Transport Properties of a Topological Insulator Based on $Bi_{0.83}Sb_{0.17}$ Nanowires

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Abstract — **We have investigated the transport properties of topological insulator based on single-crystal $Bi_{0.83}Sb_{0.17}$ nanowires. The single-crystal nanowire samples in the diameter range 200 nm – 1.1 µm were prepared by the high frequency liquid phase casting in a glass capillary using an improved Ulitovsky technique; they were cylindrical single-crystals with ($10\underline{1}1$) orientation along the wire axis. In this orientation, the wire axis makes an angle of 19.5° with the bisector axis C_1 in the bisector-trigonal plane. $Bi_{0.83}Sb_{0.17}$ is a narrow gap semiconductor with energy gap at L point of Brillouin zone ΔE= 21 meV. In accordance with the measurements of the temperature dependence of the resistivity of the samples resistance increases with decreasing temperature, but at low temperatures decrease in the resistance is observed. This effect, decrease in the resistance, is a clear manifestation of the interesting properties of topological insulators - the presence on its surface of a highly conducting zone. The Arrhenius plot of R in samples d=1.1 µm and d=200 nm indicates a thermal activation behavior with an activation gap ΔE= 21 and 40 meV, respectively, which proves the presence of the quantum size effect in these samples. We found that in the range of diameter 1100 nm - 200 nm when the diameter decreases the energy gap is growing exponentially. We have investigated magnetoresistance of $Bi_{0.83}Sb_{0.17}$ nanowires at various magnetic field orientations. From the temperature dependences of Shubnikov de Haas oscillation amplitude for different orientation of magnetic field we have calculated the cyclotron mass m_c and Dingle temperature T_D for longitudinal and transverse (B||C3 and B||C2) directions of magnetic fields, which equal $1.96 \cdot 10^{-2}$ m_0, 9.8 K, $8.5 \cdot 10^{-3}$ m_0 , 9.4 K and $1.5 \cdot 10^{-1}$ m_0 , 2.8 K respectively. The observed effect are discussed.**

Index Terms — **topological insulator, Bi-Sb, nanowires, quantum size effect, quantum oscillations.**

I. INTRODUCTION

A topological insulator is a material with a bulk electronic excitation gap generated by the spin-orbit interaction, which is topologically distinct from an ordinary insulator. This distinction, characterized by a *Z2* topological invariant, necessitates the existence of gapless electronic states on the sample boundary. In two dimensions, the topological insulator is a quantum spin Hall insulator, which is a close cousin of the integer quantum Hall state. The strong topological insulator is predicted to have surface states whose Fermi surface encloses an odd number of Dirac points and is associated with a Berry's phase of π. This defines a topological metal surface phase, which is predicted to have novel electronic properties. The first topological insulator to be discovered was the alloy $Bi_{1-x}Sb_x$, the unusual surface bands of which were mapped in an angle-resolved photoemission spectroscopy (ARPES) experiment [1,2]. The semiconducting alloy $Bi_{1-x}Sb_x$ is a strong topological insulator due to the inversion symmetry of bulk crystalline Bi and Sb.

Bismuth-Antimony alloys ($Bi_{1-x}Sb_x$) constitute a materials system that has been attracting considerable attention in recent decades. This class of materials is considered to be one of the best materials candidates for thermoelectrics and refrigeration in the cryogenic temperature range. Bismuth is a semimetal with strong spin–orbit interactions, which have an indirect negative gap between the valence band at the T-point of the bulk Brillouin zone and the conduction band at L-points [3,4] Substituting bismuth with antimony change the critical energies of the band structure (see Fig. 1). At an Sb concentration of x=0.04, the gap ΔE between La and Ls closes and a massless, three-dimensional (3D) Dirac point is realized. As x is further increased this gap re-opens with inverted symmetry ordering, which leads to a change in sign of ΔE at L-point in the Brillouin zone. For concentrations greater than x=0.07 there is no overlap between the valence band at T and the conduction band at L, and the material becomes an inverted-band insulator. Once the band at T drops below the valence band at L, at x=0.09, the system evolves into a direct-gap insulator whose low-energy physics is dominated by the spin–orbit coupled Dirac particles at L. [5] In the first Brillouin zone of bulk $Bi_{1-x}Sb_x$, there are one T point, three L points and six H points, as shown in Fig. 2.

The unusual metallic surfaces of these topological insulators may result in new spintronic or magnetoelectric devices. Furthermore, in combination with superconductors, topological insulators could lead to a new architecture for topological quantum bits.

In the present paper we report measurements of

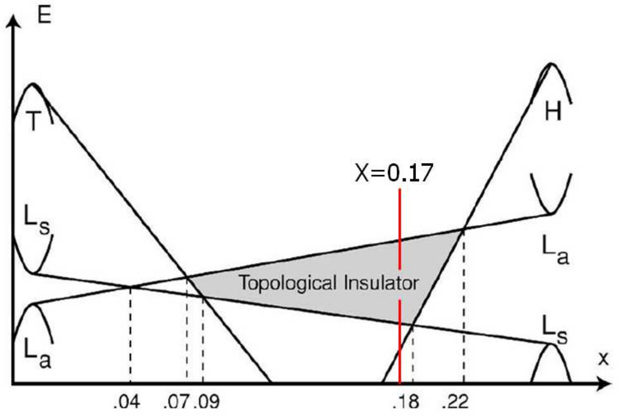

Fig. 1. Schematic representation of band energy evolution of $Bi_{1-x}Sb_x$ as function of x.

temperature dependences of resistance as well as magnetic field dependences of magnetoresistance of topological insulator $Bi_{0.83}Sb_{0.17}$ nanowires in glass coating.

II. SAMPLES AND EXPERIMENT

Individual $Bi_{0.83}Sb_{0.17}$ nanowires were fabricated using the Ulitovsky technique (see schematic diagram at inset on Fig. 3.), by which a high-frequency induction coil melts a $Bi_{0.83}Sb_{0.17}$ boule within a borosilicate glass (Pyrex) capsule, simultaneously softening the glass. Glass capillaries containing $Bi_{0.83}Sb_{0.17}$ filament [6] were produced by drawing material from the glass. The nanowire samples in the diameter range 200 nm – 1.1 µm were cylindrical single-crystals with (10$\underline{1}$1) orientation along the wire axis. In this orientation, the wire axis makes an angle of 19.5° with the bisector axis C_1 in the bisector-trigonal plane (see Fig. 2). Bulk Bi–Sb crystals are difficult to grow successfully and require special techniques to avoid constitutional supercooling and the resulting segregation. However, in the Ulitovsky technique due to the high frequency stirring and high speed crystallization (> 10^5 K/s) is possible to obtain homogeneous monocrystalline $Bi_{0.83}Sb_{0.17}$ nanowires. Encapsulation of the $Bi_{0.83}Sb_{0.17}$ filament in glass protects it from oxidation and mechanical stress. Scanning electron microscope cross sections of the 1.0 µm $Bi_{0.83}Sb_{0.17}$ wire in its glass coating is shown in Fig. 3.

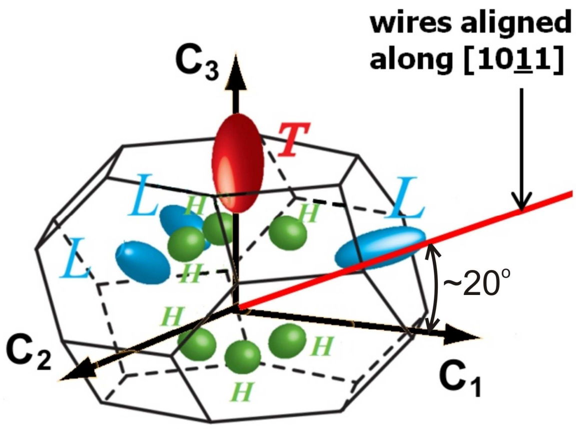

Fig. 2. The Brillouin zone of Bi-Sb, showing the Fermi surface of the three electron pockets at the L-points, one T-point hole pocket and the six hole pockets at the H-points. The orientation of the (10$\underline{1}$1) wires is also indicated.

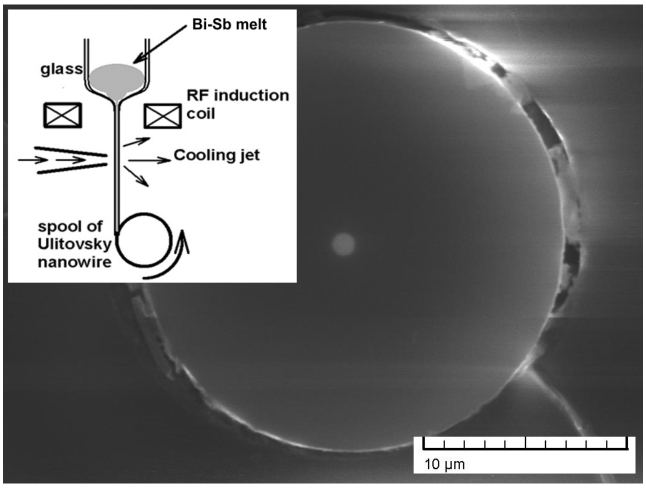

Fig. 3. Scanning electron microscope cross sections of the 1.0 µm $Bi_{0.83}Sb_{0.17}$ wire in its glass coating. The inset illustrates the Ulitovsky method for synthesizing long, small-diameter wires in a glass fiber.

The samples for the measurements were cut from long wires and were from 3 mm down to 1 mm in length and were mounted on special foil-clad fiber-glass plastic holders. Electrical contact to the copper foil was made with In-Ga eutectic. This type of solder consistently makes good contacts, as compared to other low-melting-point solders.

The temperature dependence of the resistance measured in a helium cryostat using a Cernox thermometer.

Magnetic field-dependent resistance *R(B)* measurements in the 0 to 14 T range were carried out at the International High Magnetic Field and Low Temperatures Laboratory (Wroclaw, Poland), and we employed a device that tilts the sample axis with respect to the magnetic field and also rotates the sample around its axis. Shubnikov-de Haas oscillations measured using the technique of magnetic field

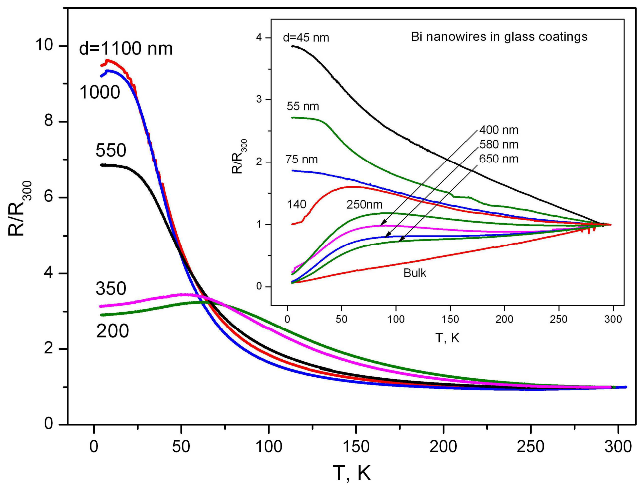

Fig. 4. Temperature dependences of the relative resistance for $Bi_{0.83}Sb_{0.17}$ nanowires. Insert: Temperature dependences of the relative resistance for Bi nanowires.

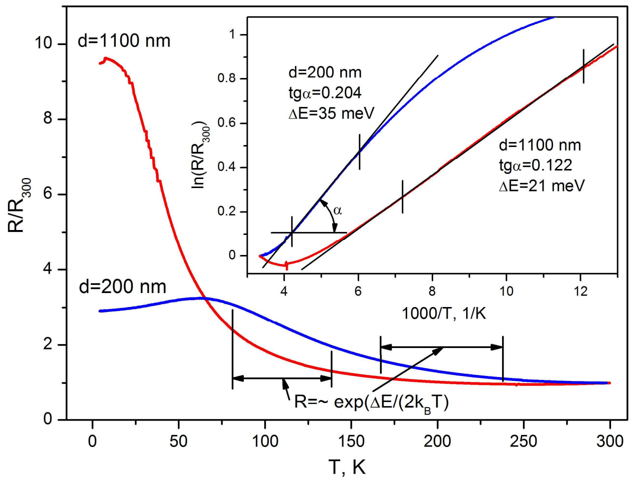

Fig. 5. Temperature dependencies of the relative resistance for 1100 nm and 200 nm $Bi_{0.83}Sb_{0.17}$ nanowires. The temperature ranges, within which the law of resistance exponential growth is valid, are also shown. Insert: The Arrhenius plot of R/R_{300} in 1100 nm and 200 nm $Bi_{0.83}Sb_{0.17}$ nanowires indicates a thermal activation behavior with an activation gap ΔE= 21 and 35 meV, respectively.

modulation with amplitude of 75 Oe that allowed us to register amplitude of the oscillations directly at the lock-in amplifier output.

III. RESULTS AND DISCUSSION

Quantum confinement effects in semimetal Bi nanowires, which decrease the effective band overlap energy, E_0, become relevant for quantum wires with the diameter $d \approx 2\hbar\sqrt{2m^{*}E_0}$, where m^{*} is the effective mass transverse to the wire axis. Detailed calculations [7] show that a semimetal-to-semiconductor transition occurs for $d \approx$ 55 nm for wires oriented along the trigonal direction. Insert in Fig. 4 presents the temperature dependence of relative resistance R/R_{300} for Bi nanowires with d varied from 650 nm down to 45 nm. The temperature dependence of the resistance of a bulk sample is also presented. According to the semimetal-to-semiconductor transformation, the *R(T)* dependences exhibit a “semiconductor” behavior. Quantum confinement effect in semiconducting $Bi_{0.83}Sb_{0.17}$ nanowires increases the energy gap ΔE and thus increases the resistance. However, at low temperature conductivity of the topological surface states reduces the resistance. The greater the relative amount of surface states volume with decreasing nanowires diameter, the stronger the effect of reducing resistance. Temperature dependencies of the relative resistance R/R_{300} for 1100 nm and 200 nm $Bi_{0.83}Sb_{0.17}$ nanowires are shown in Fig. 5. The temperature ranges, within which the law of resistance exponential growth ($R=\sim exp(\Delta E/(2k_BT)$)) is valid, are also shown. The Arrhenius plot (see the insert) of R/R_{300} in 1100 nm and 200 nm $Bi_{0.83}Sb_{0.17}$ nanowires indicates a thermal activation behavior with an activation gap ΔE= 21 and 35 meV, respectively. With decreasing diameter of the nanowires, shift the temperature range of exponential growth of resistance into a higher temperature region (see Fig. 5 and insert in Fig. 6) can be explained as follows: firstly, an increase in the energy gap increases the effective temperature of energy spectrum smearing; secondly, with decreasing nanowires diameter increases relative volume of high-conductive surface region and reducing the resistance of the nanowire will be noticeable at higher temperature. Fig. 6 shows dependence of energy gap ΔE on $Bi_{0.83}Sb_{0.17}$ nanowires diameter. At least in the region of diameter 1100 - 200 nm it is well approximated by the equation of the exponential energy gap growth with decreasing nanowires diameter $\Delta E \sim exp(-d)$.

Tashkin and Ando in their work [8], investigating the Shubnikov de Haas (ShdH) and de Haas–van Alphen oscillations in high-quality bulk crystal of a topological insulator $Bi_{0.91}Sb_{0.09}$, discovered the existence on the crystal surface of the two-dimensional Fermi surface. This 2D

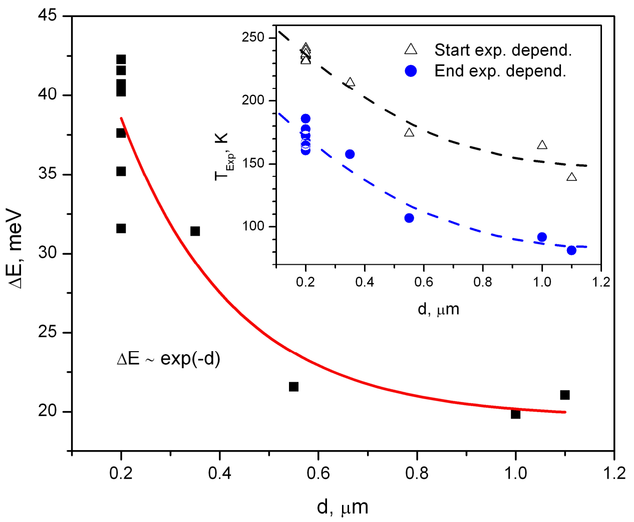

Fig. 6. Dependence of energy gap ΔE on $Bi_{0.83}Sb_{0.17}$ nanowires diameter. Insert shows the temperature ranges, depending on the nanowires diameter, within which the resistance increases exponentially.

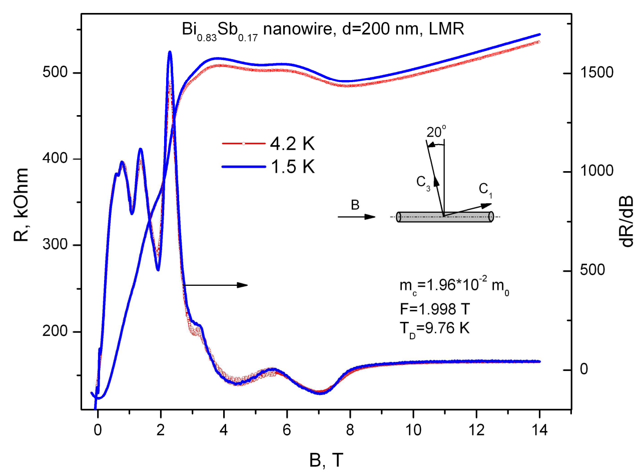

Fig. 7. Magnetic field dependence of the longitudinal magnetoresistance for 200 nm $Bi_{0.83}Sb_{0.17}$ nanowire, T = 4.2 and 1.5 K.

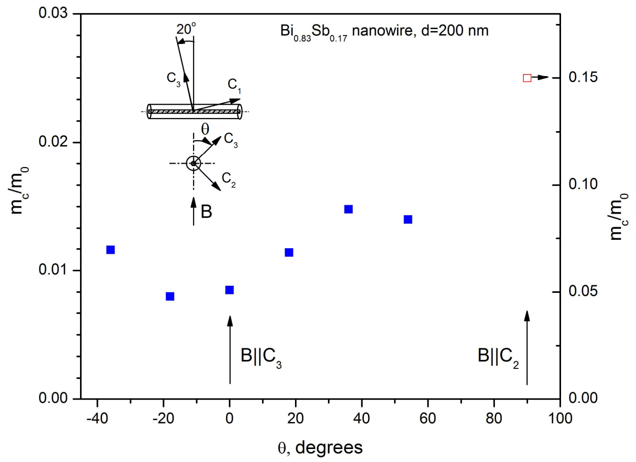

Fig. 8. Angular dependence of cyclotron mass m_c of carriers obtained from Shubnikov de Haas oscillations for

Fermi surface lies in the bisectix plane (perpendicular to the C_1 axis). Two prominent features are readily recognized: first, the absolute value of m_c in the magnetic field perpendicular to the surface is extremely small, measuring only $0.0057m_0$, which is smaller than the cyclotron mass in pure Bi for any direction. Second, $m_c(\theta)$ diverges at θ =0° and shows the 1/sinθ dependence, that is, characteristic of a 2D Fermi surface, giving unambiguous evidence for the 2D nature. We were interested to verify whether there is such a two-dimensional surface carriers in our 200 nm nanowire of topological insulator $Bi_{0.83}Sb_{0.17}$. In our nanowires C_1 axis is inclined from the nanowires axis by ~20 degrees, which assumes carrying out the investigation of longitudinal magnetoresistance. Magnetic field dependence of the longitudinal magnetoresistance (LMR) for 200 nm $Bi_{0.83}Sb_{0.17}$ nanowire at T = 4.2 and 1.5 K are shown in Fig. 7. From the temperature dependence of ShdH oscillation amplitude we have calculated the cyclotron mass m_c = 1.96*10^{-2} m_0, which was 3.5 times higher than in the Tashkin and Ando work [8]. From the dependence of the ShdH oscillation amplitude on the longitudinal magnetic field the Dingle temperature T_D=9.8 K was determined.

We have measured transverse magnetoresistance (TMR) when B□I. And in this case Shubnikov de Haas oscillations at various orientation of magnetic field were observed. Cyclotron mass for various direction of transverse magnetic field were calculated. Fig. 8 shows angular dependence of cyclotron mass m_c of carriers for 200 nm $Bi_{0.83}Sb_{0.17}$ nanowire. For $B||C_3$ and $B||C_2$ directions of magnetic fields, the cyclotron masses and Dingle temperatures equal 8.5*10^{-3} m_0, 9.4 K, and 1.5*10^{-1} m_0, 2.8 K respectively. Cyclotron mass along the C_3 axis is less than the cyclotron mass along the C_1 axis in 2.2 times, which was not observed in [8].

Unfortunately, in 200 nm $Bi_{0.83}Sb_{0.17}$ nanowire with $(10\underline{1}1)$ orientation along the wire axis we cannot confirm the presence of a surface 2D Fermi surface, possibly due to the fact that in this crystallographic orientation of nanowire core the C_1 axis intersects nanowires surface at a small angle (~20^o). For observation and use of the unique properties of 2D surface carriers the $Bi_{0.83}Sb_{0.17}$ nanowires with trigonal orientation, i.e. when the C_3 axis is located along the nanowires axis, and the C_1 axis perpendicular to the surface of the nanowire, are required.

IV. CONCLUSION

We have investigated temperature dependences of resistance of topological insulator $Bi_{0.83}Sb_{0.17}$ nanowires with diameter 200 nm < d < 1100 nm, obtained by radio frequency casting in glass capillary. Due to quantum size effect, the energy gap ΔE increases with decreasing diameter of the nanowires. The Arrhenius plot of R in samples with various diameter indicates a thermal activation behavior with an activation gap ΔE= 20 and 35 meV for d= 1100 nm and 200 nm, respectively. Surface states manifest itself as decreasing resistivity at low temperatures. The energy gap ΔE with decreasing diameter of the nanowires d from 1100 nm down to 200 nm increases exponentially $\Delta E\sim exp(-d)$. From the temperature dependences of Shubnikov de Haas oscillation amplitude for different orientation of magnetic field we have calculated the cyclotron mass m_c for longitudinal and transverse ($B||C_3$ and $B||C_2$) directions of magnetic fields, which equal 1.96*10^{-2} m_0, 8.5*10^{-3} m_0 and 1.5*10^{-1} m_0 respectively. We have determined the Dingle temperature for these directions of magnetic field, T_D=9.8 K for LMR, 9.4 K and 2.8 K for TMR. The occurrence in thin $Bi_{0.83}Sb_{0.17}$ nanowires with $(10\underline{1}1)$ orientation along the wire axis a two-dimensional surface Fermi surface lying in the bisectrix plane (perpendicular to the C_1 axis) has not been confirmed. For observation and use of the unique properties of 2D surface carriers the $Bi_{0.83}Sb_{0.17}$ nanowires with trigonal orientation, i.e. when the C_3 axis is located along the nanowires axis, and the C_1 axis perpendicular to the surface of the nanowire, are required.

ACKNOWLEDGMENTS

This work was supported by ASM grant 13.820.05.12/BF and US National Science Foundation PREM.

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