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Magnetic Properties of $NdFe_{0.9}Mn_{0.1}O_3$

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In our paper we study effect of Mn for Fe substitution on magnetic properties of $NdFe_{x-1}Mn_xO_3$ compounds for $x = 0$ and 0.1, which have been grown by the OFZ technique. The Néel temperature decreases from $T_{N1} = 691$ K to $T_{N1} = 621$ K, and the anomaly in AC susceptibility, related to spin reorientation, vanishes with Mn substitution. Low temperature heat capacity measurement for sample with $x = 0.1$ revealed that substitution of Mn for Fe shifts a Schottky-type anomaly at T_{sh} to higher temperatures. Another anomaly is generated by doping at $T_{max} = 11$ K. The anomaly is smeared out by magnetic field, confirming its magnetic origin.

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Magnetic properties of $NdFeO_3$ are mostly determined by three magnetic interactions (Fe-Fe, Fe-Nd and Nd-Nd), which are present in this material. Magnetic ordering of Fe^{3+} ions creates a canted antiferromagnetic ordering below the Néel temperature at about $T_{N1} = 690$ K [1]. Upon cooling the magnetic moments of Fe^{3+} exhibit reorientation from the *a*-axis to the *c*-axis in the spin reorientation region (103–165 K) [2]. Low temperature heat capacity measurements revealed a Shottky anomaly at about 2 K and a sharp maximum at $T_{N2} = 1.05$ K [3]. Neutron diffraction measurements confirmed magnetic ordering for Nd-Fe sublattice below 1 K and long-range ordering due to Nd-Nd interaction below 0.4 K [4, 5]. In our paper we study the effect of Mn substitution for Fe in $NdFeO_3$.

$NdFe_{x-1}Mn_xO_3$ ingots with $x = 0.0$ and 0.1 have been grown by the optical floating zone (OFZ) technique in the four mirrors furnace. The X-ray powder diffraction pattern and EDX analysis taken from the top and the end of ingots revealed that samples are single phase materials. Both samples adopt orthorhombic crystal structure (space group *Pbnm*) with lattice parameters $a = 5.5889(2)$ nm, $b = 7.7619(3)$ nm, $c = 5.4521(2)$ nm for $x = 0$ and $a = 5.6011(9)$ nm, $b = 7.748(8)$ nm, $c = 5.4483(9)$ nm for $x = 0.1$, respectively. Magnetization and AC susceptibility were measured on a SQUID magnetometer on MPMS in temperatures range from 2 to 720 K and magnetic flux density up to 5 T. Measurements of heat capacity were performed on PPMS in temperature range from 2 K to 200 K and in magnetic fields up to 3 T.

Transition from paramagnetic to canted antiferromagnetic state is accompanied with sharp peak in $\mu(T)$ curves

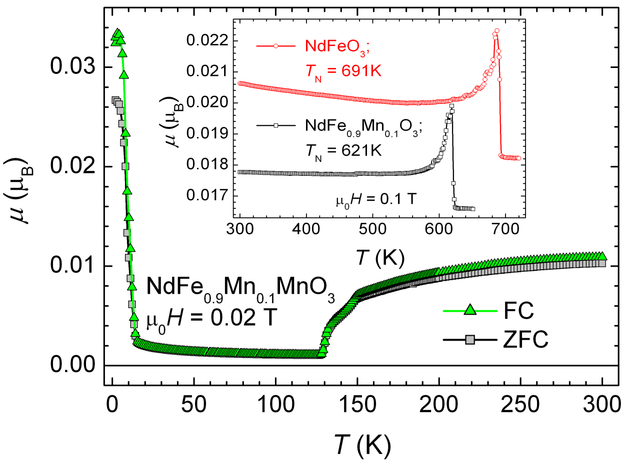

Fig. 1. Low temperature magnetization of $NdFe_{0.9}Mn_{0.1}O_3$ was measured in ZFC and FC regimes; inset shows high temperature magnetization for both samples in vicinity of the Néel temperature.

(see inset of Fig. 1), which can be attributed to Hopkinson effect. Such a peak is a very characteristic feature shown by a number of ferromagnetic materials. In our case this peak indicates that ferromagnetic component can be strong. The Néel temperature decreases from 691 K to 621 K with Mn doping. The spin reorientation in the sample with $x = 0.1$ is indicated by steep decrease of magnetization in the range between 150 K and 125 K (Fig. 1), but the relatively flat curve down to 15 K is unusual in comparison with $NdFeO_3$. The rise of magnetization below 15 K indicates increasing Nd-Fe magnetic interactions which start to develop at higher temperature in comparison with $NdFeO_3$.

The spin reorientation is not accompanied by any anomaly in the AC in phase susceptibility of $NdFe_{0.9}Mn_{0.1}O_3$ (Fig. 2.) or out of phase susceptibility. Frequency dependent anomaly in the AC susceptibil-

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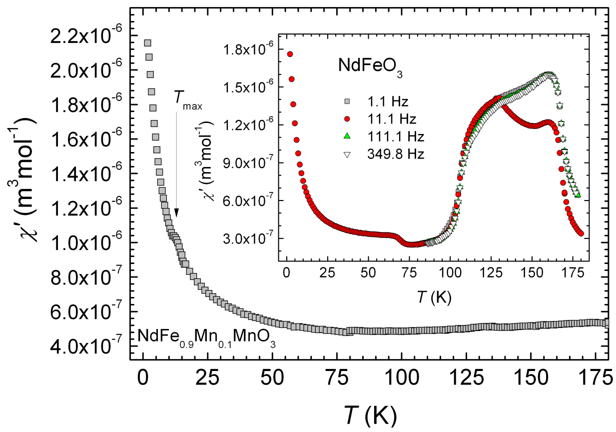

Fig. 2. In phase AC susceptibility of $NdFe_{0.9}Mn_{0.1}O_3$; inset shows frequency dependence of the in phase AC susceptibility for $NdFeO_3$.

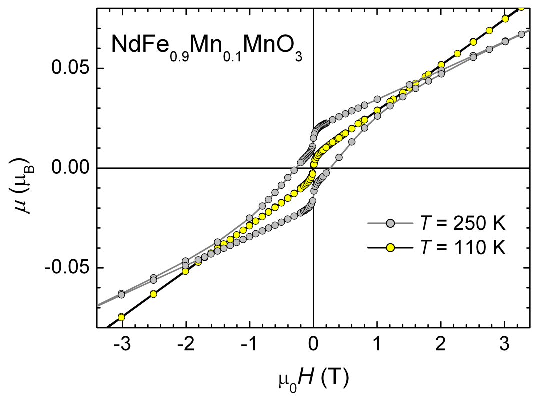

Fig. 3. Hysteresis loops for $NdFe_{0.9}Mn_{0.1}O_3$ above the spin reorientation transition.

ity (in phase data) is a characteristic feature of $NdFeO_3$ (see inset of Fig. 2). It seems that doping with Mn changes mechanism of spin reorientation. Small anomaly at $T_{max} = 12$ K, marked by the arrow, we associated with new magnetic ordering in $NdFe_{0.9}Mn_{0.1}O_3$.

Large area of hysteresis loop indicating ferromagnetic contribution is typical for $NdFe_{0.9}Mn_{0.1}O_3$ above the spin reorientation transition (Fig. 3). The shape of loop changes on cooling: the area of loop is negligible in range between 110 K and 15 K, high field susceptibility increases rapidly. In the vicinity of second magnetic transition the area of loop increases and the loop changes its shape reflecting creation of ferromagnetic interaction in the sample (Fig. 4).

Substitution of Mn for Fe shifts the Schottky-type anomaly from $T_{sh} = 2$ K for $NdFeO_3$ [3] to higher temperatures, reaching value $T_{sh} = 2.76$ K for $NdFe_{0.9}Mn_{0.1}O_3$. Another anomaly at about $T_{max} = 11$ K is generated by doping. The anomaly is smeared out by magnetic field, confirming magnetic origin of the anomaly (Fig. 5).

In conclusion, the substitution of Mn for Fe shifts the Shottky-type anomaly to higher temperatures and re-

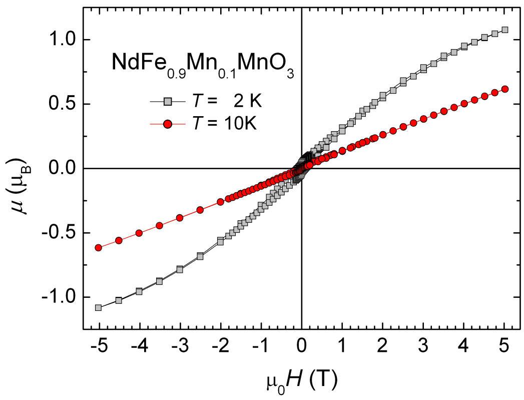

Fig. 4. Hysteresis loops for $NdFe_{0.9}Mn_{0.1}O_3$ below the spin reorientation transition.

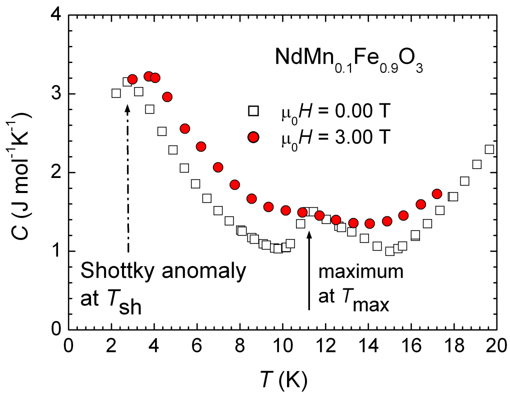

Fig. 5. Temperature dependence of heat capacity shows a Shottky-type of anomaly at T_{N2} and another anomaly at T_{max}.

duces Fe-Fe magnetic interactions leading to a decrease of T_{N1}. Anomalies in AC susceptibility and heat capacity data at T_{max} indicate new magnetic interactions in $NdFe_{x-1}Mn_xO_3$.

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