Magnetostriiction measurement of GdRu$_2$Si$_2$ single crystal

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Abstract. We report on the strongly anisotropic thermal expansion (TE) and magnetostriiction (MS) of a GdRu$_2$Si$_2$ single crystal measured along the principal crystallographic directions (the $a$- and $c$- axis, respectively) down to 2K and magnetic fields up to 14T. The MS (positive along the $c$-axis and negative in the perpendicular direction) reflects the three magnetic field induced transitions, for the field applied along the $c$-axis with a significant hysteresis (0.05T) for the transitions in low fields. Independently on the magnetic field direction there is a remanent MS along the $a$-axis after removing the field, suggesting irreversible evolution of magnetic structures.

1. Introduction

The studied compound is one of the large family of RT$_2$X$_2$ (R – rare-earth or actinide, T – transition metal, X – p-element, usually Si or Ge) compounds. In these ternary intermetallics a large variety of physical phenomena have been observed, covering also interesting phenomena like mixed valence materials, heavy fermion, dense Kondo behavior and superconductivity. The crystal structure is usually ThCr$_2$Si$_2$-type (body centered tetragonal, I4/mmm), which is built up of layers of atoms of some kind stacked along the $c$-axis (R-T-X-T). The layered character of this structure is reflected in physical (namely magnetic) properties of these compounds. Most of these materials are antiferromagnets, which exhibit metamagnetic (MT) transitions to the field forced ferromagnetic alignment of R moments for the magnetic field applied along the $c$-axis (easy magnetization axis).

GdRu$_2$Si$_2$ was reported as antiferromagnetic [1,2], as well as the neighboring compounds. The magnetic studies [3] performed on a single crystal shows unexpectedly a significant anisotropy, several MT transitions for temperatures below $T_N \sim 47$ K and second order-to-order magnetic phase transition at $T_t \sim 40$ K.

Due to the presence of Gd$^{3+}$ ion, this compound is interesting also from the theoretical point of view – a symmetry breaking distortion is expected in this class of compounds, but it was not proved [4]. The lack of the experimental data in this area has motivated us to perform the study of elastic properties under the magnetic field and at low temperatures.

Here we present results of magnetostriiction study on the single crystalline GdRu$_2$Si$_2$ sample in fields up to 14 T and in the temperatures down to 2 K.

2. Results

The GdRu$_2$Si$_2$ single crystal sample was grown using modified Czochralski method in tri-arc furnace. Crystal quality was checked by x-ray diffraction. A part of sample with the dimensions $0.96(4) \times 1.04(4) \times 1.80(4)$ mm$^3$ was used for measurements. The thermal expansion (TE) and
magnetostriction (MS) were measured using the microdilatometric capacitance cell [4], recently implemented in the commercial PPMS machine (Quantum Design), capable to control sample environment condition in the range 2-350 K and magnetic fields up to 14 T. The thermal expansion and magnetostriction were measured along the $a$- and $c$- direction for fields applied along the $a$- and $c$- direction, both in longitudinal and transversal geometry.

The temperature dependence of TE measured along all the principle directions is depicted on Fig. 1. The $T_N$ transition at 44 K is visible for all curves whereas $T_t$ transition at 37 K exhibits itself (as a change in slope of linear thermal coefficient $\alpha$) only in the basal plane. In the nonmagnetic region the sample changes its linear dimensions monotonously, in the vicinity of $T_N$ there is an upturn and contraction along the $c$-axis and expansion in the basal plane. With decreasing temperature, there is slight change in curvature in $dx/x$ curve (or change of slope in $\alpha$) for measurement in the basal plane, whereas evolution for the measurement along the $c$-axis doesn’t show any signature for the $T_t$ transition.

If we perform the same measurement under applied magnetic field along the $a$-axis we are able to distinguish a new field-induced magnetic phase that reflected itself as a drop (measurement along the $a$-axis) or small pit (measurement along the $c$-axis) at the temperature 17K. The identical experiment performed for the field applied along the $c$-axis does not show any anomaly below $T_N$ for either direction as expected with regard to the proposed magnetic phase diagram in [3]. The temperature dependence of TE in 14T for all four geometrical conditions doesn’t show any anomaly as it is expected for forced ferromagnetic state.

The results of magnetostriction measurements performed after cooling in zero field (ZFC) are in Fig. 2. For the field applied along the $c$-axis there are clearly seen two consecutive transitions (2.1 and
Fig. 2 Magnetostriction measured along main crystallographic axis with respect to magnetic field applied along the a-and the c-axis. Arrows show increasing/decreasing field.

2.3 T) for both directions. In higher fields there is a linear expansion (c-axis) and contraction (a-axis) with a saturation behavior above ~9.5 T in both directions. The relative changes of linear dimension in this saturated state are $2.36 \times 10^{-4}$ for the c-axis and $-0.46 \times 10^{-4}$ for the a-axis, respectively, yielding volume increase of $1.44 \times 10^{-4}$. With decreasing field there is a significant hysteresis (~0.05T) in the longitudinal geometry for both low field transitions and the ZFC state is obtained, contrary to the transversal geometry where a prolongation (~$10^{-5}$) with respect to the ZFC state was found.

The same measurements performed for the field applied along the a-axis shows the signatures of three field-induced transitions. The sample nonlinearly prolongates in both directions up to 2 T. For the c-axis the expansion continues linearly after the 2T transition up to ~10T (with change of slope and step-like anomaly reflecting MT transition), where the magnetostriction reaches saturation. The a-axis direction starts shrink for field above 2T and after the step-like anomaly at 4T reaches saturation at ~10T. The saturation values for relative changes (with respect to the ZFC state) are $2.35 \times 10^{-4}$ for the c-axis and $-0.61 \times 10^{-4}$ for the a-axis, respectively leading to the volume change $1.13 \times 10^{-4}$. We have not observed any significant hysteresis on any curve with decreasing field. The ZFC state is not revealed, there is a prolongation of about $0.25 \times 10^{-4}$ along the a-axis.

3. Conclusions

Presented results are in good agreement with previous reports based on magnetization data evaluation. The ‘double’ phase transition (of the first order) for field applied along the c-axis and its signature in MS data (prolongation along c-axis, expansion and then contraction in basal plane) may be connected with sudden two-step spin reorientation. The MS data for the field applied along the a-axis suggest a continuous change of spin direction and/or propagation vector. For both directions of magnetic field it is possible to induce a new magnetic configuration (probably connected with rotation of an in-plane component of magnetic moment), which remains stable after removing the magnetic field.

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