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Magnetization study of single-crystalline $ErFe_5Al_7$

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ABSTRACT

The field and temperature dependence of the magnetization of a $ErFe_5Al_7$ single crystal (tetragonal crystal structure of the $ThMn_{12}$-type) has been studied in magnetic fields up to 14 T. The compound is a ferrimagnet with Curie temperature $T_C = 201$ K and a compensation point $T_{comp} = 34$ K. $ErFe_5Al_7$ displays easy-plane anisotropy. Anisotropy is also present in the basal plane, the easy-magnetization direction is the [1 0 0] axis with the spontaneous magnetic moment $M_s = 1.28\ \mu_B$/f.u. at $T = 2$ K. The compound exhibits field-induced magnetic transitions along the [1 0 0] and [1 1 0] axes. The transition along [1 0 0] is observed at $T < 40$ K and its critical field $H_{cr,100}$ displays complex non-monotonous temperature dependence. Along [1 1 0] magnetization jumps occur in a very narrow temperature interval $T = 31$–40 K. $H_{cr,110}$ is a very sharp function of temperature. Much higher fields are required to induce the transition at $T < 31$ K. At low temperatures strong hysteresis is observed, the coercivity is as high as $H_c \approx 2.5$ T along the [1 0 0] and [1 1 0] axes at $T = 2$ K.

1. Introduction

Intermetallic compounds based on rare-earth and late 3d elements crystallizing in the tetragonal $ThMn_{12}$-type structure (space group $I4/mmm$) form a wide group of magnetic materials (for a review see Ref. [1]). Some of them, e.g., $NdFe_{11}TiN_x$, $SmFe_{11}Ti$ and $SmFe_{10}V_2$ are considered as potential materials for permanent magnets [2–4]. On the other hand, some compounds of this group are interesting objects from the fundamental point of view due to their peculiar magnetic properties. A particularly interesting case is represented by RFe_5Al_7 (R = Sm–Lu, Y) with competitive exchange and anisotropic interactions. RFe_5Al_7 compounds with magnetic heavy rare-earth elements are highly-anisotropic ferrimagnets [5,6], which makes their single crystals indispensable in magnetic studies.

Magnetic studies of ferrimagnetic $DyFe_5Al_7$ and $HoFe_5Al_7$ single crystals confirmed that both compounds display strong magnetic anisotropy [7,8]. The magnetic moments are confined to the basal plane. At low temperatures, due to strong rare-earth contribution, anisotropy is also present within the basal plane of the tetragonal lattice, the easy-magnetization direction (EMD) is the [1 0 0] axis in $DyFe_5Al_7$ and the [1 1 0] axis in $HoFe_5Al_7$. Measurements of magnetization and acoustic properties in static and pulsed magnetic fields up to 60 T revealed two first-order field-induced magnetic transitions along the EMD at low temperatures in both compounds [9,10]. The transitions are a result of the interplay among the Zeeman energy, anisotropy energy and the 3d-4f exchange interactions. The latter couple the 3d sublattice with the much more anisotropic 4f sublattice.

As regards the magnetic anisotropy of the Fe sublattice in RFe_5Al_7, it was examined on a $GdFe_5Al_7$ single crystal since for Gd the orbital quantum number is $L = 0$ [11]. Although the anisotropy of the Fe sublattice is considerably lower than that of Dy and Ho, at low temperatures both the anisotropy between the easy plane and the hard c axis and the anisotropy within the easy plane were observed as well.

Other RFe_5Al_7 compounds with magnetic heavy rare-earth elements appear to be interesting as well. The present paper reports the results of a magnetic study of the $ErFe_5Al_7$ compound performed on a single crystal. Apart from strong magnetic anisotropy, one might also expect field-induced transitions from the initial magnetic structure (the Er and Fe magnetic sublattices are polarized collinearly in the opposite directions [12]) as the magnetic moments of the Er and/or Fe sublattices rotate in an applied magnetic field.

2. Experimental details

The $ErFe_5Al_7$ single crystal was grown by a modified Czochralski method in a tri-arc furnace from a stoichiometric mixture of the pure elements (99.9% Er, 99.98% Fe and 99.999% Al) using a tungsten rod as a seed under 10 mm/h pulling speed. The crystal structure was determined by a standard powder X-ray diffraction analysis performed on a part of the single crystal crushed into a fine powder. The

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diffraction patterns were refined by means of Rietveld analysis [13] which confirmed the $ThMn_{12}$-type crystal structure and the absence of extraneous phases. The lattice parameters, a = 867.1 pm, c = 503.7 pm, are in good agreement with the literature [6]. The back-scattered Laue patterns were used to check the monocrystalline state and to cut the samples for the magnetization measurements.

Temperature and field dependencies of magnetization at T = 2–280 K were measured along the principal crystallographic directions [1 0 0], [1 1 0] and [0 0 1] of a 30 mg sample using a standard PPMS-14 magnetometer (Quantum Design) in magnetic fields up to 14 T.

3. Results and discussion

Fig. 1 presents magnetization curves of the $ErFe_5Al_7$ single crystal along the principal crystallographic directions at several selected temperatures. The compound displays a spontaneous magnetic moment along the [1 0 0] and [1 1 0] axes, whereas there is no spontaneous component along the [0 0 1] axis. Therefore, the magnetic moments of $ErFe_5Al_7$ lie in the basal plane of the tetragonal lattice, the [0 0 1] axis is the hard-magnetization direction, in agreement with neutron-diffraction data [12]. Anisotropy is also present within the basal plane as evident from the difference between the magnetization curves along the [1 0 0] and [1 1 0] axes. The EMD is the [1 0 0] axis with the spontaneous magnetic moment $M_s = 1.28\ \mu_B$/f.u. at T = 2 K. Assuming that the magnetic moment of the Er sublattice is equal to that of a Er^{3+} ion, $M_{Er} = 9\ \mu_B$/f.u., the magnetic moment of the Fe sublattice can be determined as $M_{Fe} = M_{Er} - M_s = 7.72\ \mu_B$/f.u. This corresponds to 1.54 μ_B per Fe atom. The spontaneous moment ratio along the [1 1 0] and [1 0 0] axes, $M_s^{110}/M_s^{100} \approx \cos 45^\circ$, corresponds well to the tetragonal symmetry and reflects proper orientation of the single crystal. At low temperatures (see the curves at T = 2 K in Fig. 1) the [1 1 0] and [1 0 0] magnetization isotherms intersect at about 3 T and then the magnetization along the [1 1 0] axis continues to grow and does not follow that along the easy [1 0 0] axis as would be expected if 3 T was the field $H_{a,p}$ of the in-plane anisotropy. At elevated temperatures, the field where the [1 1 0] curve reaches the [1 0 0] one, is indeed $H_{a,p}$, above which both curves coincide (see the curves at T = 60 K in Fig. 1). The in-plane anisotropy gradually weakens as temperature increases. It is still present at T = 100 K but disappears around T = 140 K.

It is also seen in Fig. 1 that after the domain-wall motion is completed, the signal along the basal-plane directions continues to grow in $ErFe_5Al_7$. The reason is the weak Er–Fe exchange interaction that gives rise to the high susceptibility. Field-induced non-collinearity of the magnetic moments appears as the initial collinear ferrimagnetic structure is broken, and the magnetic moments rotate towards the field direction. Strong paraprocess was also observed in $DyFe_5Al_7$ [7], $HoFe_5Al_7$ [8] and $GdFe_5Al_7$ [11].

Fig. 2 shows the spontaneous magnetic moments along the [1 0 0] and [1 1 0] axes of the $ErFe_5Al_7$ single crystal as a function of temperature. The M_s values were determined from the magnetization isotherms using Arrott plots. The curves represent ferrimagnetic temperature dependencies of M_s. A compensation of the Er and Fe sublattices is observed at T_{comp} = 34 K, and M_s of $ErFe_5Al_7$ drops to zero at T = 209 K. The temperature dependence of the specific heat C_p of the $ErFe_5Al_7$ single crystal in the vicinity of the magnetic ordering temperature is shown in the inset in Fig. 2. C_p exhibits a weak anomaly at the Curie temperature T_C = 201 K (no other anomalies are observed on the $C_p(T)$ dependence to T = 2 K). Non-zero M_s values at higher temperatures mean that application of the Arrott plots is not completely correct in the case of ferrimagnets with very different sublattices, a low magnetic moment is induced by an external magnetic field in $ErFe_5Al_7$ at $T > T_C$. For this reason, only zero-field measurements are expected to provide the proper value of the magnetic ordering temperature. Its value for $ErFe_5Al_7$ is taken to be T_C = 201 K.

The magnetization curve along the [1 0 0] axis of the $ErFe_5Al_7$ single crystal at T = 2 K displays a step-wise anomaly with a broad hysteresis (see Fig. 1). The observed first-order field-induced magnetic transition is shown in detail in Fig. 3 that presents the temperature evolution of the [1 0 0]-axis magnetization curve in the range T = 2–40 K. Initially, the critical field of the transition $H_{cr,100}$ (we mark this transition field $H_{cr,100}$ since another magnetic transition is also observed along the [1 1 0] axis, see Fig. 4) decreases with increasing temperature. At T = 2 and 10 K the transition has a trapezoid shape. A more complicated two-step anomaly is observed with decreasing magnetic field at T = 15 K. Yet another transition shape is seen at T = 20 K: magnetization experiences a jump with increasing magnetic field, whereas with decreasing field the magnetization is a smooth function of field without any anomaly. Surprisingly, at T = 25 and 30 K the transition field increases with temperature, and the transition shape changes yet again. At T = 32 K the transition is observed in a much lower field and looks very similar to that at T = 20 K. At $T > T_{comp}$ magnetization still displays the transition, its field grows with temperature. It means that

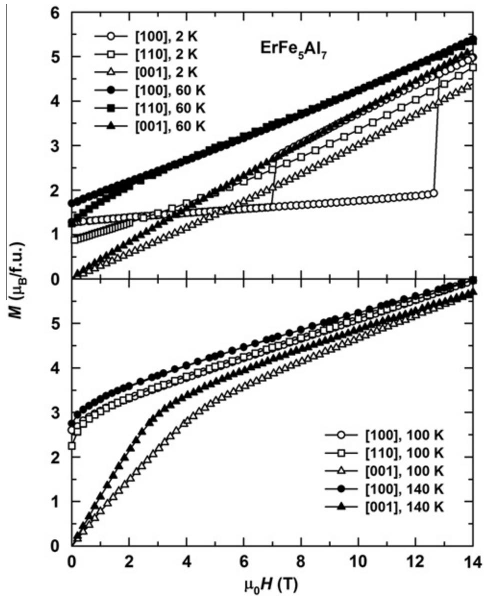

Fig. 1. Magnetization isotherms measured along the principal axes of the $ErFe_5Al_7$ single crystal at selected temperatures.

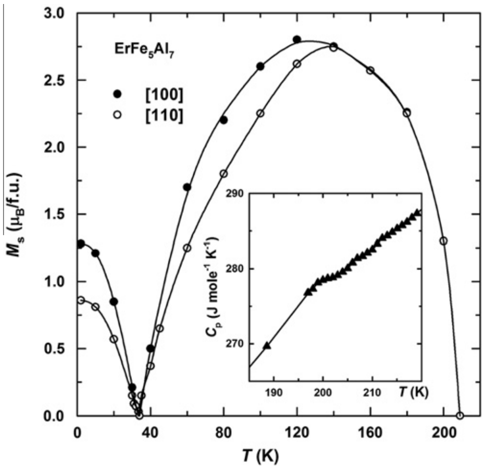

Fig. 2. Temperature dependence of the spontaneous magnetic moment M_s obtained from Arrott plots along the [1 0 0] axis and its projection onto the [1 1 0] axis of the $ErFe_5Al_7$ single crystal. The inset shows the temperature dependence of the specific heat C_p in the vicinity of the Curie temperature T_C = 201 K.