TEMPERATURE DEPENDENCE OF THE COERCIVE FORCE OF FERRIMAGNETS NEAR THE COMPENSATION TEMPERATURE

B. P. GORANSKIĬ and A. K. ZVEZDIN

Moscow Institute of Electronic Engineering

Submitted February 15, 1969

Zh. Eksp. Teor. Fiz. 57, 547–550 (August, 1969)

The behavior of the coercive force of ferrimagnets near the compensation temperature is investigated theoretically in the molecular-field approximation for a single-domain model. It is shown that at the temperatures indicated the maximum of the coercive force should split into two. This agrees with the experimental data for polycrystalline samples of gadolinium iron garnets.

THE spontaneous magnetization of a ferrimagnet vanishes at the compensation temperature Θ_c. Near this temperature, there are a number of anomalies in the behavior of the physical properties of ferrimagnets. Thus, in[1,2] a sharp increase of the coercive force was observed near Θ_c. Later[2,3] it was found that in polycrystalline gadolinium iron garnets the coercive force H_c decreases sharply in the direct vicinity of the compensation point itself, as a result of which a splitting of the $H_c(T)$ peak takes place. Rare-earth iron garnets have a large paraprocess magnetization, from the very lowest temperatures to the Curie point, owing to the relatively weak exchange field produced by the iron sublattices and acting on the rare-earth ion[4].

This fact must be taken into account in the analysis of the magnetization-reversal process near Θ_c, where the spontaneous magnetization is very small. It is shown in this paper that the anomalous behavior of H_c can be due to the influence of the paraprocess of the rare-earth sublattice under the condition that the magnetization reversal is via uniform rotation. Within the framework of this model, we calculate the hysteresis loops and the temperature dependence of the coercive force.

Let us examine the magnetization reversal of a one-domain single crystal. It can be assumed that in rare-earth iron garnets, in the region of the point Θ_c, the magnetization of the "resultant" iron sublattice does not depend on the magnetic field (i.e., there is no paraprocess) or on the temperature, while the magnetization of the rare-earth sublattice is described in first approximation by the Curie-Weiss law[1)][5]. We shall assume that the anisotropy energy of the iron sublattice greatly exceeds the anisotropy energy of the rare-earth sublattice. This is well satisfied in gadolinium iron garnet[6]. Then the free energy of a two-sublattice ferrimagnet can be written, in the molecular-field approximation, in the form

$$F = F_0 - \mathbf{MH} - K[(\alpha_1\alpha_2)^2 + (\alpha_1\alpha_3)^2 + (\alpha_2\alpha_3)^2], \quad (1)$$

where

$$\mathbf{M} = \mathbf{M}_1 + \mathbf{M}_2, \quad (2)$$

$$\mathbf{M}_1 = \chi\mathbf{H}_{\text{eff}} = \chi(\mathbf{H} - \beta\mathbf{M}_2). \quad (3)$$

Here $\mathbf{M}$ is the total magnetization, $\mathbf{M}_1$ and $\mathbf{M}_2$ are the magnetizations of the gadolinium and iron sublattices, $\mathbf{H}$ is the magnetic field applied along the easy axis of the crystal, $\mathbf{H}_{\text{eff}}$ is the effective molecular field produced by the resultant iron sublattice and acting on the rare-earth sublattice, χ is the paraprocess susceptibility of the rare-earth sublattice, β is the parameter of the c-ad sublattice exchange interaction, K is the constant of the cubic crystallographic anisotropy of the resultant iron sublattice, and α_1, α_2, and α_3 are the angles between $\mathbf{M}_2$ and the cubic axes.

Recognizing that the susceptibility χ satisfies the Curie-Weiss law, and that the spontaneous magnetization of the ferrimagnet M_S vanishes at the point Θ_c, we can rewrite with the aid of (2) and (3) the expression (1) in the form

$$F = -\left(1 - \frac{\Theta_K}{T}\right)\mathbf{M}_2\mathbf{H} - K[(\alpha_1\alpha_2)^2 + (\alpha_1\alpha_3)^2 + (\alpha_2\alpha_3)^2]. \quad (4)$$

In expression (4) we have omitted the terms that do not depend on the angles[2)]. Our problem is to find the equilibrium magnetization $\mathbf{M}$ of the ferrimagnet as a function of the temperature T and of the magnetic field $\mathbf{H}$ applied along the preferred direction.

To obtain the sought dependence, it is necessary to find the minimum of the expression for the free energy $F(\mathbf{M}, T)$ relative to the vector $\mathbf{M}$. Actually it is possible to find the minimum of expression (4) for the free energy $F(\mathbf{M}_2, T)$ with respect to $\mathbf{M}_2$, and then use (2) to obtain an expression for $\mathbf{M} = \mathbf{M}(\mathbf{H}, T)$.

As a result of minimization of the free energy, we obtain for the projection of the magnetization of the ferrimagnet on the preferred direction

for $T \geq \Theta_c \pm \Delta$

$$M(H,T) = \begin{cases} M_s(T) + \chi(T)H \geqslant 0, & H \geqslant -\dfrac{AK(T)}{M_s(T)}, \\ -M_s(T) + \chi(T)H \leqslant 0, & H \leqslant \dfrac{AK(T)}{M_s(T)}; \end{cases} \quad (5a)$$

1)For iron garnets in which the compensation point lies in the low-temperature region, the dependence of the magnetization of the rare-earth sublattice on the magnetic field and on the temperature is described by the Brillouin function.

2)Expression (4) for the free energy at K = 0 agrees with the corresponding results obtained by Tyablikov [7] for a two-sublattice ferrite on the basis of a variational theorem. To verify this, it is necessary to expand the expressions obtained in [7] for the free energy and for the magnetization of the rare-earth sublattice in powers of the parameter $\mu_1 H_{\text{eff}}/kT$, retain terms up to second order inclusive, and take into account the fact that the iron sublattice is saturated.

For $\Theta_c < T < \Theta_c + \Delta$

$$M(H,T)=\begin{cases} M_s(T)+\chi(T)H\geqslant 0, & H\geqslant -\dfrac{M_s(T)}{\chi(T)},\\ M_s(T)+\chi(T)H\leqslant 0, & -\dfrac{M_s(T)}{\chi(T)}\geqslant H\geqslant -\dfrac{AK(T)}{M_s(T)},\\ -M_s(T)+\chi(T)H\geqslant 0, & \dfrac{M_s(T)}{\chi(T)}\leqslant H\leqslant \dfrac{AK(T)}{M_s(T)},\\ -M_s(T)+\chi(T)H\leqslant 0, & H\leqslant \dfrac{M_s(T)}{\chi(T)}. \end{cases} \quad (5b)$$

Here $M_S = (1 - \Theta_c/T)M_2$; A is a quantity that depends on the orientation of the magnetic field H relative to the crystallographic axes; in particular, A = 4/3 for H directed along [111].

For the coercive force of a two-sublattice ferrimagnet near the compensation point, we obtain the expression

$$H_c(T)=\begin{cases} \dfrac{AK(T)}{|1-\Theta_c/T|M_2} & \text{for } |T-\Theta_c|\geqslant\Delta,\\ \dfrac{|1-\Theta_c/T|M_2}{\chi(T)} & \text{for } |T-\Theta_c|<\Delta. \end{cases} \quad (6)$$

It follows from (5) that the temperature interval Δ, determined from the equality of the fields $H_1 = AK/M_S(T)$ and $H_2 = M_S(T)/\chi$, is equal to

$$\Delta \approx \frac{\Theta_c}{M_2}(AK\chi)^{1/2}. \quad (7)$$

The maximum of the coercive force is

$$H_{c\,max} = (AK/\chi)^{1/2}. \quad (8)$$

The hysteresis loops M(H, T) and a plot of $H_c(T)$ of the ferrimagnet near Θ_c are shown in Figs. 1 and 2 respectively. The analysis of the process of reversal of magnetization of a one-domain ferrimagnet near Θ_c demonstrates the important role of the paramagnetic contribution $\delta M = \chi H$ to the total magnetization of the sample. At a temperature $T - \Theta_c \geq \Delta$, where the contribution δM is smaller than or equal to the spontaneous magnetization, the coercive force is given by the well known expression $H_c = AK/M_S$. This quantity is defined as a field in which a state with a vector $\mathbf{M}_S$, directed opposite to the magnetic field, becomes unstable; at this value of the field, the magnetization of the sample reverses sign. Directly near Θ_c, at $T - \Theta_c < \Delta$, the paramagnetic contribution to the magnetization $\delta M = \chi H$ becomes larger than M_S when $AK/M_S > H > M_S/\chi$, and therefore the total magnetization vanishes during the reversal of the magnetization of the sample before the turning of the spontaneous magnetization takes place. This leads to a decrease in the coercive force at $T - \Theta_c < \Delta$.

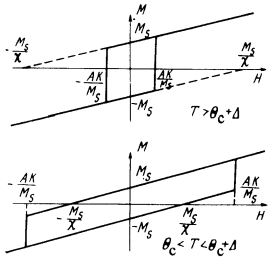

FIG. 1

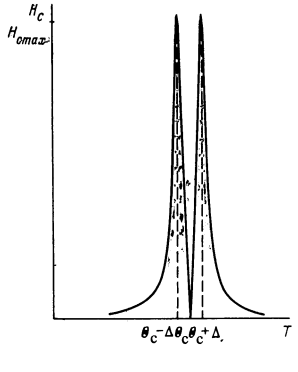

FIG. 2.

FIG. 1. Hysteresis loop of one-domain ferrimagnet near the compensation temperature.

FIG. 2. Temperature dependence of the coercive force of a ferrimagnet near the compensation temperature.

Let us estimate the values of Δ at $H_{c\,max}$ for gadolinium iron garnet. We assume for $Gd_3Fe_5O_5$ the values $K = 6.7 \times 10^3$ erg/cm³ and $\chi = 6 \times 10^4$ cm^{-3}. Substituting these values and A = 4/3 (for the [111] direction) in (7) and (8), we get $\Delta \sim 3.8^\circ$ and $H_{c\,max} \sim 3.8 \times 10^3$ Oe.

For samples consisting of randomly oriented grains with cubic anisotropy, we can expect a decrease in the value of the coercive force. Actually, the inhomogeneity of the compensation temperature over the sample leads to a smoothing of the peaks of the coercive force and to a decrease of $H_{c\,max}$. Lyubutin[3] obtained for $Gd_3Fe_5O_{12}$ the values $\Delta \sim 3.5^\circ$ and $H_{c\,max} \sim 3.5 \times 10^2$ Oe.

We note that better conditions for the observation of the splitting of the coercive force near the compensation temperature are realized apparently in finely-dispersed samples, where the process of magnetization reversal of the individual non-interacting particles corresponds most closely to the model of uniform rotation. In experiments[8] performed on large $Gd_3Fe_5O_{12}$ crystals, no distinct splitting of the maximum of the coercive force was observed. This may be connected with the fact that an important role is played in the reversal of magnetization of large single crystals also by the motion of the domain boundaries.

In recent papers[9] the reversal of magnetization of ferrimagnets near Θ_c was investigated with the aid of the Faraday effect. We note that the hysteresis loops of the magnetization and of the angle of rotation of the plane of polarization of light, and the temperature dependence of their coercive forces near Θ_c, may not coincide in shape. Thus, for example, in the optical band, the Faraday rotation angle is determined by the magnetization of the iron sublattice, and therefore it reverses sign, with reversal of magnetization, at a field $H_1 = AK/M_S$ at which the turning of the iron sublattice takes place. We see that in this case there is no splitting of the coercive-force maximum. The value of H_1 as $T \to \Theta_c$ is limited by the turning of the sublattices, which begins at $T \sim \Theta_c$ in a field $H_{cr} \sim \sqrt{AK\beta}$ (for $Gd_3Fe_5O_{12}$, we have $H_{cr} = 10^4$ Oe).

The authors are grateful to K. P. Belov for a discussion of the work and for useful remarks.

[1] K. M. Bol'shova and T. A. Elkina, Vestnik MGU 4, 85 (1959).

[2] K. P. Belov and A. V. Ped'ko, Zh. Eksp. Teor. Fiz. 39, 961 (1960) [Sov. Phys.-JETP 12, 666 (1961)].

[3] I. S. Lyubutin, ibid. 7, 1937 (1965) [sic!].

[4] K. P. Belov and S. A. Nikitin, Phys. Stat. Solidi 12, No. 1 (1965).

[5]K. P. Belov, M. A. Belyanchikova, R. Z. Levitin, and S. A. Nikitin, Redkozemel'nye ferro- i antiferromagnetiki (Rare Earth Ferro- and Antiferromagnets), Nauka, 1965.
[6]R. F. Pearson, J. Phys. et Rad. 20, 409 (1959).
[7]S. V. Tyablikov, Metody kvantovoĭ teorii magnetizma (Methods of Quantum Theory of Magnetism), Nauka, 1965.
[8]J. P. Hanton, IEEE Trans. Magnetics 3, 505 (1957).
[9]C. D. Mee, Contemporary Physics 8, 4, 385.

Translated by J. G. Adashko
62