Nano-Angle Resolved Photoemission Spectroscopy on Topological insulator Sb$_2$Te$_3$ nanowires responsible of quantum transport

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Abstract. Using high-resolution Nano-Angle Resolved Photoemission Spectroscopy (Nano-ARPES), we have determined the electronic structure of the surface and bulk states of topological insulator Sb$_2$Te$_3$ nanowires, which have been also characterized by magnetoresistance measurements. The observed Aharonov-Bohm-type oscillations could be unambiguously related to the transport by topological protected surface states directly recorded by photoemission. We have measured Nano-ARPES on individual nanowires of a few nanometers wide to provide direct evidence of the existence of the nontrivial topological surface states, as well as their doping. Our findings are consistent with theoretical predictions and confirm that the surface states of intrinsically doped unidimensional topological insulator nanowires are responsible for the quantum transport.

1. Introduction

Topological insulators (TIs) are a new type of fascinating materials that recently has attracted enormous interest. This new state of matter, known as the time-reversal-invariant Z2 TIs is created when the spin-orbit coupling (SOC) is strong enough to invert the conduction and valence bands in the material[1, 2, 3, 4]. They are characterized by an insulating bulk and a conducting surface state, which is protected by time reversal-symmetry (TRS) and it is resistant to scattering from non-magnetic impurities[5]. Their unique bandstructure with a gap less Dirac-cone (linear $E$ vs $k$ dispersion relation) residing in the bulk bandgap makes TIs ideal systems for a broad range of applications in condensed-matter physics, materials science, nanoelectronics, spintronics, as well as energy harvesting among others.

In the case of three dimensional (3D) TIs, such as Bi$_2$Se$_3$, Bi$_2$Te$_3$ and Sb$_2$Te$_3$ it was predicted and observed by ARPES that the surface states span the bulk energy gap and have a linear Dirac-like dispersion with chiral spin-momentum locking [6, 7, 8, 9]. However, probing the surface state...
Figure 1. Synthesis and characterisation of Sb$_2$Te$_3$ nanowires. (a) Schematic of the Au-catalyzer CVD furnace used to synthesize the nanowires. (b) X-ray diffraction pattern of an ensemble of Sb$_2$Te$_3$ nanowires. The best fit of the peak verifies the rhombohedral structure of space group (R$ar{3}$m) (JCPDS card 00-015-0875). (c) Schematic description of the Sb$_2$Te$_3$ nanowires investigated, indicating the width, thickness and length of the nanowire as ($L_x$), ($L_z$), and ($L_y$), respectively. (d) SEM image of an individual as-grown Sb$_2$Te$_3$ nanowire.

in transport experiments still poses a major challenge. In particular, the well-known Aharonov-Bohm oscillations (ABO) observed when a magnetic flux $\Phi_0$ is penetrating the TIs nanowires, can easily be masked or perturbed by the bulk intrinsic defects or unintentional doping.

Figure 2. Aharonov-Bohm oscillations of the topological surface states. (a) Optical image of a typical circuit used to measure the nanowires (NW) transport. (b) Zoomed view of panel (a). (c) Schematic diagram of a Sb$_2$Te$_3$ nanowire under a magnetic field along the wire length. (d) Magnetoresistance versus magnetic field for three TIs nanowires of different cross-sectional areas (width). (e) Typical I-V curves of the same TIs nanowires reported in panel (d).

As the surface contribution can be straightforward enhanced by using TIs, like nanowires, ribbons or quantum wells due to their high surface-to-volume ratio, we report here a combined study on Sb$_2$Te$_3$ nanowires of magnetotransport experiments together with Nano-ARPES, which validates that the ABO-type effect observed in TI nanowire transport is due to the contribution of the topologically protected surface states to the quantum transport. Both the bandstructure determined by nanoARPES and the transport data confirm that the nanowires are intrinsically p-doped type.

2. Synthesis and general characterisation of the Sb$_2$Te$_3$ nanowires
Sb$_2$Te$_3$ nanowires were synthesized by Au-catalyzer chemical vapor deposition (CVD) in a horizontal tube furnace (Lindberg/Blue M) with Sb and Te powder as source materials, following the technical details from Lee et al., [10]. Nanowires were carefully characterized by
scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS). Powder X-ray diffraction has been used to determine their structural properties. Figure 1 shows the SEM image of one particular Sb$_2$Te$_3$ nanowire as well as a typical X-ray diffraction spectrum with the corresponding peak assignments, ensuring the monocrystal character of the nanowires investigated. Following the nomenclature of the schematic nanowire described in Fig. 1c, we have investigated a large set of nanowires with width ($L_x$), thickness ($L_z$), and length ($L_y$) ranging from 42 to 86 nm, from 29 to 73 nm and from 1.8 to 2.0 nm, respectively.

Figure 3. Electronic band structure of an individual Sb$_2$Te$_3$ nanowire. (a) Reciprocal three dimensional Brillouin zone with their respective surface projections. (b) Crystal lattice of the Sb$_2$Te$_3$ material composed of a typical stacks of quintuple layers of Sb and Te along the main crystal axis. (c) Nano-ARPES intensity map, showing the $E$ vs $k$ dispersion relation along the $\bar{\Gamma}\bar{M}$ symmetry direction in the Brillouin zone of a typical Sb$_2$Te$_3$ nanowire. (d) Zoomed view around the Fermi level of the spectrum in panel (c). (e) An energy distribution curve taken from the nanoARPES map in panel (c), at the $\bar{\Gamma}$ point. (f) Momentum distribution curve at the Fermi level from spectra in panel (c).

3. Quantum transport measurements
Transport measurements, in principle should be able to show straightforward the low-dimensional surface topologic electronic states in TIs materials. For instance, if conduction occurs mainly through the 2D channel, the conductance would scale with the geometry of the sample surface rather than that of the bulk. Moreover, under magnetic fields, oscillations of the magnetoresistance should vary periodically with the inverse magnetic field (1/B). However, despite extensive transport experiments on bulk TIs materials, there has been no report of a conducting surface layer, and the predicted transport properties of the topological features have not been clearly identified.

Several complete transport studies have recently reported in TIs nanowires and nanoribbons, where the ABO have been clearly observed[11, 12, 13]. However, the electronic
structure of the TIs nano-objects has not been inspected, and consequently neither the surface states nor the doping of the TIs nano-objects could have been determined. Figure 1 shows the set-up of the transport measurements, as well as our main transport results. In particular Fig.2d depicts the low-temperature (T = 1.8 K) magnetoconductance versus the B field (depicted in Fig.2c as an black arrow) parallel to the nanowire axis, for three different nanowire width. Panel Fig.2e of the same figure shows the typical I-V curves of the corresponding nanowires reported in Fig.2d. In agreement with theoretical predictions, the area encircled by the TIs surface states, \( S \) (the cross-sectional area of the wire) defines the ABO period, i.e. \( \Delta B = \Phi_0 / S \) [11, 12]. In our case, for the product \( \Delta B \times S \), values of the order of 4-5 \( \times 10^{-15} \) T m\(^2\) have been obtained, which are in excellent agreement with the theoretical expected value of the magnetic flux quantum \( \Phi_0 = \hbar/e \), where \( \hbar \) is Planck’s constant and \( e \) is the electron charge.

4. Electronic bandstructure of Sb\(_2\)Te\(_3\) nanowires

After follow a careful protocol of cleaning the nanowires under ultra high vaccum conditions, using several Ar\(^+\) sputtering cycles, we have recorded Nano-ARPES images disclosing the electronic band structure of individual Sb\(_2\)Te\(_3\) nanowires. They look rather similar to the bulk and TI experimental and theoretical band structured reported previously for Sb\(_2\)Te\(_3\) bulk and films samples [8, 9, 14]. Figure 3 depicts our main results, they have been obtained using the recently developed NanoARPES set-up in the SOLEIL synchrotron[15] All the bulk bands of the Sb\(_2\)Te\(_3\) nanowires are clearly identified and indicated by white points. The characteristic TIs surface states responsible of the quantum transport have been also observed close to the Fermi level. They have been marked by dashed yellow lines in the figure. Since the Fermi level cuts the linear Dirac dispersion slightly below the Dirac point, within the gap of the bulk bands, we can confirm not only the robustness of the TI surface states in the nanowires, but also the p-doped type character of these surface states. This data clearly indicate that the nontrivial topological surface states are responsible of the quantum transport measured in the nanowires.

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6. References

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