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THE MAGNETIC PROPERTIES OF $SmFe_{11-x}Co_xTi$ SINGLE CRYSTALS

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The effect of substituting atoms of Co for Fe on the magnetic properties of $SmFe_{11-x}Co_xTi$ ($x = 0, 1, 2, \ldots, 6$) single crystals in pulsed magnetic fields up to 120 kOe at temperatures of 4.2 to 300 K was studied. The concentration dependences of the magnetic anisotropy constants K_1 and K_2 and anisotropy fields H_a were determined. Magnetic phase transitions induced by an applied field were observed.

At present, rare-earth metal compounds have been the focus of attention of researchers concerned with the search for new materials that can be used in permanent magnets. The object of our study was the $SmFe_{11-x}Co_xTi$ ($x = 0, 1, 2, \ldots, 6$) system with a $ThMn_{12}$-type structure. Our purpose was to study the effect of substituting atoms of Co for Fe on the magnetic properties of these compounds in magnetic fields up to 120 kOe. Note that the substitution of Co for Fe increases the Curie temperatures of the compounds, which is of utmost importance for using these materials in permanent magnets [1].

The structural and magnetic properties of the $SmFe_{11-x}Co_xTi$ system were considered in [2, 3]. It was claimed in [2] that single-phase materials with $ThMn_{12}$-type structures could only be prepared for $x < 2$, while compounds with $x > 2$ contained considerable amounts of a phase with the Th_2Zn_{17} structure. In [3], the properties of $Sm(Fe_{1-x}Co_x)_{10.8}Ti_{1.2}$ compounds with the $ThMn_{12}$ structures were studied, but the composition variations were limited to $x \leqslant 0.3$.

In [4], the magnetic properties of $SmFe_{11-x}Co_xTi$ compounds were studied in magnetic fields up to 20 kOe. The $SmFe_{11-x}Co_xTi$ compounds with $0 \leqslant x \leqslant 6$ were shown to have $ThMn_{12}$ structures over the whole concentration range.

We took measurements on $SmFe_{11-x}Co_xTi$ compounds in pulsed magnetic fields up to 120 kOe at 4.2 to 300 K. This enabled us to study not only the magnetocrystalline anisotropy of these highly anisotropic compounds but also magnetic phase transitions in them, which is of interest both scientifically and for practical applications.

PREPARATION OF SAMPLES AND EXPERIMENTAL PROCEDURE

The procedure for the preparation of $SmFe_{11-x}Co_xTi$ samples and quality control techniques were the same as described in [4].

The magnetic properties of $SmFe_{11-x}Co_xTi$ compounds were studied in pulsed magnetic fields up to 120 kOe. The pulsed fields were generated following the standard procedure by discharging a battery of capacitors through a multiturn solenoid cooled by liquid nitrogen. The field pulse width was 7–10 ms. Magnetization was measured by the induction method with the help of differential coils [5]. Signals from samples were integrated and fed to the y-input of an oscilloscope. The signal proportional to the field was passed through an RC circuit from the measuring coil to an x-input of the oscilloscope. The obtained $\sigma(H)$ magnetization *vs.* field dependence was recorded by photographing. The measurement errors were 5% for the field and 7% for the magnetization values. Magnetization measurements at low temperatures were performed

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Table 1

The Principal Magnetic Characteristics of $SmFe_{11-x}Co_xTi$ Compounds

Composition	σ_s, G cm^3/g		H_a, kOe		T_c, K
	78 K	300 K	78 K	300 K	
$SmFe_{11}Ti$	143	126	212	102	600
$SmFe_{10}Co_1Ti$	145	132	203	98	720
$SmFe_9Co_2Ti$	145.5	134	180	71	820
$SmFe_8Co_3Ti$	146	135	123	48	870
$SmFe_7Co_4Ti$	144	132	72	35	920
$SmFe_6Co_5Ti$	141	129	40	25	960
$SmFe_5Co_6Ti$	138	124	—	—	975

by inserting the holder with the sample and the differential coils into a flow helium cryostat. Temperature was measured by a Cu–Fe–Cu thermocouple.

RESULTS AND DISCUSSION

The magnetization *vs.* field dependences for $SmFe_{11-x}Co_xTi$ ($x = 0, 2, 5, 6$) measured at $T = 4.2$ K along the easy magnetization axis $\sigma_{\parallel}(H)$ and the hard magnetization axis $\sigma_{\perp}(H)$ are shown in Fig. 1. The saturation magnetization depends on the concentration of cobalt, and for $SmFe_{11}Ti$, $\sigma_s = 143$ G cm^3/g, whereas for $SmFe_5Co_6Ti$, $\sigma_s = 138$ G cm^3/g. The highest saturation magnetization was obtained for $SmFe_8Co_3Ti$, $\sigma_s = 146$ G cm^3/g. The σ_s values measured in pulsed magnetic fields closely agree with those obtained in permanent fields at $H < 20$ kOe [4]. The principal magnetic characteristics of the $SmFe_{11-x}Co_xTi$ system are given in Table 1. The magnetic anisotropy field H_a was determined as the field corresponding to the intersection of the $\sigma_{\parallel}(H)$ and $\sigma_{\perp}(H)$ curves.

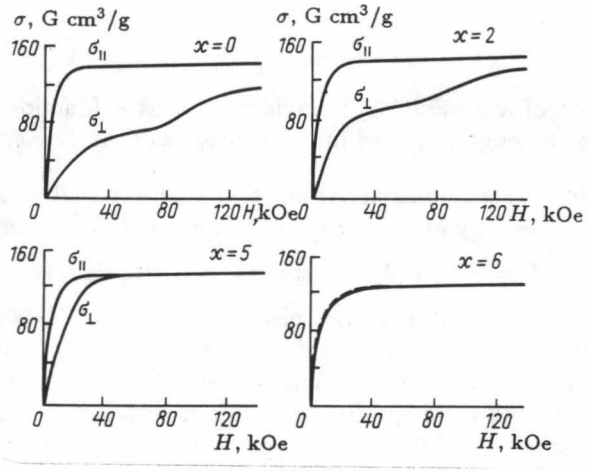

Fig. 1

Magnetization curves of $SmFe_{11-x}Co_xTi$ single crystals measured at $T = 4.2$ K along the easy and hard magnetization axes ($0 \leqslant x \leqslant 6$).

Table 2

Magnetic Anisotropy Constants K_1 and K_2 (10^7 erg/cm^3)

Composition	$T = 4.2$ K		$T = 78$ K		$T = 300$ K	
	K_1	K_2	K_1	K_2	K_1	K_2
$SmFe_{11}Ti$	7.6	2.2	7.5	2.2	3.4	0.3
$SmFe_{10}Co_1Ti$	7.6	2.2	7.5	2.2	3.5	0.3
$SmFe_9Co_2Ti$	7.0	2.0	7.0	1.8	3.0	0.3
$SmFe_8Co_3Ti$	5.6	1.3	5.6	1.2	2.6	0.3
$SmFe_7Co_4Ti$	4.5	1.1	4.4	1.0	1.5	0.2
$SmFe_6Co_5Ti$	2.9	0.6	2.9	0.5	0.8	0.2

There are no literature data on the magnetic anisotropy fields H_a of $SmFe_{11-x}Co_xTi$ compounds with cobalt concentrations $x \geqslant 3$. The results presented in Table 1 fill up the gap.

The magnetization curves for $SmFe_8Co_3Ti$ obtained at 4.2, 78, and 300 K are shown in Fig. 2.

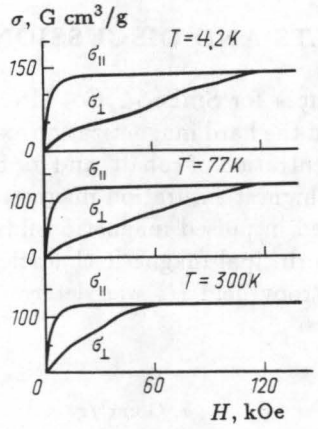

Fig. 2

Specific magnetization of a $SmFe_8Co_3Ti$ single crystal as a function of applied magnetic field, measured along the easy and hard magnetization axes at $T = 4.2$, 77, and 300 K.

The behavior of magnetization of a uniaxial ferromagnet in an external magnetic field should be analyzed taking into account not only the energy of anisotropy but also the Zeeman energy [6]

$$E = K_1 \sin^2\theta + K_2 \sin^4\theta - HI_s \cos(H\hat{}I_s), \qquad (1)$$

where K_1 and K_2 are the first and second magnetic anisotropy constants, I_s is the saturation magnetization, and θ is the angle made by the vector $\mathbf{I}_s$ and the axis c of the crystal. An analysis of magnetization along the hard magnetization axis shows that the compounds under consideration can be divided into two groups, viz., compounds exhibiting a smooth increase of magnetization with increasing strength of the applied field and compounds that show a more rapid increase of magnetization after a certain critical field is attained.

For compounds of the first group, high-order terms in (1) can be ignored, whereas these terms make a noticeable contribution to the magnetic anisotropy energy of the compounds of the second group.

We calculated the magnetic anisotropy constants K_1 and K_2 by mathematically processing magnetization curves as recommended in [7]. The error of determining the constants was $\sim 10\%$. The values of K_1 and K_2 at 4.2, 78, and 300 K are listed in Table 2.

According to this table, at room temperature, the anisotropic constants K_2 of $SmFe_{11-x}Co_xTi$ compounds with $0 \leqslant x \leqslant 3$ are almost an order of magnitude lower than the K_1 constants. However, at low temperatures, the K_2 constants increase almost tenfold.

The jumpwise growth of magnetization $\sigma_\perp(H)$ along the hard magnetization axis (see Figs. 1 and 2) is likely to be caused by phase transitions induced by the applied magnetic field. A similar behavior was observed earlier for other systems [8]. Bends in the $\sigma_\perp(H)$ curves are seen most clearly for $SmFe_{11-x}Co_xTi$ with low cobalt contents ($x \leqslant 2$).

Note that unlike $SmFe_{11-x}Co_xTi$, $YFe_{11-x}Co_xTi$ compounds give $\sigma_\perp(H)$ curves without sharp bends. Although the metallic radius of yttrium is close to that of trivalent samarium, and although its electron shell is similar to those of rare-earth ions, the yttrium ion does not possess a localized magnetic moment and does not contribute to the magnetic anisotropy of $YFe_{11-x}Co_xTi$ compounds. It follows that the occurrence of phase transitions in $SmFe_{11-x}Co_xTi$ may be a consequence of the special features of the electronic configuration of the samarium ion, whose excited state energy levels make up a comparatively closely spaced multiplet near the ground state. This contributes to admixing to the ground state of closely lying excited energy states, which results in the formation of a noncollinear spin structure in strong magnetic fields and the appearance of high-order anisotropy constants in expression (1) for the energy of anisotropy.

CONCLUSIONS

1. Substituting cobalt for iron in $SmFe_{11-x}Co_xTi$ sharply decreases the anisotropy constants and increases the Curie temperature T_c; the K_2 constants are always substantially smaller than the K_1 constants.
2. The anomalies of the $\sigma(H)$ curves are indicative of changes in the energy state of samarium atoms in strong magnetic fields.

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REFERENCES

1. A. V. Andreev, A. N. Bogatkin, N. V. Kudrevatykh, et al., *Fiz. Met. Metalloved.*, vol. 68, no. 1, p. 70, 1989.
2. S. F. Cheng and V. R. Sinha, *Magn. Magn. Mat.*, vol. 75, no. 3, p. 330, 1988.
3. M. Solzi and R. H. Xue, *Magn. Magn. Mat.*, vol. 80, no. 1, p. 44, 1990.
4. O. A. Zolotukhin, V. V. Zubenko, T. I. Ivanova, et al., *Moscow Univ. Phys. Bull.*, no. 5, p. 73, 1993.
5. Yu. F. Popov, Ph. D. (Phys.-Math.) Thesis, Moscow State Univ., Moscow, 1971.
6. K. P. Belov, *Orientation Transitions in Magnetic Materials Containing Rare-Earth Metals* (in Russian), Moscow, 1979.
7. C. J. Long and F. Grandjean (Editors), *Supermagnets. Hard Magnetic Materials,* Kluwer Academic, Netherlands, 1991.
8. D. Melville and W. I. Khan, *IEEE Trans. Magn.*, no. 6, p. 1012, 1976.
9. Y. C. Yang and S. Hong, *Solid State Commun.*, vol. 68, no. 2, p. 175, 1988.

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