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Magnetic Properties of $TbFe_{0.25}Ge_2$, $TbSn_{0.4}Ge_{1.4}$ and $NdSn_{0.6}Ge_{1.775}$ Compounds

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The magnetic data of $TbFe_{0.25}Ge_2$, $TbSn_{0.4}Ge_{1.4}$ and $NdSn_{0.6}Ge_{1.775}$ compounds are reported. These compounds crystallize in the orthorhombic crystal structures described by the space group *Cmcm* (No. 63) and they are antiferromagnets with the Néel temperatures equal to 19.5, 22 and 3.7 K, respectively.

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1. Introduction

The magnetic properties of the rare-earth intermetallic compounds are the subject of intensive investigations in purpose to determine the new magnetic materials with peculiarity properties.

Our research in recent years focused on the ternary intermetallic compounds which crystallize in the orthorhombic crystal structure of $CeNiSi_2$-type [1] described by the space group *Cmcm* (No. 63). In this crystal structure, the atoms in the unit cell form the layers stacked along the *b*-axis. A large number of compounds with 1:1:2, 1:x:2 and 1:1:1 stoichiometry crystallizes in this structure type. The majority of these compounds are antiferromagnets at low temperatures [2–4].

In 1:1:2-type compounds the atoms occupy four nonequivalent sites while in 1:x:2 and 1:1:1 compounds the vacancies are detected. The influence of these vacancies on the magnetic ordering is the interesting problem for investigations.

In this work, the magnetic data for $TbFe_{0.25}Ge_2$, $TbSn_{0.4}Ge_{1.4}$, and $NdSn_{0.6}Ge_{1.775}$ are reported. The obtained data are compared with the results obtained for other isostructural compounds.

2. Experimental and results

The samples of the compounds with stoichiometry mentioned above (each of total weight: $1 \div 2$ g), were prepared by arc-melting the high-purity elements in argon atmosphere. Afterwards, the samples were annealed at 870 K for one week to improve their homogeneity.

The X-ray analyses of the samples performed at room temperature indicated that all compounds have the orthorhombic crystal structure (*Cmcm*). The magnetic measurements were carried out using a vibrating sample magnetometer (VSM) option of the Quantum Design PPMS platform.

Three types of magnetic measurements were performed: cooling at low temperatures at zero magnetic field (ZFC) and at field FC equal to $H = 50$ Oe (to determine the phase transition temperatures), then scanning from 1.9 K up to 300 K in a magnetic field of 1 kOe (to determine the values of the effective magnetic moment μ_{eff} and the paramagnetic Curie temperatures θ_{p}) and finally measuring the magnetization curves up to 90 kOe at 1.9 K (to determine the values of the magnetic moment in the ordered state).

Temperature dependence of the magnetic susceptibility of $TbFe_{0.25}Ge_2$ gives the maximum at 19.5 K (see inset at Fig. 1). Below 40 K the difference between ZFC and FC curves is observed. The reciprocal magnetic susceptibility obeys the Curie–Weiss law with the paramagnetic Curie temperature equal to -36.7 K and the effective magnetic moment equal to 10.0 μ_{B}/f.u. The value of magnetic moment is larger than free Tb^{3+} ion value (9.72 μ_{B}). The magnetization is linear as a function of the external field up to critical value of 50 kOe. Magnetic moment at $T = 1.9$ K and $H = 90$ kOe is equal to 3.09 μ_{B}/f.u. and is much smaller than free Tb^{3+} ion value (9.0 μ_{B}).

Our data are in good agreement with those reported in [5] concerning the results obtained in low field. The new data reveal the presence of a metamagnetic phase transition at low temperatures and the influence of an external magnetic field on the magnetic susceptibility below and above Néel temperature.

The temperature dependence of the magnetic susceptibility of $TbSn_{0.4}Ge_{1.4}$ measured in the magnetic field of 50 Oe, gives the maximum at 22 K and an additional small anomaly at 13.2 K. Below 28 K the difference between ZFC and FC curves is observed. In the field of 1 kOe the minimum at 13.2 K disappeared. Above the Néel temperature the reciprocal magnetic susceptibility measured in the magnetic field equal to 1 kOe obey the Curie–Weiss law with the paramagnetic Curie temperature equal to -40 K and the effective magnetic moment equal to 9.73 μ_{B}/f.u. The magnetization curve indicate the metamagnetic phase transition with the critical field $H_{\mathrm{cr}} = 63.8$ kOe. The magnetic moment at $T = 1.9$ K and $H = 90$ kOe is equal to 2.45 μ_{B}/f.u. and is much smaller than the free Tb^{3+} ion value (9.0 μ_{B}).

In $\chi(T)$ for $NdSn_{0.62}Ge_{1.775}$ on ZFC curve the two maxima at 3.7 and 5.1 K are also observed. The first

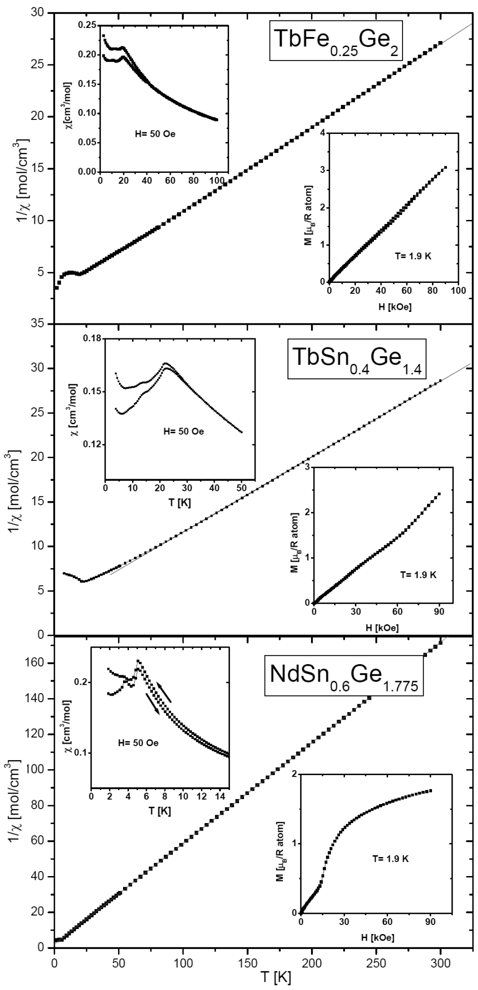

Fig. 1. Temperature dependence of the reciprocal magnetic susceptibility measured at 1 kOe magnetic field for (a) $TbFe_{0.25}Ge_2$, (b) $TbSn_{0.4}Ge_{1.4}$, and (c) $NdSn_{0.6}Ge_{1.775}$. Insets show: the upper ones — temperature dependence of the magnetic susceptibilities: ZFC (lower curve) and FC (upper curve) and the lower ones — magnetization curve up to 90 kOe at $T = 1.9$ K.

maximum disappears on the FC curve. The reciprocal magnetic susceptibility obeys the Curie–Weiss law with $\theta_\mathrm{p} = -3.7$ K and $\mu_\mathrm{eff} = 3.72\ \mu_\mathrm{B}$. The magnetization curve indicates the metamagnetic transition at $H_\mathrm{cr} = 13$ kOe to the ferromagnetic phase. The magnetic moment at $T = 1.9$ K and $H = 90$ kOe is equal to $1.735\ \mu_\mathrm{B}$/f.u.

3. Summary

The data presented in this work indicate that all investigated compounds are antiferromagnets at low temperatures. The presented results are generally in good agreement with the previous data [3–5] concerning the values of the effective magnetic moments and Néel temperature. The new data determined the metamagnetic phase transition at $T = 1.9$ K and showed the difference between ZFC and FC curves below and above the Néel temperature. This last result suggests that above the Néel temperature the short range ordering exists. With decrease of temperature at T_N the long-range antiferromagnetic order is stable. The additional anomaly observed for $TbSn_{0.4}Ge_{1.4}$ and $NdSn_{0.6}Ge_{1.775}$ below T_N is probably connected with the change of the magnetic properties. The neutron diffraction experiment is necessary to answer the question about the nature of these changes.

The determined value of the Néel temperature equal to 22 K for $TbSn_{0.4}Ge_{1.4}$ compound is lower than for stoichiometric TbSnGe equal to 29 K [3] or 31 K [4]. This suggests that an atomic disorder influences the magnetic interactions.

In contrary the magnetic properties of $TbFe_{0.25}Ge_2$ indicates the strong influence of the Fe atoms on the magnetic order in Tb-sublattice. In isostructural $TbFe_{0.4}Ge_2$ compound, the long-range order is not observed up to 1.57 K [6] while in $HoFe_{0.33}Ge_2$ [7] and $ErFe_{0.3}Ge_2$ [8] the antiferromagnetic ordering at low temperatures was detected.

There is no data in the literature to compare the results of the magnetic properties obtained for $NdSn_{0.62}Ge_{1.775}$ compound.

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