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SEMICONDUCTORS

The Charge Transport Mechanism in a New Magnetic Topological Insulator $MnBi_{0.5}Sb_{1.5}Te_4$

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Abstract—A new layered magnetic topological insulator with the composition $MnBi_{0.5}Sb_{1.5}Te_4$ is obtained. The electrical conductivity in the plane of the layers and in the direction normal to the layers is studied in the range of temperatures of 1.4–300 K. It is found that a "metallic" character of the temperature dependence of the resistivity $\rho(T)$ is observed in the range of temperatures of 50–300 K in both directions. Below $T = 50$ K, the value of ρ increases and demonstrates an uncommon temperature dependence with a characteristic feature in the region of the critical temperature $T_c = 23$ K. The increase in the resistance in the temperature range of 50–23 K is determined by the spin fluctuations and magnetic phase transition. Below T_c and down to 1.4 K, $\rho(T)$ demonstrates a behavior characteristic for the weak localization effect, which is confirmed by the analysis of the data obtained when studying magnetoresistance.

Keywords: topological insulators, resistivity, phase transitions, weak localization, magnetoresistance, layered crystals

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1. INTRODUCTION

A new surge of the interest in topological insulators has been recently observed in view of the discovery of magnetic topological insulators [1–5]. Topological insulators were for the first time theoretically predicted way back in 1980s [6]. Entire classes of topological insulators including three-dimensional (3D) topological phases of various compounds have been discovered by now [7–17].

As is known, the bulk of a material with a topological phase is an insulator, and the surface, a metal. The conductive properties of the surface result from the strong spin-orbital interaction and symmetry relative to the time reversal which lead to the appearance of spin-polarized topological surface states with the dispersion of the Dirac type, i.e., linear dependence of energy on momentum like in graphene. The practical interest in topological insulators is determined by the fact that the surface states are protected from back scattering on nonmagnetic impurities and defects by the symmetry of time reversal and, because of this, the charge carriers can move along the surface of the bulk material with no energy loss in these states. Therefore, the implementation of dissipationless charge transport is possible.

As opposed to the nonmagnetic analogues, magnetic topological insulators can have a gap in the Dirac cone, which makes it possible to observe a series of unique physical phenomena such as the quantum anomalous Hall (QAH) effect, magnetoelectric effect,

axion electrodynamics, and Majorana fermions [1, 18–21]. Magnetic topological insulators are also in demand in the new field of modern electronics—spintronics, mainly in the information transfer, recording, and storage means.

The first attempts to open a gap in the topological surface state were implemented by the doping of nonmagnetic topological insulators, e.g., of the Bi_2Te_3 type, with magnetic impurities of Mn, Cr, Fe, etc. [22–24]. However, the fundamental challenge of doping is the impossibility of uniform distribution of the doping impurities throughout the volume. This leads to the fact that the transport phenomena will be determined by the smallest of all the local gaps with a substantial decrease in the temperature of implementation of the above physical phenomena. Another possible way of achieving the formation of a gap in the Dirac cone is the formation of an ultrathin film of a two-dimensional ferromagnetic with the magnetic moment directed normally to the film on the surface of a nonmagnetic three-dimensional topological insulator. Some of the theoretically predicted systems [25–28] have been recently experimentally implemented by molecular beam epitaxy [26, 28]. Another class of materials, in which the split of the Dirac state occurs, is magnetically ordered topological insulators themselves. An antiferromagnetic topological insulator $MnBi_2Te_4$ has been recently proposed and experimentally implemented [2]. Photoemission measurements [2, 4] and infrared spectroscopy of the plasma edge of free carriers [29] showed that, in this compound, the Fermi level crosses the conduction band, i.e., lies above the bulk band gap.

Note that the practical observation of the dissipationless charge transport in topological insulators faces great difficulties. The matter is that, in topological insulators, in addition to the surface charge carriers, there are topologically unprotected bulk carriers at an even greater concentration which can predominate in the total charge transport mechanism. To decrease the contribution from the bulk charge carrier, it is necessary that Fermi level is in the band gap. Such an adjustment (tuning) of the position of the Fermi level can again be achieved either by doping or using solid solutions. In theory, the extreme members of the series of solid solutions $MnBi_{2-x}Sb_xTe_4$–$MnBi_2Te_4$ and $MnSb_2Te_4$ are antiferromagnetic topological insulators [2, 30, 31]. The antiferromagnetic topological state has been experimentally firmly established only for $MnBi_2Te_4$ [2]. The situation with $MnSb_2Te_4$ still remains unclear in view of the strong mixing of the atoms between the sublattices of Mn and Sb in the real samples of this compound. Based on the data of the Hall measurements and position of the Fermi level, the transition of conductivity from the *n*-type to the *p*-type in solid solutions $MnBi_{2-x}Sb_xTe_4$ with the increase in the fraction of antimony x occurs at $x > 0.6$ [32, 33].

This work reports the preparation and study of the electrical and galvanomagnetic properties of a solid solution of a magnetic topological insulator $MnBi_{0.5}Sb_{1.5}Te_4$.

2. EXPERIMENTAL

The production technology and characterization of the magnetic topological insulators of the $MnBi_2Te_4(Bi_2Te_3)_n$ family is described in detail in [34]. A layered compound $MnBi_{0.5}Sb_{1.5}Te_4$ crystallizes to a rhombohedral structure (the $R\text{-}3m$ space group) with the c axis normal to the plane of the layers. Figure 1 presents the X-ray diffraction pattern for a compound $MnBi_{0.5}Sb_{1.5}Te_4$. The determined lattice parameter in the direction of the c axis is about 41 Å.

The electrical and galvanomagnetic (the Hall effect, magnetoresistance) effects in the layered crystals of $MnBi_{0.5}Sb_{1.5}Te_4$ were studied by a standard four-probe method according to a selective procedure on the alternating current with a frequency of 20.5 Hz using Lock-in Amplifier-SR830. The value of the current did not exceed 1 mA. The studies were performed in a wide range of temperatures of 1.4–300 K. Strong magnetic fields of up to 80 kOe were obtained using a superconducting solenoid. During the galvanometric measurements, the sample was placed into the center of the solenoid.

The anisotropy of electrical conductivity in the layered crystals of $MnBi_{0.5}Sb_{1.5}Te_4$ was studied by an improved combined four-probe Montgomery method [35] suitable for the samples prepared in the form of thin plates with small sizes. It is easy to obtain such plates from layered materials by their natural cleaving in the plane parallel to the layers. Four contacts are pairwise applied onto the opposite surfaces of the sample under study in the rectangular geometry.

Figure 2 presents the temperature dependences of the resistivity in the plane of the layers ($\rho_\parallel$) and in the

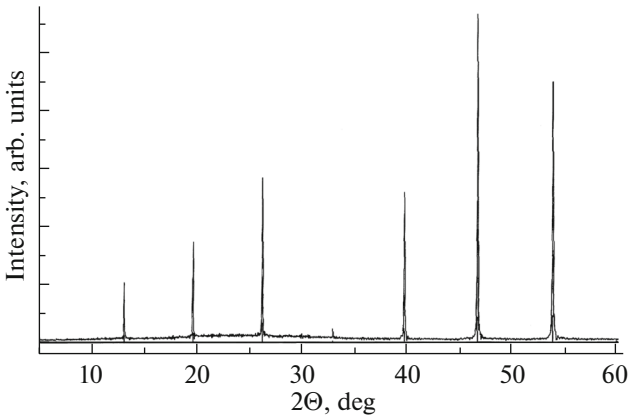

Fig. 1. X-ray diffraction pattern of a compound $MnBi_{0.5}Sb_{1.5}Te_4$.

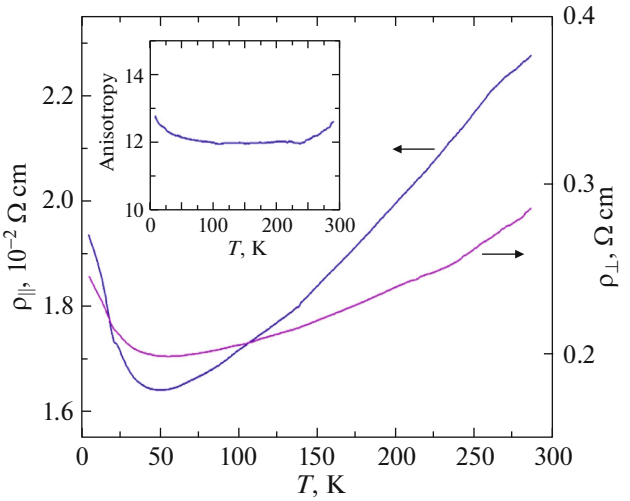

Fig. 2. Temperature dependences of the resistivity of a compound $MnBi_{0.5}Sb_{1.5}Te_4$ in the plane of the layers ($\rho_\parallel$) and in the direction normal to the layers ($\rho_\perp$). The inset: the temperature dependence of the anisotropy of electrical conductivity $\rho_\perp/\rho_\parallel$.

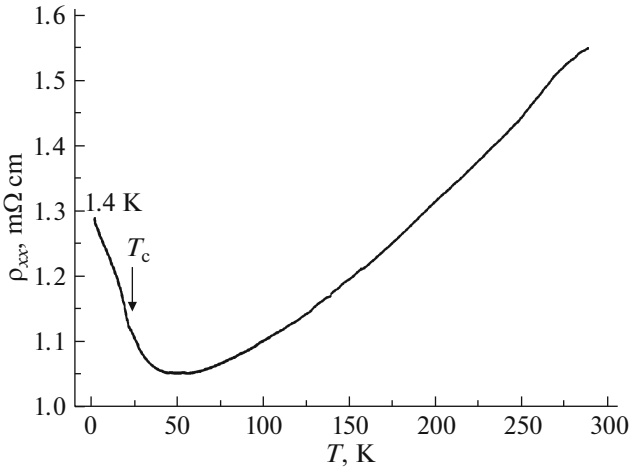

Fig. 3. Temperature dependence of the resistivity $\rho_{xx}(T)$ of a compound $MnBi_{0.5}Sb_{1.5}Te_4$ in a wide region of temperatures of 1.4–300 K.

direction normal to the layers ($\rho_\perp$) of a compound $MnBi_{0.5}Sb_{1.5}Te_4$ in a wide region of temperatures of 1.5–300 K. The inset presents the temperature dependence of the anisotropy of electrical conductivity $\rho_\perp/\rho_\parallel$. As is seen, the anisotropy of electrical conductivity slightly changes with temperature, which evidences the same mechanism of charge transport in the plane of the layers and in the direction normal to the layers.

For a more detailed analysis, let us address the electrical conductivity in the plane of the layers in a different configuration of the contacts which also makes it possible to study the Hall effect. Figure 3 presents the temperature dependence of the resistivity $\rho_{xx}(T)$ of a compound $MnBi_{0.5}Sb_{1.5}Te_4$ in a wide region of temperatures of 1.4–300 K.

As is seen from Fig. 3, the temperature dependence of the resistivity $\rho_{xx}(T)$ in the region of temperatures of 50–300 K has a characteristic "metallic" behavior, thus, the value of the resistivity decreases with the decrease in temperature. Such a temperature dependence is also characteristic for a classic semiconductor Bi_2Te_3 [36]. The above is determined by the fact that the presence of a significant number of intrinsic point structural defects, so-called antisite defects and substitutional defects, is already initially characteristic for these crystals upon the synthesis from a melt with a stoichiometric composition. Because of this, the grown single crystals of $MnBi_{0.5}Sb_{1.5}Te_4$ have a significant concentration of the charge carriers. According to the studies of the Hall effect, a compound $MnBi_{0.5}Sb_{1.5}Te_4$ is a *p*-type semiconductor with the hole concentration in this sample of 1.7×10^{21} cm^{-3}. Such a high concentration of the impurities forms a significant number of local states in the band gap which form a wide impurity band that overlaps with the intrinsic band of a pure crystal. Because of this, a typical "metallic" behavior of the temperature dependence of resistivity is observed upon studying the electrical conductivity of the single crystals of $MnBi_{0.5}Sb_{1.5}Te_4$.

Further, below $T = 50$ K, the value of the resistivity increases, and the dependence $\rho(T)$ demonstrates a kink at a critical temperature $T_c \sim 23$ K (Fig. 3). This kink is determined by a magnetic phase transition. In a compound $MnBi_2Te_4$, the paramagnetic–antiferromagnetic phase transition occurs at $T = 25.4$ K [2], while in $MnSb_2Te_4$, the magnetic phase transition occurs at $T = 19$ K [32].

As the temperature further decreases, the value of the resistivity continues increasing as a result of localization of the charge carriers at low temperatures, which is characteristic for "contaminated metals" [37], to which solid solutions $MnBi_{0.5}Sb_{1.5}Te_4$ possibly belong. The localization of the charge carriers (holes in this case) is determined by the interference of the amplitudes of the trajectories with the self-crossing upon the carrier scattering on the impurities and structural defects (a so-called quantum interference additive to conductivity or weak localization). In an applied external magnetic field, the coherence of the scattering amplitudes is violated, and the resistance decreases, i.e., negative magnetoresistance is observed (Fig. 4).

It should be noted that the resistance drops from a value of 1.25 mΩ cm down to 1.05 mΩ cm (Fig. 4) at 5 K already in weak magnetic fields with the intensity H of up to 5 kOe, which correlates with the increase in the resistance (Fig. 3). This gives the evidence of the

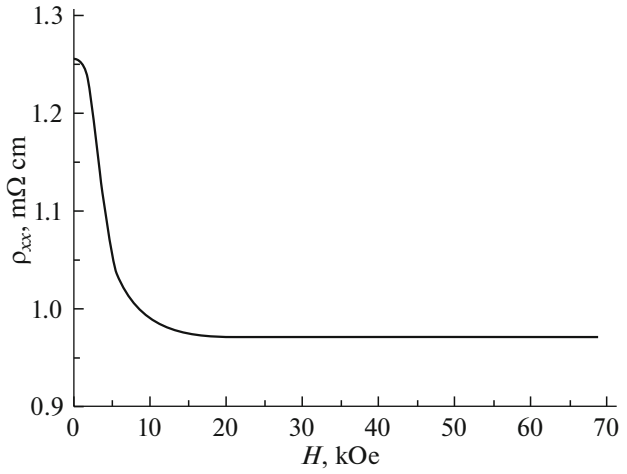

Fig. 4. Dependence of the resistivity ρ_{xx} of $MnBi_{0.5}Sb_{1.5}Te_4$ on the external magnetic field H at $T = 5$ K.

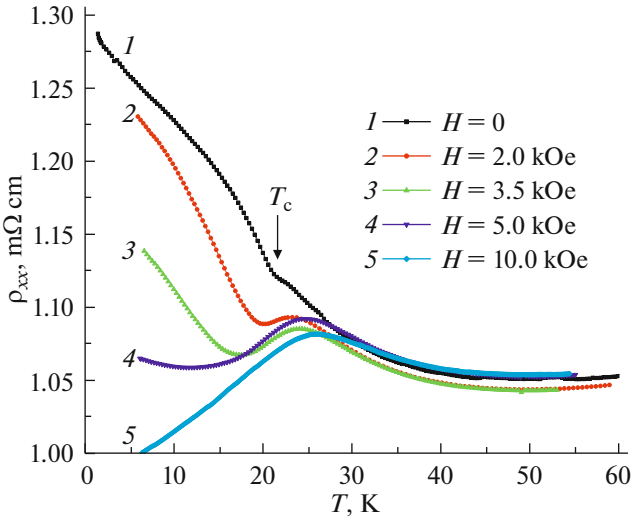

Fig. 5. Temperature dependence of the resistivity ρ_{xx} in $MnBi_{0.5}Sb_{1.5}Te_4$ at the external magnetic fields with the intensity $0 \le H \le 10$ kOe.

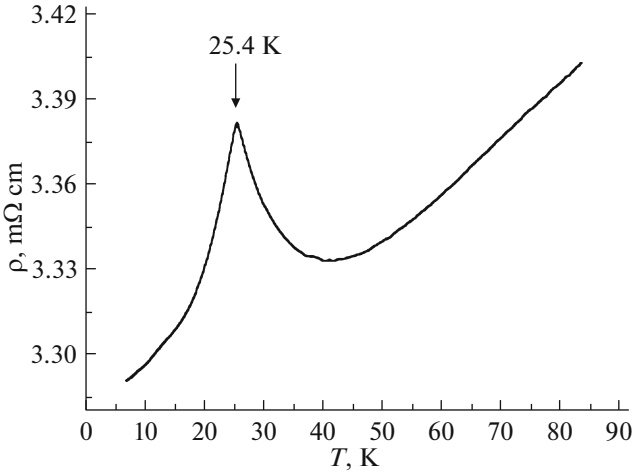

Fig. 6. Temperature dependence of the resistivity ρ of $MnBi_2Te_4$ [2].

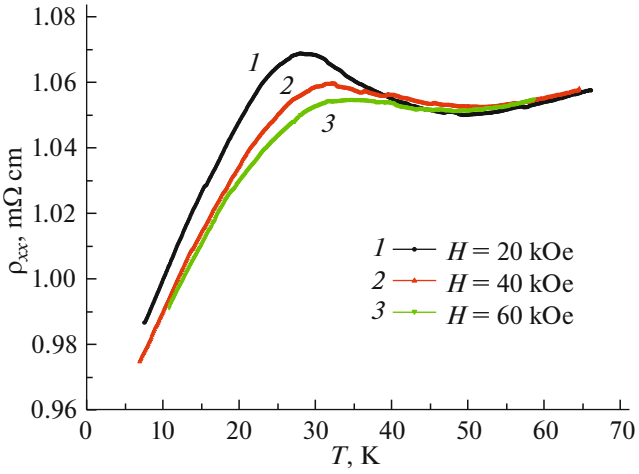

Fig. 7. Temperature dependence of the resistivity ρ_{xx} in $MnBi_{0.5}Sb_{1.5}Te_4$ at the external magnetic fields with the intensity $20 \le H \le 60$ kOe.

fact that, in this case, we observe a weak localization effect.

The effect of different-in-value external magnetic fields $H \le 10$ kOe on the temperature dependence of resistivity $\rho_{xx}(T)$ is presented in Fig. 5. As is seen from Fig. 5, the increase in the resistance induced by the localization gradually disappears with the increase in the value of the applied magnetic field (from 0 up to 10 kOe), and a peak is clearly seen in $\rho_{xx}(T)$ which is determined by the magnetic phase transition. A similar peak in the dependence $\rho_{xx}(T)$ determined by the magnetic paramagnetic–antiferromagnetic phase transition was also observed by us in the single crystals of $MnBi_2Te_4$ [2] (Fig. 6). The appearance of the peak is determined by the charge carrier scattering on the spin fluctuations upon the magnetic phase transition.

As is seen from Fig. 5, the applied field $H = 5$ kOe almost removes the increase in the resistance induced by the weak localization, which is an additional confirmation of the observation of the weak localization effect.

Comparing Figs. 5 and 6 shows that the peak in the dependence $\rho_{xx}(T)$ in $MnBi_{0.5}Sb_{1.5}Te_4$ is more diffuse when compared to $MnBi_2Te_4$. This is determined by the fact that there are more defects in the solid solution $MnBi_{0.5}Sb_{1.5}Te_4$, which leads to the diffusion of the phase transition temperature.

Further increase in the values of the external magnetic fields (from 20 up to 60 kOe) leads to a gradual decrease in the peak in the dependence $\rho_{xx}(T)$ (Fig. 7), which gives the evidence of the magnetic origin of this characteristic feature. It should however be noted that a quite strong magnetic field $H = 60$ kOe does not fully liquidate the peak in the dependence $\rho_{xx}(T)$ in the solid solution $MnBi_{0.5}Sb_{1.5}Te_4$, which indicates a quite strong exchange interaction.

3. CONCLUSIONS

We have obtained and characterized new magnetic topological insulators of a solid solution $MnBi_{0.5}Sb_{1.5}Te_4$. The same charge transport mechanism in the plane of the layers and in the direction normal to the layers has been found from the studies of the anisotropy of electrical conductivity in a wide region of temperatures of 1.4–300 K. It has been found that a "metallic" character of the temperature dependence of resistivity is observed in the range of temperatures of 50–300 K. Below $T = 50$ K, the value of the resistivity increases, and the dependence $\rho(T)$ demonstrates a kink at a critical temperature $T_c = 23$ K. The increase in the resistance in this temperature range is determined by the spin fluctuations and occurring magnetic phase transition. Below 23 K, the increase in the resistance is determined by the weak localization effect, which is indicated by the data of the studies of the effect of an external magnetic field on the electrical conductivity.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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