MAGNETOSTRICTION OF RARE EARTH IRON GARNETS IN HIGH MAGNETIC FIELDS

K. P. BELOV, R. Z. LEVITIN, and Yu. F. POPOV

Moscow State University

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The longitudinal and transverse magnetostriction of gadolinium, terbium, dysprosium and holmium iron garnets, and also of terbium and dysprosium gallium garnets, are measured in pulsed magnetic fields up to 220 kOe. It is shown that magnetostriction is highly dependent on field strength; the main contribution to this dependence, especially at low temperatures, is due to anisotropic magnetostriction, which depends on the angle between the field direction and the direction of measurement. From a comparison of the results for iron garnets and gallium garnets it is concluded that the anisotropic component of the magnetostriction is mainly due to a magnetoelastic interaction within the rare earth sublatice, whereas the volume component of magnetostriction is associated with the interaction between the rare earth and "resultant" iron sublattices.

ALTHOUGH considerable work[1-3] has been done on the magnetostriction of rare earth iron garnets (REIG), the origin and certain characteristics of this phenomenon have remained unclarified. The magnetostriction of REIG is very complex, having the following components: single-ion and exchange magnetostriction of rare earth (RE) ions, magnetostriction due to interaction between the rare-earth and iron sublattices, and single-ion and exchange magnetostriction of the iron sublattices. These components can be discriminated by measuring magnetostrictive effects over wide ranges of temperature and magnetic fields in iron garnets with different ionic substitutions.

In the present work we have investigated the longitudinal and transverse magnetostriction of polycrystalline iron garnets containing gadolinium, terbium, dysprosium, and holmium, and also of terbium and dysprosium gallium garnets, in high magnetic fields. We used piezoelectric detectors[4] in pulsed magnetic fields up to 220 kOe for the measurement of longitudinal magnetostriction and up to 90 kOe for transverse magnetostriction, at temperatures from 90° to 330°K. The absolute error of the magnetostriction measurements was 12–15%.

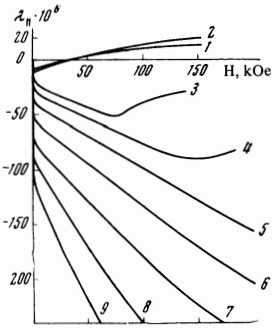

FIG. 1. Longitudinal magnetostriction of dysprosium iron garnet at different temperatures (°K): 1–280°, 2–240°, 3–214°, 4–200°, 5–180°, 6–160°, 7–140°, 8–120°, 9–100°.

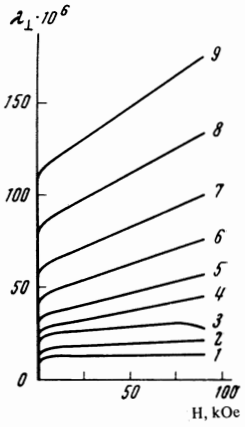

FIG. 2. Transverse magnetostriction of dysprosium iron garnet at different temperatures (°K): 1–280°, 2–240°, 3–214°, 4–200°, 5–180°, 6–160°, 7–140°, 8–120°, 9–100°.

Figures 1 and 2 show the field dependence of the longitudinal and transverse magnetostriction of dysprosium iron garnet. Strong field dependence, especially at low temperatures, is observed, but with a difference between the longitudinal and transverse cases. This indicates that the magnetostriction of dysprosium iron garnet in high fields is not a pure volume (isotropic) effect, but includes an appreciable anisotropic component that depends on the magnetization direction relative to the direction of measurement. The data enable us to distinguish the anisotropic and isotropic components. Numerous studies, such as[5], have shown that magnetostriction in a polycrystal can be represented by the equation

$$\lambda = {}^3/_2\lambda_a(\cos^2\theta - {}^1/_3) + \lambda_i \qquad (1)$$

Here the first term is the anisotropic magnetostriction, θ is the angle between the direction of measurement and the magnetization vector, and the second term is the isotropic magnetostriction of the "paraprocess."

For longitudinal magnetostriction $\theta = 0°$ and

$$\lambda_\parallel = \lambda_a + \lambda_i. \qquad (2)$$

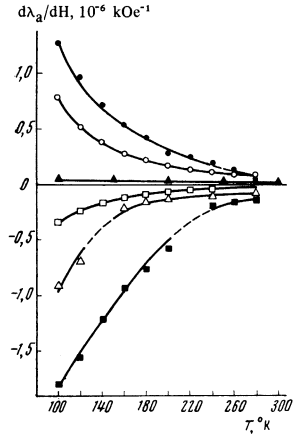

FIG. 3. Temperature dependence of anisotropic magnetostriction in a 60-kOe field: ●—terbium iron garnet, ○—terbium gallium garnet, ▲—gadolinium iron garnet, □—dysprosium gallium garnet, △—holmium iron garnet, ■—dysprosium iron garnet. For the iron garnets, above T_c the curves represent $-d\lambda/dH$ (the dashed curve segments correspond to the vicinity of T_c).

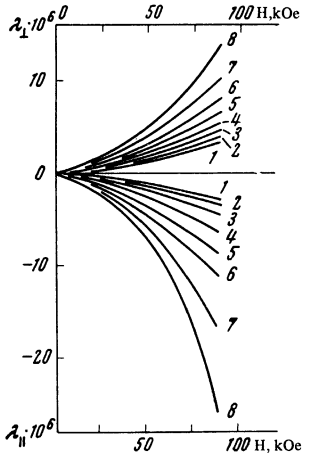

FIG. 4. Temperature (°K) dependence of longitudinal and transverse magnetostriction in dysprosium gallium garnet: 1—240°, 2—220°, 3—200°, 4—180°, 5—160°, 6—140°, 7—120°, 8—100°.

For transverse magnetostriction $\theta = 90°$ and

$$\lambda_\perp = -{}^1/_2\lambda_a + \lambda_i. \qquad (3)$$

The variation of the two components depending on the field is thus

$$\frac{d\lambda_a}{dH} = \frac{2}{3}\left(\frac{d\lambda_\parallel}{dH} - \frac{d\lambda_\perp}{dH}\right), \quad \frac{d\lambda_i}{dH} = \frac{1}{3}\frac{dV}{V\,dH} = \frac{1}{3}\left(\frac{d\lambda_\parallel}{dH} + 2\frac{d\lambda_\perp}{dH}\right). \qquad (4)$$

The temperature dependence of the anisotropic magnetostriction component is shown in Fig. 3. This component is large at low temperatures and decreases as the temperature is increased. The isotropic component is considerably smaller (see the table) and in the 200°—300°K region is independent of temperature within experimental error limits. (At lower temperatures we were unable to discriminate the isotropic component from the high anisotropic background.)

Figures 1 and 2 show that as we pass through the compensation point the sign of $d\lambda/dH$ is reversed (for both the isotropic and anisotropic terms); $T_c = 220°K$ for $Dy_3Fe_5O_{12}$.[1)] This sign reversal is easily accounted for by using the fact that below the compensation temperature the magnetization M_R of the RE sublattice exceeds the magnetization M_{Fe} of the iron sublattice and is parallel to the field, whereas above that temperature M_R is smaller than M_{Fe} and is antiparallel to the field. Thus below the compensation temperature the magnetization of the RE sublattice is enhanced, but above that temperature it is decreased, by the external field. As a consequence the sign of $d\lambda/dH$ is reversed at the compensation point. Therefore in Fig. 3 and in the table values of $(-d\lambda/dH)$ are shown for $T \geq T_c$, thus representing the variation of magnetostriction as the magnetization of the RE sublattice increases.

Our measurements showed that the anisotropic term $d\lambda_a/dH$ is also large in terbium and holmium iron garnets but is considerably smaller in gadolinium iron garnet (Fig. 3). At the same time, for all the investigated REIG the volume component of magnetostriction is approximately identical (see the table). Other investigations[7,8] have indicated low single-ion and exchange magnetostriction of the iron sublattices, which can be neglected when analyzing REIG magnetostriction.

The observed field dependence of REIG magnetostriction therefore results mainly from magnetoelastic interaction inside the RE sublattice and from magnetoelastic interaction between the RE and the "resultant" iron sublattices. To evaluate both terms at least qualitatively we measured the magnetostriction of RE gallates having garnet structure, where the magnetic iron ions are replaced by nonmagnetic gallium ions, so that the magnetostriction involves only the RE ions.

Figure 4 shows the field dependence of longitudinal and transverse magnetostriction in dysprosium gallium garnet. High anisotropic magnetostriction is observed in this compound, although the measurements were obtained considerably above the magnetic ordering temperature.[2)] Similar dependences are observed for terbium gallium garnet. Figure 3 shows the temperature dependence of the anisotropic term $d\lambda_a/dH$ in the RE gallium garnets. A comparison with RE iron garnets is difficult since at the investigated temperatures these compounds are in a different magnetic state; in iron garnets the RE ions interacting with the iron sublattice are acted upon by an exchange field of the order of 10^5 Oe, whereas in the interaction within the RE sublattices of both the iron and gallium garnets the exchange field is two orders smaller. Nevertheless, qualitative agreement is observed for $d\lambda_a/dH$ in iron and gallium garnets. According to[10], magnetostriction in gadolinium gallium garnet is much lower than in other RE gallium garnets; this also is consistent with the data for iron garnets.

We therefore conclude that the anisotropic component of REIG magnetostriction in high magnetic fields results from interaction within the RE sublattice. The drastic reduction of $d\lambda_a/dH$ for gadolinium iron garnet, where the Gd^{3+} ion is in an s state (with zero orbital angular momentum), indicates that the anisotropic magnetostriction is associated with interaction between the orbital moment of the RE ion and the crystal field of the lattice.

Our measurements indicate that the isotropic term $d\lambda_i/dH$ in the gallium garnets is small (not exceeding 0.04×10^{-6} kOe^{-1} in the range 200°—300°K) and positive (opposite in sign to REIG volume magnetostriction). It

[1)] We are not considering the immediate vicinity of T_c. Here in fields of the order 100 kOe noncollinear magnetic structures appear, thus complicating the field dependence of magnetostriction (see Figs 1 and 2 and [6,7]).

[2)] In RE gallium garnets the antiferromagnetic ordering temperatures that result from interactions within the RE sublattice are below 1°K. [9]

follows that REIG volume magnetostriction is caused mainly by the interaction between the RE and iron sublattices.

The contribution to magnetostriction that is derived from an isotropic magnetoelastic interaction between the RE and "resultant" iron sublattices can be evaluated from the experimental pressure dependences of the REIG compensation temperature and magnetization.[11,12] In the molecular field approximation the magnetization of a RE sublattice in an iron garnet can be represented by[7]

$$M_R = M_{R0} B_S \left(\frac{\mu_R}{kT} H_M \right) \quad (5)$$

Here M_{R_0} is the magnetization of the RE sublattice at 0°K, μ_R is the magnetic moment of the RE ion, and H_M is the effective molecular field acting upon the RE sublattice due to the "resultant" iron sublattice. At T_c the magnetization of the RE sublattice equals that of the iron sublattice, and from (5) we obtain the shift of the compensation temperature under isotropic pressure (assuming that the magnetization of the iron sublattice is almost independent of pressure: $dM_{Fe}/dp \approx 0$[12]):

$$\frac{1}{T_c}\frac{dT_c}{dp} = \frac{1}{H_M}\frac{dH_M}{dp}. \quad (6)$$

From thermodynamic relations it follows that

$$\frac{d\lambda_i}{dH} = -\frac{1}{3}\frac{dM_R}{dp}. \quad (7)$$

Then, as shown in[13], the volume magnetostriction resulting from the interaction between the sublattices is given by

$$\frac{d\lambda_i}{dH} = -\frac{1}{3}\chi\frac{dH_M}{dp}. \quad (8)$$

where χ is the susceptibility of the RE sublattice.

From (6) and (8) we obtain the relation between the volume magnetostriction and the pressure shift of the compensation temperature:

$$\frac{d\lambda_i}{dH} = -\frac{1}{3}\frac{\chi H_M}{T_c}\frac{dT_c}{dp}. \quad (9)$$

The table gives values of $d\lambda_i/dH$ calculated from (7) and (9) at room temperature. In these calculations we used experimental data for the pressure dependences of the REIG magnetization and the compensation temperature[11,12] and for susceptibilities and molecular fields.[8] The experimental and calculated values of $d\lambda_i/dH$ are seen to be close; this indicates that REIG isotropic magnetostriction results from the interaction between the RE and iron sublattices.

From our experimental results we conclude that the field dependence of magnetostriction in terbium, dysprosium and holmium iron garnets results mainly, especially at low temperatures, from the field dependence of anisotropic magnetostriction inside the RE sublattice. The isotropic component $d\lambda_i/dH$ is due to the magnetoelastic interaction between the RE and resultant iron sublattices.

Isotropic magnetostriction of rare earth iron garnets

	$d\lambda_a/dH$, 10^{-6} kOe^{-1}			
	$Gd_3Fe_5O_{12}$	$Tb_3Fe_5O_{12}$	$Dy_3Fe_5O_{12}$	$Ho_3Fe_5O_{12}$
Experiment	0.7±0.3	0.8±0.3	1.0±0.3	1.2±0.4
Calculated from data on the pressure dependence of REIG magnetization (Eq. 7)	0.6±0.15	1.8±0.4	1.0±0.3	—
Calculated from data on the pressure shift of the REIG compensation temperature (Eq. 9).	1.2±0.3	1.3±0.3	0.7±0.3	0.7±0.5

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