Physica B 459 (2015) 12–15

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

A comparative study of size-dependent magnetoresistance and Hall resistance of Sb_2Te_3 nanoflakes

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ARTICLE INFO

Article history:
Received 30 September 2014
Received in revised form
14 November 2014
Accepted 21 November 2014
Available online 24 November 2014

Keywords:
Magnetoresistance
Hall effect
Topological insulator

ABSTRACT

Single crystal Sb_2Te_3 topological insulator nanoflakes with the thickness of 25 nm and 456 nm were synthesized via vapor phase deposition method. The Hall resistance and magnetoresistance of the nanoflakes have been measured at temperatures 2 K and 300 K in the fields up to 9 T. The magnetoresistance and Hall resistance of the nanoflakes demonstrate significant differences, so that despite ordinary magnetoresistance and Hall effect obtained for 25 nm sample 450 nm nanoflake demonstrates unusual magnetoresistance and nonlinear Hall resistance. The sense of curvature of both $R_{xx}(B)$ and $R_{xy}(B)$ dependences is inversed at high temperature. The experimental data have been analyzed in the frame of a multichannel transport model. The difference in the behavior is attributed to the existence of the charge carriers with high and low mobility, as well as to their relative contribution (which varies depending on the temperature) to the magneto-transport of the nanoflakes.

1. Introduction

Topological insulators (TIs) represent a new state of quantum matter and attract heightened interest due to unique properties associated with the metallic gapless surface states. The unique surface states having spin-polarized nature with the spin-up and spin-down currents (protected by time-reversal symmetry) originate as the consequence of strong spin–orbit coupling, inherent for this class of materials [1]. TIs are considered as an ideal base for spintronics, quantum computations and other applications [2,3]. Several quantum transport phenomena in 3D TI such as Shubnikov de Hass (SdH) oscillations, weak antilocalization (WAL), universal conductance fluctuation (UCF), Aharonov–Bohm, Atshuler–Aronov–Spivak and Aharonov–Casher effects have already been observed in nanowires, nanoribbons and thin films [4–10]. Other interesting phenomena are the nonsaturating and linear magnetoresistance as well as an anomalous behavior of Hall resistance detected in TIs [11–17]. It has been suggested [14,15] that linear-like MR response arises from the linear Dirac surface dispersion, which according to the quantum theory of linear MR (LMR) developed by Abrikosov should result in such a phenomenon [16]. Some studies have also suggested that a modified Hikami–Larkin–Nagaoka model of quantum phase coherence can describe the magnetic-field-dependent MR [17]. The anomalous Hall effect was previously discovered in the ferromagnetic conductors and is induced by the spin-dependent scattering of charge carriers [18]. The origin of nonlinear Hall resistance in TIs was attributed to the topological nature i.e. to the contribution of the surface states and results mainly from the anomalous Hall effect of Dirac theory [11,15].

In this paper we report on fabrication of single crystalline antimony telluride Sb_2Te_3 nanoflakes and study size-dependent magnetoresistance and Hall resistance in order to reveal contribution of the surface states. The Sb_2Te_3 compound is known as *p*-type thermoelectric semiconductor and recently it has been predicted and confirmed that the compound is three-dimensional (3D) topological insulator (TI) [19,20]. The multivalley valence band of Sb_2Te_3 consists of the upper valence band, UVB (light effective mass holes) and lower valence band, LVB (heavy effective mass holes) [21]. Taking into account that the observation of the effects related to contribution of the topological surface states requires decrease of the bulk response (reduced thickness), we

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http://dx.doi.org/10.1016/j.physb.2014.11.088
0921-4526/

have chosen two samples, differing greatly in thickness ("ultrathin" – 25 nm and "bulk" – 450 nm) for comparison.

2. Experimental results

Single crystalline Sb_2Te_3 nanoflakes of various thickness were grown by vapor phase deposition on SiO_2/Si substrate from stoichiometric polycrystalline Sb_2Te_3 source material. The detailed information is published elsewhere [10,22,23]. Two nanoflakes with the thickness 25 nm and 456 nm were selected for measurements. The Sb/Te atomic ratio defined by means of Energy Dispersive X-ray Spectroscope corresponds to $(41 \pm 1)/(59 \pm 1)$ which is the same for both samples. The leading wires of Au/Ni were fabricated using electron beam lithography. The samples selected for the measurements had symmetrically positioned Hall contacts.

Transport measurements were carried out by four-probe method in physical properties measurement system (PPMS) with magnetic fields up to 9 T at temperatures of 2 K and 300 K. The magnetoresistance was defined as $(100\%) \times (R_B - R_0)/R_0$, where $R_B = R(B)$ is the resistance in magnetic field and R_0 is the resistance without magnetic field. The probe current was directed in crystallographic *ab* plane and MR was investigated for transverse directions of the magnetic field induction vector **B**. The Hall voltage was taken as half the difference between two opposite directions of the induction vector **B.**

The temperature dependence of the resistance $R(T)$ of Sb_2Te_3 nanoflakes was measured in the temperature range from 2 K to 300 K. The results for normalized resistance $R(T)/R(300\text{ K})$ are illustrated in Fig. 1. The resistance of both samples is showing metallic behavior and the thicker the sample is, the stronger the temperature dependence is observed. Such a correlation with the size of the samples appears due to the increasing of the degree of disorder (i.e. increased scattering on boundaries and defects) with decreasing the thickness of the nanoflakes. This reflects the fact that reducing the size of the sample leads to an increase of the relative contribution from the surface of the nanoflake heavily occupied by defects. The defects in the Sb_2Te_3 compound consist of Sb vacancies and Sb_{Te} antisite defects which are responsible for the generation of holes and thus an increase in defects leads to an increase in the concentration of holes. The magnetic field dependences of the transverse resistance R_{xy} of our Sb_2Te_3 nanoflakes are depicted in Fig. 2. While the transverse resistance R_{xy} of 25 nm nanoflake is practically linear at both 2 K and 300 K temperatures the transverse resistance R_{xy} of 450 nm nanoflake is nonlinear and the sense of curvature of the $R_{xy}(B)$ line is inversed at 300 K. Based on the Hall resistance results we deduced the values of the mobility $\mu = R_H/\rho = 0.0145\ m^2/V;\ 0.0075\ m^2/V$ and number of charge carriers $p = 1/(R_H q) = 3 \times 10^{26}\ m^{-3};\ 2 \times 10^{26}\ m^{-3}$ correspondingly at 2 K and 300 K for 25 nm nanoflake, where $R_H = (R_{xy} d)/B$ is Hall coefficient, ρ is the resistivity of the sample and q is the elementary charge. The concentration of holes in 25 nm nanoflake exceeds the concentrations typically observed in the bulk Sb_2Te_3. Note that due to nonlinear behavior of $R_{xy}(B)$ there is no definite value of the mobility and the number of charge carriers for 450 nm sample and both parameters μ and p become dependent on the magnetic field.

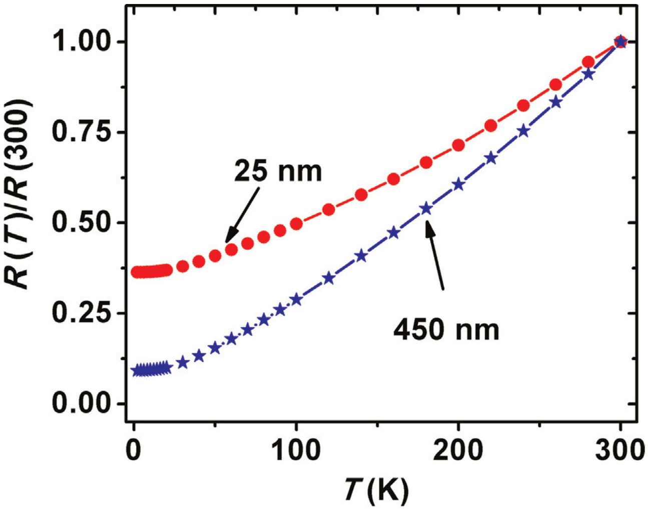

Fig. 1. The temperature dependences of normalized resistance $R(T)/R(300\text{ K})$ of Sb_2Te_3 nanoflakes.

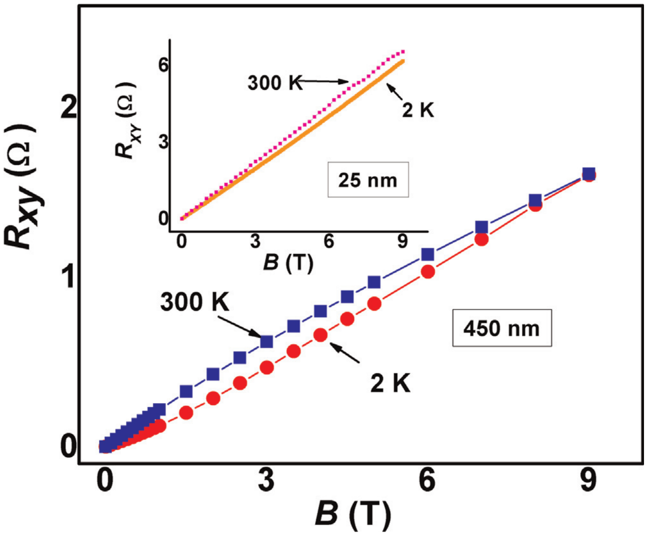

Fig. 2. The magnetic field dependence of the transverse resistance R_{xy} of Sb_2Te_3 nanoflakes.

Fig. 3 represents MR of both nanoflakes at 2 K and 300 K temperatures. While 25 nm sample demonstrates ordinary positive magnetoresistance (quadratic dependence $\sim(\mu B)^2$) throughout the range of applied magnetic fields and temperatures, the magnetoresistance of 450 nm sample is quadratic only at low fields < 1.5 T. In the high fields the longitudinal resistance $R_{xx}(B)$ of 450 nm sample behaves as $\sim B^{0.35}$ at 2 K and is linear $\sim B$ at 300 K (see Fig. 4). The sense of curvature of the $R_{xx}(B)$ line (as in the case

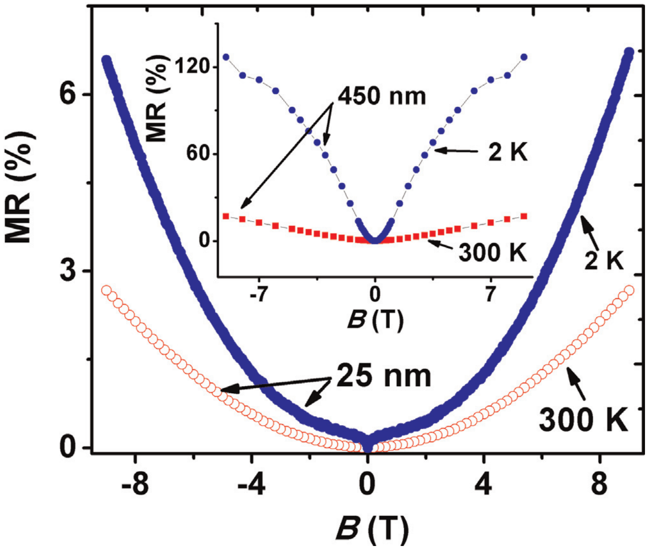

Fig. 3. The magnetoresistance of Sb_2Te_3 nanoflakes at 2 K and 300 K.