Aharonov-Bohm oscillations and weak antilocalization in topological insulator Sb2Te3 nanowires
Bacel Hamdou, Johannes Gooth, August Dorn, Eckhard Pippel, and Kornelius Nielsch

Citation: Appl. Phys. Lett. 102, 223110 (2013); doi: 10.1063/1.4809826
View online: http://dx.doi.org/10.1063/1.4809826
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v102/i22
Published by the American Institute of Physics.
Aharonov-Bohm oscillations and weak antilocalization in topological insulator Sb$_2$Te$_3$ nanowires

Bacel Hamdou, Johannes Gooth, August Dorn, Eckhard Pippel, and Kornelius Nielsch

1Institute of Applied Physics, University of Hamburg, Jungiusstrasse 11, 20355 Hamburg, Germany
2Max Planck Institute of Microstructure Physics, Weinberg 2, 06120 Halle, Germany

(Received 27 March 2013; accepted 23 May 2013; published online 6 June 2013)

Recently, it has been theoretically predicted that Sb$_2$Te$_3$ and related materials are 3D topological insulators, a phase of matter that has a bulk bandgap and gapless electronic surface states protected by time-reversal symmetry. We report on low temperature magnetoresistance measurements on single crystalline Sb$_2$Te$_3$ nanowires with different cross sectional areas and high surface-to-volume ratios, synthesized via catalytic growth. The observation of Aharonov-Bohm oscillations and weak antilocalization indicates the presence of topological surface states.

Topological insulators (TIs) represent a new state of quantum matter with a bulk band gap and gapless surface states that are protected against backscattering by time-reversal symmetry. Theoretical predictions of materials such as Bi$_2$Se$_3$, Bi$_2$Te$_3$, and Sb$_2$Te$_3$ being TIs have been experimentally confirmed by angle resolved photoemission spectroscopy (ARPES) measurements. Up to now, it has been difficult to observe surface states in TIs via electronic transport measurements because of the dominant bulk contribution to conductivity arising from unintentional doping and the small bulk band gaps typical for TI materials. However, low-dimensional solids such as nanowires (NWs) are expected to significantly enhance the contribution of surface states to electrical transport due to their large surface-to-volume ratios. Recently, Aharonov-Bohm (AB) oscillations have been observed in single crystalline Bi$_2$Te$_3$, Bi$_2$Se$_3$ nanoribbons, and β-Ag$_2$Te NWs, which suggest the presence of topological surface states. Furthermore, weak antilocalization (WAL) is an indication for strong spin-orbit coupling, which is a prerequisite for the existence of topological surface states. By these means, evidence for surface states in Bi$_2$Se$_3$Te crystals, Bi$_2$Se$_3$, and Sb$_2$Te$_3$ thin films, and Bi$_2$Te$_3$ microflakes has been found. Aharonov-Bohm oscillations and WAL have not been observed in Sb$_2$Te$_3$ NWs so far. According to Hsieh et al., surface states are not favored in Sb$_2$Te$_3$ because the Fermi level is located in the valence band due to a high level of intrinsic doping.

We report on magnetoresistance measurements on single crystalline Sb$_2$Te$_3$ NWs at low temperatures, where the magnetic field is oriented parallel to the NW axis. The Sb$_2$Te$_3$ NWs were synthesized via catalytic growth in a single-heater zone tube furnace (MTI, Inc., USA/OTF-1200X-25). Inside a 1 inch diameter quartz tube 3 mg of the source materials, Sb and Te powder (99.999% purity) were thermally evaporated at 10° Torr, a constant flow of Ar carrier gas (80 sccm) was used to transport the precursor vapors to the substrate where wire growth took place. Before synthesis, the charged furnace was evacuated to below 10 Torr and flushed several times with Ar gas to obtain an inert atmosphere. After a reaction time of 4 h, the heating power was switched off. Under constant Ar flow and pressure, the furnace was returned to room temperature by natural cooling.

The dimensions of the NWs were determined by atomic force microscopy (AFM) and scanning electron microscopy (SEM). Figures 1(c) and 1(d) show typical SEM images of the as-grown Sb$_2$Te$_3$ NWs. The morphology of the NWs is either cylindrical or rectangular with thicknesses of 52–135 nm, widths of 46–435 nm, and lengths of up to 15 µm. The presence of a gold nanoparticle at the top of each NW is consistent with a catalytic unidirectional growth process. High resolution transmission electron microscopy (HRTEM) analysis reveals the single-crystallinity and a growth direction along the [110] direction, perpendicular to the c-axis. The surface is smooth to within a few atomic layers and there is no indication of a native oxide layer. TEM based energy dispersive X-ray spectroscopy (EDX) shows a uniform chemical composition across the diameter of the NW of Sb$_{32±1}$Te$_{58±1}$, which confirms the desired Sb:Te = 2:3 phase (shown in Fig. 1(b)). Further, the EDX results show that contrary to as-grown bismuth telluride NWs recently synthesized via catalytic growth in the same tube furnace, Sb$_2$Te$_3$ NWs exhibit no tellurium depletion near the NW surface.

The as-grown NWs were mechanically transferred onto Si substrates with 300 nm SiO$_2$. Electrical contacts for current injection and voltage detection across the NWs were defined using a laser-lithography system (Heidelberg Instruments μPG 101). In order to remove any photoresist residues or surface oxide, in-situ sputter etching with Ar was used prior to the sputter-deposition of Ti (5 nm) and Pt (80 nm), followed by a lift-off process. A typical device used for electrical measurements is shown in Fig. 1(e).
By comparing two-terminal and four-terminal measurements on our Sb$_2$Te$_3$ NWs, contact resistances were found to be negligible. Thus, the modulations on top of the magnetoresistance curves result exclusively from the Sb$_2$Te$_3$ NWs. The linear IV-curves confirm that the electrodes form Ohmic contacts to the NWs over the whole temperature range, which is shown in Fig. 2(a). All electrical measurements were performed in a variable temperature cryostat system (Quantum Design PPMS) with a base temperature of 2 K in helium atmosphere, equipped with a 9 T magnet. The resistance of the NWs was determined by standard lock-in techniques.

We studied the transport properties of three individual Sb$_2$Te$_3$ NWs with different rectangular cross sectional areas of NW 1: $82 \times 52$ nm, NW 2: $92 \times 63$ nm, and NW 3: $133 \times 75$ nm. The resistivity at $T = 300$ K for the three measured NWs is $\rho = (1.15 \pm 0.07) \times 10^{-5} \, \Omega \cdot m$ on average. This value is considerably higher than the previously reported resistivities for single crystalline Sb$_2$Te$_3$ NWs$^{14}$ grown under similar conditions,$^{12}$ which are comparable to the bulk values for Sb$_2$Te$_3$ of $\rho = 0.25 \times 10^{-5} \, \Omega \cdot m$ (Ref. 15) and $\rho = 0.21 \times 10^{-5} \, \Omega \cdot m$. Minor differences in growth conditions such as the gold colloid size, the amount of elemental powders, and growth temperature therefore appear to have a strong influence on the electronic properties of the resulting NWs. Fig. 2(a) shows a typical resistance versus temperature curve at zero magnetic field. In the temperature range of 5–300 K, the resistance decreases with decreasing temperature, indicating a metallic behaviour, in which inelastic phonon scattering dominates.$^{5,6,13}$ Below around 30 K, the slope changes noticeably until the resistance saturates at around 5 K, presumably due to the absence of inelastic phonon scattering,$^{6}$ so that transport is dominated by impurity scattering of the charge carriers.$^{17}$

The results of the magnetoresistance measurements are presented in Figs. 2(b) and 2(c), exhibiting two dominant features. Around $B = 0$ T, a sharp dip occurs, and for higher fields up to $\pm 9$ T, oscillations can be clearly seen, which are periodic with magnetic field. Both features, the low magnetic

![FIG. 1. Material characterization and device. (a) High resolution TEM image of a Sb$_2$Te$_3$ NW. The inset shows the corresponding selected area electron diffraction (SAED) pattern. The chemical composition (b) was measured across the NW’s cross-section, using EDX spectroscopy. The inset shows a high-angle annular dark-field scanning transmission electron microscopy (HAADF-STEM) image of the NW, indicating the EDX line-scan. The SEM images (c) and (d) show typical transferred NWs with cylindrical (c) and rectangular (d) cross section, respectively. (c) SEM image of a typical micro device including two electrical contacts for current injection and two for voltage detection across the NW.](image1)

![FIG. 2. Temperature dependent resistance and magnetoresistance. (a) Resistance versus temperature of NW 1 at zero magnetic field in the range of 2–300 K. The insets show linear IV-curves at different temperatures, indicating Ohmic contacts and the saturating resistance in the low temperature range, respectively. (b) Resistance versus parallel magnetic field at four different temperatures. (c) Resistance versus parallel magnetic field for the three measured NWs at 2 K and (d) AB oscillations and the related index plots after subtraction of the smooth background.](image2)
field resistance dip and the oscillations are symmetric around zero field and smear out with increasing temperature. In Figure 2(d), the magnetic field position of resistance minima versus index n and the related magnetoresistance after subtracting the smooth background are plotted for the three measured NWs. The index plots show a high degree of linearity, indicating that the oscillation period remains constant up to ±9 T. We assume that these oscillations arise from the Aharonov-Bohm effect, which is a consequence of quantum interference when charge carriers encircle closed trajectories. For NWs, such AB oscillations are predicted when charge carriers retain phase coherence around the perimeter of the NW and therefore enclose a magnetic flux \( \Phi_0 = \hbar/e \), where \( \hbar \) is Planck’s constant and \( e \) is the unit charge. The enclosed area \( A \) is associated with the period of the AB oscillation for higher surface-to-volume ratios. The prefactor \( A \) is associated with the period of the AB oscillations. The corresponding areas from the AB oscillation periods (NW 1: \((4.22 \pm 0.04) \times 10^{-15} \text{ m}^2\), NW 2: \((5.97 \pm 0.07) \times 10^{-15} \text{ m}^2\), and NW 3: \((10.05 \pm 0.06) \times 10^{-15} \text{ m}^2\)) are in excellent agreement with the measured cross-sectional areas of the NWs (NW 1: \((4.26 \pm 0.36) \times 10^{-15} \text{ m}^2\), NW 2: \((5.80 \pm 0.42) \times 10^{-15} \text{ m}^2\), and NW 3: \((9.98 \pm 0.76) \times 10^{-15} \text{ m}^2\)). The resulting prefactor \( A \) is reduced from 413 nm to 77 nm as \( L_p \) increases from 2 K to 20 K. Indicated by the solid line in Fig. 3, \( L_p \) is proportional to \( T^{-1/2} \), which is expected for a 2-dimensional electron system.

The WAL effect in the three measured NWs is analysed by fitting the low-field magnetococonductivity with the Hikami-Larkin-Nagaoka formula. However, it should be noted that the geometry of a NW with surface states, corresponding to a curved 2-dimensional electron system, differs from a planar 2-dimensional system. The resulting prefactor \( \alpha \) of NW 1 \((\alpha = -0.49) \) and NW 2 \((\alpha = -0.49) \) support our hypothesis of surface state dominated transport in these NWs. Whereas for NW 3 with the lowest surface-to-volume ratio \( \alpha = -0.42 \) slightly differs from \(-1/2 \), suggesting a minor bulk contribution, which is consistent with the results of the AB analyses. The extracted temperature dependence of \( L_p \) is plotted in Figure 3 for NW 1. The coherence length \( L_p \) of NW 1 is 77 nm to 413 nm as \( T \) is reduced from 20 K to 2 K. Indicated by the solid line in Fig. 3, \( L_p \) is proportional to \( T^{-1/2} \), which is expected for a 2-dimensional electron system.

In summary, single crystalline Sb\(_2\)Te\(_3\) NWs with high surface-to-volume ratios were synthesized via catalytic growth. Magnetoresistance measurements with the magnetic field parallel to the NW axis were performed at temperatures

![Image](image336x96to540x248)

FIG. 3. Weak antilocalization analysis. Estimated phase coherence length \( L_p \) of NW 1 versus temperature. The solid line indicates a temperature dependence of \( L_p \) \( \propto T^{-1/2} \). The inset shows the conductance versus parallel magnetic field of NW 1 at 2 K (open triangles) and 4 K (open circles) and the related fits to Eq. (1).
down to 2 K for three Sb$_2$Te$_3$ NWs. Periodic Aharonov-Bohm oscillations in magnetoresistance up to $\pm 9$ T were observed. Areas extracted from the AB oscillations are in excellent agreement with the geometrical cross sectional areas of the respective NWs. The sharp dip in magnetoresistance around zero magnetic field can be attributed to weak antilocalization and is consistent with strong spin-orbit coupling. These findings indicate the presence of topological surface states. Interestingly, WAL and AB oscillations were most pronounced in NWs with small cross-sectional areas, which is consistent with the idea that the bulk contribution to conductivity is strongly suppressed for large surface-to-volume ratios. This work provides a promising starting point for further investigation of surface states in topological insulator Sb$_2$Te$_3$ NWs.

This work was supported by the German science foundation (DFG) via the German priority program SPP 1386 “Nanostructured Thermoelectrics” as well as within the Graduiertenkolleg 1286 “Functional Metal-Semiconductor Hybrid Systems.” We thank L. Akinsinde, J. Kimling, and R. Meißner for technical support.