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Electrical and Magnetic Properties of SmSb Single Crystals at Low Temperatures

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On SmSb single crystals synthesized from elements, the electrical resistance R and magnetization M were measured as functions of temperature and magnetic field. A large magnetoresistance is observed over the entire temperature range of $2-300$ K, increasing significantly with decreasing temperature. The temperature dependence of the magnetization exhibits a singularity at the transition temperature to the antiferromagnetic state $T_N = 2.3$ K. At temperatures below 8 K, de Haas–van Alphen oscillations are observed in the $M(H)$ dependences, the frequencies of which do not change upon the transition through T_N. Linear extrapolation of the dependence of the Landau indices N on the reciprocal of the magnetic field $1/B$ to zero gives the value $N_{T=2\,K} = 0.75$, which indicates the presence of the Berry phase and a nontrivial band topology in the SmSb compound.

Keywords: samarium monoantimonide, magnetization, magnetoresistance, antiferromagnetic phase transition, de Haas–van Alphen magnetic oscillations, Berry phase.

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1. Introduction

Compound SmSb relates to family of rare earth monoantimonides, which attract a lot of attention because of observation of giant magnetoresistance in them [1–6]. Recent experimental data on the study of the magnetoresistive effect and magnetic quantum oscillations in compound SmSb with intermediate valence of cations [7] demonstrated that nontrivial topology of electron bands may exist in this compound. In [7], the Shubnikov–de Haas (SdH) and de Haas–van Alphen (dHvA) oscillations in SmSb single crystals, synthesized by the flux method in the Sn melt were investigated. An analysis of the Landau level indices obtained from the SdH effect revealed the presence of a Berry phase in the SmSb compound, as well as a significant difference in the temperature dependences of the oscillation amplitudes in these effects.

This paper presents results of measurements of temperature dependences of magnetoresistance and dHvA effect for SmSb compound in the temperature region near the transition into antiferromagnetic state (above and below Neel temperature T_N). Landau level indices obtained from dHvA oscillations were analyzed. Measurements were carried out on SmSb single crystals obtained by synthesis from elements.

2. Experimental procedure

The investigated samples were cut from initial SmSb bar synthesized, in contrast to [7], by method of melting elements (Sm, Sb) in stoichiometric proportion with subsequent homogenizing annealing, similarly to the process of obtaining terbium monoantimonide [8] and had dimensions not exceeding $6 \times 3 \times 3\,\mathrm{mm}^3$.

X-ray diffraction and X-ray phase analyses of SmSb samples were carried out on diffractometer DRON-3 (Cu$K\alpha$-radiation, $\lambda_1 = 1.5405$ Å, $\lambda_2 = 1.5443$ Å). X-ray patterns of tested samples (Fig. 1) corresponded to large grained crystal, mostly oriented in direction [100], with structural type NaCl (B1) and lattice parameter $a = 6.265(2)$ Å, which is in good agreement with the data of card register (JCPDS#65-7161) for SmSb compound. Inclusions of other phases were not found. Characteristic dimensions of coherent scattering regions (CSR) of X-ray radiation (L) and microstress value (ε) in samples were obtained by approximation method within kinematic theory [9] by reflections 200 and 600, respectively. CSR value was $L \sim 2695 \pm 265$ Å, microstress value $\varepsilon \sim 0.002$, which is comparable to the error of lattice parameter measurement. Misalignment angles $\Delta\theta$ of atom planes in direction [100] were calculated on the basis of 400 reflection and did not exceed 0.02° in this direction (Fig. 1). Data presented above characterize rather well formed SmSb crystals.

Experimental research of temperature and field dependences of magnetization (M) and electrical resistance (R) of SmSb samples were carried out on vibration magnetometer of PPMS Quantum Design system in temperature region $2-300$ K and in magnetic fields with induction up to 14 T. Measurement of SmSb magnetic susceptibility (χ) was carried out in magnetic field with induction 30 mT, directed in parallel to larger sample size. Electrical resistance R was measured by four-probe DC method with current value $I = 2.5$ mA.

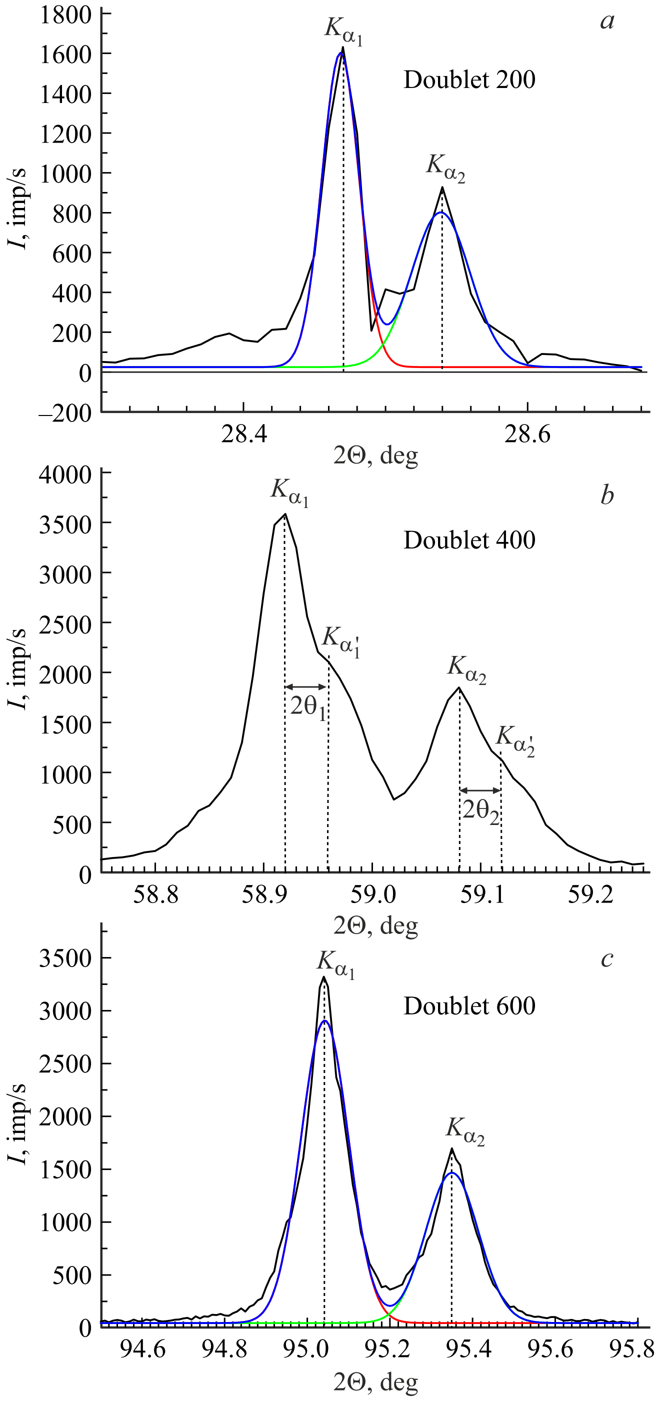

Figure 1. X-ray patterns of SmSb sample, mostly oriented in direction [100]: *a*) doublet 200 (second order of reflection); *b*) doublet 400 (fourth order of reflection); *c*) doublet 600 (sixth order of reflection). Color lines — Gaussian approximations.

3. Results and their discussion

Dependences of electrical resistance R of SmSb single crystals on temperature in magnetic field with induction up to 14 T are given in Fig. 2. From the figure it follows that dependence of resistance on temperature in SmSb is of metallic nature, besides, high magnetoresistance is observed in the entire investigated temperature region. In [10] the temperature dependence of SmSb electrical resistivity $\rho(T)$ demonstrated a small fracture at temperature of around 65 K, which authors [10] explain by „splitting of crystal electrical fields". In this paper the specified feature in behavior $R(T)$ is also observed, but at lower temperature — around 55 K, and as the magnetic field increases, it shifts to low temperature region by ~ 10 K. Analysis of behavior of electrical resistance temperature dependence $R(T)$ of SmSb, including currently unexplainable minor surges of R in temperature region $220 \div 240$ K, will be performed in the next paper.

Fig. 3 shows temperature dependences of reverse value of magnetic susceptibility — χ^{-1} of SmSb in intervals $25 \div 400$ K and $2.05 \div 5$ K (on insert) and results of

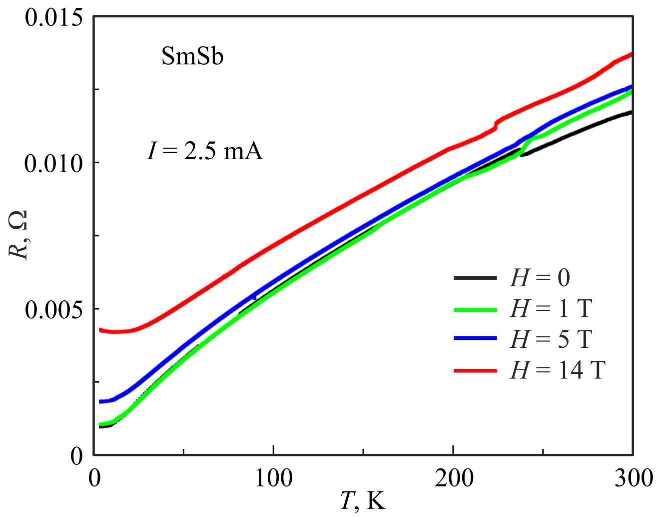

Figure 2. Temperature dependences of electrical resistance R of SmSb sample in magnetic fields 0, 1, 5 and 14 T.

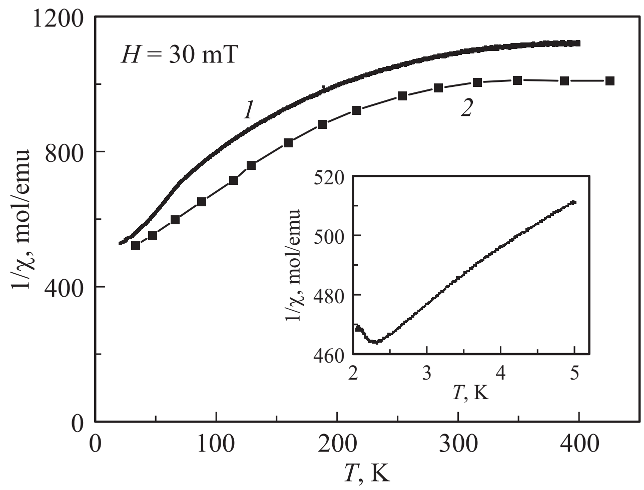

Figure 3. Temperature dependences of reverse magnetic susceptibilities $1/\chi$ for SmSb, *1* — data of this paper; *2* — [10,11]; on insert — low temperature region of the dependence.

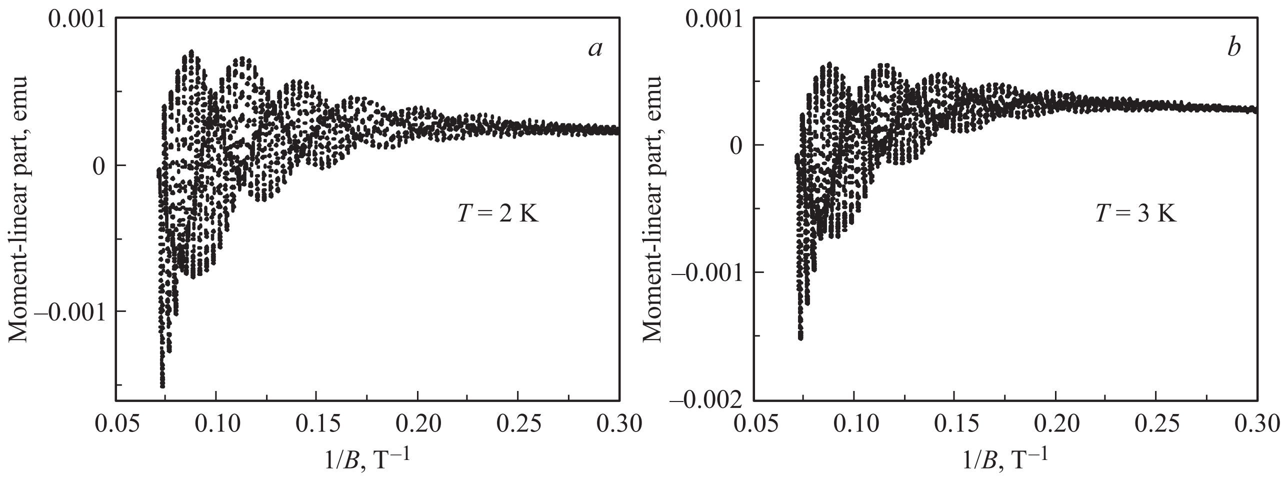

Figure 4. The dependence of the oscillatory component of the magnetic moment M of the SmSb sample on the reverse magnetic field induction B at temperatures a — $T = 2$ K; b — $T = 3$ K.

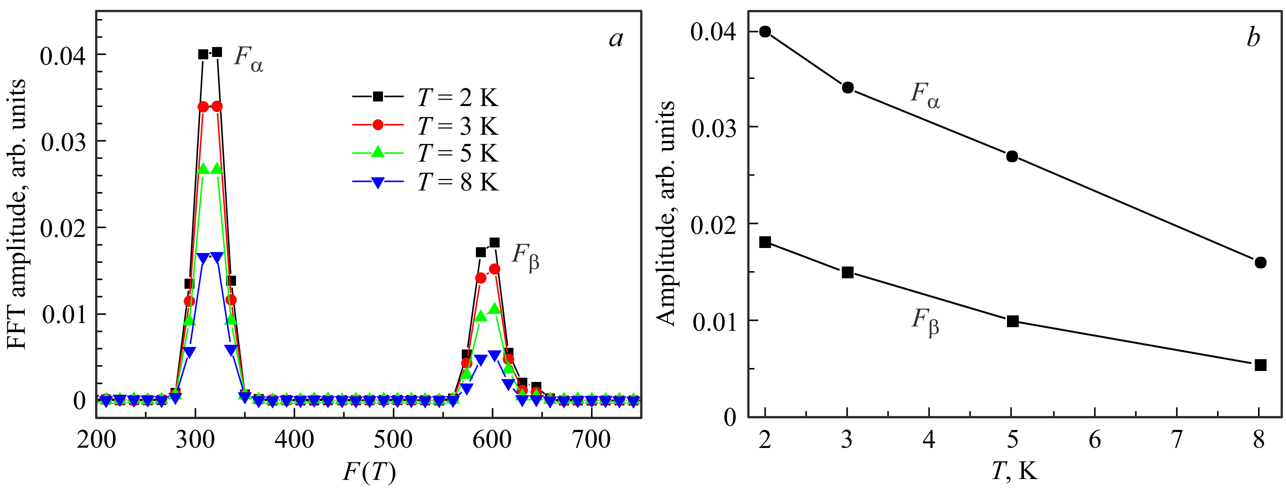

Figure 5. a — Spectrum of amplitudes of dHvA SmSb oscillations (in arb. units), at temperatures of 2, 3, 5, and 8 K, b — the temperature dependences of the amplitudes of the main oscillation frequencies dHvA F_α and F_β for SmSb (in arb. units).

similar measurements presented in papers [10,11]. With general similarity in behavior of $\chi^{-1}(T)$ dependences and close values of χ^{-1} obtained as a result of this research and in papers [10,11], principal difference is observed. Thus, minimum of $\chi^{-1}(T)$ dependence of SmSb, related to transition to antiferromagnetic state, was observed at $T = 2.31$ K, and according to [11] — at $T \sim 2.8$ K.

At temperatures below 8 K, de Haas–van Alphen (dHvA) oscillations of the magnetic moment $M(H)$ of SmSb single crystals are observed in high magnetic fields. Figures 4, a and 4, b show the dependences of the oscillatory component of the magnetic moment M_{osc} of the investigated sample on the magnitude of the reverse magnetic field induction B at temperatures 2 and 3 K, i.e., above and below the transition temperature to the antiferromagnetic state $T_{\mathrm{N}} = 2.1–2.8$ K [10–12].

As a result of the FFT analysis, the frequencies of the main oscillations F_α, F_β, $F_{2\alpha}$ were calculated using the dependences of the magnetic moment on the value of the reverse magnetic induction $M(1/B)$ and their amplitude (in arb. units) for four temperatures; the results are given in fig. 5.

Values of frequencies and temperature dependence of their dHvA oscillation amplitudes match well the results of paper [7]. However, in contrast to the latter, a slight broadening of the peaks F_α and F_β of the oscillation amplitudes was observed. Apparently, in single crystals of SmSb obtained by the synthesis from element, there is a minor misalignment of crystalline planes in direction [100], not exceeding, according to our data $\Delta\theta \sim 0.02°$, which causes minor deviation of frequencies and amplitudes of oscillations, and, as a result, the widening of peak shape.

From analysis of $M(1/B)$ oscillations, the dependences of Landau level indices N on the value of reverse magnetic field were obtained at temperatures 2 and 3 K, i.e. below and above T_{N}. Fig. 6 shows $N(1/B)$ dependence for temperature $T = 2$ K. Linear extrapolation $N(1/B)$ to zero gives value $N = 0.75$ for $T = 2$ K and $N = 0.73$ for $T = 3$ K.

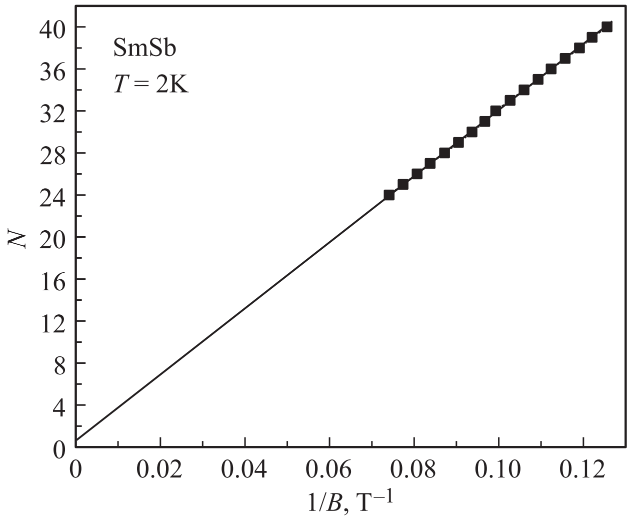

Figure 6. Dependence of the Landau indices N obtained from dHvA effect on the reciprocal of the magnetic field at $T = 2$ K.

Based on the analysis of experimental results, we can conclude that: firstly, the N values, obtained by extrapolating the values of $N(1/B \to 0)$ at temperatures above and below the Néel temperature T_N coincide within the error, that indicates the absence of a rearrangement of the electronic spectrum of the compound at antiferromagnetic transition, and secondly, these values are close to the value $N = 0.52$ obtained in [7] by a similar method based on measurements of the SdH effect in high magnetic fields. The set of data presented in this work and in [7], indicates the presence of the Berry phase in the SmSb compound and the nontrivial topology of the SmSb energy bands.

4. Conclusion

Measurements $R(T,H)$ and $M(T,H)$ were carried out on SmSb single crystals produced by synthesis from elements. Temperature dependence of resistance characterizes metallic nature of electric transfer in this compound, at the same time high magnetoresistance $R(H)$ was observed in the entire temperature range. Temperature dependences of magnetic moment and magnetic susceptibility demonstrate features at the temperature of transition to antiferromagnetic state $T_N = 2.3$ K. This T_N value is very low compared to other antiferromagnetic antimonides of rare earth elements (see [13]). Possible explanation of this fact consists in the intermediate valence of samarium cations $\nu \sim 2.7+$ [14]. Since one of fluctuating valence states of cations Sm $^7F_0$ is non-magnetic, quite low temperatures are required for ordering of magnetic moments and forming antiferromagnetic phase.

Dependences $M(H)$ at temperatures below 8 K demonstrate dHvA oscillations, the frequencies of which do not change upon passing through the temperature of antiferromagnetic ordering, which indicates the invariance of the band spectrum of the SmSb compound as a result of the antiferromagnetic transition.

Linear extrapolation of Landau indices N dependence on inverse value of magnetic field $1/B$ to zero gives value $N_{T=2\,K} = 0.75$, which indicates the presence of Berry phase and confirms nontrivial topology of bands in SmSb compound.

Acknowledgments

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Conflict of interest

The authors declare that they have no conflict of interest.

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