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Specific Features of the Transport Properties of the $Lu_{0.1}Bi_{1.9}Te_3$ Compound

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Abstract—The temperature and electric- and magnetic-field dependences of the resistivity of the $R_{0.1}Bi_{1.9}Te_3$ compound are investigated. It is shown that, in the low-temperature region, variable-range hopping conductivity is realized in this compound. In the temperature range of hopping conductivity, the electrical resistivity decreases with increasing electric-field strength in the sample, which is typical of charge-carrier tunneling from one localized state in the impurity band to another. Investigation of the transverse magnetoresistance revealed the crossover from the parabolic dependence of the magnetoresistance in low fields to the linear dependence in high fields. The established features of the transport properties of the $R_{0.1}Bi_{1.9}Te_3$ compound are characteristic of inhomogeneous and disordered semiconductors.

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At present, bismuth telluride Bi_2Te_3 is the main low-temperature thermoelectric material [1]. Its important drawback is a low thermoelectric figure of merit, which stimulates intense research aimed at enhancing the thermoelectric Q factor ZT; here, one of the promising directions is the doping of Bi_2Te_3 with, e.g., rare-earth elements [2–6]. In particular, according to the preliminary results, doping of Bi_2Te_3 with lutecium allows an increase in the thermoelectric Q factor to ~1.5 (in pure bismuth telluride, $ZT \sim 1$).

One of the possible causes of enhancement of the thermoelectric Q factor of Bi_2Te_3 upon doping with rare-earth elements is considered to be the inhomogeneous distribution of dopant atoms in the bulk of the material, which leads, in virtue of inhomogeneous structure formation, to a decrease in its thermal conductivity. Electrically inhomogeneous semiconductor materials are characterized by the occurrence of unique features of transport properties related to the implementation of specific electrical-conductivity mechanisms both upon temperature variation and in an applied magnetic field.

The aim of this study is to find and analyze the specific features of the transport properties of $R_{0.1}Bi_{1.9}Te_3$ (R = Tm, Lu, Er, or Yb) compounds characteristic of disordered and inhomogeneous semiconductors. Among these properties, the temperature dependences of the electrical resistivity, I–V characteristics, and transverse magnetoresistance are studied.

The initial powder of the investigated compounds was synthesized by the microwave solvothermal method. The synthesized powder was then compacted by cold isostatic pressing with subsequent annealing at 683 K for 2 h in an argon flow.

X-ray analysis using a SmartLab RIGAKU diffractometer (CuK_α radiation, Ni filter) showed that the obtained materials are single-phase and have a hexagonal structure with the $R3m$ space symmetry group typical of pure Bi_2Te_3; the unit-cell parameters were $a = b = 4.385$ Å and $c = 30.49$ Å and were nearly independent of the dopant type.

The electrical resistivity ρ, I–V characteristics, and transverse magnetoresistance of the samples were measured with a voltmeter-ammeter using a Cryogen free facility.

The established and investigated features described below characterized all the $R_{0.1}Bi_{1.9}Te_3$ compounds doped with rare-earth elements and did not significantly depend on the dopant used. Therefore, below we thoroughly analyze the features of the transport properties by the example of the $Lu_{0.1}Bi_{1.9}Te_3$ compound.

Figure 1 presents the temperature dependence of ρ obtained in the heating mode in the range of 2–25 K. It can be seen that the $\rho(T)$ dependence has a minimum at $T_m \approx 11$ K, which is indicative of a change in the conductivity type from "metal" (above T_m) to "semiconductor" (below T_m). Above the temperature T_m, the experimental $\rho(T)$ dependence fits the straight line in the coordinates $\rho - T^{3/2}$. This dependence is accounted for by charge-carrier scattering at acoustic phonons [7]. According to the results reported in [6], lutecium atoms in bismuth telluride

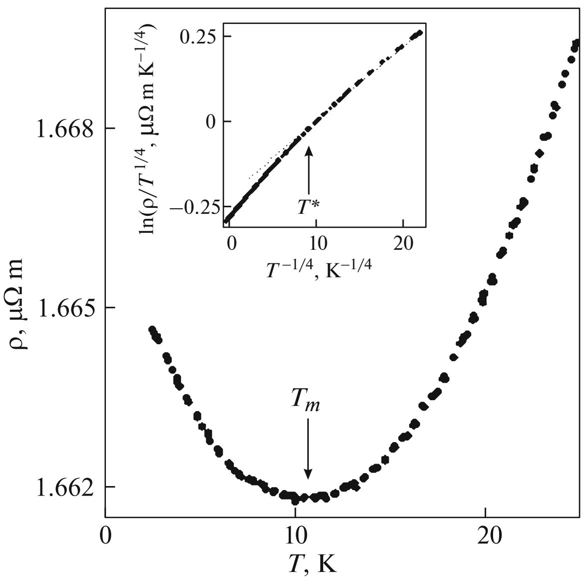

Fig. 1. Temperature dependence of the electrical resistivity of the $R_{0.1}Bi_{1.9}Te_3$ compound. The inset shows the dependence $\ln(\rho/T^{1/4}) = f(T^{1/4})$.

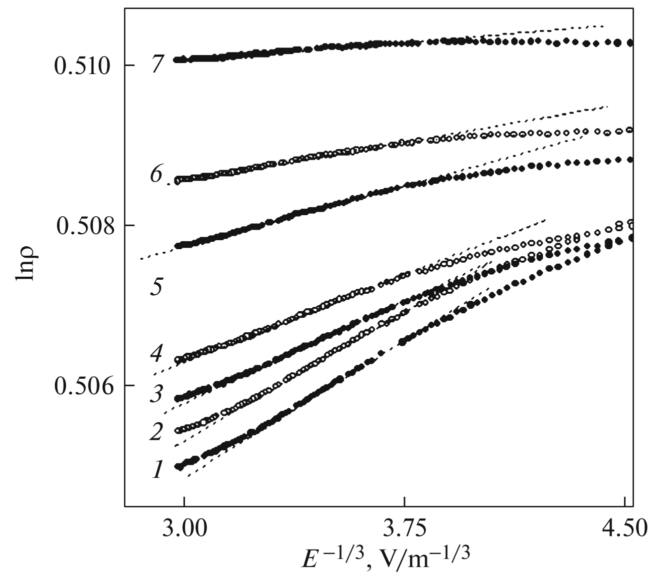

Fig. 2. Electric-field dependences of the electrical resistivity of the $R_{0.1}Bi_{1.9}Fe_3$ compound at temperatures of 2 (curve *1*), 4 (curve *2*), 8 (curve *3*), 10 (curve *4*), 13 (curve *5*), 19 (curve *6*), and 23 K (curve *7*).

behave as donors; i.e., the majority carriers are electrons.

Below the temperature T_m, the best agreement with the experiment is attained by using the variable-range hopping conductivity mechanism typical of inhomogeneous and disordered semiconductors [8]. In this mechanism, the temperature dependence of the resistivity is

$$\rho(T) = AT^{1/4}\exp\left[\left(\frac{T_0}{T}\right)^{1/4}\right], \quad (1)$$

where A and T_0 are constants.

The inset in Fig. 1 shows that, below T_m, the experimental $\rho(T)$ dependence is linear in $\ln(\rho/T^{1/4}) - T^{1/4}$ coordinates.

The hopping conductivity mechanism is indicative of carrier hops between localized states in the impurity band via tunneling. The charge-carrier tunneling processes significantly depend on the charge-carrier energy, which can be increased by increasing the density of electric current flowing through the sample during ρ measurements (or the potential difference applied to the sample). Therefore, the tunneling processes are characterized by nonlinear I–V characteristics, which are indicative of a decrease in the electrical resistivity (or an increase in the current density) with increasing electric-field strength E in the sample.

We obtained the I–V characteristics of the investigated $Lu_{0.1}Bi_{1.9}Te_3$ sample in the temperature range of hopping conductivity, which were then used to plot and analyze the $\rho(E)$ dependences. An increase in the electric-field strength leads to a significant decrease in ρ; this trend is noticeably intensified as the temperature decreases below T_m; when the sample is heated above 27 K, the electrical resistance is already close to field independent. This behavior is consistent with the charge-carrier tunneling mechanism in the case of hopping conductivity.

As is known, in the hopping-conductivity region, the $\rho(E)$ dependences are different for low fields (when $e\varepsilon_r E_r \ll kT$, where ε_r is the permittivity of the material and r is the average charge-carrier hopping length) and at high electric fields (when $e\varepsilon_r E_r \gg kT$) [9]. It is important that, in high electric fields the resistivity decreases with increasing electric field in accordance with the law $p(E) \sim \exp(E^{-1/3})$. It can be seen in Fig. 2 that, in the $\rho(E)$ dependences presented in $\ln\rho - E^{-1/3}$ coordinates, there are linear portions, which confirm the hopping conductivity mechanism in the $Lu_{0.1}Bi_{1.9}Te_3$ sample, in some temperature-dependent field ranges.

Additional confirmation of the formation of an inhomogeneous and disordered structure in the investigated material is provided by investigation of the transverse magnetoresistance (when measuring the magnetoresistance, the magnetic-field induction vector B is directed perpendicular to the current through the sample). The magnetoresistance was determined from the expression

$$MR = \frac{\Delta\rho(B)}{\rho(0)} = \frac{\rho(B) - \rho(0)}{\rho(0)}\cdot 100. \quad (2)$$

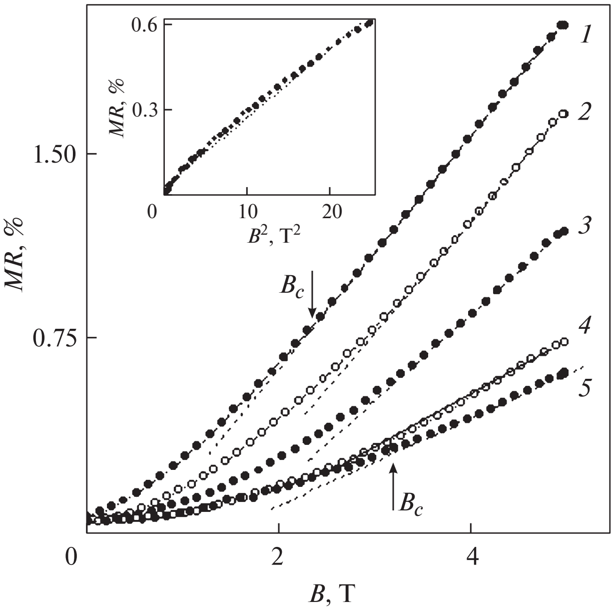

Fig. 3. Magnetic-field dependences of the electrical resistivity of the $R_{0.1}Bi_{1.9}Te_3$ compound at temperatures of 2 (curve *1*), 60 (curve *2*), 130 (curve *3*), 160 (curve *4*), and 240 K (curve *5*). The inset shows the $MR(B^2)$ dependence at 240 K.

Figure 3 shows the $MR(B)$ dependences for the $Lu_{0.1}Bi_{1.9}Te_3$ compound obtained at different temperatures. For all the temperatures, the resistance increases in a magnetic field, i.e., the magnetoresistance is positive. At temperatures above ~220 K, the $MR(B)$ dependence obeys the parabolic law $MR \sim B^2$ (see Fig. 3, the inset). This behavior is typical of most metals and semiconductors [10] and is caused by the action of the Lorentz force on moving charge carriers, which changes their free path. The crossover from the parabolic dependence in low fields to a linear dependence in high fields was observed for a gradual drop in temperature. After the crossover, B_c decreased with temperature; i.e., the linear contribution to the general $MR(B)$ dependence gradually increased.

The linear positive magnetoresistance in metals and semiconductors can be caused by several mechanisms [10–13]. One of these mechanisms is developed for structurally inhomogeneous and disordered semiconductors [12, 13]. In such semiconductors, structural inhomogeneity leads to the development of electrical inhomogeneity. In this case, a high magnetic field makes a part of the electric current flow in the direction perpendicular to the applied electric voltage, which will lead to the occurrence of the Hall contribution (linear with respect to the magnetic field) and total magnetoresistance.

Thus, the $Lu_{0.1}Bi_{1.9}Te_3$ compound exhibits the following features of the transport properties typical of inhomogeneous and disordered semiconductors: variable-range hopping conductivity in the low-temperature region and linear positive magnetoresistance.

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