ScienceDirect

Journal of Magnetism and Magnetic Materials
Volume 476, 15 April 2019, Pages 551-558

Review Articles

Magnetic, magneto-optical and specific heat studies of the low temperature anomalies in the magnetodielectric DyIG ferrite garnet

Assia Boutaba [a], Mahieddine Lahoubi [a], Vera Varazashvili [b], Shengli Pu [c]

Show more

Share Cite

https://doi.org/10.1016/j.jmmm.2018.12.071
Get rights and content

Abstract

Measurements of magnetization and Cotton Mouton effect (CM) under external magnetic field (H_{ex}) combined with specific heat experiments at $H_{ex} = 0$, were performed on dysprosium iron garnet $Dy_3Fe_5O_{12}$ (or DyIG) single crystals. The low-temperature dependences of some magnetic, magneto-optical and thermodynamic quantities, such as spontaneous magnetization, both magnetic and CM susceptibilities and the excess specific heat due to the contribution of the Dy^{3+} ions only, give rise to the appearance of two types of anomalies. The first one which is related to the 'low temperature paraprocess' effect, occurs in the region of the 'Belov point' T_B predicted at 42 K. Whereas the second one, which is due to the previous first-order spin reorientation phase transition, takes place at $T_{SR} = 15$ K. The easy axis of magnetization defined by the resultant iron sublattice magnetization vector $\mathbf{M_{Fe}}$, which remains along the ⟨1 1 1⟩ direction above T_{SR}, changes spontaneously below T_{SR} and becomes aligned along the low symmetry angular ⟨u u w⟩ phase. The results are analyzed taking into account those reported earlier, such as the negative magnetodielectric property for $H_{ex} < 10$ kOe and the Schottky effect which are related to the anomalies observed respectively in the temperature dependences of the dielectric constant at T_{SR} and the excess specific heat near T_B.

Introduction

The rare earth iron garnets with general formula $RE_3Fe_5O_{12}$ or REIGs (where RE is a trivalent rare earth ion or the yttrium) have been extensively studied over the last four decades and lot of theoretical and experimental works on bulk properties have been reported in the renowned review articles [1], [2], [3], [4] and references therein]. The REIGs which were first synthesized by Bertaut and Forrat [5] were found to have a cubic crystallographic structure containing eight molecules per unit cell with lattice parameters of

about 12 Å and described by the space group $\mathbf{Ia\bar{3}d-(O_h^{10})}$ No. 230. The first magnetization measurements of different REIGs reported for polycrystalline materials by Pauthenet in his famous thesis [6] have well illustrated the Néel theory of ferrimagnetism [7]. They were followed some years later by similar experiments carried out by Belov et al. [8] on polycrystalline specimens and on ultrapure single crystals by Geller et al. [9] and Harrison et al. [10].

In the point of view of applications, the REIGs exhibit a strong potential in various fields of science and technology. Their extraordinary magnetic and optical properties make them attractive materials for a wide range of applications ranging from optical communications, in the field of magnetic storage, magnetic recording, magnetic field sensor and magneto-optical devices based on photonic and magneto-photonic crystals [11], [12], [13] to magnetic refrigeration process due to the magnetocaloric effect [14].

The magnetodielectric (MD) effect is defined as a change in the dielectric permittivity by an applied external magnetic field. This MD effect itself is very attractive for practical applications and was observed in some materials due to magnetoelectric (ME) coupling which consists in inducing the electric polarization in an applied external magnetic field, or vice versa, inducing the magnetization in an applied electric field. REIGs, as nontraditional materials towards magnetoelectricity, have been beyond the mainstream of the intensive research. However, an interest in REIGs was renewed after the recent discovery of the ME and MD effects in TbIG and DyIG at low temperatures and in surprisingly low external magnetic fields, $H_{ex} \leq 10$ kOe [15], [16], [17], [18]. These ferrimagnets have attracted significant attention at this juncture with regard to their enhanced bulk properties. From the recent works related to the magnetic and thermodynamic properties of TbIG single crystals [19], [20], it appears in this regard, that the accurate measurements of magnetization and specific heat have contributed greatly to our better understanding of the mechanisms behind these MD and ME effects knowing that the origin of such effects in the REIG crystals still remains a puzzle [15]. The case of the Dy^{3+} ion is particularly appealing if we consider the anomalous temperature dependence of the static value of the dielectric constant, ε(T) reported by Song et al. [16]. In fact, a peak-like anomaly was observed at a transition temperature of about 17 K on the temperature dependence of ε(T) at zero H_{ex} with AC electric field, E applied on a single crystal along the $\langle 1\,\bar{1}\,0\rangle$ direction. A second feature was also reported with the measurement of the corresponding negative MD effect, [Δε/ε](T) of about 1% for $H_{ex} = 10$ kOe and applied along the 〈1 1 1〉 direction. Similar results were found in the measurements of ε(T) with E applied along the 〈1 0 0〉 direction with a peak anomaly at 16 K and a negative MD effect for $H_{ex} < 10$ kOe and applied along the 〈0 1 1〉 direction [17], [18]. The cusplike anomaly revealed at 17 K [16] in the temperature dependence of the magnetic susceptibility, χ(T) defined as M/H_{ex} measured along the direction 〈1 1 1〉 for zero field cooling and $H_{ex} = 1$ kOe field cooling, was interpreted as the results of the long-range noncollinear magnetic ordering of the Dy^{3+} moments which form the so called 'double-umbrella' structure revisited previously by one of us [21 and refs. therein]. Whereas, the sharp minimum occurred at 16 K in the temperature derivative of magnetic susceptibility, $\mathbf{d\chi_{Hex}\,(T)\,/\,dT}$ with $\mathbf{\chi_{Hex}\,(T) = M\,(T)\,/H_{ex}}$ and $H_{ex} = 1$ kOe applied along the 〈0 1 1〉 direction, was received a different interpretation from Rogers et al. [17] and Kang et al. [18] who considered that significant ferromagnetic interactions between the Dy^{3+} ions should appear below 16 K. It must be noted that this transition temperature at 16 or 17 K in both ε(T) and χ(T) coincides with the previous transition temperature, T_{SR} predicted theoretically and confirmed experimentally at 12–16 K [22], [23], [24], [25], [26]. It was found that a spontaneous first-order spin reorientation (SR) phase transition occurs from the high-symmetry 〈1 1 1〉 phase at high temperature to the low symmetry angular 〈u u w〉 phase below T_{SR}. Measurements carried out on single crystal and polycrystalline samples belonging to the substituted dysprosium-yttrium iron garnet $Dy_xY_{3-x}IG$ system showed that the transition temperature was found almost independent of the Dy concentration, x with a value equal to 13.5 ± 1.5 K [27]. The different interpretations of the observed MD effects were based on the field induced change from canted to a coaxial spin structure as well as the magnetic domain rotation [16] or

on the magnetic reordering of the Dy^{3+} ions only [17], [18] without taking into account the change of the net iron sublattice magnetization vector $\mathbf{M}_{Fe}$ during the SR phase transition. Therefore, in order to precise the role of the SR phase transition ⟨1 1 1⟩ ↔ ⟨u u w⟩ in the MD effect observed at T_{SR}, we decided to revisit some magnetic and magneto-optical properties of DyIG at low temperatures.

In addition, the study of the connection of the far-infrared spectra of the magnetic exchange resonances and optical phonons to magnetic and dielectric properties of DyIG [17], [18] has also revealed an anomalous temperature dependence of the frequency of the ligand-field and crystal-field excitations for T < 45 K. This concerns particularly, the region of the 'low-temperature point', T_B predicted by Belov [28] and estimated at 42 K from the maxima observed in the temperature dependences of the paraprocess of the forced magnetostriction, $[d\lambda_p/dH_{ex}](T)$ and the paraprocess of magnetic susceptibility, $\chi_p(T)$ [29]. This T_B point, named firstly as the "locking-temperature", was evaluated at a higher value (80 K) from the temperature dependence of the inverse of magnetic susceptibility, $\chi^{-1}(T)$ deduced by isothermal magnetization [6]. Whereas a peak was found at 50 K in the excess of specific heat, $C_p^{ex}(T)$ deduced on the basis of experimental data C_p(DyIG) obtained on polycrystalline sample [30]. Such anomalies can be interpreted partially on the basis of the theoretical and experimental works of Belov on ferrimagnets as REIGs possessing a 'weak sublattice' of the most heavy RE^{3+} ions [28]. Without making any microscopic hypothesis, this author has attributed such anomalies to the occurrence of a "sharp change of the long-range magnetic order in the 'weak sublattice' of the RE^{3+} ions in the crystallographic site {24c}. The interactions energy of the RE^{3+} ions with the effective exchange field is comparable with the thermal energy and the calculations based of the molecular field approximation yield the following relation: $\mathbf{T_B} = \frac{\mu_B g_S S (H_{exch})_{eff}}{k_B}$, where g_s is the Landé-g factor of the spin S of the RE^{3+} ions and $(H_{exch})_{eff}$, the effective exchange field induced by the 'strong sublattice', mainly the Fe^{3+} ions in the (24d) sublattice or by the unidirectional exchange anisotropy of the J_{cd} interactions". Then, another major unresolved question that we may have to pay specific attention is how one can ascertain the anomalous features due to the T_B point only knowing that the Schottky effect causes anomaly in the same temperature region. As it was reported previously in the C_p studies of TbIG and DyIG [30], this Schottky effect seems contributed in part to C_p^{ex} due to Tb^{3+} ions deduced from C_p(TbIG) [19], [20] and would be expected to produce a superimposed Schottky contribution in the anomaly revealed in the experimental C_p(DyIG)/C_p(YIG) ratio [31].

Section snippets

Experimental details

The flux grown crystals are prepared by the standard $PbO/PbF_2/B_2O_3$ method as already described elsewhere [19], [20], [31]. The first set of DyIG specimens is composed on two spherical samples, #1 and #2 which will be used for magnetization and specific heat measurements. They respective diameters are about 4.5 and 3 mm while their weights are equal to 376.82 and 203.08 mg. For magneto-optical experiments, polished plates 300–800 μm thick cut in the (1 1 1) plane (sample #3) are used. The…

Magnetization

Shown in Fig. 1, is the forced rotation magnetization measured at 4.2 K and at H_{ex} = 35 kOe. At this temperature, this limited value for H_{ex} is not high enough to make the sample single domain and can no longer achieve its saturation of magnetization. Here, one can observe that $M_{sat}(\alpha)$ presents two flat maxima when α takes a value corresponding of an easy axis of magnetization (EAM) located between the ⟨1 1 1⟩ and ⟨1 0 0⟩ axes. The magnetization is rotated from ⟨1 1 1⟩ towards ⟨1 0 0⟩ in…

Conclusion

We have reported new experimental investigations based on precise measurements carried out on DyIG single crystals at low temperatures. The results of magnetization and Cotton Mouton effect under an external magnetic field H_{ex} with specific heat data obtained at $H_{ex} = 0$ are reported. Anomalies are observed near $T_{SR} = 15$ K where the iron spin reorientation phase transition occurs and in the region of low-temperature point $T_B = 42$ K predicted by Belov. Whereas the first-order nature of the T_{SR}…

Acknowledgements

This work was supported in part by the Algerian Ministry of Higher Education and Scientific Research and in part by a previous joint-cooperation project through the Algerian-French C.M.E.P program between Badji Mokhtar-Annaba University, Annaba, Algeria and Joseph Fourier University-C.N.R.S., Grenoble, France. P. Lethuillier and J. Voiron, researchers at the Laboratoire Louis Néel, C.N.R.S. – reorganized as the Institut Néel – Grenoble, France, are acknowledged for their technical assistance.…

References (47)

R. Moretti *et al.*
Geochim. Cosmochim. Acta (1998)

T.K. Vien *et al.*
Opt. Commun. (1975)

M. Guillot *et al.*
J. Magn. Magn. Mater. (1983)

M. Guillot *et al.*
J. Magn. Magn. Mater. (1982)

D.T.T. Nguyet *et al.*
J. Sci.: Adv. Mater. Devices (2016)

A.K. Zvezdin
Field induced phase transitions in ferrimagnets

M. Lahoubi *et al.*
J. Alloys Compd. (1998)

M. Lahoubi *et al.*
J. Magn. Magn. Mater. (2015)

F. Sayetat
J. Magn. Magn. Mater. (1986)

M. Lahoubi *et al.*
Physica B (2000)

View more references

Cited by (7)

The enhancement of the Ce-solubility limit and saturation magnetization in the Ce<inf>0.25</inf>Bi<inf>x</inf>Pr<inf>y</inf>Y<inf>2.75-x-y</inf>Fe<inf>5</inf>O<inf>12</inf> garnet synthesized by the conventional ceramic method
2020, Ceramics International

Show abstract

Optimized growth of compensated ferrimagnetic insulator Gd<inf>3</inf>Fe<inf>5</inf>O<inf>12</inf>with a perpendicular magnetic anisotropy
2021, Chinese Physics B

Anomalies in the magnetic properties of some terbium-yttrium iron garnets at low temperatures
2020, IOP Conference Series: Materials Science and Engineering

Magnetic materials and systems: Domain structure visualization and other characterization techniques for the application in the materials science and biomedicine
2020, Inorganics

Experimental Investigation on the Low-Temperature Anomalies in Dysprosium Iron Garnet (DyIG)
2019, Journal of Superconductivity and Novel Magnetism

Effects of a high DC magnetic field on spin reorientation in dysprosium- yttrium iron garnets at low temperatures
2019, AIP Advances

View all citing articles on Scopus

Recommended articles (6)

Research article

Morphology and magnetic properties of FeCo particles synthesized with different compositions of Co and Fe through co-precipitation, flux treatment, and reduction
Journal of Magnetism and Magnetic Materials, Volume 476, 2019, pp. 229-233

Show abstract

Research article

Broadband transverse susceptibility in multiferroic Y-type hexaferrite $Ba_{0.5}Sr_{1.5}Co_2Fe_2O_{22}$
Journal of Magnetism and Magnetic Materials, Volume 476, 2019, pp. 478-482

Show abstract

Research article

Nonstoichiometry defects and microinhomogeneities in multicomponent manganites

Journal of Magnetism and Magnetic Materials, Volume 476, 2019, pp. 371-375

Show abstract

Research article

Investigation of electronic, magnetic and structural properties of the $Fe_{1-x}Mn_xRh$

Journal of Magnetism and Magnetic Materials, Volume 476, 2019, pp. 325-328

Show abstract

Research article

Electric-field control of the degenerate shell in a triangular graphene quantum dot

Journal of Magnetism and Magnetic Materials, Volume 476, 2019, pp. 225-228

Show abstract

Research article

Study of the structural, mechanical, electronic and magnetic properties of quaternary YFeCrX (X = Al, Ga, In, Si, Ge, Sn, P, As, Sb) Heusler alloys

Journal of Magnetism and Magnetic Materials, Volume 476, 2019, pp. 398-411

Show abstract

View full text

© 2018 Elsevier B.V. All rights reserved.

Copyright © 2023 Elsevier B.V. or its licensors or contributors.
ScienceDirect® is a registered trademark of Elsevier B.V.