the same, thereby ensuring clearly pronounced resonant peaks. With decreasing field, the domain structure becomes less stable, for the point of instability of the domain structure under consideration is approached ($\omega'_{\parallel\,\alpha=90^\circ} = 0$, $H' \approx 2.1$). Naturally, owing to the presence of even small inhomogeneities in the properties of the sample (magnetic anisotropy, elastic stresses, etc.). these conditions of instability set in not at once, but gradually and earlier than predicted by the theory. When the instability point is approached under such conditions, domains of other types should appear even before the instability of the entire domain structure sets in. On approaching the instability point, the number and relative volume of the domains of other types will increase. Because of this, the resonance conditions become more and more inhomogeneous, and this should lead to a "smearing" of the absorption peaks and to a sharp change in their form.

In this connection, it is of interest to consider the behavior of the absorption curves corresponding to the branch EF. As was already noted, the absorption peaks in this case are observed only in asymmetrical excitation. On approaching the point F, they spread out and go over into the absorption band with further decrease of the frequency. In the case of symmetrical excitation, a less intense absorption band is observed in the region of the branch EF. For lower frequencies and weaker fields, this absorption band becomes almost of the same intensity as the absorption band in asymmetrical excitation. Apparently, in this case the appearance of the domains of other types disturbs the homogeneity of the conditions for the boundary-displacement resonance and leads to an appreciable absorption of the microwave-field energy in the case of symmetrical excitation, owing to the displacement of the domain boundaries of the new type.

When the field is oriented along the [100] axis, the branches AB, ACD, AG, and EF correspond to the resonant peaks for transverse excitation. The branch AB belongs to the FMR in a sample magnetized to saturation; the branch AG belongs to a resonance of the same type as the resonance for the branch AD with the orientation along the [011] axis. All the branches of type AG are characterized by a sharp decrease of the intensity of the peaks with decreasing frequency. By way of an example of such a dependence, Fig. 2 shows additionally a plot of the intensity I of the peaks of the branch AG against the frequency. The dependence of the resonant frequencies of the branches ACD and EF is very similar to the analogous dependences of the resonant frequencies of the transverse mode and of the domain displacements for the yttrium garnet with the field oriented along the [011] axis (see Fig. 2a of[1]). For the case of the yttrium garnet, it was established that a branch similar to the branch EF of Fig. 2 is determined by the resonance of the boundary displacement. It should be emphasized that, in Ni ferrite, just as for the yttrium garnet, prior to the appearance of the resonance of the displacement boundary, the frequencies of the transverse type are in very good agreement with the theoretical curve (section AC) calculated without allowance for the coupling with the boundary displacement. When resonant peaks of the branch EF appear, a deviation of the experimental point from the theoretical curve is observed also for the Ni ferrite. Unfortunately, when the field is oriented along the [100] axis, there is no preferred excitation of the boundary displacement (see Eq. (6) of[2]), analogous to the asymmetrical excitation for the [011] axis. Therefore, in this case one can only assume, in analogy with the results for the [011] axis, that the EF branch in Fig. 2 corresponds to the boundary-displacement resonance. It should be noted that the deviation of the experimental points of the branch CD from the theoretical curve exists also in that region of the fields, where no clearly pronounced resonance of the boundary displacement ($H' < 5$) is observed.

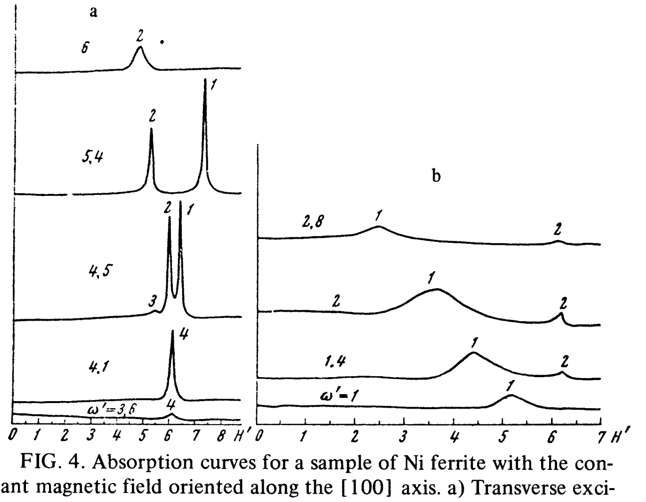

FIG. 4. Absorption curves for a sample of Ni ferrite with the constant magnetic field oriented along the [100] axis. a) Transverse excitation: 1—resonant peaks of the branch AB, 2—of the branch AD, 3—of the branch AF; 4—of the branch AG; b) Longitudinal excitation: 1—resonant peak of the branch MN, 2—of the branch KL.

In the case of longitudinal excitation, two branches of resonant frequencies, KL and MN, are obtained (Fig. 2).

For the branch MN, there is fair agreement between the experimental points and the theoretical curve for the longitudinal mode, and an appreciable discrepancy is observed only in the region of relatively weak fields ($H' < 3.5$). The absorption peaks for this branch (Fig. 4b) are very broad and have an asymmetrical form, especially for strong fields ($H' > 3$). These peaks reach maximum intensity in the central part of the branch MN, although their width is not decreased thereby.

The branch KL is apparently the analog of the branch AG, but only in the case of longitudinal excitation. The intensity of the peaks of this branch (Fig. 4b) is much lower than the intensity of the peaks of the branch MN, but they have a smaller width and a sufficiently distinctly pronounced maximum. Unlike the branch AG, the maximum intensity of the peaks of the branch KL occurs in the central part of the branch. The origin of the resonant absorption for this branch, as well as that of the branch AG, is still unclear.

The foregoing comparison of the experimental data with the theoretical relations, principally with respect to the resonant frequencies for the longitudinal modes, shows that in the case when the field is oriented along [100] and [011], in a definite range of fields, the single-crystal Ni ferrite has in the main a perpendicular domain structure.

The measurements were performed with a single crystal prepared by E. V. Rubal'skaya in the laboratory of Yu. M. Yakovlev, to whom the authors express their gratitude.

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Translated by J. G. Adashko
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