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Quantum oscillations in nanowires of topological insulator $Bi_{0.83}Sb_{0.17}$

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ABSTRACT

Three dimensional topological insulators (TIs) are novel materials with a conducting surface covering an insulating bulk interior. We examine the topological properties of nanowires of TI $Bi_{0.83}Sb_{0.17}$ and observed that they display oscillations of the magnetoresistance (MR) that can be interpreted as topological surface electronic transport. In this work, we study the nanowires at various magnetic field orientations, at low temperatures (1.5 K ≤ T < 5 K), and for field strengths up to 14 T. In the 4 T < B < 10 T range we observe B-periodic, Aharonov–Bohm (AB) oscillations of longitudinal MR with two periods, namely, one flux quantum Φ_0 and half of flux quantum $\Phi_0/2$ ($\Delta B_1 = \Phi_0/S$, $\Delta B_2 = \Phi_0/2S$, where S is the cross-sectional area of the nanowire). The periods depend on the angle α between the magnetic field and the wire axis according to a cosine law that indicates that the phenomenon is governed by the axial flux enclosed by the nanowire. In additional to the high magnetic field oscillations, in the low magnetic field range, B < 4 T, we observe a conductance maximum for zero magnetic field and the first magnetoresistance maximum for $\Phi = \Phi_0/2$.

1. Introduction

The properties of bulk, three-dimensional topological insulators (TIs), such as $Bi_{1-x}Sb_x$, Bi_2Se_3, and Bi_2Te_3 are attributed to strong spin–orbit coupling and band inversion. The TIs are characterized by a finite energy gap in the interior and a conducting surface. Also, surface states have a gapless spectrum and the directions of momentum and electron spin are correlated where the electron spin is tangential to the surface and perpendicular to its momentum [1,2]. Due to these properties, electrons are not affected by scattering as long as time reversal symmetry is preserved. The existence of surface gapless electrons with linear dispersion of the Dirac type was experimentally proved by angular resolution photoelectron spectroscopy (ARPES), the $Bi_{1-x}Sb_x$ alloys being the first discovered TI [3,4].

In the presence of a magnetic flux Φ, Aharonov–Bohm (AB) oscillations [5] may occur in TI nanowires. In a closed trajectory, electrons undergo quantum interference and their amplitude is periodically modulated by the magnetic field. For a normal metal, the period of these oscillations is $\Phi_0 = h/e$ (flux quantum). AB oscillations with period $h/2e$ known as Altshuler–Aronov–Spivak (AAS) [6] oscillations are also observed. AB oscillations were observed in various conducting rings, tubes, and solid cylinders consisting of tubes, such as multiwall carbon nanotubes (MWNTs), and arrays of a 270-nm Bi nanowire [7] and individual bismuth nanowires in a diameter range of 200–800 nm [8]. Clearly, AB oscillations can be expected in the case of a nanowire with an insulating interior. However, the AB oscillation in a TI nanowire is special mainly because the surface states of TIs are massless and gapless. Theoretically, an axial magnetic flux drives periodic topological transitions in the surface bands because the mode energy depends on the Berry phase and AB phase around the perimeter. The magnetoresistance oscillates with the change in the magnetic field along the nanowire because the density of states at the Fermi level changes periodically as each subband of the confined surface energy band intersects the Fermi energy. This phenomenon has been reported for nanowires of Bi_2Te_3, and Bi_2Se_3, which are conventional TIs [9–15].

Bi and Sb are essentially semimetals. However, the substitution of bismuth with antimony changes the critical energies of the band structure. The $Bi_{1-x}Sb_x$ semiconducting alloy is a strong TI owing to the inversion symmetry of bulk crystalline Bi and Sb [16]. At concentrations higher than $x = 0.09$, the system turns into a direct-gap insulator, while the energy structure is determined by the spin–orbit coupling at L. Here we study nanowires with $x = 0.17$, which, in the bulk is a semiconductor with an L-point gap of 21 meV. In our previous studies [17–19], the temperature dependences of resistivity and Shubnikov–de Haas (SdH) oscillations of glass-insulated $Bi_{0.83}Sb_{0.17}$ nanowires with varying diameters (75 nm ≤ d ≤ 1100 nm), which were prepared by

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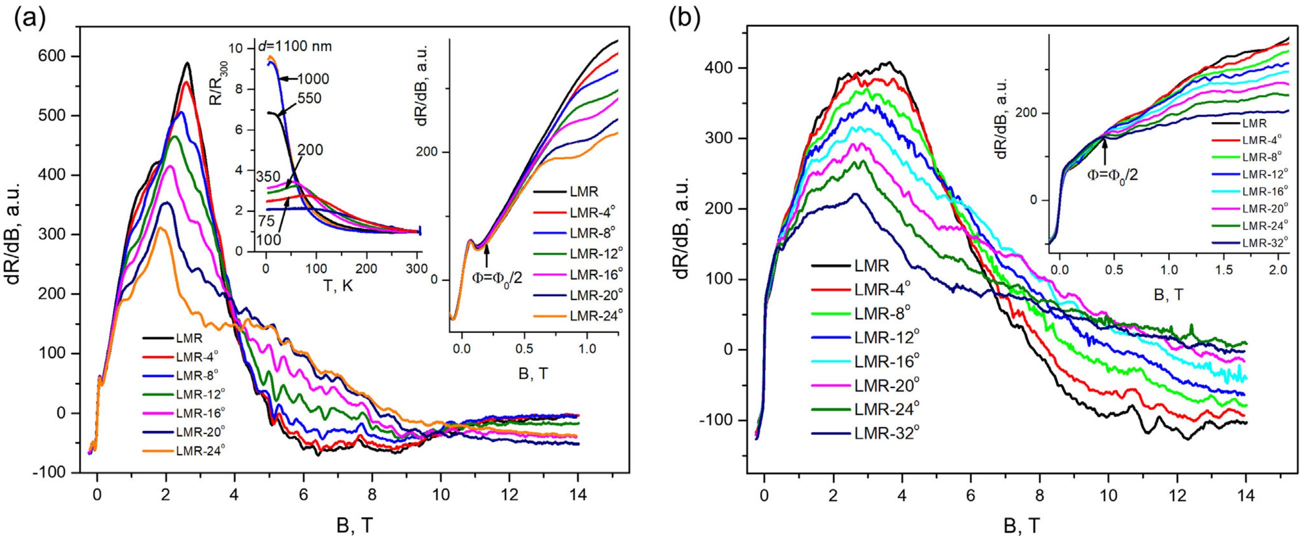

Fig. 1. Dependences of the MR derivative for $Bi_{0.83}Sb_{0.17}$ nanowires on magnetic fields of various orientations at $T = 1.5$ K; nanowire diameter d = (a) 90 and (b) 75 nm. The left inset in panel (a) shows the temperature dependence of the relative resistance for $Bi_{0.83}Sb_{0.17}$ nanowires. The right inset in panel (a) and the inset in panel (b) show an increased scale of MR derivatives.

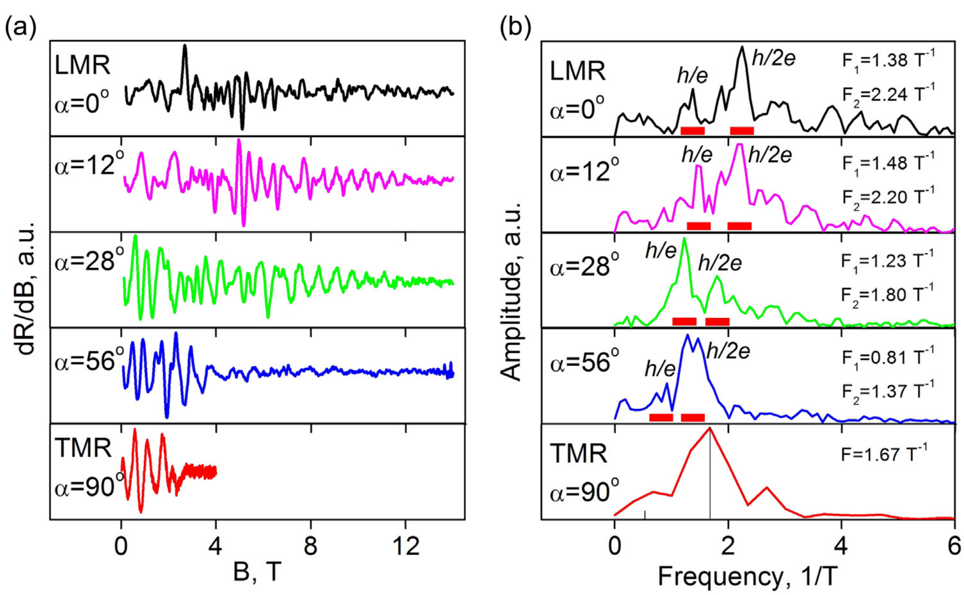

Fig. 2. (a) Magnetic field dependence of the MR for the 90-nm nanowire at $T = 1.5$ K (monotonic parts are subtracted) at various angles α between magnetic field B and the nanowire axis; (b) FFT spectra of MR derivative for the 90-nm $Bi_{0.83}Sb_{0.17}$ nanowire at $T = 1.5$ K and various angles α between the direction of magnetic field B and the nanowire axis.

the Ulitovsky technique, were studied in a temperature range of 1.5–300 K and a magnetic field range of 0–14 T. Owing to the quantum size effect, with a decrease in the nanowire diameter d from 1100 to 75 nm, energy gap ΔE increases as follows: $\Delta E \sim 1/d$ (for diameter $d = 1.1$ μm and $d = 75$ nm, $\Delta E = 21$ and 45 meV, respectively). The SdH oscillations observed in $Bi_{0.83}Sb_{0.17}$ nanowires at $T = 1.5$ K show that the charge carriers have very high mobility (μ_S = 26 700–47 000 $cm^2V^{-1}s^{-1}$). From the linear dependence of the conductivity of the nanowire on the nanowire diameter at $T = 4.2$ K, the square resistance R_{sq} of the surface states of the nanowire was calculated; it was as low as 70 Ω. Surface states are evident as resistivity decreasing at low temperatures, an extremely high charge carrier mobility, a Dirac case spectrum of carriers confirmed by the Landau-level fan diagrams for SdH oscillations, and a linear dependence of conductivity on the circumference of the nanowire [19]. In the present paper, we report on measurements of the magnetic field dependence of the MR (AB oscillations) of TI $Bi_{0.83}Sb_{0.17}$ nanowires in glass insulation.

2. Samples and experimental details

High purity Bi (99.999%) and Sb (99.999%) were used to prepare the alloy. Individual $Bi_{0.83}Sb_{0.17}$ nanowires were prepared using the Ulitovsky technique [19]. 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, a process which simultaneously softens the glass and melts the metal, followed by the drawing of a glass capillary containing the nanowire. One problem with BiSb alloy metallurgy is constitutional supercooling; owing to the high-speed of crystallization (> 10^5 K/s) involved in the Ulitovsky technique, it is possible to obtain homogeneous single-crystal $Bi_{0.83}Sb_{0.17}$ nanowires. In the present study, we used samples with diameter d = 75 and 90 nm. The nanowires were single crystals with the $(10\bar{1}1)$ orientation along the wire axis. In this orientation, the wire axis makes an angle of 19.5° with the C_1 bisector axis in the bisector–trigonal plane. Furthermore, encapsulation of the $Bi_{0.83}Sb_{0.17}$ wire in glass (outer diameter of the glass coating is 15–20 μm) protects it from oxidation and mechanical stress.

The samples for measurements were cut from long wires, with

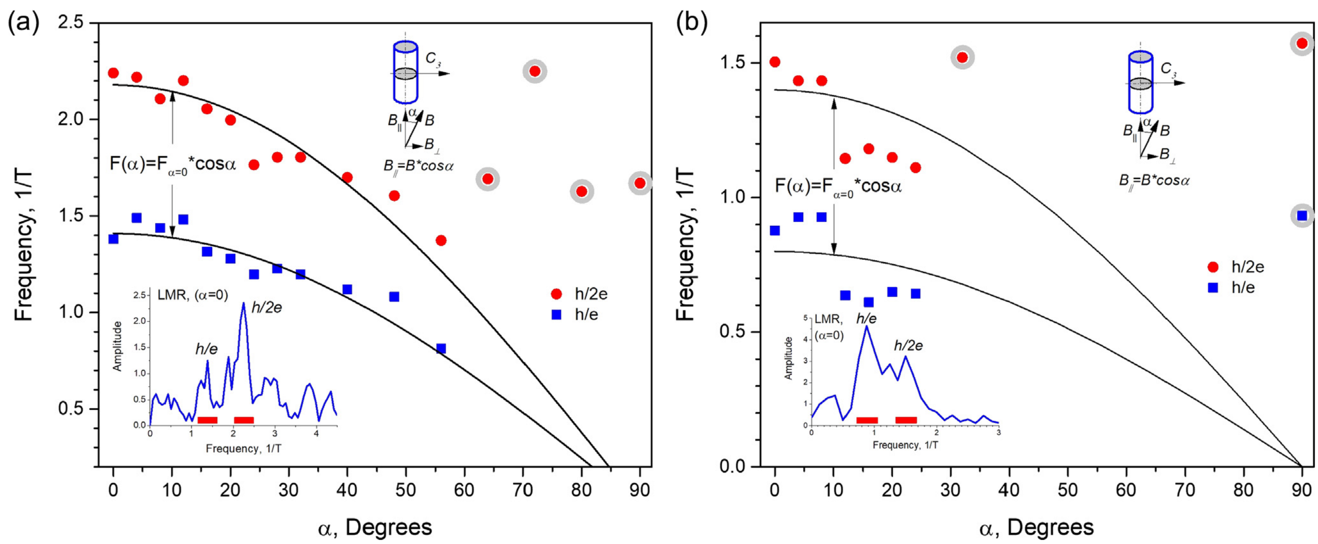

Fig. 3. Dependences of frequencies of h/e (filled squares) and $h/2e$ (filled circles) harmonics of the FFT spectra of MR derivative on angle α between the direction of magnetic field B and the nanowire axis. The frequencies of h/e and $h/2e$ harmonics are consistent with the fitting plots of $F(\alpha) = F(0)\cos\alpha$. Insert at the top: schematic diagram of the magnetic field direction relative to the nanowire axis; insert at the bottom: FFT spectrum of the LMR derivative; nanowire diameter d = (a) 90 and (b) 75 nm.

samples ranging in length from 3 to 0.5 mm. Electrical contact between the nanowire and the copper foil was made using an In–Ga eutectic solder. This type of solder consistently provides good contacts compared with other solders with low melting points.

Magnetic field-dependent resistance $R(B)$ measurements in a range of 0–14 T were carried out at the International Laboratory of High Magnetic Fields and Low Temperatures (Wroclaw, Poland) employing a device that tilts the sample axis with respect to the magnetic field and rotates the sample around its axis.

3. Results and discussion

Fig. 1 shows the dR/dB of $Bi_{0.83}Sb_{0.17}$ nanowires with d = 75 and 90 nm for various orientations of the nanowire with respect to the magnetic field. The *R(B)* show a strong relative maxima with a transition to negative dR/dB. This is reminiscent of the Chambers peak, a semiclassical effect [7]. The magnitude of the magnetic field corresponding to this transition depends on the nanowire diameter: B_c = 4.5 and 6.5 T for diameters d = 90 and 75 nm, respectively (a more in-depth study of these experimental results will be presented in a separate publication). Temperature dependences of relative resistance R/R_{300} for $Bi_{0.83}Sb_{0.17}$ nanowires are shown in the left insert in Fig. 1a. The *R(T)* dependences exhibit a "semiconductor" behavior. The decrease in resistance at low temperatures is attributed to the fact that the conductivity of topological surface states reduces the total nanowire resistance. The greater the relative effect of surface states with decreasing nanowire diameter, the stronger the effect of decreasing resistance. Fig. 2 shows the results of processing the data of the dependence of the MR derivative on the magnetic field for 90-nm nanowire. We subtracted the non-oscillating background and performed a fast Fourier transform (FFT) of the obtained data. The oscillation parts of magnetic field derivative of the MR are shown in Fig. 2a. A large modulation of the MR decreasing in intensity with increasing magnetic fields was observed. It should be noted that there are pronounced oscillations for the case of a transverse magnetic field, when the magnetic flux through the cross section of the nanowire is zero. The FFT results are shown in Fig. 2b. The LMR derivative oscillates periodically with B with period $\Delta B_1 = 1/F_1$ = 0.72 T. The measured ΔB_1 agrees with the expected period for an AB oscillations of $\Phi_0/S = h/(eS)$ = 0.65 T for 90-nm nanowire (where S is the cross-sectional area of the nanowire). $h/2e$-period oscillations, $\Delta B_2 = 1/F_2$ = 0.47 T, were also observed (Fig. 2b, LMR). Periods of the h/e and $h/2e$ oscillations depend on the angle α as follows: $\Delta B(\alpha) = \Delta B(0)/\cos\alpha$; this finding suggests that the magnetic field along the nanowire longitudinal direction is dominant. The angular dependence $\Delta B(\alpha) = \Delta B(0)/\cos\alpha$ is valid up to the inclination angle of the magnetic field of $\alpha = 56^\circ$ (in a 90-nm nanowire). Angular dependence of the same characteristics was observed in TI SnTe nanowires [20] and Dirac semimetal Cd_3As_2 nanowires [21]. Fig. 3 shows all Fourier Transforms (FFT) data for 90-nm and 75-nm $Bi_{0.83}Sb_{0.17}$ nanowires measured at T = 1.5 K. The most intriguing is the presence of MR oscillations equidistant in the magnetic field when the magnetic field is perpendicular to the nanowires axis, when the magnetic flux through the nanowire cross section is zero. Similar and even more pronounced oscillations of the transverse MR in 45-nm bismuth nanowires at a temperature of T = 1.5 K were observed previously [17,18]. It was assumed that, in 45-nm Bi nanowires, the self-organization of helical edge states of bilayers led to the formation of series-connected stacks of bilayers, each of which had a closed conducting loop in a transverse magnetic field. Apparently, a similar interpretation can be applied to $Bi_{0.83}Sb_{0.17}$ nanowires; however, additional studies are required to clarify the nature of these oscillations in a transverse magnetic field. Additionally to the high magnetic field oscillations, in the low magnetic field range, $B < 4$ T, the nanowire exhibit a conductance minimum for zero magnetic field. This minimum evidences the presence of the low energy topological mode [15]. Here the lowest magnetic field minima is at 0.2 T, indicating a deviation from the expected behavior for a topological insulator nanowire at the Dirac point. This behavior, where the nanowire is self-doped has been observed previously, for example by Cho *et al* [15]. We also observed the first peak of the magnetoresistance at $\Phi_0/2$. The peak at 0.07 T is an artefact.

4. Conclusions

We have studied the magnetoresistance of 75-nm and 90-nm $Bi_{0.83}Sb_{0.17}$ nanowires in glass insulation at low temperatures at various directions of magnetic field. These nanowires have unique properties, such as a high surface conductivity (square resistance R_{sq} = 70 Ω, $\mu_S \sim$ 40 000 $cm^2V^{-1}s^{-1}$), and are characterized by a finite energy gap ($\Delta E \approx$ 45 meV) in the bulk interior core. We have discovered the AB oscillations with two periods, namely, one flux quantum Φ_0 and half of flux quantum $\Phi_0/2$ ($\Delta B_1 = \Phi_0/S$, $\Delta B_2 = \Phi_0/2S$, where S is the cross-sectional area of the nanowire). The Φ_0 period oscillations are closely related to the formation of a 1D band of a topological insulator nanowire.

CRediT authorship contribution statement

Leonid Konopko: Conceptualization, Investigation, Formal analysis, Writing - original draft, Writing - review & editing. **Albina Nikolaeva:** Investigation, Formal analysis, Writing - review & editing. **Tito E. Huber:** Conceptualization, Formal analysis, Writing - original draft, Writing - review & editing. **Krzysztof Rogacki:** Investigation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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