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Magnetic properties and magnetoresistance effect of $Y_{1-x}Gd_xMn_6Sn_6$ (x=0–1) compounds*

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The magnetic properties and magnetoresistance effect of $Y_{1-x}Gd_xMn_6Sn_6$ (x=0–1) compounds have been investigated by magnetization and resistivity measurements in the applied field range (0–5 T). Compounds with x=0.4–1 display ferrimagnetic behaviours in the whole magnetic ordering temperature range, while compounds with x=0–0.2 display a field-induced metamagnetic transition, and the threshold fields decrease with increasing Gd content. The compounds with x=0.1–0.2 undergo an antiferromagnetic to ferromagnetic transition with increasing temperature. The cell-parameter a and c and cell-volume V of compounds (x=0–1) increase with increasing Gd content. It was found that the saturation magnetization M_s of the compounds (x=0.4–1) decreases, while the ordering points of the compounds (x=0–1)increase with increasing Gd content. A large MR effect was observed in the compound with x=0.2, and the maximum absolute value of MR at 5 K under 3 T is close to 19.3%.

Keywords: $Y_{1-x}Gd_xMn_6Sn_6$ compounds, magnetic properties, metamagnetic transition, magnetoresistance effect

PACC: 7530, 7590

1. Introduction

In the past ten years, the structure and magnetic properties of the hexagonal $HfFe_6Ge_6$-type RMn_6X_6 compounds (R=rare earth metal, X=Ge, Sn) have been studied[1–6] extensively, by means of magnetic measurements and neutron diffraction. The structure of these compounds can be described as being built of alternate (001) layers containing R and Mn atoms, along c-axis with sequence -Mn-R-Mn-Sn-Sn-Mn-R-Mn-. These compounds behave as abundant magnetic behaviours as functions of the nature of the R elements. On the other hand, previous studies[7–9] of RMn_2Ge_2 and RMn_6Ge_6 compounds have shown that these compounds display field-induced transitions and metamagnetic behaviours. For these compounds with metamagnetic behaviours, they usually bring in a large magnetoresistance (MR) effect. It is generally agreed that the MR effect originates from spin-dependent scattering of conduction electrons. Therefore, this effect is regarded as an important criterion for materials displaying a magnetic transition. But very few work studied about the MR effect in RMn_6X_6 compounds has been done so far. A previous study[10] of $YMn_6Sn_{6-x}Ga_x$ (x=0–1.8) compounds shows that Ga substitution leads to a transition from antiferromagnetic to ferromagnetic state, and a MR as large as 32% has been observed at 5K for the sample with x=0.2. In order to clarify the inherent relationship between the MR effect and metamagnetic transition, in this paper we have studied the magnetic properties and MR effect of $Y_{1-x}Gd_xMn_6Sn_6$ (x=0–1) compounds by substitution of magnetic Gd atoms for nonmagnetic Y atoms.

2. Experiment

$Y_{1-x}Gd_xMn_6Sn_6$ alloys with x=0–1 were prepared by arc melting the raw materials in an argon atmosphere of high purity. The elements used were of at least 99.9% purity. An excess of Y and Gd (5%) and Mn (15%) was added to compensate the loss

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during the arc melting. The ingots were remelted at least three times to ensure homogeneity. The ingots were subsequently sealed in an evacuated quartz tube and annealed at 1023 K for ten days, then quenched into water. The crystal structure of the ingots was measured by x-ray diffraction (XRD) with Cu$K\alpha$ radiation.The magnetic properties were measured by a vibrating sample magnetometer (VSM) and a superconducting quantum interference device (SQUID). The MR measurement was carried out using the standard four-probe dc technique with an electric current (100 mA) parallel to the magnetic field. The sample used in MR measurements was a square cross-section rod of dimensions 10mm×2mm×2 mm.

3. Results and discussion

XRD patterns indicate that all samples with the composition Y_{1-x} $Gd_xMn_6Sn_6$ (x=0–1) are single-phase compounds with a hexagonal $HfFe_6Ge_6$-type structure (space group $P6/mmm$), but with a minor impurity of Mn_3Sn_2 for the sample with x=0.1. The corresponding cell parameters a and c and the unit-cell volume V are listed in Table 1. Because the atomic radius of Gd atom is larger than that of Y atom, the unit-cell volume and cell-parameters a and c increase with increasing Gd content, as shown in Fig.1.

The thermal magnetization curves of $Y_{1-x}Gd_x$ Mn_6Sn_6 (x=0–1) compounds at 40000 A/m, measured with VSM and SQUID are plotted in Fig.2. It can be seen that the compound (x=0) displays an antiferromagnetic behaviour. The compounds (x=0.4–1) display ferrimagnetic behaviours in the whole magnetic ordering temperature range. The compounds (x=0.1–0.2) exhibit a transition from antiferromagnetic to ferromagnetic state with increasing temperature. A slight decrease of magnetization is detected around 270 K for the compound with x=0.1. This is probably related to the presence of a small amount of ferromagnetic Mn_3Sn_2 impurity phase. As mentioned in the introduction, the magnetic properties of RMn_6X_6 compounds (R=rare earth metal, X=Ge, Sn) depend strongly on the nature of R elements. Since Y is a non-magnetic atom, the substitution of magnetic Gd atom for non-magnetic Y atom leads to an enhancement of the interaction between R and Mn sublattices, and thus results in a ferromagnetic couplings of the Mn sublattice. But the couple between R and Mn sublattices is antiferromagnetic, then with increasing Gd content, the $Y_{1-x}Gd_xMn_6Sn_6$ (x=0.1–1) compounds display a transition from antiferromagnetic to ferromagnetic (ferrimagnetic) state. The phase transition temperature of $Y_{1-x}Gd_xMn_6Sn_6$ (x=0–1) compounds, obtained from thermal magnetization curves, are listed in Table 1. The ordering points of the $Y_{1-x}Gd_xMn_6Sn_6$ (x=0.2–1) compounds increase with increasing Gd content. This may be attributed to the enhancement of interactions between the R and Mn sublattices, which is caused by the substitution of magnetic Gd atoms for non-magnetic Y atoms.

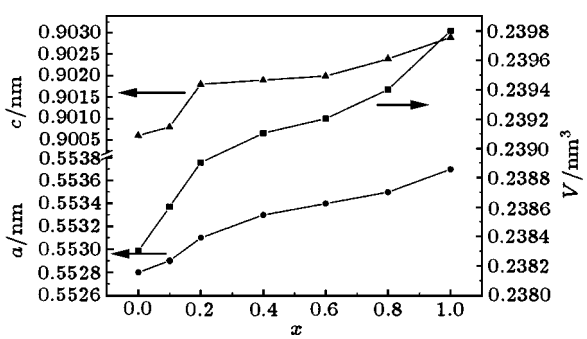


Fig.1. Cell-parameter a and c and cell-volume V versus content x for $Y_{1-x}Gd_xMn_6Sn_6$ (x=0–1) compounds.

Table 1. Structural and magnetic data of $Y_{1-x}Gd_xMn_6Sn_6$ compounds.

x	a/nm	c/nm	V/nm^3	Magnetic structure	T_C/K	T_N/K	M_S/(emu/g)
0	0.5528	0.9006	0.2383	AF		328	–
0.1	0.5529	0.9008	0.2386	AF-F	400		–
0.2	0.5531	0.9018	0.2389	AF-F	382		–
0.4	0.5533	0.9019	0.2391	F	396		45.69
0.6	0.5534	0.9020	0.2392	F	423		37.89
0.8	0.5535	0.9024	0.2394	F	435		33.29
1.0	0.5537	0.9029	0.2398	F	450		27.77

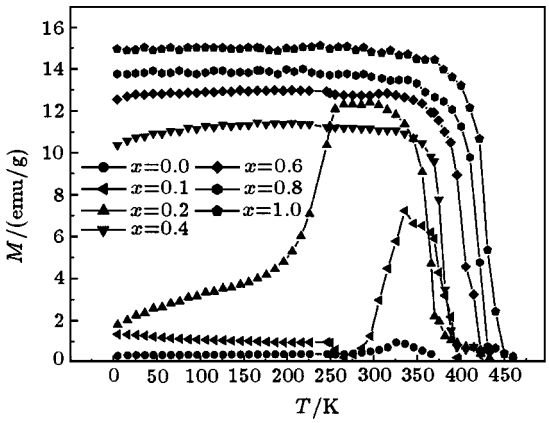


Fig.2. Magnetization versus temperature at 40000 A/m for $Y_{1-x}Gd_xMn_6Sn_6$ (x=0–1) compounds.

The magnetization curves of $Y_{1-x}Gd_xMn_6Sn_6$ (x=0–1) compounds at 5 K measured by SQUID are plotted in Fig.3. In the investigated field range (0–5 T), the magnetization curve of the compound with x=0 does not saturate, displaying a field-dependent magnetic transition with threshold field of about 1.8 T. The linear variation of the magnetization curve of the compound with x=0 in the field range below the threshold field, is probably due to the magnetic moment of the Mn sublattice turning to the direction parallel to the magnetic field. It is worth noting that the magnetization curve in the magnetic field range above the threshold field departs from linear variation, and displays a transition from an antiferromagnetic state to a ferromagnetic one. While a spontaneous magnetization is observed for the compounds (x=0.4–1), their magnetization increases quickly with increasing magnetic field, and almost saturates at 5 T with the maximum saturation magnetization 45.69 emu/g for the compound with x=0.4. The magnetization curves of compounds (x=0.1,0.2) were measured by first increasing the field from 0 to 5 T, and then decreasing the field from 5 T to 0 T. It can be seen that the magnetization curves exhibit the distinct hysteresis and metamagnetic behaviours, with threshold fields being 1 T and 0.3 T for x=0.1 and x=0.2, respectively. The threshold fields of compounds (x=0–0.2) decrease with increasing Gd content. It can be seen that the antiferromagnetic interaction also decreases when the Gd content increases. The saturation magnetization M_s of compounds (x=0.4–1), obtained by extrapolating linear variations of magnetization curves $M(H)$ to H=0, are listed in Table 1. The saturation magnetization M_s decreases with increasing Gd content. This may be due to the antiparallel arrangement of magnetic moments between Gd and Mn atoms.

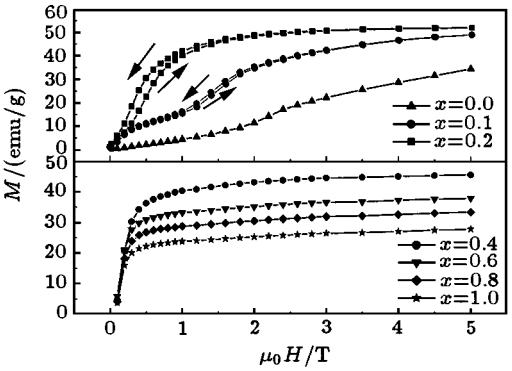


Fig.3. Magnetization versus field at 5 K for $Y_{1-x}Gd_xMn_6Sn_6$ (x=0–1) compounds.

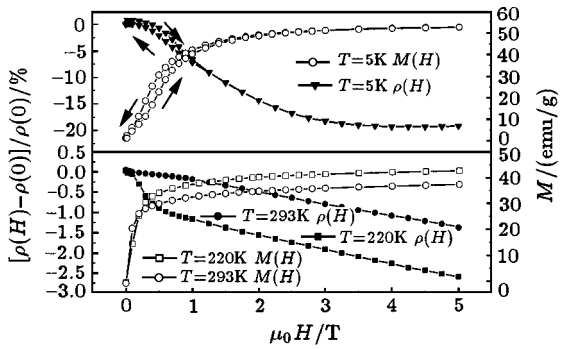


Fig.4. Magnetization and MR versus field at temperatures 5, 220 and 293 K for the compound with x=0.2.

Figure 4 gives the field dependence of MR and magnetization of the compound (x=0.2) at temperatures 5, 220 and 293 K. MR was obtained by calculating from the formula $[\rho(H)-\rho(0)]/\rho(0)\times100\%$. The maximum absolute values of MR are 19.3%, 2.6% and 1.4% obtained at 5, 220 and 293 K, respectively, which decrease with increasing temperature. The absolute value of MR for the compound (x=0.2) at 5 K first slowly increases in the lower magnetic field range with increasing magnetic field, then increase sharply with increasing magnetic field from 0.3 to 4 T, and subsequently almost maintain constant with further increasing field from 4 to 5 T. The sharp increase of negative MR shows that in the compound with x=0.2 a transition takes place from an antiferromagnetic to a ferromagnetic state, while the absolute value of MR varies very little at 220 and 293 K with increasing magnetic field.

The field dependences of MR and magnetization measured by first increasing field from 0 to 5 T, and then decreasing field from 5 to 0 T, also are plotted in Fig.4. Both curves display a distinct hysteresis. It is seen that the transition from antiferromagnetic to ferromagnetic state is of first order. In addition, both curves are almost saturated in the applied magnetic field range. It is generally agreed that the MR effect originates from the spin-dependent scattering of conduction electrons. The spin-dependent scattering of conduction electrons in the antiferromagnetic state is stronger than that in the ferromagnetic state. With increasing magnetic field to above-threshold field of 0.3 T, in the compound with x=0.2 a field-induced transition takes place from antiferromagnetic to ferromagnetic state. Therefore, a large MR effect could be observed in the compound with x=0.2 in the magnetic field range above 0.3 T. The physical mechanism of MR effect is almost the same as in the magnetic multi-layer. In addition, the threshold field (0.3 T) occurring from metamagnetic transition almost accords with that occurring from the MR effect. So MR effect is closely associated with the metamagnetic transition.

4. Conclusion

We have studied the magnetic properties and magnetoresistance effects of $Y_{1-x}Gd_xMn_6Sn_6$ (x=0–1) compounds. We found that the cell-parameter a and c and the cell-volume V increase with increasing Gd content. The saturation magnetization M_s of $Y_{1-x}Gd_xMn_6Sn_6$ (x=0.4–1) compounds decrease, and ordering points of $Y_{1-x}Gd_xMn_6Sn_6$ (x=0–1) compounds increase with increasing Gd content. The compounds (x=0.1, 0.2) undergo an antiferromagnetic to ferromagnetic transition with increasing temperature. The compounds (x=0–0.2) display field-induced transitions. The MR effect of $Y_{1-x}Gd_xMn_6Sn_6$ (x=0.2) compounds can be observed at 5, 220 and 293 K, The maximum absolute values of MR are 19.3%, 2.6% and 1.4% at 5, 220 and 293 K, respectively.

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