MAGNETIC PROPERTIES OF THE COBALTITES- GALLATES OF SAMARIUM $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ IN THE TEMPERATURE RANGE 5-300K

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Abstract

Using a solid-state reaction method the ceramic samples of the cobaltites-gallates of samarium $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ ($0 \leq x \leq 0.5$) were synthesized. In these samples a magnetic dilution of the Co^{3+} ions by diamagnetic Ga^{3+} ions took place. The parameters of the crystal lattice were determined. Molar magnetic susceptibility (χ_{mol}) of $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ was investigated at 5-300K in a magnetic field of 0.8 T. Analysis of the results obtained showed that in the temperature range 10-60K the effective magnetic moment of the Sm^{3+} ions practically didn't depend on the x and its value ($0.50 - 0.59\mu_{\text{B}}$) was less than the theoretical value ($0.84\mu_{\text{B}}$) indicating the "partial freezing" of the orbital magnetic moment by the crystal field of the perovskite structure. Temperature-independent contribution (χ_0) in χ_{mol} increases at growth of x at 10-60K.

Keywords and phrases: perovskite, cobaltites-gallates of samarium, magnetic susceptibility, effective magnetic moment, Van-Vlieck polarization paramagnetism.

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Increase of χ_{mol} for $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ at growth of x presumably is due to the increase of temperature independent Van-Vleck paramagnetism of Sm^{3+} ions rather than transition of the Co^{3+} ions in paramagnetic state.

1. Introduction

Cobaltites of rare-earth elements LnCoO_3 (Ln-lanthanum and other rare-earth metals) with the crystal structure of the distorted perovskite have a number of unique magnetic, electrical, electrochemical, catalytic, and sensory properties. These properties are largely determined by the spin state of the cobalt Co^{3+} ions, depending on the temperature, the degree of distortion of the perovskite crystal lattice, and other factors [1, 2].

It is established [3-9] that at temperatures close to the 0K the Co^{3+} ions are presumably in a low-spin (LS) state (electron configuration of the $3d^6$ -electrons is $t_{2g}^6e_g^0$, $S = 0$), and cobaltites LnCoO_3 are diamagnetic dielectrics. In the lanthanum cobaltite LaCoO_3 in the temperature range 35-100K a part of the Co^{3+} ions transforms from the (LS) to the intermediate-spin (IS) ($t_{2g}^5e_g^1$, $S = 1$) or high-spin (HS) ($t_{2g}^4e_g^2$, $S = 2$) state, and it becomes a paramagnetic semiconductor. At the temperatures above 500K in LaCoO_3 an increase in population of energy levels of Co^{3+} ions in the IS- and HS-state is observed, which is accompanied by the occurrence of diffuse phase transition semiconductor-metal, leading to the significant increase of the electrical conductivity. In the cobaltites of other rare-earth elements LnCoO_3 , where ionic radius of Ln^{3+} is smaller than the ionic radius of La^{3+} , the spin transition of Co^{3+} ions occurs at temperatures above 300K [4, 8, 9]. In this connection in [10] investigation of magnetization and magnetic susceptibility of samarium cobaltite SmCoO_3 in the range 4.2-300K is carried out taking

into account the fact that the magnetic behaviour of SmCoO_3 at these temperatures is determined mainly by the Sm^{3+} ions, because Co^{3+} ions are in the LS-state and they are diamagnetic. Co^{3+} ions in the LnCoO_3 crystal lattice are located in the center of an octahedron, whose vertices are occupied by oxygen ions, and crystal field of cubic symmetry “freezes” the orbital magnetic moment of unscreened $3d$ -electrons. For this reason, the effective magnetic moment of the Co^{3+} ions ($\mu_{\text{eff}, \text{Co}^{3+}}$) is basically a spin one [11]. Magnetic properties of rare-earth ions are determined by $4f$ -electrons which are largely screened from the influence of crystal field by $5s^2$ - and $5p^6$ -electrons, and the effective magnetic moment of rare-earth elements ions is determined by the total spin angular momentum ($J = L \pm S$). Ions of rare-earth elements in the LnCoO_3 crystal lattice are surrounded by 12 oxygen ions, whose symmetry of the arrangement is described by the point group of symmetry C_s (distorted cuboctahedron). As it is shown in [12], the crystal field of such symmetry can lead to the “partial freezing” of the orbital moment of rare-earth ions and, consequently, to decrease of its effective magnetic moment that was observed for the Sm^{3+} ions in the samarium cobaltite SmCoO_3 [10]. Magnetic dilution of paramagnetic ions leads to a decrease of their interaction and as a rule to the decrease of influence of crystal field on their magnetic properties.

In [13-15] influence of partial substitution of Co^{3+} ions by diamagnetic Ga^{3+} ions in LaCoO_3 , NdCoO_3 on magnetic susceptibility and Co^{3+} ions spin state in solid solutions $\text{LaCo}_{1-x}\text{Ga}_x\text{O}_3$, $\text{NdCo}_{1-x}\text{Ga}_x\text{O}_3$ was studied. It is found that such a substitution of Co^{3+} ions by Ga^{3+} ions leads to the stabilization of Co^{3+} ions in low-spin LS-state.

The aim of this work is to study at 5-300K magnetization, magnetic susceptibility and effective magnetic moment of Sm^{3+} , Co^{3+} ions in the solid solutions $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ ($0 \leq x \leq 0.5$), where the partial substitution of the Co^{3+} ions by diamagnetic Ga^{3+} ions in SmCoO_3 takes place.

2. Experimental

Cobaltites-gallates $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ ($x = 0; 0.1; 0.2; 0.3; 0.4; 0.5$) were prepared by a solid-state reaction method from the samarium (Sm_2O_3), cobalt (Co_3O_4), gallium oxides (Ga_2O_3) in air at 1523K for 5 hours. All oxides had «chemically pure» grade. Samarium oxide was preheated in air at 1273K for 2h.

X-ray diffraction patterns were obtained by using a D8 ADVANCED diffractometer with CuK_α -radiation. Crystal lattice parameters of the samarium cobaltites-gallates were determined by the X-ray Table Processor as well as Rietveld method using ICDD JCPDS data.

Molar magnetization (σ_{mol}) at 5-300K in magnetic field up to 14 T as well as molar magnetic susceptibility (χ_{mol}) at 5-300K in magnetic field 0.8 T were measured for the $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ using vibration method by means of a universal high-field measuring system (Cryogenic Ltd., London, 4IS). The signal from the empty sample holder was subtracted from the signal for the filled sample holder. Magnetic measurements were made in the Scientific-Practical Materials Research Center of NAS of Belarus.

3. Results and Discussion

Analysis of X-ray diffraction patterns of $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ samples showed (see Figure 1) that at $0 \leq x \leq 0.5$ a continuous series of $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ solid solutions with a structure of orthorhombically distorted perovskite was formed. Crystal lattice parameters a , b , c of

these samples obtained by RTP linearly increased from 5.2847Å, 5.3499Å, 7.4971Å for SmCoO_3 to 5.3385Å, 5.4340Å, 7.5895Å for sample with $x = 0.5$, respectively (see Figure 2). Note that for SmCoO_3 Rietveld method gives: $a = 5.2832\text{Å}$, $b = 5.3445\text{Å}$, $c = 7.4959\text{Å}$ whereas the data of [2] are: $a = 5.289\text{Å}$, $b = 5.354\text{Å}$, $c = 7.541\text{Å}$.

The samples $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ with $0.2 \leq x \leq 0.5$, in addition to the basic phase of solid solutions with orthorhombically distorted perovskite structure, also contained a small amount of the $\text{Sm}_4\text{Ga}_2\text{O}_9$ phase (Figure 1, curves 3-6). It should be noted that because of the low volatility of the samarium, cobalt oxides the total content of the magnetic Sm^{3+} , Co^{3+} ions in the $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ samples remained unchanged and therefore the presence of a small amount of the $\text{Sm}_4\text{Ga}_2\text{O}_9$ phase should not substantially affect the value of the magnetic susceptibility of these samples.

Figure 1. X-ray diffraction patterns of $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ samples at different degree of substitution (x): 0 (1), 0.1 (2), 0.2 (3), 0.3 (4), 0.4 (5), 0.5 (6) (* – phase $\text{Sm}_4\text{Ga}_2\text{O}_9$).

Figure 2. Parameters of crystal lattice (a, b, c) of solid solutions $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$.

To confirm this assumption we have synthesized samarium gallate $\text{Sm}_4\text{Ga}_2\text{O}_9$ by the above method. $\text{Sm}_4\text{Ga}_2\text{O}_9$ had monoclinic structure and its crystal lattice parameters were: $a = 7.6461\text{\AA}$, $b = 10.8514\text{\AA}$, $c = 11.5635\text{\AA}$, $\beta = 109.018^\circ$, $V = 907.064\text{\AA}^3$. Magnetic susceptibility of this phases have been investigated at 5-300K (see Figure 3). On the basis of these data, effective magnetic moment of samarium ions ($\mu_{\text{eff}, \text{Sm}^{3+}}$) has been evaluated and it was equal to $0.41\mu_B$ for the 10-70K temperature interval.

Figure 3. Temperature dependence of molar magnetic susceptibility (χ_{mol})(a) and inverse value (χ_{mol}^{-1})(b) for $\text{Sm}_4\text{Ga}_2\text{O}_9$.

Dependence of the molar magnetization (σ_{mol}) of the $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ samples on the magnetic field (H) at 300K are linear up to $H = 10 \text{ T}$ (Figure 4(a)). At 5K σ_{mol} linear dependence on H realizes up to $H \approx 1 \text{ T}$, while

for $H > 1$ T slowing down in the growth of the magnetization (tendency to the saturation) with increasing field H is observed (Figure 4(b)).

Figure 4. Dependence of the molar magnetization (σ_{mol}) on the magnetic field (H) at 300K (a) and 5K (b) for $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ samples at different degree of substitution x .

Temperature dependences of molar magnetic susceptibility (χ_{mol}) determined in the temperature range 5-300K in a magnetic field 0.8 T for $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ ($0 \leq x \leq 0.5$) are shown in Figure 5(a). It is seen that increase of the degree of substitution of paramagnetic Co^{3+} ions by diamagnetic Ga^{3+} ions for $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ does not lead at a certain temperature to the invariability (constancy) or decrease of the molar magnetic susceptibility (χ_{mol}), as it should be observed at invariability of magnetic state of Sm^{3+} , Co^{3+} ions. On the contrary it leads to the increase of the molar magnetic susceptibility (χ_{mol}) and magnetization (σ_{mol}). Consequently, the magnetic state of Sm^{3+} , Co^{3+} ions for $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ differs from their state in SmCoO_3 .

According to the literature data [8, 10] Co^{3+} ions in SmCoO_3 below 300K are in the LS-state, i.e., they are diamagnetic and the magnetic properties of SmCoO_3 at low temperatures are caused mainly by Sm^{3+} ions. Temperature dependence of the reciprocal molar magnetic susceptibility ($1/\chi_{\text{mol}}$) for $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ within whole temperature interval 5-300K is strongly nonlinear (Figure 5(b)) and thus cannot be described by the Curie-Weiss law.

Figure 5. Temperature dependence of molar magnetic susceptibility (χ_{mol}) (a) and reciprocal molar magnetic susceptibility ($1/\chi_{\text{mol}}$) (b) for $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$.

In this connection processing of the temperature dependences of the magnetic susceptibility for solid solutions $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ is carried out (as in [10] for SmCoO_3) by construction dependences of $\chi_{\text{mol}}T$ product on the temperature [16] for the narrow temperature ranges. For all $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ samples $\chi_{\text{mol}}T$ is a linear function of temperature (Figure 6(b)) in the interval 10-60K, while at higher temperatures there is another linear plot with different slope to the temperature axis (Figure 6(a)). Note that this classical model does not take into account splitting of the ground state of Sm^{3+} ions which was used in [10] for SmCoO_3 . Furthermore, one cannot agree with the authors of [10] that for SmCoO_3 Curie-Weiss law is not valid at 4.2-300K. Analysis of the corresponding figure from their paper allows us to make a conclusion that dependence $\chi^{-1} = f(T)$ is practically linear at ~225-300K. Thus revealing the linear parts on the curves is not a simple problem.

Figure 6. Temperature dependence of the product of molar magnetic susceptibility (χ_{mol}) on the temperature (T) for samples $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ in the temperature range 5-300K (a) and 10-60K (b).

For SmCoO_3 linear dependence of $\chi_{\text{mol}}T$ on T is observed in a broad range of temperatures (10-125K) (Figure 6(a), curve 1). Thus, the molar magnetic susceptibility of SmCoO_3 and $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ solid solutions in the temperature range 10-60K can be represented as a sum of two contributions: the first is described by the Curie-Weiss law ($\chi_{c,\text{mol}} = C_{\text{M}}/T$) and the second is temperature-independent one (χ_0)

$$\chi_{\text{mol}} = C_{\text{M}}/T + \chi_0, \quad (1)$$

where C_{M} is molar Curie constant.

From the Equation (1), it is resulted that

$$\chi_{\text{mol}}T = C_{\text{M}} + \chi_0T, \quad (2)$$

i.e., $\chi_{\text{mol}}T$ product depends linearly on the temperature.

By least-squares method for $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ samples coefficients a and b of the equation of linear dependence $\chi_{\text{mol}}T = aT + b$ are evaluated. Using the coefficients a and b of these equations molar Curie constants C_{M} ($C_{\text{M}} = b$) and temperature-independent contributions χ_0 ($\chi_0 = a$) were calculated. These contributions are due mainly to the polarization paramagnetism of Van-Vleck for Sm^{3+} ions as well as diamagnetism of the Sm^{3+} , Co^{3+} , Ga^{3+} , O^{2-} ions (Table 1). If we assume that cobalt Co^{3+} ions below 60K for all $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ samples studied are mainly in the LS-state [8, 10] their magnetic susceptibility is due to the magnetic moment of samarium Sm^{3+} ions. In this connection, the effective magnetic moment of samarium Sm^{3+} ions ($\mu_{\text{eff},\text{Sm}^{3+}}$) for $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ was calculated by the formula (3):

$$\mu_{\text{eff},\text{Sm}^{3+}} = \sqrt{\frac{3k \cdot C_{\text{M}}}{N_{\text{A}} \cdot \mu_{\text{B}}^2}}, \quad (3)$$

where k is Boltzmann constant, N_{A} is Avogadro constant, and μ_{B} is Bohr magneton.

The values obtained for the effective magnetic moment of Sm^{3+} ions for $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ for the 10-60K temperature interval are given in the Table 1.

Table 1. Molar Curie constant (C_M), temperature-independent contribution in the magnetic susceptibility (χ_0), the effective magnetic moment of Sm^{3+} ions ($\mu_{eff, \text{Sm}^{3+}}$) for $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ in the temperature range 10-60K

$\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3, x$	$C_M \cdot 10^2, \text{cm}^3/\text{mol}$	$\chi_0 \cdot 10^3, \text{cm}^3/\text{mol}$	$\mu_{eff, \text{Sm}^{3+}}, \mu_B$
0	3.421	1.221	0.52
0.1	3.177	1.237	0.50
0.2	3.687	1.679	0.54
0.3	4.420	1.838	0.59
0.4	3.773	2.078	0.55
0.5	4.332	2.231	0.59

These data show that the effective magnetic moment of Sm^{3+} ions ($\mu_{eff, \text{Sm}^{3+}}$) in $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ ($0 \leq x \leq 0.5$) practically does not depend on the x and its value ($0.50 - 0.59\mu_B$) is less than the theoretical value $0.84\mu_B$ [11] (for the free Sm^{3+} ions without polarization paramagnetism of Van-Vleck). Note that for SmCoO_3 magnetic moment $\mu_{eff, \text{Sm}^{3+}}$ equals to $0.52\mu_B$ and this value is close to the corresponding value ($0.47\mu_B$) obtained in [10] for the temperatures above 20K. Contribution (χ_0) in magnetic susceptibility of $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ for the temperature interval 10-60K gradually increases with increasing degree of substitution x (Table 1). It means that an increase in the polarization paramagnetism of Van-Vleck takes place, caused, probably, by decrease in the gap between the ground and excited states of Sm^{3+} ions during the magnetic dilution of the Co^{3+} ions. It may be due to an increase of the parameters a, b, c

as well as the degree of orthorhombic distortion of the perovskite structure ($\varepsilon = (b - a) / a$) : from $1.234 \cdot 10^{-2}$ for SmCoO_3 to $1.789 \cdot 10^{-2}$ for $\text{SmCo}_{0.5}\text{Ga}_{0.5}\text{O}_3$. For SmCoO_3 χ_0 is equal to $1.221 \cdot 10^{-3} \text{cm}^3 / \text{mol}$. This χ_0 value is somewhat smaller than $1.46 \cdot 10^{-3} \text{cm}^3 / \text{mol}$ value obtained in [10] for SmCoO_3 in the temperature range 10-300K, but considerably larger than the theoretical value $0.676 \cdot 10^{-3} \text{cm}^3 / \text{mol}$ for the free Sm^{3+} ions [10]. The results of our study of the magnetic susceptibility for $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ show that the orientational contribution ($\chi_{c, \text{mol}} = C_M / T$), depending on the temperature according to the Curie law, is less while the polarization temperature-independent contribution (χ_0) is more than those for the free Sm^{3+} ions. This indicates a “partial freezing” of the orbital angular moment and a large polarizability of the electron shell of Sm^{3+} ions in the crystal field of orthorhombically distorted perovskite structure.

Unfortunately in our opinion at present it is not possible to account for the above fact that modified Curie-Weiss law is valid only for narrow temperature intervals. It is the experimental fact.

If at temperatures below 300K the cobalt Co^{3+} ions in the samarium cobaltite SmCoO_3 are in the LS-state and they are diamagnetic, the molar magnetic susceptibility for this compound is determined by:

$$\chi_{\text{mol}, \text{SmCoO}_3} = \chi_{c, \text{mol}, \text{Sm}^{3+}} + \chi_{0, \text{SmCoO}_3}, \quad (4)$$

where χ_{0, SmCoO_3} is the sum of contributions due to the diamagnetism of the Sm^{3+} , Co^{3+} , Ga^{3+} , O^{2-} ions and Van-Vleck paramagnetism of Sm^{3+} ions; $\chi_{c, \text{mol}, \text{Sm}^{3+}}$ is temperature dependent (according to the Curie-Weiss law) contribution of the Sm^{3+} ions.

For the 10-60K temperature range the effective magnetic moment of samarium Sm^{3+} ions for $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ ($0 \leq x \leq 0.5$) varies only slightly (Table 1). Therefore, one can assume that a gradual increase in molar magnetization (σ_{mol}) (Figure 4) and molar magnetic susceptibility (χ_{mol}) (Figure 5(a)) observed at a certain temperature for solid solutions $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ with increasing (x) is caused both an increase of the contribution (χ_0) and the presence of Co^{3+} ions in the IS-state. According to this assumption, the molar magnetic susceptibility for $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ ($\chi_{\text{mol}, \text{SmCo}_{1-x}\text{Ga}_x\text{O}_3}$) at a certain temperature may be expressed by the equation:

$$\chi_{\text{mol}, \text{SmCo}_{1-x}\text{Ga}_x\text{O}_3} = \chi_{c, \text{mol}, \text{Sm}^{3+}, \text{SmCo}_{1-x}\text{Ga}_x\text{O}_3} + \chi_{c, \text{Co}^{3+}, \text{SmCo}_{1-x}\text{Ga}_x\text{O}_3} + \chi_{0, \text{mol}, \text{SmCo}_{1-x}\text{Ga}_x\text{O}_3}, \quad (5)$$

where $\chi_{0, \text{mol}, \text{SmCo}_{1-x}\text{Ga}_x\text{O}_3}$ is the sum of temperature-independent contributions due to the diamagnetism of the Sm^{3+} , Co^{3+} , Ga^{3+} , O^{2-} ions and Van-Vleck paramagnetism of Sm^{3+} ions for $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$. Since in the 10-60K temperature range $\chi_{c, \text{mol}, \text{Sm}^{3+}, \text{SmCo}_{1-x}\text{Ga}_x\text{O}_3} = \chi_{c, \text{mol}, \text{Sm}^{3+}, \text{SmCoO}_3}$, then from Equations (4) and (5), one can obtain:

$$\Delta\chi_{\text{mol}} = \chi_{\text{mol}, \text{SmCo}_{1-x}\text{Ga}_x\text{O}_3} - \chi_{\text{mol}, \text{SmCoO}_3} = \chi_{c, \text{Co}^{3+}, \text{SmCo}_{1-x}\text{Ga}_x\text{O}_3} + \Delta\chi_0.$$

Hence it appears that

$$\chi_{c, \text{Co}^{3+}, \text{SmCo}_{1-x}\text{Ga}_x\text{O}_3} = \Delta\chi_{\text{mol}} - \Delta\chi_0, \text{ where } \Delta\chi_0 = \chi_{0, \text{SmCo}_{1-x}\text{Ga}_x\text{O}_3} - \chi_{0, \text{SmCoO}_3}. \quad (6)$$

Calculations of $\chi_{c, \text{Co}^{3+}, \text{SmCo}_{1-x}\text{Ga}_x\text{O}_3}$ conducted by means of (6) in the temperature range 10-60K showed that for the samples $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ at $x = 0.3$ (Figure 7, curve 1); 0.5 the $\chi_{c, \text{Co}^{3+}, \text{SmCo}_{1-x}\text{Ga}_x\text{O}_3}$ values were positive.

For $\text{SmCo}_{0.7}\text{Ga}_{0.3}\text{O}_3$ for the 5-60K temperature interval magnetic susceptibility $\chi_{c, \text{Co}^{3+}}$ was calculated by using Equation (6) (Figure 7, curve 1).

Reciprocal value ($1/\chi_{c, \text{Co}^{3+}}$) within 5-40K interval varied linearly (Figure 7, curve 2). By the least squares method equation of linear dependency ($\chi_{c, \text{Co}^{3+}, \text{SmCo}_{1-x}\text{Ga}_x\text{O}_3}^{-1} = a + bT$) was obtained. Using coefficients a and b , constants C_M and Θ were calculated ($C_M = 0.012\text{cm}^3 / \text{mol}$ and $\Theta = -2.9\text{K}$). The effective magnetic moment of the paramagnetic Co^{3+} ions $\mu_{\text{eff}, \text{Co}^{3+}}$ for $\text{SmCo}_{0.7}\text{Ga}_{0.3}\text{O}_3$ (for 1 mol of Co^{3+} ions, taking into account that $1 - x = 0.7$) was calculated by the formula (3) and it was equal to $0.37\mu_B$.

Figure 7. Temperature dependence of magnetic susceptibility) ($\chi_{c,Co^{3+}}$) (curve 1) and reciprocal magnetic susceptibility ($1/\chi_{c,Co^{3+}}$) (curve 2) in the temperature range 5-60K for $SmCo_{0.7}Ga_{0.3}O_3$.

A fraction of Co^{3+} ions in the IS-state relative to the total content of Co^{3+} ions in $SmCo_{0.7}Ga_{0.3}O_3$ (y) was evaluated by the Equation (7):

$$\mu_{eff,Co^{3+}}^2 = (1 - y)\mu_{eff,Co_{LS}^{3+}}^2 + y\mu_{eff,Co_{IS}^{3+}}^2, \quad (7)$$

where $\mu_{eff,Co^{3+}} = 0.37\mu_B$, $\mu_{eff,Co_{LS}^{3+}} = 0$, and $\mu_{eff,Co_{IS}^{3+}} = 2.828\mu_B$. It is obtained that y equals to 1.71%.

Therefore, increase of the molar magnetic susceptibility at increasing of the substitution degree x of Co^{3+} ions by diamagnetic Ga^{3+} ions in $SmCoO_3$ with the formation of solid solutions $SmCo_{1-x}Ga_xO_3$ ($0 \leq x \leq 0.5$) on the whole is due to the increase of the temperature

independent contribution stipulated by Van-Vleck paramagnetism (χ_0) of the Sm^{3+} ions. A fraction of the Co^{3+} ions being in a paramagnetic state is insignificant at 10-60K.

4. Conclusion

Synthesis of the samarium cobaltites-gallates $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ ($x = 0; 0.1; 0.2; 0.3; 0.4; 0.5$) is carried out by a conventional solid-state reaction method at 1523K. X-ray diffraction analysis showed that within the above range of x solid solutions were formed. Parameters a , b , c of the orthorhombically distorted perovskite crystal lattice increased linearly at x increase. Molar magnetic susceptibility χ_{mol} for $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ is determined in the temperature range 5-300K in a magnetic field of 0.8 T. It is found that increasing x for $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ does not lead at a certain temperature to the absence of change or to a decrease of χ_{mol} as it should be observed at invariability of the magnetic state of Sm^{3+} , Co^{3+} ions but on the contrary to the increase of χ_{mol} . This implies that the magnetic state of Sm^{3+} , Co^{3+} ions for solid solutions $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ differs from their state in a pure SmCoO_3 . In this paper, it is confirmed by the analysis of the values of the effective magnetic moment of Sm^{3+} ions ($\mu_{\text{eff}, \text{Sm}^{3+}}$) and temperature-independent contribution (χ_0) due to the Van-Vleck polarization paramagnetism for the Sm^{3+} ions in $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ within the temperature range 10-60K. It is found that for the samples $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ for the 10-60K temperature interval the effective magnetic moment of Sm^{3+} ions ($\mu_{\text{eff}, \text{Sm}^{3+}}$) practically does not depend on the degree of substitution x and it equals to $(0.50 - 0.59)\mu_{\text{B}}$.

It is also observed, that increase of the χ_{mol} at growth of the substitution degree x in SmCoO_3 with the formation of solid solutions $\text{SmCo}_{1-x}\text{Ga}_x\text{O}_3$ ($0 \leq x \leq 0.5$) takes place. It may be due to the increase of the contribution χ_0 of the Sm^{3+} ions. A fraction of the Co^{3+} ions being in a paramagnetic state is insignificant at 10-60K.

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