Visual observation of coexisting phases in the magnetic phase transition in noncollinear GdIG

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The magneto-optical method was used to investigate the canting of the magnetic sublattices of GdIG near T_c in a magnetic field $\mathbf{H} \parallel [100]$. A first-order phase transition was observed between the noncollinear ferrite states induced by the field. Visual observations were used to construct on the phase diagram, in the $(H\text{-}T)$ plane, the region of coexistence of the noncollinear phases of GdIG. The critical field above which the transition between the low-temperature and high-temperature phases occurs smoothly, in analogy with the liquid-vapor transition above the critical point, was found to be $H_c^* = 21.5$ kOe.

Application of an external magnetic field of intensity higher than critical causes a collinear ferrite to go over into the noncollinear (canted) state[1] in which the angles between the directions of the magnetic moments of the sublattices differ from 0 and 180°. In the case of an isotropic ferrite, the start of the canting of the sublattices can be regarded as a magnetic orientational second-order phase transition.[2] In real ferrites, the magnetic anisotropy complicates the canting process, by changing, at certain orientations of the magnetic field relative to the crystallographic axis, the type of the transition from the collinear to the canted states, and by allowing new phase transitions between different noncollinear states.[3] We present below the results of an experimental investigation of the canting of the sublattices of gadolinium iron garnet near its magnetic-compensation temperature T_c at $\mathbf{H} \parallel [100]$. In this case, the lines separating the collinear and the canted states remain lines of second-order phase transition, but in the immediate vicinity of T_c the magnetic anisotropy gives rise to a line of magnetic first-order phase transitions between the various noncollinear structures, terminating at the critical point (T_c^*, H_c^*). We have observed a first-order phase transition between the field-induced noncollinear states of the GdIG. Visual observations were used to construct in the $(H-T)$ plane the region of the coexistence of the noncollinear phases. The value of the critical field H_c^* was determined.

The employed experimental method was based on the magnetooptical effect of the rotation of the plane of polarization of $\mathbf{H} \parallel \mathbf{k}$. This effect, owing to the essentially different partial contributions of the different sublattices, made it possible to determine the angle of rotation of the magnetooptical active sublattice and discriminate visually the canted states. States that differ from one another only in the azimuthal angle of the moments of the sublattices cannot be resolved in this geometry. The usual optical scheme for the observation of magnetic domains in transparent crystals was supplemented with a recording system in which the light beam was modulated over the polarization plane. During the time of the experiment, the temperature of the sample was maintained constant within ± 0.01 °K, or else was varied smoothly at an approximate rate 2×10^{-3} °K/sec; the temperature gradient did not exceed 0.01 °K/mm.

Visual observations with almost crossed polarizers have shown that in addition to the temperature region in which the continuous and uniform (over the sample) rotation of the sublattice takes place there exists also a narrow temperature interval in which the sample breaks up into domains that have different sublattice-rotation angles. The domain picture depends on the heat treatment and on the state of the sample surface. Figure 1 shows photographs, obtained with crossed polarizers, of the characteristic domain formations in a mechanically polished and annealed GdIG plate of approximate thickness 70 μ. The photographs illustrate the growth of the new (high-temperature) noncollinear phase, which results from the jumplike motion of the boundaries and the appearance of new nuclei.

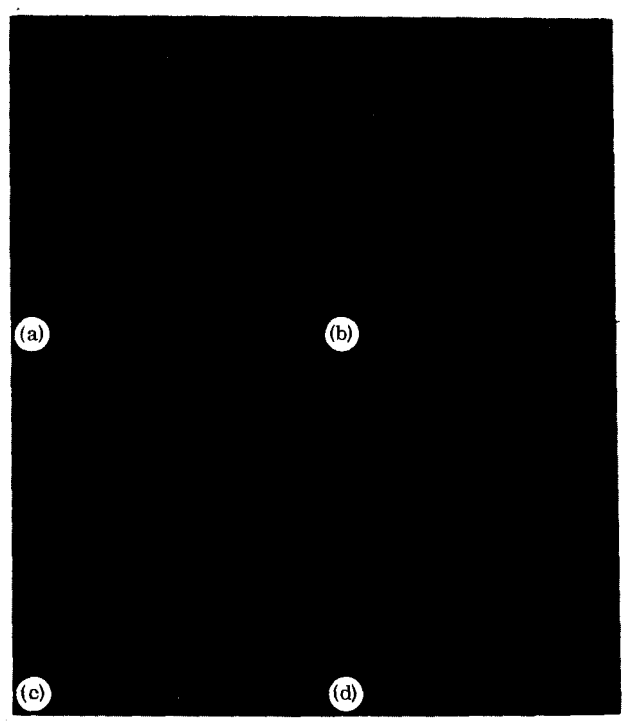

FIG. 1. Domain structure produced in the case of spin reorientation in noncollinear GdIG. The analyzer and polarizer are crossed, $H = 7$ kOe, T, °K: a—284.8; b—285.1; c—285.2; d—285.3. Photograph a shows the dimensions of the section of a sample of 75 μ diameter, in which the Faraday rotation was measured.

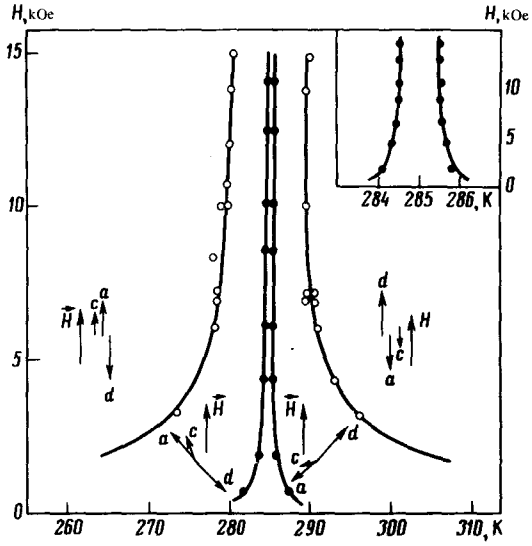

FIG. 2. Phase diagram of GdIG near T_c at H ∥ [100]. The inside region (shown in the insert) is the region of coexistence of the noncollinear phases.

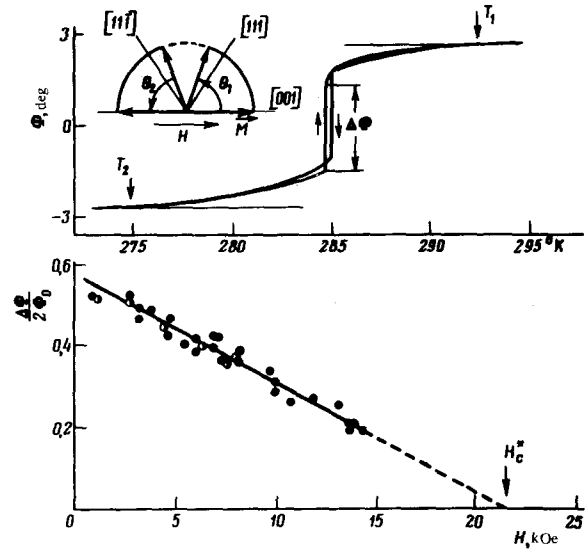

FIG. 3. Difference of the Faraday rotation in coexisting magnetic phases: a—jump of rotation on passing of the interphase boundary through the investigated section of the sample; b—dependence of the difference of the Faraday rotation in neighboring phases on the magnetic field intensity.

The formation of the observed domain structure cannot be due to the demagnetization fields, since the difference between the magnetizations of the sample in the low- and high-temperature noncollinear phases does not exceed several Gauss, and the period of the domain structure due to the action of the demagnetization fields should exceed the dimensions of the sample. In addition, the temperature interval in which a domain structure can produce by this mechanism should not exceed $(T_c - T_c^*) \sim 0.01$ °K. The causes of the magnetic stratification of the noncollinear ferrite in the course of the phase transition in the region of T_c should be analogous to those that lead to the appearance of a domain structure in antiferromagnets.[4] In particular, the domain structure may become energywise favored in a real sample with lattice defects, owing to the decrease in the elastic energy of the crystal in the domain walls as a result of the magnetoelastic interaction. The form of the observed domain structures, namely the preferred direction of the interphase boundaries and the penetration of one phase into the other in the form of thin needles and wedges, all offer evidence that the domain-structure formation has an elastic character.

By determining the temperatures at which the domain structure appears and vanishes, we determined the boundaries of the region of coexistence of the noncollinear phases on the H—T plane (Fig. 2). However, it is difficult to obtain the critical field H_c^* in this manner, since the angles of rotation of the sublattices in neighboring phases become close to one another with increasing field, and the contrast of the domain picture is significantly decreased. By using a registration scheme and by placing a diaphragm in the image plane, we were able to measure the difference between the Faraday rotations in neighboring domains. The rotation jump observed when the interphase boundary passes through a section of a sample with approximate diameter 75 μ is illustrated in Fig. 3a. The size of the jump is determined by the angles of rotation of the moments of the iron sublattices in the coexisting phases. If we neglect the contribution of the gadolinium sublattice in the small cant angle between the moments of the octahedral and tetrahedral sublattices $\mathbf{M}_a$ and $\mathbf{M}_d$, then this jump is equal to $\Delta\Phi = \Phi_0(\cos\theta_1 + \cos\theta_2)$, where Φ_0 is the spontaneous rotation and θ_1 and θ_2 are the smaller angles between the vectors $\mathbf{M} = \mathbf{M}_d + \mathbf{M}_a$ and $\mathbf{H}$ in the neighboring domains. The insert of Fig. 3a shows schematically the motion of the vector $\mathbf{M}$ in the magnetic field when the sample is cooled from temperatures above T_c to $T < T_c$. By plotting the quantity $\Delta\phi/2\phi_0$ against the magnetic field intensity and by extrapolating the obtained linear dependence to $\Delta\phi/2\phi_0 = 0$, we obtain for the critical field H_c^* the value 21.5 kOe, above which the transition between the low-temperature and high-temperature phases occurs smoothly, in analogy with a liquid-vapor transition above the critical point. The crystal field, calculated with allowance for the canting of all the three sublattices of GdIG is 10.5 kOe. Better agreement with experiment can apparently be obtained by taking into account the energy of the magnetoelastic interaction, which can extend the region of the metastable states.

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