MAGNETOSTRICTION OF SINGLE-CRYSTAL TERBIUM AND HOLMIUM IRON GARNETS AT LOW TEMPERATURES

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The magnetostriction of $Tb_3Fe_5O_{12}$ and $Ho_3Fe_5O_{12}$ single crystals is investigated at temperatures between 4.2 and 80 °K. A sharp increase of the magnetostriction is observed with decreasing temperature. At 4.2° K the magnetostriction of terbium iron garnet reaches an enormous value. Thus $\lambda_{[111]} = 2420 \times 10^{-6}$ and $\lambda_{[100]} = 1200 \times 10^{-6}$. An anomalous dependence of $\lambda_{[111]}$ on the field strength is observed in holmium iron garnet near the temperature of liquid helium. The anomaly is apparently due to the noncollinearity of the holmium magnetic moments in the garnet structure. The results are compared with the single-ion theory of magnetoelastic interaction of Neel ferrimagnetic substances.[9]

THE magnetostriction of terbium and holmium iron garnets has previously been measured at helium temperatures on polycrystalline samples.[1] Investigations of the magnetostriction of single crystals of $Tb_3Fe_5O_{12}$ and $Ho_3Fe_5O_{12}$ were carried out only down to the temperature of liquid nitrogen (78–300 °K).[2,3]

In this work we used a capacitor method to measure the temperature and field dependences of the longitudinal magnetostriction of terbium and holmium iron garnet single crystals in the temperature range of 4.2–80 ° K. The measurements were carried out on spheres 2 mm in diameter in a superconducting solenoid which made it possible to obtain magnetic fields up to 25 kOe.[4]

1. Terbium iron garnet (TbIG). Figure 1 shows the magnetostriction isotherms of terbium iron garnet obtained for the easy ([111]) and difficult ([100]) directions of magnetization. It is seen that near the temperature of liquid helium the magnetostriction reaches enormous values ($\sim 10^{-3}$), and the H dependence of λ in the [100] direction does not exhibit any appreciable tendency towards saturation. In addition it is interesting to note that complete saturation is also not observed in the λ(H) curves in the direction of easy magnetization. This may be connected with the inaccurate alignment of the single crystal along the [111] axis (the sample was oriented with the aid of x rays with an accuracy of $\sim 1°$). The possibility is, however, not ruled out that the absence of saturation in the λ(H) curves in the [111] direction is due to noncollinearity of the magnetic structure appearing in TbIG at helium temperatures.

The absence of saturation of the magnetostriction with magnetic field does not make it possible to calculate the magneto-elastic coupling constants (B_1 and B_2) at 4.2° K. The calculation of B_1 and B_2 was therefore carried out for T = 80 ° K where the $\lambda_{[111]}$(H) and $\lambda_{[100]}$(H) curves exhibit saturation (the nature of the λ(H) dependence at 80 ° K is the same as at 55° K (Fig. 1)). The measurements yield for TbIG at 80 °K

$$B_1 = -{}^3/_2(c_{11} - c_{12})\lambda_{100} = -164 \cdot 10^6 \text{ erg/cm}^3,$$
$$B_2 = -3c_{44}\lambda_{111} = -1010 \cdot 10^6 \text{ erg/cm}^3. \quad (1)$$

Here the c_{ik} are elastic constants which have been determined at 300 ° K for yttrium iron garnet[5] (measurements of Young's modulus of polycrystal-

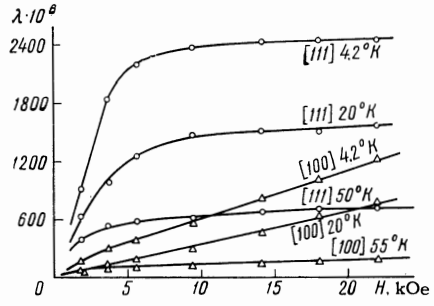

FIG. 1. Isotherms of magnetostriction of single-crystal terbium iron garnet in the [100] and [111] directions.

line Y–Tb iron garnets carried out by us in the temperature range between 4.2 and 300° K indicate that the elastic constants of TbIG and YIG are close in their values and do not change appreciably with the temperature).

The temperature dependence of the magneto-elastic interaction constants B_1 and B_2 is given by the theory of the magneto-elastic interaction in the single-ion approximation:[9]

$$B_{1,2}(T) = \sum_n B^{\gamma,\varepsilon}(n)\hat{I}_{5/2}[\mathcal{L}^{-1}(m_n)], \qquad (2)$$

where $B^{\gamma}(n)$ and $B^{\epsilon}(n)$ are temperature-independent magneto-elastic interaction constants of each of the n sublattices; $\hat{I}_{5/2}[\mathcal{L}^{-1}(m_n)]$ is the hyperbolic Bessel function whose argument is the inverse Langevin magnetization function of the given sublattice. Assuming that the temperature dependences of the magnetizations of the iron sublattices of TbIG are the same as for yttrium iron garnet and making use of the data of [9] for YIG, we obtained for the terbium sublattice:

$$B^{\gamma}(c) = 485\cdot 10^6 \text{ erg/cm}^3,$$
$$B^{\varepsilon}(c) = 5775\cdot 10^6 \text{ erg/cm}^3.$$

These values exceed by two orders of magnitude the corresponding of the magneto-elastic interaction constants of the sublattices a and d; the magneto-elastic contribution of the latter can, therefore, be neglected in calculating the temperature dependences of the magnetostriction of TbIG.

To determine the temperature dependence of the magnetization of the terbium sublattice, we used the vector sum of the magnetizations of the terbium and yttrium iron garnets according to the data of [6]. The results of a calculation in accordance with (1) and (2) are shown in Fig. 2 by dashed lines. The solid lines in this figure are the experimental data for H = 23 kOe; the points mark the values of the magnetostriction obtained by extrapolation to H = 0; the triangles are the data of [2]. It is seen from Fig. 2 that the agreement between the theoretical and experimental data in the [111] direction is quite satisfactory; for [100] the discrepancy is rather large. The appreciable difference between the theoretical and experimental results is apparently due to the inapplicability of the single-ion model for considering the magnetostriction properties of terbium iron garnet.[6]

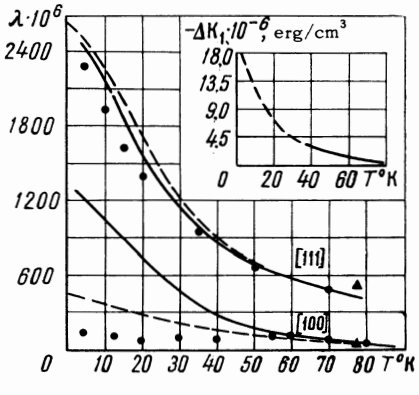

FIG. 2. Temperature dependence of the magnetostriction of terbium iron garnet and of the magneto-elastic contribution (ΔK_1) to the magnetic-anisotropy energy. Dashed lines – theoretical data (H = 0); solid lines – experimental data (H = 23 kOe): ● – experimental data (H = 0), ▲ – experimental data of [2].

Our results enable us to estimate qualitatively the magneto-elastic contribution (ΔK_1) to the energy of the magnetocrystalline anisotropy for TbIG. The that ΔK_1 increases sharply with decreasing temperature and attains at 4.2° K a value $\sim 1.6 \times 10^7$ erg/cm^3. We note, however, that the values of ΔK_1 obtained in the temperature range 4.2–35°K must be considered to be very approximate, since in our experiments we did not attain saturation of the magnetostriction in the [100] direction [in this temperature range the $\Delta K_1(T)$ dependence is shown in Fig. 2 by a dashed line]. Unfortunately we cannot compare the obtained values of ΔK_1 with the magnetic anisotropy constant of terbium iron garnet, because such measurements have so far not been carried out at helium temperatures.

2. Holmium iron garnet (HoIG). Measurements of the magnetostriction of holmium iron garnet carried out by us have shown that the magnetostriction of HoIG increases with decreasing temperature. In the region of the temperature of liquid helium no saturation is attained on the λ(H) curves in the [100] direction up to fields of 25 kOe. In the easy magnetization direction—[111]—saturation of the magnetostriction with the field is observed only at temperatures above 30° K. Near 4.2° K the nature of the magnetostriction isotherms in the [111] direction changes. Figure 3 shows the dependences

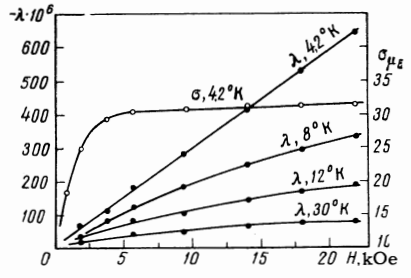

FIG. 3. Dependence of the magnetostriction and the magnetization of holmium iron garnet in the [111] direction on the magnetic field.

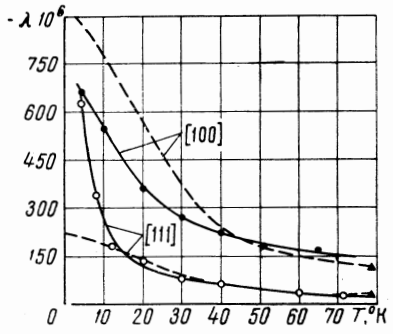

FIG. 4. Temperature dependence of the magnetostriction of single-crystal holmium iron garnet: dashed line – theoretical data (H = 0); solid lines – experimental data (H = 23 kOe); ▲ – experimental data from [3].

of the magnetostriction on the magnetic field for a HoIG single crystal in the [111] direction. It is seen that the magnetostriction at 4.2° K increases almost linearly with the field, and extrapolation to H = 0 yields a strictional deformation close to zero.

The same figure shows the dependence of the magnetization (σ) on the field at 4.2° K obtained by means of a ballistic method without regluing the HoIG single crystal after measuring the magnetostriction. It is seen that, starting from a field of 5 kOe, the magnetization increases rather little. True, here too there is no complete saturation, a fact which could generally speaking be attributed to inaccuracy in the alignment of the HoIG single crystal along the [111] axis. However, a similar course of the σ(H) dependence at 4.2° K has previously been observed in [7], where the authors attributed the small increase of the magnetization in strong magnetic fields to the noncollinearity of the magnetic moments of holmium. We note that neutron studies at 4.2° K have also established that the magnetic moments of holmium make an angle ~60° with the [111] axis.[8]

It can be assumed that the increase of the magnetostriction of holmium iron garnet in the [111] direction at 4.2° K is due to the disturbance of the angular configurations of the magnetic moments of holmium, i.e., exchange magnetostriction occurs. The noncollinearity of the magnetic moments appears, apparently, only at temperatures below 12–15° K. The latter confirms the comparison of the theoretical and experimental dependences of the magnetostriction of HoIG on the temperature shown in Fig. 4.

The theoretical λ (T) dependences were obtained, as in the case of TbIG, from (1) and (2). The corresponding magneto-elastic coupling constants for the holmium sublattice are according to our measurements

$$B^{\gamma}(c) = -1050 \cdot 10^6 \text{ erg/cm}^3,$$
$$B^{\varepsilon}(c) = -498 \cdot 10^6 \text{ erg/cm}^3 .$$

It is seen from Fig. 4 that the theoretical and experimental values of the magnetostriction in the [111] direction are in agreement at temperatures above ~ 15° K. The discrepancy between the theoretical and experimental data at lower temperatures is obviously due to the fact that the phenomenological theory of magneto-elastic interaction[9] is only applicable to ferrimagnets with collinear magnetic moments.

In conclusion the authors consider it their pleasant duty to thank Professor K. P. Belov, under whose direction this work was carried out and Professor A. I. Shal'nikov for attention to this work and useful advice.

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181