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Theoretical aspects of the process of technical magnetization of rare earth terbium ferrite garnet in the temperature range of magnetic compensation

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Abstract. The article presents an interpretation of the results obtained from studies of the process of technical magnetization of terbium ferrite garnet near the magnetic compensation temperature point, which were carried out within the framework of the thermodynamic theory of domain structures. The model used for changing the domain position of a rare-earth magnet with changes in the magnetic field and temperature makes it possible to qualitatively describe the identified patterns of the process of technical magnetization of ferrite garnet during a transition near the temperature of magnetic compensation.

1 Introduction

Rare earth ferrite garnets (REFG) have already found wide application as materials for various instruments and devices of optoelectronics and integrated optics. In the temperature range, rare earth ferrite garnets have a point called the magnetic compensation temperature (T_c = 248,6 K). From a practical point of view, one of the most important characteristics of magnetic materials i.e. rare earth ferrite garnets are the dynamic properties of domain boundaries in the domain structure realized in it, and the high temperature of magnetic compensation T_c. The dynamics of domain boundaries largely determine the performance and switching speed of a device, for example, magneto-optical transparency, magneto-optical shutters, memory cells, etc. [1,2]. Relatively recently, in [3], it was shown that the state of domain boundaries in REFG crystals can be controlled using a nonuniform electric field. The results obtained suggest an innovative use of REFGs for data storage and processing, which are of particular importance for the theory of phase transitions in low-dimensional systems. The above determines the interest in studying the domain structure (DS) of REFGs near the magnetic compensation temperature point, which belongs to the field of physics of multiaxial ferrimagnets. These data have so far remained poorly studied experimentally, and existing

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theories do not provide an unambiguous prediction of the change in the DS of the REFG at $T \rightarrow T_c$. So, for example, according to [4], due to the fact that when the temperature in the magnetic compensation region the magnetostatic energy of the sample tends to zero, the DS becomes energetically unfavorable, and in a certain temperature range in the vicinity of T_c the crystal becomes homogeneous (monodomain) state.

From the magnetic phase diagram of the REFG it follows that near T_c, from an energy point of view, a state with magnetic moments of the iron M_{Fe} and rare-earth M_R sublattices that are canted relative to each other can become favorable; as a result, at $T \rightarrow T_c$, the DS of the crystal should exist [5].

2 Research methods

Since at present there is no definitive microscopic theory of the state of motion of a domain walls in an REFG, when interpreting the results obtained from studying the process of technical magnetization of ferrite garnet $Tb_3Fe_5O_{12}$ near T_c, we will proceed from the thermodynamic theory of a strip 180^0 DS. The magnetic state of the REFG near the T_c state of the crystal with a strictly antiparallel orientation of the vectors M_{Fe} and M_R leads to the fact that at the point of magnetic compensation $M_s \neq 0$ and the magnetostatic energy of a sample of finite dimensions does not vanish, as a result of which the DS becomes energetically favorable [6,7]. The latter leads to the fact that in the immediate vicinity of T_c the domain configuration of the sample becomes more complicated: against the background of "light" domains there are "dark" domains in the form of wedges and vice versa, the length and width of which changes with changes in T. Therefore, the presented model, which explains the process of technical magnetization of REFGs, fully reflects the existence of a 180^0 stripe DS in the crystal in the region of magnetic compensation temperature.

3 Results and discussion

Under an external magnetic field H in a defect-free ferromagnet, the change in domain boundaries is oriented between its magnetostatic and Zeeman energies, which are determined from the geometric dimensions of the rare-earth ferromagnet under study. The displacement of the domain wall along the easy magnetization axis is determined [7]:

$$2M_sH = \lambda l \tag{1}$$

l - is the displacement value of the domain boundary,
H – External magnetic field,
M_s - Saturation magnetization of a magnetically ordered sample,
λ – Restoring force constant or elasticity coefficient

However, in a sample of significant size, the main factor determining the state of domain boundaries is the areal location of pinning centers in its crystal lattice, i.e. dislocations, impurities: from an energy point of view, it is advantageous for the plane of the domain wall to contain pinning centers [7]. It is obvious that the pinning of domain walls significantly affects the effect of technical magnetization: in particular, the jump-like dynamics of the Faraday Effect observed in weak magnetic fields with temperature changes is associated with the pinning of domain walls on defects in the crystal lattice of the sample. Consequently, for the full motion of the domain wall to begin, the magnetic field H must exceed the pinning magnetic field H_p. Following based on (1), the magnitude of the field of technical saturation of magnetization can be represented as

$$H_{ts} = H_p + \frac{\lambda w}{4M_s} \tag{2}$$

w - Domain width in the sample,

$l = \frac{w}{2}$ - Possible displacement of the domain boundary.

The magnitude of the Faraday effect can be rewritten as

$$F = \frac{\Phi_F}{\theta_F} = \frac{2AM_s(H - H_p)}{k} \tag{3}$$

A - is the proportionality coefficient.

Since $\theta_F \propto M_s$, we can assume that the dependences *F*(*H*) and *F*(*T*) fully reflect the course of the field magnetization and temperature dependences of the crystal.

In a crystal, the pinning centers of domain boundaries are microscopic concentrations of nonmagnetic impurities. Then

$$H_p = \vartheta M_s,$$

ϑ - is the defectiveness coefficient of the crystal [14].

In this case, we will use the known dependence of the saturation magnetization on the temperature $M_s(T)$ of the $Tb_3Fe_5O_{12}$ ferrite garnet. Taking into account the above dependence, it is possible to calculate from (2) and (3) the dependence $H_n(T)$ and *F*(*T*), and compare them with the corresponding experimental results.

Calculations according to (2) and (3) were performed using a standard computer program for searching the likelihood function, which ensures a minimum shift of the calculated curve from the points obtained in the experiment, and using the dependence of saturation magnetization on temperature $M_s(T)$ from [8]. The pairs ϑ, λw and A/λ, ϑ were used as fitting parameters, respectively. It was assumed that the coefficients ϑ and λ do not depend on temperature and the relatively weak change in the value of *w* in the range $200 \leq T \leq 295$ K was neglected (when calculating the dependence $H_{ts}(T)$) compared to the dependence $1/M_s(T)$.

Since changes in the saturation magnetization vector M_s of the studied ferrite garnet in the range $200 \leq T \leq 295$ K are difficult to describe analytically (see [8]), calculations of the dependences *F*(*T*) and $H_{ts}(T)$ were carried out in two stages. First, functions (2) and (3) were fitted, respectively, to the experimental dependences $\Phi_F/\theta_F(M_s)$ and $H_{ts}(M_s)$, then the calculated curves $\Phi_F/\theta_F(M_s)$ and $H_{ts}(M_s)$ were digitized and each value of M_s was automatically compared with the corresponding temperature, after which the digital graphs of the dependences $\Phi_F/\theta_F(M_s)$ and $H_{ts}(M_s)$ were transformed into smooth curves *F*(*T*) and $H_{ts}(T)$.

In Figure 1 and Figure 2 comparisons of the calculations of the functions $H_{ts}(T)$ and *F*(*T*) with the experimental results are presented.

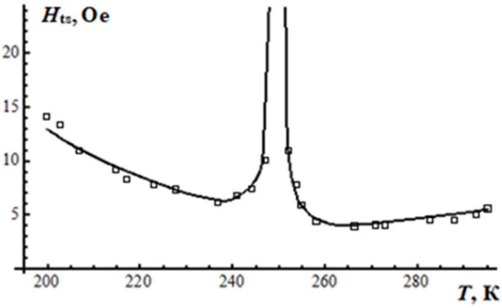

Fig. 1. Dependence of the external magnetic field strength on temperature, where the REFG transforms into a single-domain (uniformly magnetized) state: solid line – calculation according to (2), dots – experiment.

The experimental dependence of the field strength H_{ts} on the temperature at which the sample transforms into a single-domain state was obtained as a result of visual observation, with a change in the magnetic field *H* and temperature *T*, of the process of appearance and disappearance of domain boundaries in the image of the sample. In experimental studies, a sample of rare-earth ferrite garnet was cooled to the minimum permissible temperature under our conditions, then an external magnetic field was created and the intensity increased, at which no boundaries between domains remained in the image of the sample. Then the temperature of the sample was gradually warmed up to room temperature, subjected to demagnetization in an alternating magnetic field, and the magnetization procedure was repeated at different temperatures.

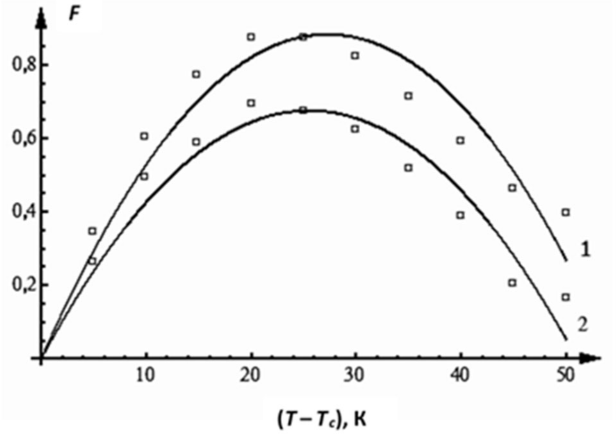

Fig. 2. Temperature dependences of the ratio ΦF/θF, obtained at different magnetic field strengths: curve 1 – 3 Oe, curve 2 – 2 Oe. Dots – experiment, solid lines – calculation according to (3).

From the obtained dependence $H_{ts}(T)$ it follows that in the temperature range $200 \leq T \leq 295$ K, with the exception of a narrow interval $T_c \pm 1.5$ K, (in this temperature range it was not possible to achieve a uniformly magnetized state of the sample up to a field strength $H = 60$ Oe) the single-domain position of the observed sample is obtained with a magnetic field higher than $H > 15$ Oe, and the magnetic field H_{ts} changes non-monotonically near the magnetic compensation temperature T_c: at $T \rightarrow T_c$ the H_{ts} reading first decreases, after which it sharply increases its value.

Experimental results presented in Figure 2 are determined on the basis of the dependences $\Phi_F(T)$ corresponding to the cooling of the sample (the value of the intersection of the dependences $\Phi_F(T)$ with the abscissa axis is taken as the magnetic compensation temperature T_c), as well as the dependence of the spontaneous Faraday effect on temperature. When constructing theoretical curves 1 and 2 in Figure 2, the obtained calculated parameters differ by approximately 10%, which in order of magnitude corresponds to the error of the experimental measurement results. The same applies to the ϑ indicators, calculated as a result of fitting the curves calculated from (2) and (3) to the experimental values, which proves the internal consistency of the theoretical model used.

From a comparison of the graphs shown in Figure 1 and Figure 2, it is clear that relations (2) and (3) well describe the experimental results: visual observation of the change in the DS of the sample during its magnetization and the temperature dependence of the Faraday effect. A rather noticeable deviation of the experimental data (Figure 2) to the left from the calculated dependences $F(T)$ can probably be explained by the pinning effect, leading to the inertia of the process of abrupt change in the position of the domain boundary in the sample with decreasing temperature. As for the linear quasi-horizontal sections of the dependence $\Phi_F(T)$ observed in a magnetic field H > 4 Oe, it is obvious that when the magnetizing field strength reaches the value Hts characteristic of a certain temperature region, the DW shifts

$l = \frac{w}{2}$, and, accordingly, in this temperature range the magnitude of the Faraday effect reaches saturation.

4 Conclusion

Consequently, we can conclude that, despite some reservations and mathematical approximations, the used model of changes in the domain structure of the crystal with changes in the magnetic field H and temperature T allows us to describe at a qualitative level all the identified patterns of the process of technical magnetization of ferrite garnet $Tb_3Fe_5O_{12}$ in the region of magnetic compensation temperature.

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