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Magnetic properties of $Nd_6Ga_{3-x}B_xFe_{11}$ intermetallic compounds

Z. G. Zhao[a,b,c], X. K. Sun[a,c], Y. C. Chuang[a] and F. R. de Boer[b,*]
[a]*Institute of Metal Research, Academia Sinica, Wenhua Road 72, Shenyang 110015 (People's Republic of China)*
[b]*Van der Waals-Zeeman Laboratory, University of Amsterdam, Valckenierstraat 65, 1018 XE Amsterdam (Netherlands)*
[c]*International Centre for Material Physics, Academia Sinica, Shenyang 110015 (People's Republic of China)*

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Abstract

The structure and magnetic properties of the compounds $Nd_6Ga_3Fe_{11}$ and $Nd_6Ga_{2.5}B_{0.5}Fe_{11}$ have been investigated. It is found that substitution of boron for gallium enhances the *3d–3d* exchange interaction, the saturation magnetization of the compounds as well as the room-temperature magnetic anisotropy field. At 1.5 and 77 K jumps are observed in the magnetization curves measured with the field parallel and perpendicular to the alignment direction of the samples. The critical field of the jump decreases with increasing temperature and upon boron substitution. A spin reorientation is found in $Nd_6Ga_{2.5}B_{0.5}Fe_{11}$ at about 130 K.

1. Introduction

The compound $Nd_6Ga_3Fe_{11}$ crystallizes in the $La_6Ga_3Co_{11}$-type tetragonal structure [1]. Recently, Li et al. [2] have reported that first order magnetization process (FOMP) phenomena exist at low temperatures in $R_6Ga_3Fe_{11}$ compounds (R = Nd, Pr, Sm). The present work has studied the effect of substitution of B for Ga on the structure and magnetic properties of $Nd_6Ga_3Fe_{11}$. For this purpose samples of $Nd_6Ga_3Fe_{11}$ and $Nd_6Ga_{2.5}B_{0.5}Fe_{11}$ have been prepared and investigated.

2. Experimental details

The compounds $Nd_6Ga_3Fe_{11}$ and $Nd_6Ga_{2.5}B_{0.5}Fe_{11}$ were prepared by melting together appropriate amounts of pure Nd, Ga, Fe and Fe–B alloy containing 20% B in an arc furnace under a purified argon atmosphere. To ensure homogeneity, the ingots were inverted and melted twice. The as-cast ingots were annealed at 700 °C for two weeks in an argon atmosphere. By X-ray diffraction the annealed samples were found to possess the $La_6Ga_3Co_{11}$-type tetragonal structure and to contain a small amount of α-Fe.

Magnetically aligned samples were prepared by mixing fine powder with a resin-doped epoxy solution at room temperature and by letting the mixture solidify in a mold with a cylindrical hole in an external magnetic field of 0.8 T. Magnetization curves were measured in an extracting-sample magnetometer at 1.5, 77 and 300 K in magnetic fields up to 6 T. The Curie temperatures were determined by measuring the temperature dependence of the a.c.-susceptibility.

*Author to whom correspondence should be addressed.

3. Results and discussion

The lattice constants *a* and *c* of the compounds were derived from X-ray diffraction patterns by means of a least-squares method. The results are listed in Table 1. Due to the partial substitution of B for Ga, the *a*-axis increases slightly, but the *c*-axis decreases remarkably, resulting in a marked change in the *c/a* ratio from 2.822 for $Nd_6Ga_3Fe_{11}$ to 2.812 for $Nd_6Ga_{2.5}B_{0.5}Fe_{11}$. The magnetocrystalline anisotropy of the compound is dominated by the rare-earth anisotropy [2]. The large decrease in the *c/a* ratio may result in a change of the crystal field acting on the rare-earth ions so that a large difference of magnetic anisotropy in $Nd_6Ga_3Fe_{11}$ and $Nd_6Ga_{2.5}B_{0.5}Fe_{11}$ can be expected.

In Table 1, it is seen that the Curie temperature of $Nd_6Ga_3Fe_{11}$ increases considerably upon partial substitution of B for Ga. Also the saturation magnetization increases upon substitution of B for Ga. If we assume that the magnetic moment of Nd does not change upon B substitution, the increase of the saturation moment must be attributed to an increase of the Fe moment, which may explain the increase of T_C.

The magnetization curves of $Nd_6Ga_3Fe_{11}$ at 1.5, 77 and 300 K for the field applied parallel and perpendicular to the alignment direction of the samples are

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TABLE 1. Structural and magnetic properties of $Nd_6Ga_{3-x}B_xFe_{11}$ compounds

Compound	a (nm)	c (nm)	c/a	T_c (K)	$M(\mu_B/F.U)$ at 6 T			$\mu_oH_{cr1}(T)/\mu_oH_{cr2}(T)$		
					1.5 K	77 K	300 K	1.5 K	77 K	300 K
$Nd_6Ga_3Fe_{11}$	0.811	2.296	2.822	430	27.6	26.9	13.4	1.8/4.4	-/3.4	-
$Nd_6Ga_{2.5}B_{0.5}Fe_{11}$	0.812	2.283	2.812	490	30.0	28.1	17.7	1.6/4.2	-/3.2	-

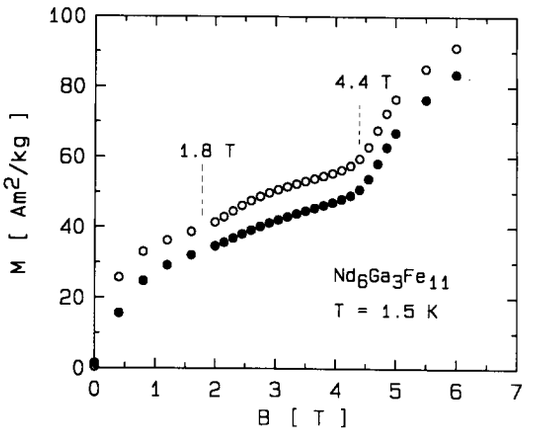

Fig. 1. Magnetization curves at 1.5 K of $Nd_6Ga_3Fe_{11}$ for the field parallel (open circles) and perpendicular (filled circles) to the alignment direction.

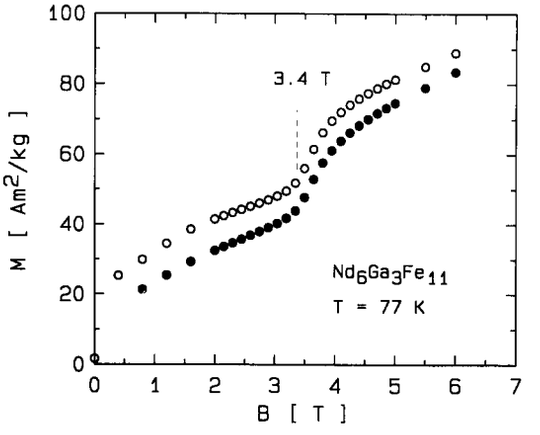

Fig. 2. Magnetization curves at 77 K of $Nd_6Ga_3Fe_{11}$ for the field parallel (open circles) and perpendicular (filled circles) to the alignment direction.

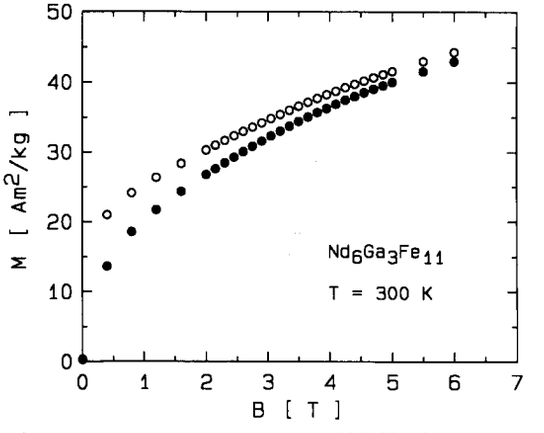

Fig. 3. Magnetization curves at 300 K of $Nd_6Ga_3Fe_{11}$ for the field parallel (open circles) and perpendicular (filled circles) to the alignment direction.

shown in Figs. 1–3. It can be seen in Fig. 1 that at 1.5 K two transitions exist in the magnetization curves. These transitions take place at 1.8 and 4.4 T. In the

perpendicular magnetization curve the transition at the lowest field is only weakly discernible. Both magnetization curves do not saturate at the maximum field of 6 T. At 77 K, only one transition is observed in both the parallel and the perpendicular magnetization curve, the critical fields both being about 3.4 T (Fig. 2). This transition seems to be equivalent to the one occurring at 4.4 T at 1.5 K. The transition which at 1.5 K takes place at 1.8 T has disappeared at 77 K. Also at this temperature both magnetization curves do not saturate. At 300 K, the magnetization curves do not saturate and display no anomalies (Fig. 3). From the poor effect of the magnetic alignment procedure on the room-temperature magnetization curves we conclude that at this temperature the compound $Nd_6Ga_3Fe_{11}$ certainly has no uniaxial anisotropy. By extrapolation of the two curves, a value for the anisotropy field of about 7.5 T can be estimated. Values for the magnetization at 1.5, 77 and 300 K at the maximum field of 6 T are given in Table 1, together with the values for the compound $Nd_6Ga_{2.5}B_{0.5}Fe_{11}$ to be discussed below.

Figures 4–6 show the magnetization curves of $Nd_6Ga_{2.5}B_{0.5}Fe_{11}$ at 1.5, 77 and 300 K for the field applied parallel and perpendicular to the alignment direction. Like in the case of $Nd_6Ga_3Fe_{11}$, two transitions are observed in the parallel magnetization curve at 1.5 K (Fig. 4). The critical fields of the transitions are slightly lower now: 1.6 T and 4.2 T. In the perpendicular magnetization curve only the transition at 4.2 T can be distinguished. At 77 K, only one transition is observed in both the parallel and the perpendicular magnetization curve at the same field value of about 3.2 T (Fig. 5), again at a slightly lower field value than in $Nd_6Ga_3Fe_{11}$ (Fig. 2). In Fig. 6 it can be seen that the jump has disappeared at 300 K and that, in contrast with $Nd_6Ga_3Fe_{11}$, the parallel magnetization curve saturates at very low fields. The perpendicular magnetization

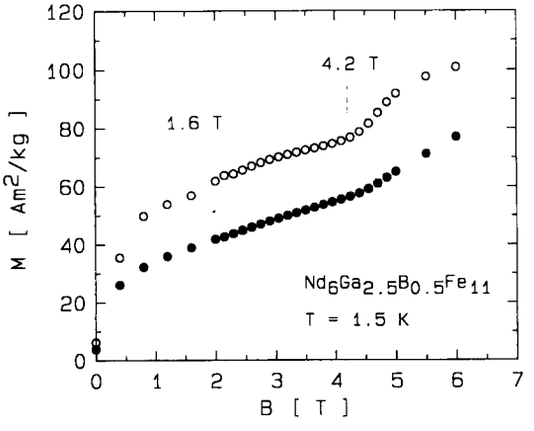

Fig. 4. Magnetization curves at 1.5 K of $Nd_6Ga_{2.5}B_{0.5}Fe_{11}$ for the field parallel (open circles) and perpendicular (filled circles) to the alignment direction.

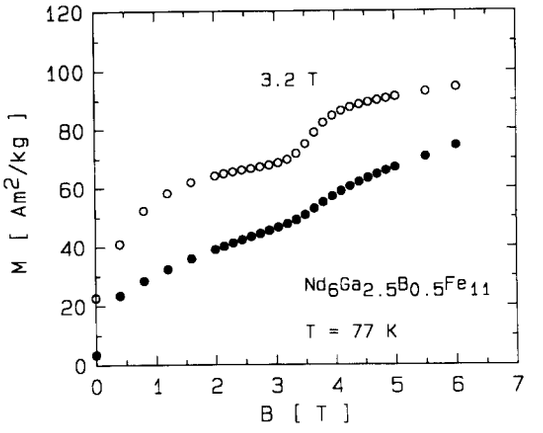

Fig. 5. Magnetization curves at 77 K of $Nd_6Ga_{2.5}B_{0.5}Fe_{11}$ for the field parallel (open circles) and perpendicular (filled circles) to the alignment direction.

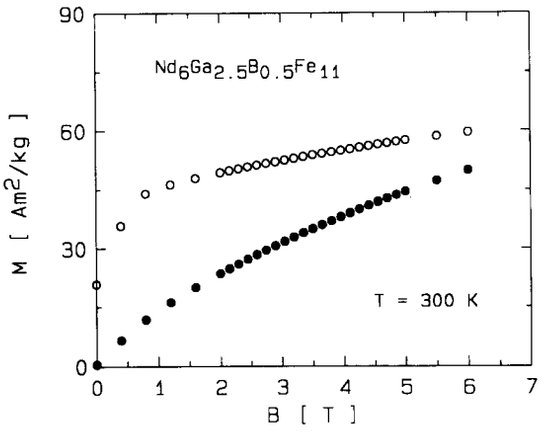

Fig. 6. Magnetization curves at 300 K of $Nd_6Ga_{2.5}B_{0.5}Fe_{11}$ for the field parallel (open circles) and perpendicular (filled circles) to the alignment direction.

increases nearly linearly with increasing field. The compound $Nd_6Ga_{2.5}B_{0.5}Fe_{11}$ appears to exhibit uniaxial anisotropy at this temperature. By extrapolating the parallel and perpendicular magnetization curves, an anisotropy field of about 9.5 T is found. It should be mentioned that this anisotropy field is even higher than that of the $Nd_2Fe_{14}B$, which is about 8 T at room temperature [3]. The magnetic anisotropy constants, K_1 and K_2 of $Nd_6Ga_{2.5}B_{0.5}Fe_{11}$ at 300 K were determined by the Sucksmith–Thompson method to be 172 J kg^{-1} and 75 J kg^{-1}, respectively. If we compare Fig. 6 with Figs. 4 and 5, it is evident that the perpendicular magnetization curves become more curved at lower temperatures. This may arise from a deviation of the easy magnetization direction in this compound from the c-axis at lower temperatures. If this is the case, a spin reorientation has to occur between 300 and 77 K.

In order to investigate the possible occurrence of spin reorientations in $Nd_6Ga_3Fe_{11}$ and $Nd_6Ga_{2.5}B_{0.5}Fe_{11}$, the temperature dependence of the a.c.-susceptibility

was measured between 4.2 and 300 K. The experimental results obtained between 77 and 300 K are displayed in Fig. 7 in which an anomaly can be seen for $Nd_6Ga_{2.5}B_{0.5}Fe_{11}$ at about 130 K. On the basis of the above discussion of the magnetization curves of this compound, it is very likely that above 130 K $Nd_6Ga_{2.5}B_{0.5}Fe_{11}$ has uniaxial anisotropy, whereas below this temperature the anisotropy is no longer uniaxial. For $Nd_6Ga_3Fe_{11}$, the a.c. susceptibility does not display any anomaly in the temperature range from 4.2 to 300 K. In this compound, the easy magnetization direction is not uniaxial and probably of basal-plane type in the whole temperature range.

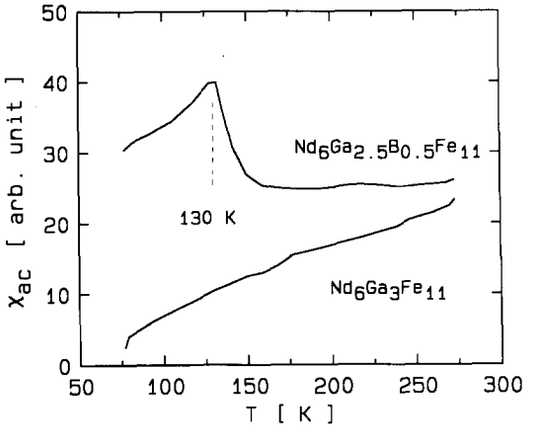

Fig. 7. Temperature dependence of the a.c. susceptibility of $Nd_6Ga_3Fe_{11}$ and $Nd_6Ga_{2.5}B_{0.5}Fe_{11}$.

In conclusion, the Curie temperature and the magnetic moment of $Nd_6Ga_3Fe_{11}$ increase appreciably by substitution of B for Ga. This substitution also remarkably affects the magnetic anisotropy, which at room temperature changes from not-uniaxial in $Nd_6Ga_3Fe_{11}$ to uniaxial in $Nd_6Ga_{2.5}B_{0.5}Fe_{11}$. For the latter compound the anisotropy field at room temperature amounts to about 9.5 T which is higher than for $Nd_2Fe_{14}B$.

Acknowledgments

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