Magnetic intermediate state in dysprosium orthoferrite

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(Submitted January 31, 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **25**, No. 5, 258–262 (5 March 1977)

A visual polarization method was used to observe and investigate the magnetic intermediate state produced in dysprosium orthoferrite in a magnetic field when the crystal goes over from the antiferromagnetic state (G_y) into the weakly ferromagnetic state (G_xF_z). The region of the existence of the intermediate state is outlined in the (HT) plane. The dependences of the phase concentrations and of the domain dimensions on the magnetic field intensity are determined. It is shown that the observed domain structure of the magnetic ordered state is close to thermodynamic equilibrium.

PACS numbers: 75.30.Kz, 75.60.Ch

We have investigated the magnetic intermediate state (MIS)[1] that is produced in $DyFeO_3$ following a spin-orientation phase transition of the type $G_y \rightarrow G_xF_z$ (antiferromagnet—weak ferromagnet), induced by a magnetic field $\mathbf{H} \parallel c$. The magnetic measurements point to an abrupt character of this transition, and a theoretical analysis indicates that the transition $G_y \rightarrow G_xF_z$ should be of first order.[2] We use in the experiment a $DyFeO_3$ plate 40 μ thick, cut perpendicular to the axis from a crystal grown by the hydrothermal method. The surfaces of the plate were subjected to chemical and mechanical polishing.

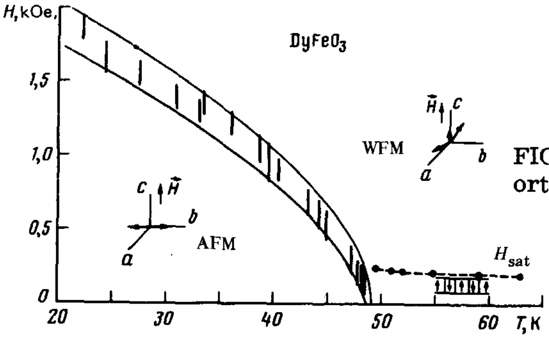

FIG. 1. Phase diagram of dysprosium orthoferrite near the Morin point.

When the antiferromagnetic (AFM) state is destroyed, coexistence on an AFM phase and of a weakly ferromagnetic (WFM) phase is observed in a magnetic-field interval ΔH. The phases coexist in the form of well pronounced alternating strip domains. The positions of the ΔH intervals as functions of the temperature are shown in Fig. 1. The characteristic form of the domain structure as a function of H is illustrated in Fig. 2. The WFM is initiated, as a rule, near the edges of the plate, in the form of cylindrical domains that coalesce frequently into one edge domain of variable thickness and width. When the field is slightly increased, creased, strip domains grow almost simultaneously, from the edge domains. The domains tend to arrange themselves periodically, and when the

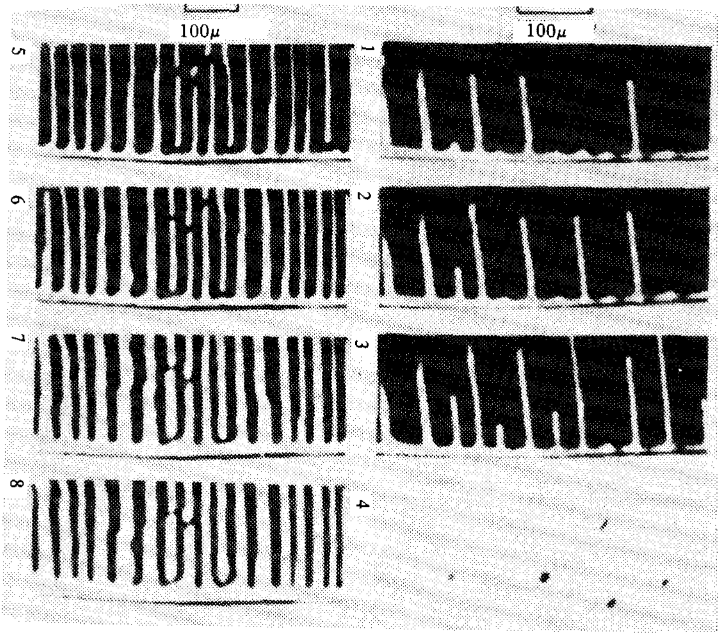

FIG. 2. Domain structure of the magnetic intermediate state (crossed polarizers, light regions—WFM phase, dark—AFM phase). $T=42.5$ K, H(Oe) $=658(1)$, $662(2)$, $670(3)$, $852(4)$, $710(5)$, $728(6)$, $754(7)$, $768(8)$. The arrows on frame 7 mark the characteristic formations in the form of steps.

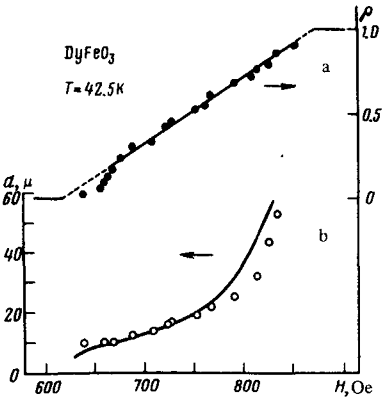

FIG. 3. Plots of the concentration (a) and of the domain width (b) of the WFM phase in the MIS against the magnetic field intensity, $T = 42.5$K.

MIS is produced a tendency to a jumplike doubling of the period of the structure (frames 1—3) appears. After a second value is reached, the period of the structure ceases to change and remains constant in a field range amounting to more than one-third of the total interval of the existence of the MIS. The growth of the new phase in the fields is due to the increase of the width of the domains (frames 5—9). The domain width changes via rapid motion of the steps (frame 7), the lowest speed of which is approximately 1/5 of the domain width. With further increase of the field, the period of the structure again increases, and the rate of change of the width of the AFM domain slows down. Cylindrical domains of the AFM phase are then produced and collapse (frame 4). The form of the domain structure and its period are practically independent of the path of the motion of the given point in the (HT) plane. In the entire field interval H, with the exception of the outermost sections, the concentration of the phases, defined as the normalized sum of the widths of all the domains crossing the central line of the sample changes in accordance with a clearly pronounced linear law (Fig. 3a).

To describe the domain structure of the MIS at phase concentration $\rho \ll 1$ and $(1-\rho) \gg 0$ we can use an approximation in which the internal magnetic field, averaged over a sample section much larger than the dimension of the domain, remains constant and equal to the transition field.[1] The phase concentration in this case varies linearly

$$\rho = \frac{H - H_{\mathrm{tr}}}{N_z[M + (\chi_{\mathrm{WFM}} - \chi_{\mathrm{AFM}})H_{\mathrm{tr}}} .$$

Here H_{tr} is a transition field, N_z is the demagnetizing factor of the plate, and χ_i is the susceptibility of the phases in the direction of the c axis. $M \gg \Delta\chi H_{\mathrm{tr}}$,[2] then the interval ΔH is determined by the magnetic moment of the WFM phase, $\Delta H = N_z M$. The value of ΔH determined by extrapolating the linear function $\rho(H)$ to 0 and 1 is 235 Oe. It practically coincides with the field $H_{\mathrm{sat}} = 240$ Oe at which the WFM domains vanish near T_M. The very close quantitative agreement between ΔH and H_{sat} should not be considered as greatly significant, for if ΔH determined by extrapolating the straight line $\rho(H)$ is close to the value of $N_z M$, then the saturation field H_{sat}, determined by the vanishing of the WFM domains, can be smaller than $N_z M$ by an amount[3] $\sim 8(\sigma/2t)^{1/2}$, which can reach about 15% of the saturation field.

It is convenient to compare the observed sizes of the domains in the MIS with the sizes of the domains in the WFM phase near T_M at $H=0$. Assuming the magnetic moment of the WFM phase to be constant we can write for the width of the domain $d=\rho D$, where the period D is equal to[1,4]

$$D = \left(\frac{\sigma t}{F(\rho) M^2} \right)^{1/2}.$$

Here t is the plate thickness, σ is the surface energy of the domain boundary, $F=1.71/4$ in the case of the WFM phase and $F=1.71/16$ in the case of the MIS at $\rho=1/2$. The ratio of the domain dimensions is

$$\frac{d_{\text{MIS}}}{d_{\text{WFM}}} = 2\left(\frac{\sigma_{\text{MIS}}}{\sigma_{\text{WFM}}} \right)^{1/2}.$$

The average experimental values of $2d_{\text{WFM}}$ and $2d_{\text{MIS}}$ are respectively equal to 25 and 37 μ, whence $\sigma_{\text{WFM}}/\sigma_{\text{MIS}}=1.83$, i.e., the energy of the 180-degree domain wall between the WFM domains is almost double the energy of the 90-degree boundary between the phases in the MFS. This ratio of the energies of the domain walls agrees with the concept that both boundaries belong to the same type and differ only in the spin-rotation angles.[5] The dependence of the average observed width of the WFM domains in the MIS agrees qualitatively with the theoretical $d(H)$ dependence for a thermodynamic-equilibrium MIS domain structure (Fig. 3b). The $d(H)$ curve in the figure is normalized to the experimental value of d at $\rho=1/2$. In its calculation we have used the result of[4] where we investigated the domain structure of the intermediate state in superconductors.

At the edges of the region of the existence of the MIS, the domains of the new phase should appear simultaneously and should be arranged periodically. The value of the period can be estimated by using the results of.[1] Our estimates yield for it a value close to $N_z t/2\pi \approx 2t$. The period of the resultant domain structure (Fig. 2, frames 1—3) is close to 72 μ and amount to $1.8t$. We note also that when MIS are produced and vanish one observes frequently cylindrical WFM and AFM domains, which should be thermodynamically stable at the edges of the region of the existence of the MIS.[6]

Summarizing, it can be stated that the transition $G_y \rightarrow G_x F_z$ in DyFeO_3 is indeed a first-order transition, and the magnetic phases that coexist in the investigated sample form a stable MIS, the domain structure of which is close to thermodynamic equilibrium.

In conclusion, the authors thank A.E. Borovik, K.L. Dudko, and V.A. Popov for a useful discussion.

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