ELECTRON TRANSPORT, TRANSVERSE AND LONGITUDINAL MAGNETORESISTANCE, AND SHUBNIKOV–DE HAAS OSCILLATIONS IN $Bi_{0.83}Sb_{0.17}$ TOPOLOGICAL INSULATOR SEMICONDUCTOR WIRES

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Abstract

The paper describes results of experimental studies of the dependence of the resistance, transverse and longitudinal magnetoresistance, as well as the Shubnikov–de Haas (SdH) oscillations of $Bi_{0.83}Sb_{0.17}$ semiconductor single-crystal wires with diameters of (75–1100) nm, as a function of the thickness, in a temperature range of (3.1–300) K at magnetic fields of up to 14 T. The wires were prepared by liquid-phase casting. It has been found that the temperature dependences of the resistance of wires with $d < 0.5$ μm have two regions exhibiting a semiconductor and a metallic behavior of the resistance, the two regions being separated by a maximum, which is shifted to the high-temperature region with a decrease in the wire diameter d. It has been revealed that the energy gap ΔE increases by a factor of 2 with a decrease in wire diameter d, due to the occurrence of the quantum size effect. The "metallic" behavior of conductivity is attributed to surface states characteristic of topological insulators, which is most clearly evident in thin wires at temperatures of $T < 50$ K. It has been shown that, in the presence of a uniform magnetic field H, the field dependences of the longitudinal and transverse magnetoresistance in quasi-one-dimensional systems can undergo a significant change depending on the ratio of quantum wire radius to the magnetic length $R = (ch/eH)^{1/2}$, as well as on the decrease in the mean free path of carriers due to scattering on the wire surface. The SdH oscillation periods exhibit anomalies that are typical neither to bulk $Bi_{1-x}Sb_x$ samples nor to semimetallic wires based on $Bi_{1-x}Sb_x$ alloys. This fact points to the essential role of surface states of topological insulators in 1D-systems, which lead to the occurrence of new effects that are not characteristic of other systems.

Keywords: semiconductor nanowires, topological insulator, size effects, Shubnikov–de Haas oscillations, magnetoresistance

Rezumat

În lucrare sunt prezentate rezultatele studiilor experimentale ale dependențelor de grosime ale rezistenței, magnetoresistenței transversale și longitudinale, oscilațiile Shubnikov de Haas ale firelor monocristaline semiconductoare $Bi_{0.83}Sb_{0,17}$, obținute prin turnarea din fază lichidă cu diametre de (75-1100) nm în intervalul de temperaturi (3,1-300) K și câmpuri magnetice de până la 14T. S-a constatat, că dependențele de temperatură ale rezistenței firelor cu diametrul d < 0,5 µm au 2 zone (una cu comportament semiconductor și alta cu comportament metalic al rezistenței), ele fiind separate de un maximum, care se deplasează spre zona temperaturilor ridicate cu micșorarea diametrului firelor d. S-a stabilit, că gapul energetic ΔE crește de 2 ori odată cu micșorarea diametrului firelor d, ca urmare a apariției efectului de confinare cuantică, iar comportamentul „metalic" al conductivității se datorează stărilor de suprafață caracteristice pentru izolatorii topologici, care se manifestă cel mai clar în firele subțiri la temperaturi de T < 50K. Se arată, că dependențele de câmp ale magnetoresistenței longitudinale și transversale în sistemele cvasi-unidimensionale în prezența unui câmp magnetic uniform H se pot schimba semnificativ în funcție de raportul dintre raza firului cuantic către lungimea magnetică $R=(ch/eH)^{1/2}$, precum și de micșorarea parcursului liber al purtătorilor datorită împrăștierii pe suprafața firului. Perioadele oscilațiilor ShdH au anomalii, care nu sunt tipice atât pentru mostrele masive de $Bi_{1-x}Sb_x$, cât și pentru firele semimetalice pe bază de aliaje $Bi_{1-x}Sb_x$, ceea ce indică rolul semnificativ al stărilor de suprafață în izolatorii topologici în sistemele-1D, care conduc la noi efecte și nu sunt caracteristice altor sisteme.

Cuvinte cheie: nanofire semiconductoare, izolator topologic, efecte de confinare dimensională, oscilații Shubnikov–de Haas, magnetorezistență.

1. Introduction

$Bi_{1-x}Sb_x$ alloys are a unique material, interest in which has not faded for decades; in recent years, due to the discovery of a topological phase in condensed media [1–3], interest in semiconductor alloys has increased. A topological insulator (TI) is an insulator that is characterized by the presence of a metallic state on the surface. The conductive properties of the surface are a consequence of the spin–orbit interaction, which leads to the appearance of spin-split topological surface states with Dirac-type dispersion, i.e., a linear dependence of energy on momentum $E = hkv_F$. Surface states inside a bulk band gap with a linear dispersion law have been first observed for $Bi_{1-x}Sb_x$ semiconductor alloys using angle-resolved photoelectron spectroscopy [4]. In recent years, a large number of studies on TIs, in particular, $Bi_{1-x}Sb_x$ semiconductor alloys, have been reported [5, 6]. Most of the studies have been focused on bulk samples. $Bi_{1-x}Sb_x$ alloys are narrow-gap semiconductors with a smooth transition from the semimetallic to semiconductor state [7] and a maximum energy gap of ΔE = 21 meV near 17–18 at % Sb. A schematic rearrangement of the energy spectrum of $Bi_{1-x}Sb_x$ alloys is shown in Fig. 1.

Of particular interest are studies of the properties of TIs for objects, in which the band gap ΔE can be changed due to the quantum size effect [8–10], while changing the film thickness or the wire diameter, rather than due to a variation in the alloy composition.

These studies require single-crystal samples having different diameters and a certain crystallographic orientation. A significant change in the band gap ΔE occurs for diameters

$d < 0.5$ μm.

This paper describes studies of the magnetotransport properties of $Bi_{0.83}Sb_{0.17}$ single-crystal wires prepared by liquid-phase casting in a temperature range of 3.1–300 K at magnetic fields of up to 14 T. In these wires having different diameters, on the one hand, the size quantization effect takes place and, on the other hand, the presence of TI surface states leads to significant features of the temperature dependences of the resistance, longitudinal (LMR) and transverse magnetoresistance (TMR), their angular dependences, and Shubnikov–de Haas (SdH) oscillations.

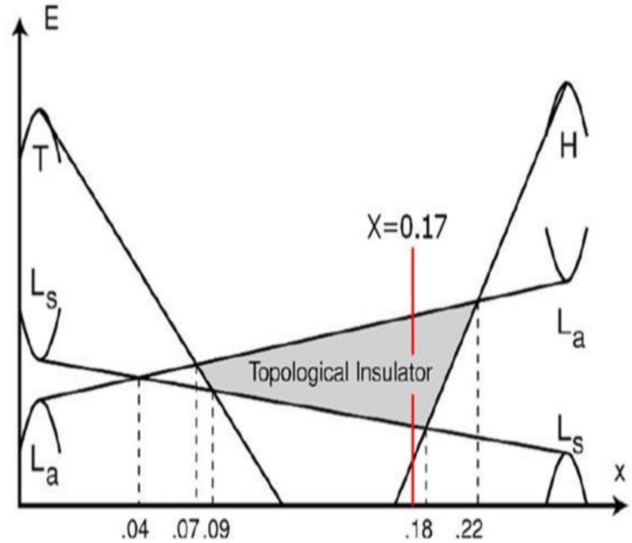

Fig. 1. Schematic rearrangement of the band structure of $Bi_{1-x}Sb_x$ as a function of x ($0 \le x \le 0.25$) at 4.2 K. The arrow shows the composition of the studied wires.

2. Experimental

Glass-insulated $Bi_{0.83}Sb_{0.17}$ wires with a thickness of 75 nm to 1 μm were prepared by liquid-phase casting in accordance with the Ulitovsky method [12–14]. Studies on a scanning electron microscope showed that the samples had a strictly cylindrical shape. The monocrystallinity and crystallographic orientation of the wires were determined using X-ray rotation diffraction patterns. Both pure Bi wires and Bi–17at%Sb wires of all studied diameters had the (1011) orientation along the wire axis (Fig. 2a) [12–14].

The C_1 bisector axis is deviated by an angle of 19° from the wire axis, while the C_2 binary axis is strictly perpendicular to the wire axis (Fig. 2), as confirmed by the rotation diagrams of TMR in a magnetic field of 14 T at 4.2 K.

The measurements were conducted by the two-probe method. The solder was the InGa eutectic; at 300 K, it is in a liquid state and readily wets the wire edges to provide the ohmicity of the contacts. Figure 3 shows a glass-insulated wire on a substrate with InGa contacts at the edges. The ohmicity of contacts at 300 and 4.2 K was controlled by measuring the current–voltage characteristics. The resistivity of the wires of all studied diameters (75–1100 nm) at 300 K was 135×10^{-6} Ω cm within the measurement error.

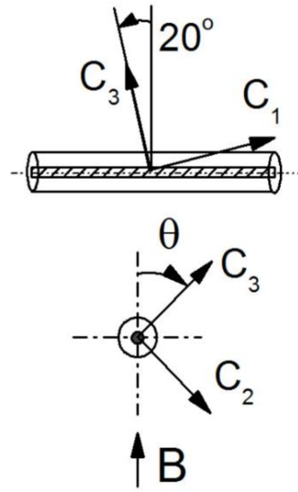

Fig. 2. (a) Schematic representation of a glass-insulated wire and the direction of the crystallographic axes with respect to the wire axis and (b) the direction of rotation of the magnetic field in a plane perpendicular to the wire axis.

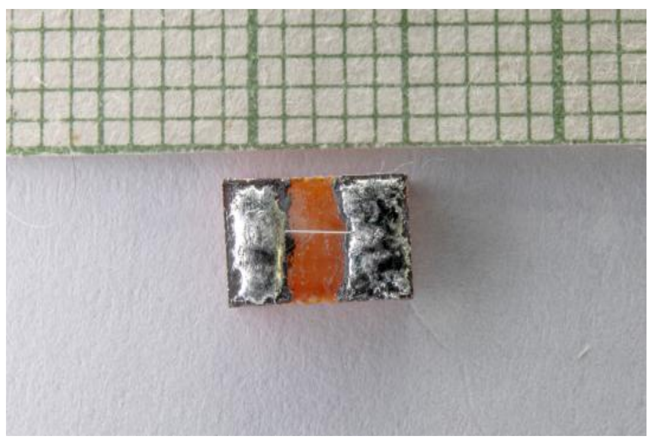

Fig. 3. A glass-insulated $Bi_{0.83}Sb_{0.17}$ wire on a substrate with two InGa eutectic contacts.

The rotation diagrams of TMR and magnetic field dependences in perpendicular ($H \perp I$) and parallel magnetic fields were studied in the field of a superconducting solenoid in magnetic fields of up to 14 T at temperatures of 4.2–300 K using a special rotary device. The device made it possible to rotate the sample in a magnetic field in different planes with respect to the wire axis, while adjusting the angle of deviation from the wire axis in certain crystallographic directions.

The rotation diagrams of TMR are identical for wires of all the diameters and coincide with the respective rotation diagrams of the TMR of bulk samples [5, 6], being different only in quantitative values; this fact confirms the same crystallographic orientation of the wires of all the studied diameters. The MR anisotropy increases with an increase in wire diameter *d*. Measurements in strong magnetic fields (up to 14 T) in a temperature range of 1.3–300 K were conducted in a superconducting solenoid. The MR of $dR/dH(H)$ derivatives of SdH oscillations in magnetic fields of up to 14 T were studied at the International Laboratory of High Magnetic Fields and Low Temperatures (Wroclaw, Poland).

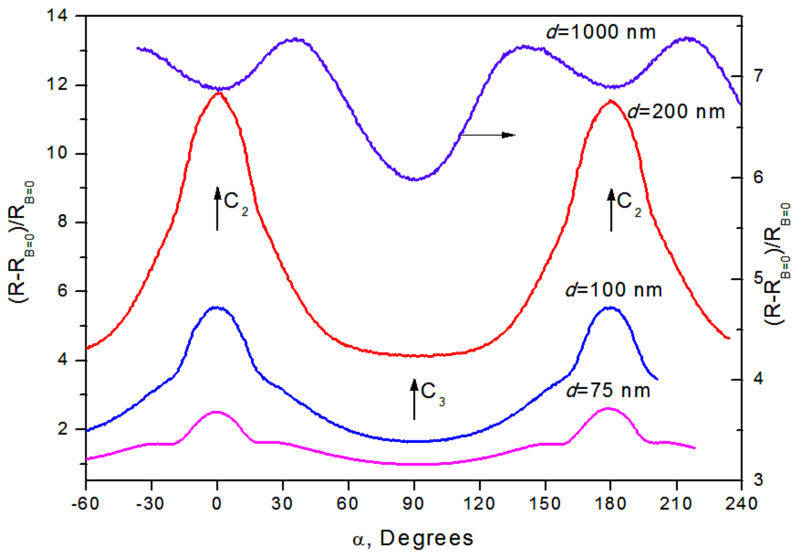

Fig. 4. Rotation diagrams of the TMR $\Delta R/R_0(\alpha)$ at $T = 1.5$ K and $H = 14$ T for $Bi_{0.83}Sb_{0.17}$ wires with the different diameters.

3. Results and Discussion

Temperature dependences of the relative resistance $R_T/R_{300}(T)$ of wires with the different diameters in a temperature range of 4.2–300 K are shown in Fig. 5. Unlike the case of pure Bi wires [11, 12], the resistance of the wires at 4.2 K increased with an increase in diameter d. The $R_{4.2}/R_{300}(d^{-1})$ dependence is linear; it exhibits two slopes and an inflection point at $d = 350$–400 nm (inset in Fig. 5).

With a decrease in temperature from 300 to 80 K, the resistance increased with a decrease in wire diameter d. Thus, the following two regions are clearly observed in the temperature dependences of the resistance of the wires with $d < 500$ nm: (i) 300–80 K with a semiconductor behavior of $R(T)$, where the resistance increases with a decrease in d, and (ii) 70–4.2 K, where the resistance decreases with a decrease in wire diameter d and exhibits a "metallic" behavior of conductivity $R(T)$. The regions are separated by a maximum in $R(T)$ (Fig. 6a). The position of the maximum R_{max} linearly depends on wire diameter d (insert in Fig. 6a).

In a temperature range of 40–300 K, the $R_T/R_{300}(T)$ dependences have exponential portions with $\rho_T = \rho_0 * \exp(\Delta E/2k_0T)$ dependences, the slope of which increases with a decrease in wire diameter d. The ΔE value calculated for wires with the different diameters is shown in Fig. 6b. For the wires with $d = 1000$ nm, $\Delta E = 21$ meV, which is consistent with the values obtained for bulk $Bi_{1-x}Sb_x$ samples of an identical composition. With a decrease in the wire diameter, the ΔE value increases in accordance with the following law: $\Delta E \sim 1/d$; for the wires with $d = 75$ nm, it is 45 meV, i.e., two times higher than that in bulk samples and in the wires with $d = 1100$ nm.

The $\Delta E \sim 1/d$ dependence suggests that the increase in the energy gap ΔE is attributed to the quantum size effect [8], which is observed in both pure Bi wires and semimetallic $Bi_{1-x}Sb_x$ wires [11–13].

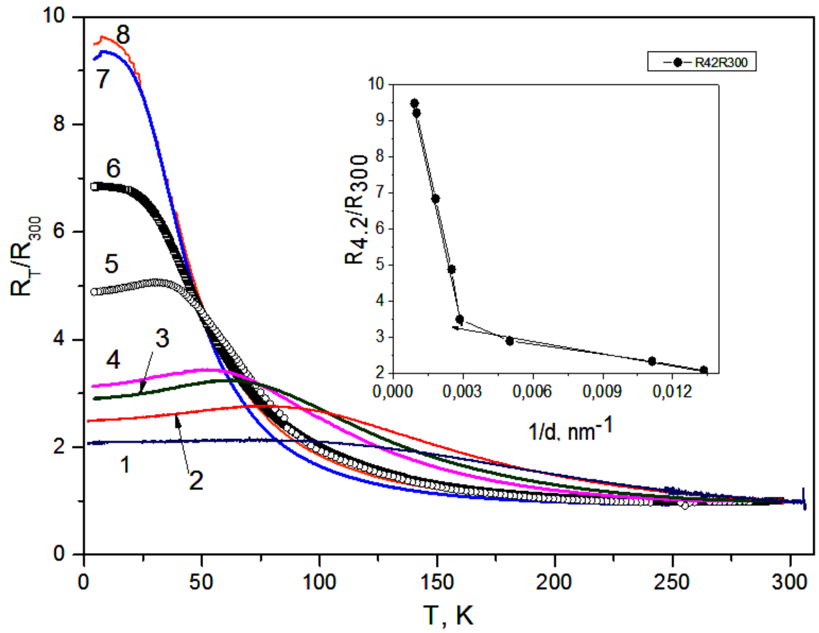

Fig. 5. Temperature dependences of relative resistance $R_T/R_{300}(T)$ for Bi–17at%Sb wires with the different diameters: d = (*1*) 75, (*2*) 100, (*3*) 200, (*4*) 350, (*5*) 450, (*6*) 550, (*7*) 900, and (*8*) 1100 nm.

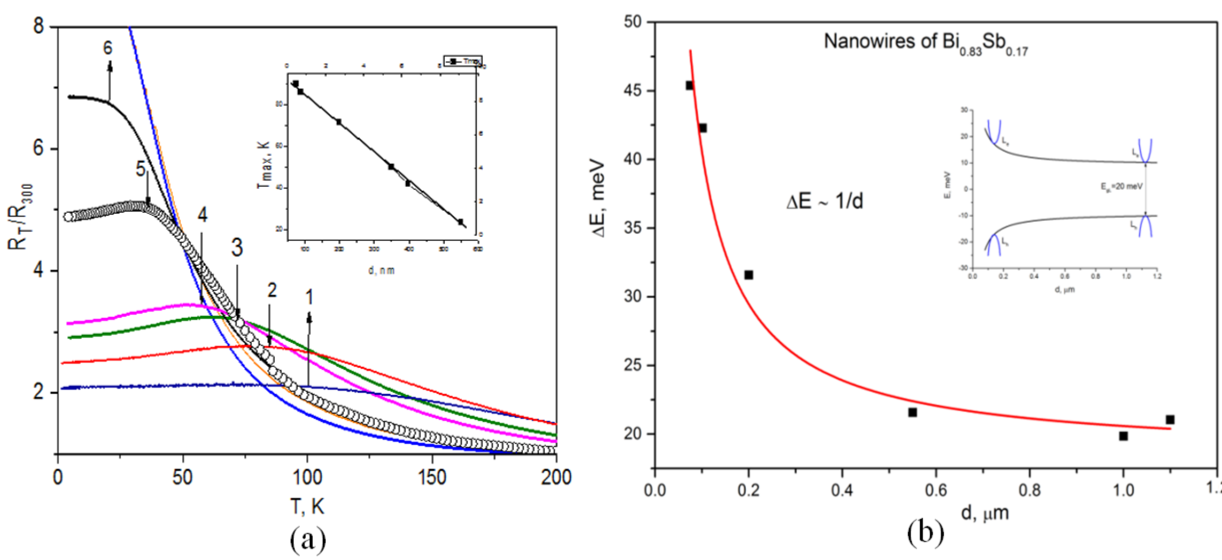

Fig. 6. Temperature dependences of relative resistance $R_T/R_{300}(T)$ in a temperature range of 50–300 K for Bi–17at%Sb wires with the different diameters: d = (*1*) 75, (*2*) 100, (*3*) 200, (*4*) 350, (*5*) 450, (*6*) 550, (*7*) 900, and (*8*) 1100 nm (vertical arrows indicate the position of maxima T_{max} in $R_T/R_{300}(T)$). Inset: (a) the dependence of the T_{max} value in the $R_T/R_{300}(T)$ temperature dependence and (b) the dependence of energy gap ΔE on wire diameter d calculated from the $R(T) = \exp(\Delta E/2K\,T)$ dependence.

At temperatures of $T < T_{max}$, the $R(T)$ dependence of the wires with $d < 0.5$ μm undergoes a significant change, namely, a transition from the semiconductor to metallic behavior, which represents the effect of surface states characteristic of TIs. The result is an overall increase in resistance $R_{4.2}/R_{300}(d)$ with an increase in d, which is associated with a decrease in the role of surface states in the wires with an increase in wire diameter d.

4. Magnetoresistance

The LMR ($H \parallel I$) and TMR ($H \perp I$) of Bi–17at%Sb wires with the different diameters were studied at $H \parallel C_3$ and $H \parallel C_2$ in magnetic fields of up to 14 T at temperatures of $T = 4.2$ K. Figure 7 shows dependences of the LMR of wires with the different diameters.

As in the case of pure Bi wires, $R_H/R_0(H)$ has a maximum followed by a region of negative MR. The H_{max} value is linearly shifted to the region of stronger magnetic fields with a decrease in wire diameter d; this fact indicates the occurrence of a galvanomagnetic size effect [15].

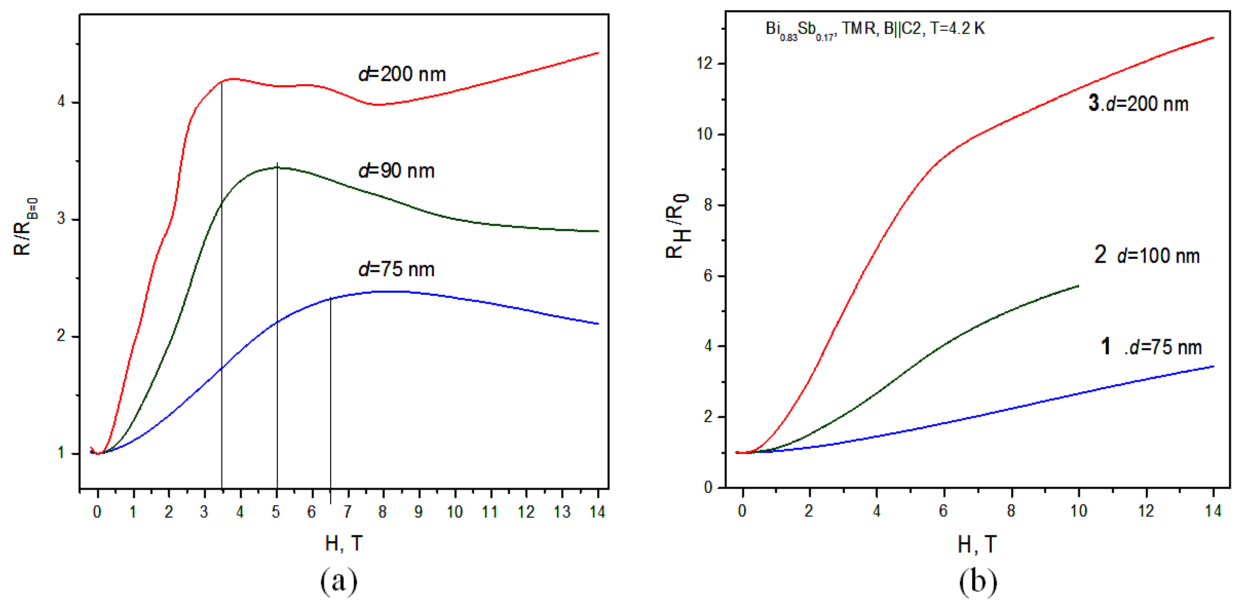

Fig. 7. Field dependences of (a) LMR ($H \parallel I$) and (b) TMR ($H \perp I$ and $H \parallel C_2$) $R_H/R_0(H)$ at 4.2 K for wires with the different diameters.

According to the galvanomagnetic size effect, $H_{max} = D_{max}\ c/ed$, where D_{max} is the maximum diameter of the extreme cross section of the Fermi surface. For pure Bi wires, $D_{max} = 2.2 \times 10^{-21}$ (T cm)/s is the maximum diameter of the extreme cross section of the Fermi surface at point L for two electron ellipsoids localized symmetrically with respect to the bisector–trigonal plane containing the wire axis. For the $Bi_{0.83}Sb_{0.17}$ semiconductor wires described in this paper, $D_{max} = 8.9 \times 10^{-21}$ (T cm/s), which is four times higher than the D_{max} value in pure bismuth and two times higher than that in Bi–8at%Sb wires [16]; this fact is apparently attributed to the presence of cross sections of the Fermi surface of surface states.

In a transverse magnetic field $H \parallel C_2$ (Fig. 7b), the MR of the wires increases with an increase in diameter d in the entire magnetic field range; for the wire with $d = 200$ nm at $H = 14$ T, it is four times higher than the value for the wire with $d = 75$ nm; this fact is associated with the occurrence of the classical size effect [16].

Figure 8a shows dependences of the relative MR $R_H/R_0(H)$; dependences of the $dR/dH(H)$ derivative for the $Bi_{0.83}Sb_{0.17}$ wire with d = 200 nm at 4.2 K are shown in Fig. 8b.

In weak magnetic fields (H < 2 T), the LMR exceeds the TMR (inset in Fig. 8a); in a magnetic field of 14 T, at $H \parallel C_2$ binary axis, the TMR is four times higher than the LMR.

The $R_H/R_0(H)$ MR derivatives exhibit SdH oscillations, the amplitude of which increases with an increase in magnetic field H. To determine the SdH oscillation period, dependences of the quantum number of SdH oscillations $n(H^{-1})$ were plotted for three directions of the magnetic field (inset in Fig. 8b).

In magnetic fields of H < 1.5 T, SdH oscillations are observed at $H \parallel C_1$ (LMR) and $H \parallel C_3$ with maximum SdH periods of $\Delta_3(H^{-1})$ = 0.5 and 1 T^{-1}, respectively. In magnetic fields of H > 4 T, the calculated SdH oscillation periods for three directions of the magnetic field are minimal; they are $\Delta_1(H^{-1})$ = 0.05 T^{-1} for both $H \parallel C_1$ (LMR) and $H \parallel C_3$. Thus, the maximum SdH oscillation frequency F =1/Δ was 18–20 T for both $H \parallel C_2$ and $H \parallel C_3$ in magnetic fields of H > 3 T. The minimum period $\Delta_1(H^{-1})$ = 0.014 T^{-1} was observed at $H \parallel C_2$ in stronger magnetic fields (H > 3 T).

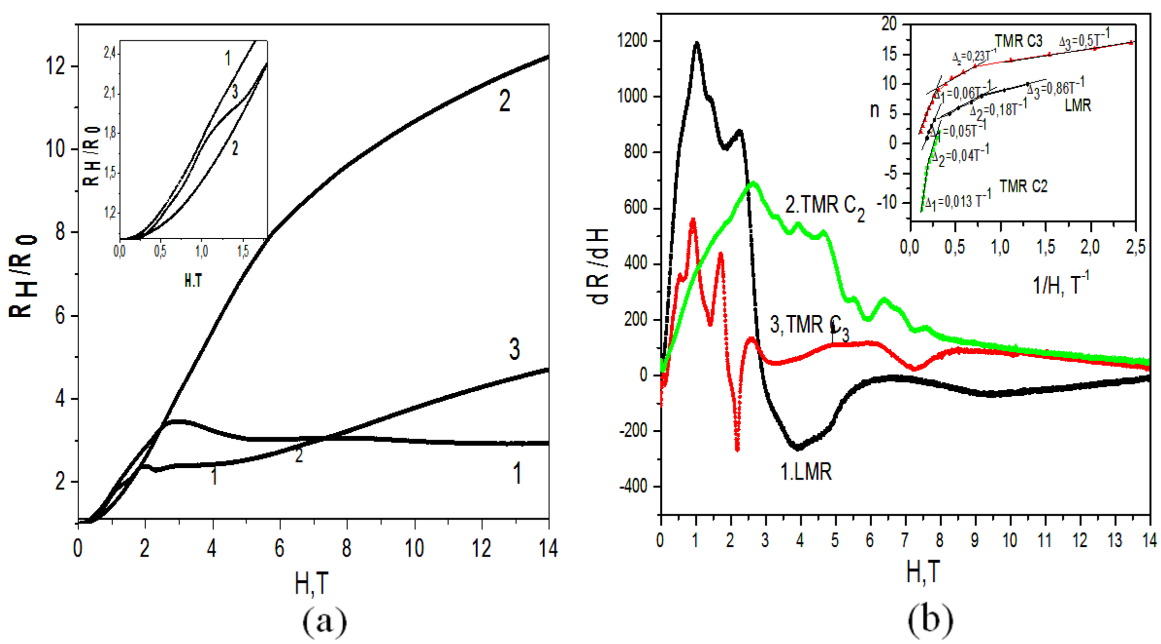

Fig. 8. (a) Field dependences of the LMR (H ∥ I) and TMR (H⊥I) $R_H/R_0(H)$ for a Bi–17at%Sb wire with d = 200 nm at 4.2 K: (1) H ∥ I, (2) H⊥I, H ∥ C_2, and (3) H ∥ C_3; the inset shows the initial portion of the curves up to 2 T; (b) dR/dH(H) derivatives of curves (1)–(3); the inset shows the dependence of quantum number n of SdH oscillations on H^{-1}.

Comparison of the SdH oscillation periods with respective values obtained for bulk $Bi_{0.91}Sb_{0.09}$ samples [5, 6] shows a significant difference in the periods for all directions of the magnetic field. The (H^{-1}) < 0.5 T^{-1} values in bulk samples were obtained only at $H \parallel C_3$ (±30°); the maximum values of the periods of Δ = 1.7 and 1.5 T^{-1} were observed at $H \parallel C_2$ and $H \parallel C_3$, respectively. This significant difference in the SdH oscillation frequencies can be attributed to the specific features of the manifestation of surface states in low-dimensional 1D TI structures, which lead to the appearance of new cross sections of the Fermi surface, an unambiguous interpretation of which requires further studies, in particular, those on the angular dependences of SdH oscillations and on SdH oscillations for wires with large diameters.

5. Conclusions

A comprehensive study of the thickness dependences of resistance, TMR, LMR, and SdH oscillations in $Bi_{0.83}Sb_{0.17}$ single-crystal semiconductor wires with diameters of 75–1000 nm has shown the following: the occurrence of the quantum size effect, that is, an increase in the energy gap with a decrease in wire diameter d ($\Delta E \sim 1/d$); the presence of surface states, that is, a metallic behavior of the temperature dependence of the resistance at low temperatures in thin wires; the occurrence of the classical size effect, that is, a negative LMR, a maximum in the LMR exhibiting a linear dependence on wire diameter d, and a decrease in the TMR with a decrease in the wire diameter. The considerable difference of the SdH oscillation periods from the values observed for bulk samples suggests that the surface states of TIs in low-dimensional 1D-structures play a significant role and lead to the occurrence of new effects that are not typical of bulk samples and require further studies for an unambiguous interpretation.

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