Journal of Magnetism and Magnetic Materials 464 (2018) 44–49

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Research articles

Colossal magnetostriction and electrostriction of bismuth-substituted neodymium iron garnet films

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ARTICLE INFO

Keywords:
Thermal expansion
Magnetostriction
Electrostriction

ABSTRACT

Electro- and magnetostriction mechanisms and temperature behavior of the length of bismuth-substituted neodymium iron garnet films on glass and gallium gadolinium garnet have been investigated. Electric- and magnetic-field and temperature dependences of the electro- and magnetostriction constants have been determined. It has been established that the magnetostriction constant changes its sign upon temperature variation. The experimental data are explained using a model of dipole glass with the magnetoelectric and magnetoelastic interaction.

1. Introduction

Bi-substituted rare-earth iron garnets have been used as optical isolators and other magnetooptical (MO) devices since they exhibit a large MO effect in the visible light region. Bi-substituted garnets are expected to be used as spatial light modulators, waveguide-type isolators, and MO indicators [1–3]. The MO effects are enhanced with increasing Bi substitution due to the change in the spin-orbit interaction contributed to by the 6p orbital of Bi [4–6] for example, Faraday rotation reaches 25°/μm around 530 nm in a fully Bi-substituted rare-earth iron garnet, $Bi_3Fe_5O_{12}$ (BIG). Therefore, garnets substituted with a large amount of Bi have been attracting attention as materials for MO applications [7–10].

The magnetic and structural characteristics of thin films depend on a substrate used. In particular, the lattice constant of the $Nd_xBi_{1-x}Fe_{5-y}Ga_yO_{12}$ film in the (1 1 1) direction is smaller than that in the (1 0 0) direction by 0.2% [11]. In bulk neodymium-substituted yttrium iron garnet samples, the first (K1) and second (K2) anisotropy constants are comparable; below 80 K, the constant K2 is larger than the constant K1 [12]. The magnetostriction constants are negative and their absolute value in $Yt_{2.5}Nd_{0.5}Fe_5O_{12}$ slightly grows with a decrease in temperature down to 77 K [13]. The magnetostriction of these compounds is determined by the single-ion character of a rare-earth element caused by the paraprocess.

The bismuth ferrite films exhibit the magnetoelectric properties [14], which originate from the electric polarization [15,16] and magnetic order [17,18]. The authors of [16] observed the magnetic-field-driven electric polarization of domain walls in the 10-μm-thick $(BiLu)_3(FeGa)_5O_{12}$ films grown by liquid-phase epitaxy on the (2 1 0) $Gd_3Ga_5O_{12}$ substrate. In the films grown on the (1 1 1) substrates, the electric polarization is not observed. These effects are related to the nonuniformity of the magnetoelectric interaction and electric-field-driven magnetic anisotropy variation [19]. The linear magnetoelectric effect was found in the 90-nm-thick bismuth ferrite films on (0 0 1) $Y_3Al_5O_{12}$ garnet (YAG) by a resonant technique with the electric field modulation [20]. The giant linear magnetoelectric effect in garnet ferrite films is revealed by the polarimetric method in magnetic fields up to 10 kOe [21]. The linear magnetoelectric interaction was attributed to the strong spin-orbit coupling and occurrence of a local magnetic inhomogeneity.

Multiferroic materials are characterized by the strong interrelation of the magnetic and electric subsystems, which is implemented in single-phase ferromagnetic materials by means of the spin-lattice and electron-lattice interactions. Study of single-phase materials with the high magnetostriction and large piezoelectric modulus in multiferroics is important for deeper understanding of electromagnetic phenomena in solids and creation of the new generation of solid-state electronic devices.

Yttrium iron garnet has a cubic symmetry with the inversion center [22] and undergoes a structural transition with the triclinic lattice distortion below 130 K [23]. The electric polarization can originate from the structural strain, which breaks the inversion center by means of epitaxial stresses of the film on a substrate or cation substitution over dodecahedral sites, as well as from the surface electronic states or

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https://doi.org/10.1016/j.jmmm.2018.05.038
Received 27 March 2018; Received in revised form 15 May 2018; Accepted 15 May 2018
Available online 16 May 2018
0304-8853/

magnetic domain structure induced by demagnetizing fields. The latter can be excluded when the measurements are performed in the external magnetic field stronger than the saturation field by an order of magnitude. The effect of epitaxial stresses can be elucidated by using two types of substrates and different substitutes (neodymium and gallium). The role of elastic stresses can be established from the magneto- and electrostriction data.

The aim of this study was to clarify a mechanism of magneto- and electrostriction and thermal expansion of the bismuth–neodymium iron garnet films deposited onto glass and garnet substrates.

2. Results and discussion

2.1. Thermal expansion of the films

We investigated the films of two types: $Nd_1Bi_2Fe_5O_{12}$(450 nm)/$Nd_2Bi_1Fe_4Ga_1O_{12}$(90 nm) films deposited onto glass and $Nd_{0.5}Bi_{2.5}Fe_5O_{12}$(450 nm) films on a (1 1 1) single-crystal $Gd_3Ga_5O_{12}$ garnet (GGG) substrate. The films were grown epitaxially. Using the bilayer film enable to switch the direction of the magnetic moment and modulate the value of the Faraday angle of rotation in a magnetic field.

The relative change in the length of films was determined with ZFLA-3-11 strain gauges with a resistance of 140 Ω. One strain gauge was located on the film, the other on the substrate. The difference between resistances of two gauges (on the film (R_f) and on the substrate (R_s)) $\delta L = (R_f - R_s)/R_s = (L_f - L_s)/L_s$ was measured. The magnetostriction constant was determined from the variation in the strain gauge resistance $\lambda = (R(H) - R(0))/R(0) = (L(H) - L(0))/L(0)$ in a magnetic field. Fig. 1a shows the relative change in the length of a film deposited onto glass upon temperature variation. The thermal expansion coefficient $d(\delta L)/dT$ of the film has several anomalies; in particular, the relative change in the film length sharply drops at T = 194, 294, and 445 K and the film is strongly expanded at T = 358 and 416 K. Above room temperature, the film is expanded upon heating and attains its maximum length at the Curie temperature. The change in the $d(\delta L)/dT$ sign around room temperature is related to the dipole glass formation. The maximum expansion of the film in the vicinity of the transition temperature can be caused by the iron ion spin fluctuations, which lead to the expansion of the film due to the magnetoelastic interaction.

The temperature dependence of the thermal expansion of the $Nd_{0.5}Bi_{2.5}Fe_5O_{12}$ film on the iron garnet substrate is qualitatively different (Fig. 1b). Above 160 K, the thermal expansion of the film sharply increases and exhibits a small maximum at 298 K. The interaction between the film and GGG substrate is stronger than in the case of amorphous glass. Epitaxial strain, followed by fast lattice relaxation and relaxed for thicknesses above a few tens of nanometers [1]. On the interface the deformation exists within the 20–30 lattice constants. Part of the volume of the film changes with a temperature similar to the substrate, and the expansion of the rest of the film is due to various types of interactions in the film. Thus, the substrate is responsible for the thermal expansion of the film.

2.2. Magneto- and electrostriction of the films

Fig. 2 presents the magnetostriction constant of the film deposited onto glass as a function of the magnetic field applied perpendicular to the film. Around room temperature, one can observe the nonlinear λ(H) dependence. In a magnetic field of H = 12 kOe, the magnetostriction

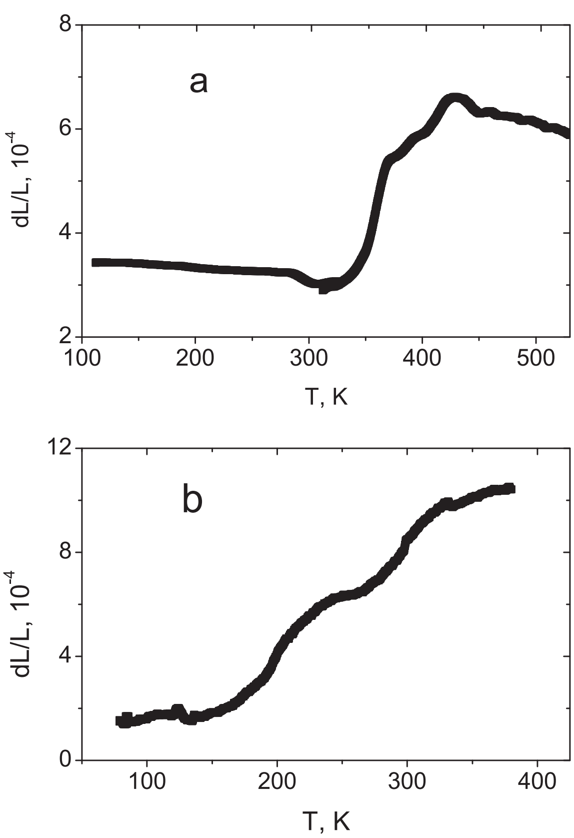

Fig. 1. Relative change in the length of $Nd_1Bi_2Fe_5O_{12}$ (450 nm) / $Nd_2Bi_1Fe_4Ga_1O_{12}$ (90 nm) films on a glass substrate (a) and $Nd_{0.5}Bi_{2.5}Fe_5O_{12}$ (450 nm) on a $Gd_3Ga_5O_{12}$ single crystal substrate (GGG) as a function of temperature.

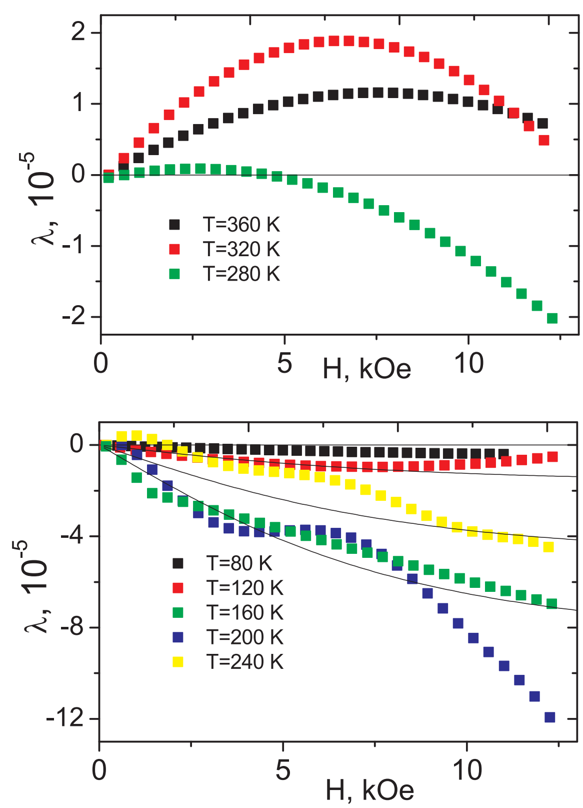

Fig. 2. The magnetostriction constant $\lambda = (L(H) - L(0))/L(0)$ of the film $Nd_1Bi_2Fe_5O_{12}$(450 nm)/$Nd_2Bi_1Fe_4Ga_1O_{12}$(90 nm) on glass substrates at a fixed temperature as a function of the magnetic field. Theoretical values of λ, calculated from the expression (9) (solid lines).