Quantum Interference and Surface States Effects in Topological Insulator $Bi_{0.83}Sb_{0.17}$ Nanowires

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***Abstract* — We investigate the transport properties of topological insulator (TI) $Bi_{0.83}Sb_{0.17}$ nanowires. Single-crystal nanowire samples with diameters ranging from 75 nm to 1.1 µm are prepared using high frequency liquid phase casting in a glass capillary; cylindrical single crystals with (10$\underline{1}$1) orientation along the wire axis are produced. $Bi_{0.83}Sb_{0.17}$ is a narrow-gap semiconductor with an energy gap at the L point of the Brillouin zone, ΔE = 21 meV. The resistance of the samples increases with decreasing temperature, but a decrease in resistance is observed at low temperatures. This effect is a clear manifestation of TI properties (i.e., the presence of a highly conducting zone on the TI surface). We investigate the magnetoresistance of $Bi_{0.83}Sb_{0.17}$ nanowires at various magnetic field orientations. Shubnikov-de Haas oscillations are observed in $Bi_{0.83}Sb_{0.17}$ nanowires at T = 1.5 K, demonstrating the existence of high mobility (μ_S = 26700 - 47000 $cm^2V^{-1}s^{-1}$) two-dimensional (2D) carriers in the surface areas of the nanowires, which are nearly perpendicular to the C_3 axis. From the linear dependence of the nanowire conductance on nanowire diameter at T = 4.2 K, the square resistance R_{sq} of the surface states of the nanowires is obtained (R_{sq} = 70 Ohm). The oscillations of longitudinal magnetoresistance (MR) of 75 and 100-nm $Bi_{0.83}Sb_{0.17}$ nanowires with two periods ΔB_1 and ΔB_2 proportional to Φ_0 and $\Phi_0/2$ were observed, where $\Phi_0 = h/e$ is the flux quantum. A derivative of MR was measured at various inclined angles. In the range 0 – 60 degrees of inclined angle of magnetic field, the observed angle variation of the periods is in agreement with the theoretical dependence $\Delta B(\alpha) = \Delta B(0)/\cos\alpha$ of the flux quantization oscillations. However, the equidistant oscillations of MR exist in transverse magnetic fields under certain rotation angles. The observed effects are discussed.**

***Index Terms* — topological insulator, Bi-Sb, nanowires, quantum oscillations, Aharonov-Bohm oscillations.**

I. INTRODUCTION

A topological insulator (TI) is a material with non-trivial topological order that behaves as an insulator in its interior but whose surface contains conducting states, meaning that electrons can only move along the surface of the material. TI is a material with a bulk electronic excitation gap generated by the spin-orbit interaction. This distinction, characterized by a Z_2 topological invariant, necessitates the existence of gapless electronic states on the sample boundary. In two dimensions (2D), the TI is a quantum spin Hall insulator. A strong TI is expected to have surface states whose Fermi surfaces enclose an odd number of Dirac points. This defines a topological metal surface phase that is predicted to have novel electronic properties. The first TI 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 TI owing to the inversion symmetry of bulk crystalline Bi and Sb. In recent decades, considerable attention has been paid to bismuth-antimony alloys ($Bi_{1-x}Sb_x$) of various compositions. This class of materials is considered to be one of the best candidates for thermoelectric application in the cryogenic temperature range. Bismuth is a semimetal with strong spin-orbit interactions, which has an indirect negative gap between the valence band at the T point of the bulk Brillouin zone and the conduction band at the L points [3,4]. Substituting bismuth with antimony changes the critical energies of the band structure (see Fig. 1a). At an Sb concentration of x = 0.04, the gap ΔE between L_a and L_s closes, and the massless, three-dimensional (3D) Dirac point is created. At concentrations greater than x = 0.09, the system develops into a direct-gap insulator, the low-energy physics of which is dominated by the spin-orbit coupled Dirac particles at L [5]. Here we study nanowires with x = 0.17, that in the bulk, are semiconductors with an L-point gap of 21 meV. The unusual metallic surfaces of these TIs may result in the development of new spintronic or magnetoelectric devices. Furthermore, in combination with superconductors, TIs could lead to a new architecture for topological quantum bits. It is well known that quantum interference effects are present in superconducting devices and in very small pure metallic rings and cylinders. In particular, in the presence of magnetic flux, Aharonov-Bohm (AB) oscillations [6] may occur in doubly connected systems. For a normal metal, the period of these oscillations is $\Phi_0 = h/e$ (the flux quantum). Such effects should vanish once the elastic mean free path of the electrons is smaller than the system size. For the disordered cylindrical samples with short mean free path (compared with the circumference of the cylinder) the AB oscillations with period proportional to $h/2e$ was predicted by Altshuler, Aronov, and Spivak (AAS) [7]. AB and AAS oscillations have been observed in various conducting rings, tubes, solid cylinders that consist of tubes, such as multiwall carbon nanotubes (MWNTs), and Bi nanowires [8-11].

In the present paper, we report measurements of the temperature dependence of resistance as well as those of magnetic field dependence of the magnetoresistance of TI $Bi_{0.83}Sb_{0.17}$ 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 in inset of Fig. 1b). This technique involves a high-frequency induction coil melting of a $Bi_{0.83}Sb_{0.17}$ boule within a borosilicate glass (Pyrex) capsule in an argon atmosphere, simultaneously softening the glass. Glass capillaries, each containing a $Bi_{0.83}Sb_{0.17}$ filament [12], were produced by drawing material from the glass. Nanowire samples with diameters ranging from 75 nm to 1.1 µm were prepared. The nanowires are 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. Because bulk Bi-Sb crystals are difficult to grow successfully, special techniques must be employed to avoid constitutional supercooling and the resulting segregation. With the Ulitovsky technique - owing to the high frequency stirring and high speed crystallization (>10^5 K/s) involved - it 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. A scanning electron microscope image of a cross-section of the 1.0-µm $Bi_{0.83}Sb_{0.17}$ wire in its glass coating is shown in Fig. 1b.

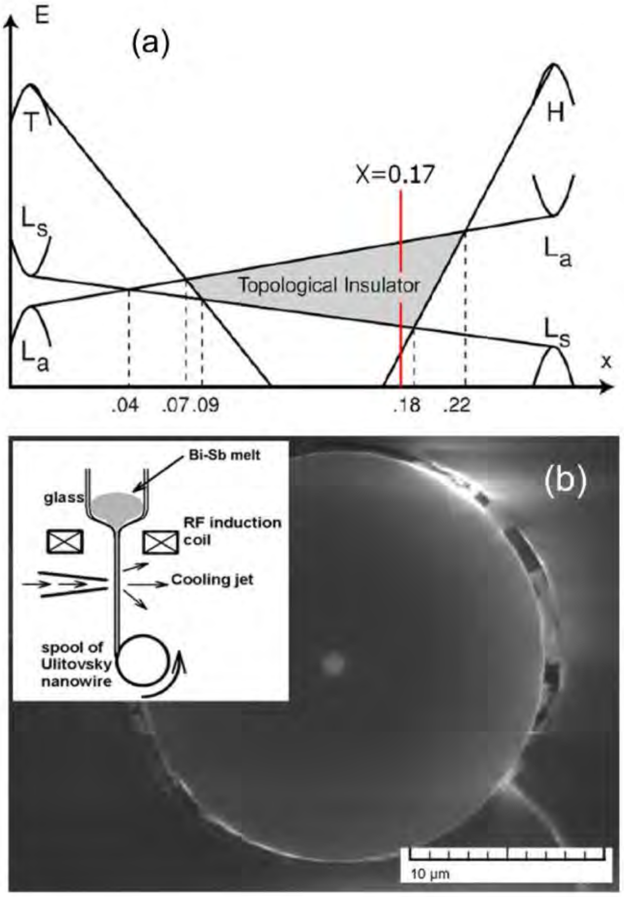

Fig. 1. (a): Schematic representation of band energy evolution of $Bi_{1-x}Sb_x$ as function of x. (b): Scanning electron microscope cross sections of the 1.0-µm glass-insulated $Bi_{0.83}Sb_{0.17}$ microwire. Inset: the Ulitovsky method for preparation of long glass-insulated wires with small diameters.

The samples for the measurements were cut from long wires, with samples ranging in length from 3 mm to 0.5 mm. They were then mounted on special foil-clad fiberglass plastic holders. Electrical contact between the nanowire and the copper foil was made with In-Ga eutectic solder.

We carried out magnetic field-dependent resistance $R(B)$ measurements in the range of 0 to 14 T at the International Laboratory of High Magnetic Fields and Low Temperatures (Wroclaw, Poland) and employed a device that tilts the sample axis with respect to the magnetic field and also rotates the sample around its axis. We used the magnetic field modulation technique to measure Shubnikov–de Haas (SdH) and AB oscillations. The amplitude of the oscillatory field is 45 Oe. This technique, that is very sensitive, allowed us to register the amplitude of the oscillations directly at the lock-in amplifier output.

III. RESULTS AND DISCUSSION

Quantum confinement effects, which influence the alloy band parameters have been predicted for alloy $Bi_{1-x}Sb_x$, films [13]. In a $Bi_{1-x}Sb_x$ thin film, deviations of the L-point gap to the lowest order approximation depends upon the film thickness t as ~ t^{-1} [14].Similar quantum confinement effects can be expected in $Bi_{1-x}Sb_x$ nanowires [15]. The insert in Fig. 2 shows the temperature dependence of the relative resistance R/R_{300} for Bi nanowires with d values varying from 650 nm down to 45 nm. According to the semimetal-to-semiconductor transformation, the $R(T)$ dependences exhibit a "semiconductor" behavior. However, at low temperatures, the resistance tends to saturate. We interpret the saturation by considering that the conductivity of the topological surface states reduces the overall nanowire resistance. The temperature dependence values of the relative resistance R/R_{300} for $Bi_{0.83}Sb_{0.17}$ nanowires are shown in Fig. 2. With decreasing nanowire diameter, the temperature ranges of exponential growth of resistance $R(T) \sim \exp(\Delta E/2k_B T)$ shifts into a higher temperature, which can be explained as follows: First, a rise in the energy gap increases the effective temperature of the smearing of the energy spectrum. Second, the relative influence of the surface states increases with decreasing nanowire diameter and reduced resistance of the nanowire will be noticeable at higher temperatures.

In 200-nm nanowires of $Bi_{0.83}Sb_{0.}17$ we measured transverse magnetoresistance (TMR) when $B \perp I$ for several orientations of the magnetic field near the direction $B \parallel C_3$ and at $B \parallel C_2$. In this case, SdH oscillations at various orientations of the magnetic field were observed. Using experimental data obtained at two different temperatures (T

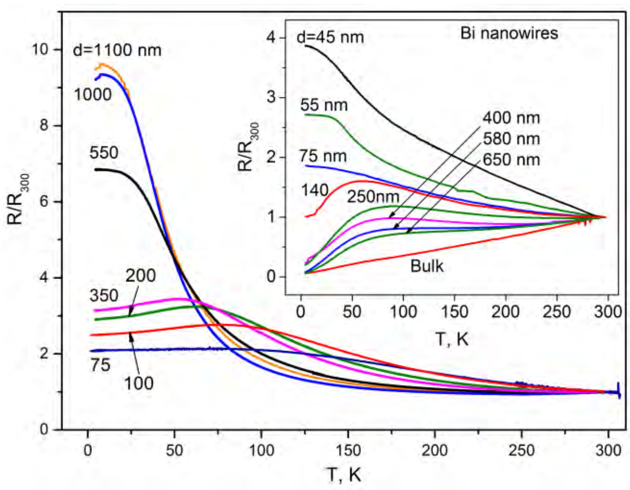

Fig. 2. Temperature dependences of the relative resistance for $Bi_{0.83}Sb_{0.17}$ nanowires. Insert: Temperature dependences of the relative resistance for Bi nanowires.

= 3 K and 1.5 K), we calculated the cyclotron masses for various directions of the transverse magnetic field. Figure 3 shows the 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 $8{:}5 \times 10^{-3}$ m_0, 9.4 K, and $1{:}5 \times 10^{-1}$ m_0, 2.8 K, respectively. Landau-level fan diagrams for SdH oscillations in *dR/dB* measured at 3 K and 1.5 K at $B /\!/ C_3$ are shown in the insert in Fig. 3. All the data lie on a straight line that intersects the *N* axis at 0.4, suggesting the Dirac case spectrum. The slope of the extrapolated straight line gives frequency *F* of 0.9 T. The obtained frequency, which is directly related to the cross-section of the Fermi surface *A* via Onsager relation $F = (\hbar/(2\pi e))A$, gives Fermi wave vector $k_F = 0.0052$ Å^{-1}, which

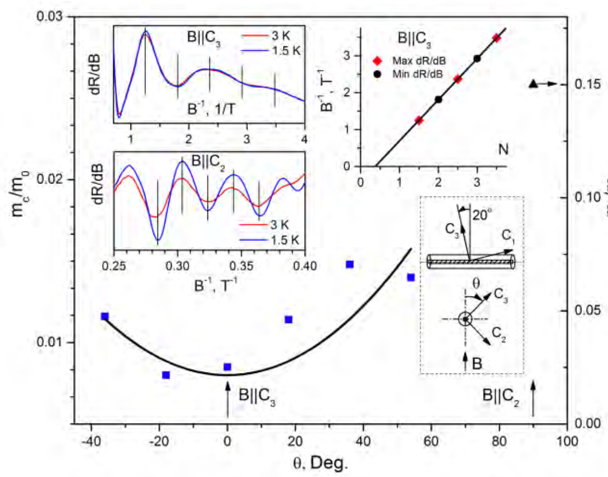

Fig. 3. Angular dependence of cyclotron mass m_c of carriers obtained from SdH oscillations for 200-nm $Bi_{0.83}Sb_{0.17}$ nanowire, B ⊥ I. The left two panels of the insets show SdH oscillations in dR/dB measured at 3 and 1.5 K at B ∥ C_3 and B ∥ C_2 crystallographic axes. The right two panels show Landau-level fan diagrams for SdH oscillations in dR/dB measured at 3 and 1.5 K at B ∥ C3.

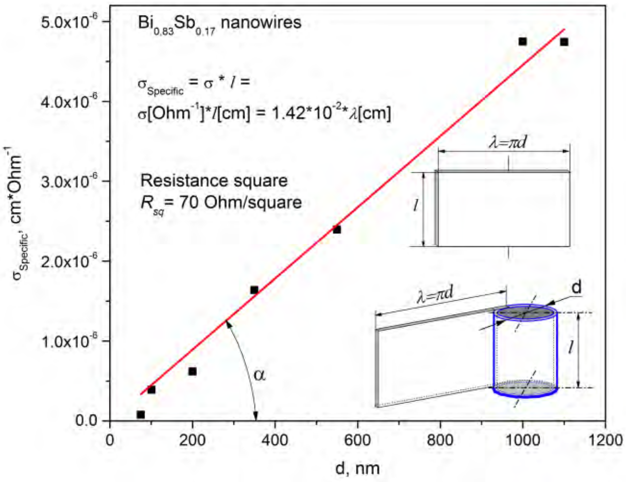

Fig. 4. Dependence of specific conductivity of $Bi_{0.83}Sb_{0.17}$ nanowires on nanowire diameter at T =4.2 K. The data are well approximated by a straight line; the square resistance R_{sq} of surface states, R_{sq}=70 Ohm is calculated from the line slope. Inset: Schematic drawing of the transformation of 2D surface states of nanowires into 2D film.

corresponds to the surface carrier density $n_S = k_F^2/4\pi = 2.2 \times 10^{10}$ cm^{-2}. Knowing the Dingle temperature and the cyclotron mass, we calculated the surface carrier mobility $\mu_S = 26\,700$ $cm^2V^{-1}s^{-1}$. However, in other surface areas that are nearly perpendicular to the C_3 axis, we obtained significantly greater mobilities ($\mu_{Smax} = 47\,000$ $cm^2V^{-1}s^{-1}$) comparable with data in Ref. [16]

Because there is an excitation gap in $Bi_{0.83}Sb_{0.17}$ nanowires, transport in nanowire samples at low temperatures will be dominated by the surface states. The conductance will be proportional to the circumference of the nanowire rather than the area [5]. The dependence of the specific conductivity $\sigma_{Specific}$ of $Bi_{0.83}Sb_{0.17}$ nanowires on nanowire diameter at $T = 4.2$ K is shown in Fig. 4, $\sigma_{Specific} = \sigma \times l$, where σ is the sample conductance and l is the sample length. The data are well approximated by a straight line, which proves that the surface states play a key role in nanowire conductance. The square resistance R_{sq} of the surface states of the nanowires is calculated to be 70 Ohm. The square resistance is inversely proportional to the product $n_S \times \mu_S$, where n_S is the 2D carrier density and μ_S is the 2D carrier mobility. If the 2D carrier concentration $n_S = 2{:}2 \times 10^{10}$ cm^{-2} obtained for the surface area normal to the C_3 axis was the same in all surface areas, we would have huge 2D mobility. However, the surface carrier concentration is much higher in other surface areas.

We discovered the oscillations of longitudinal magnetoresistance (MR) of 75 and 100-nm $Bi_{0.83}Sb_{0.17}$ nanowires with two periods ΔB_1 and ΔB_2 proportional to Φ_0 and $\Phi_0/2$, where $\Phi_0 = h/e$ is the flux quantum (see Fig. 5 and Fig. 6). Observation of AB oscillations confirms the existence of a highly conducting layer on the surface of the $Bi_{0.83}Sb_{0.17}$ nanowire. A derivative of MR was measured at various inclined angles. In the range 0 – 60 degrees of inclined angle of magnetic field, the observed angle

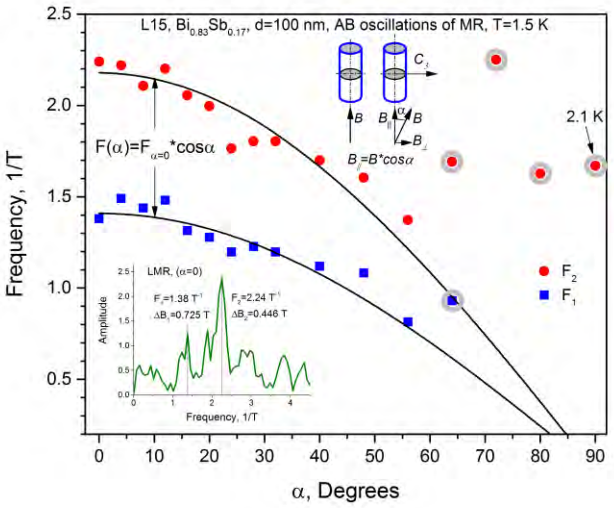

Fig. 5. Dependences of frequencies of Aharonov–Bohm oscillations of magnetoresistance on inclined angle of magnetic field for 100 nm $Bi_{0.83}Sb_{0.17}$ nanowire. Inserts: FFT spectra of the longitudinal magnetoresistance oscillations. Schematic drawing of the sample arrangement in a magnetic field.

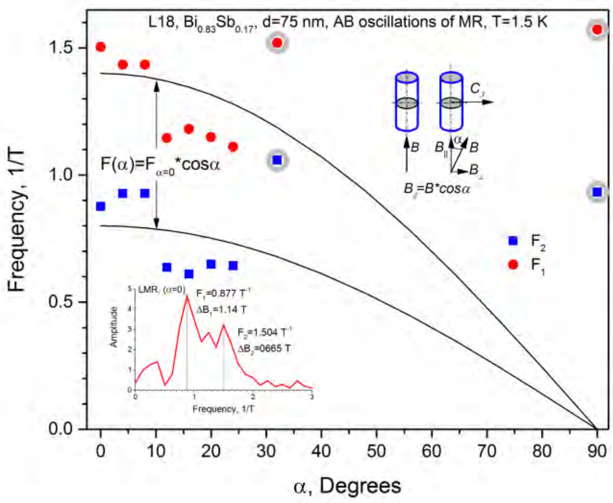

Fig. 6. Dependences of frequencies of Aharonov–Bohm oscillations of magnetoresistance on inclined angle of magnetic field for 75 nm $Bi_{0.83}Sb_{0.17}$ nanowire. Inserts: FFT spectra of the longitudinal magnetoresistance oscillations. Schematic drawing of the sample arrangement in a magnetic field.

variation of the periods is in agreement with the theoretical dependence $\Delta B(\alpha) = \Delta B(0)/\cos\alpha$ of the flux quantization oscillations. However, the equidistant oscillations of MR exist in transverse magnetic fields under conditions where the magnetic flux through the cylinder $\Phi = 0$. Bi-Sb has a layered crystal structure along the C_3 axis. When there are few layers in the cross section of the nanowire, they can exhibit specific properties of edge states, which, possibly, will lead to the self-organization of these states and, similarly to Bi nanowires [10,11], to the appearance of AB oscillations in a transverse magnetic field.

IV. CONCLUSION

We have investigated the temperature dependence of resistance of TI $Bi_{0:83}Sb_{0:17}$ nanowires with varying diameters (75 nm $\leq d \leq$ 1100 nm), obtained by radio frequency casting in a glass capillary. Surface states manifest themselves as decreasing resistivity at low temperatures. The SdH oscillations observed in $Bi_{0.83}Sb_{0.17}$ nanowires at T = 1.5 K demonstrate the existence of high mobility (μ_S = 26 700 - 47 000 $cm^2V^{-1}s^{-1}$) 2D carriers in the surface areas of the nanowires, which are nearly perpendicular to the C_3 axis. From the linear dependence of nanowire conductance on nanowire diameter at T = 4.2 K, we calculated the square resistance R_{sq} of the surface states of the nanowires to be only 70 Ohm. The oscillations of longitudinal MR of 75 and 100-nm $Bi_{0.83}Sb_{0.17}$ nanowires with two periods ΔB_1 and ΔB_2 proportional to Φ_0 and $\Phi_0/2$ were observed, where $\Phi_0 = h/e$ is the flux quantum. A derivative of MR was measured at various inclined angles. In the range 0 – 60 degrees of inclined angle of magnetic field, the observed angle variation of the periods is in agreement with the theoretical dependence $\Delta B(\alpha) = \Delta B(0)/\cos\alpha$ of the flux quantization oscillations. However, the equidistant oscillations of MR exist in transverse magnetic fields under certain rotation angles.

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