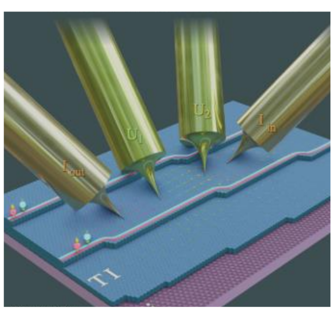
Probing Edge State Conductance in Ultra-Thin Topological Insulator Films

A. Leis, J. K. Hofmann,+ M. Schleenvoigt, K. Moors, H. Soltner, V. Cherepanov, P. Schüffelgen, G. Mussler, D. Grützmacher, B. Voigtländer, F. Lüpke, F. S. Tautz

Peter Grünberg Institut, Forschungszentrum Jülich, 52425 Jülich, Germany

Quantum spin Hall (QSH) insulators have unique electronic properties, comprising a band gap in their 2D interior and 1D spin-polarized edge states in which current flows ballistically. In scanning tunneling microscopy (STM), the edge states manifest themselves as an enhanced local density of states (LDOS). However, there is a significant research gap between the observation of edge states in nanoscale spectroscopy, and the detection of ballistic transport in edge channels which typically relies on transport experiments with microscale lithographic contacts. Here, few-layer films of the 3D topological insulator $(Bi_xSb_{1-x})_2Te_3$ are studied [1], for which a topological transition to a 2D topological QSH insulator phase has been proposed. The samples were grown on silicon-on-insulator substrates by MBE [1]. After the growth, a vacuum transfer into the room temperature 4-tip STM was carried out. Indeed, an edge state in the LDOS is observed within the band gap. Yet, in nanoscale transport experiments with a four-tip STM (Fig. 1), two-quintuple-layer (QL) films do not exhibit a ballistic conductance in the edge channels, as the measured 4-point resistance is fully in accord with finite element calculations using the measured terrace conductivities [2] (Fig. 2). Thus, no QSH edge states are present at the 2 QL films. This demonstrates, that the detection of edge states in spectroscopy can be misleading with regard to the identification of a QSH phase. In contrast, nanoscale multi-tip transport experiments are a robust method for effectively pinpointing ballistic edge channels, as opposed to trivial edge states, in quantum materials.



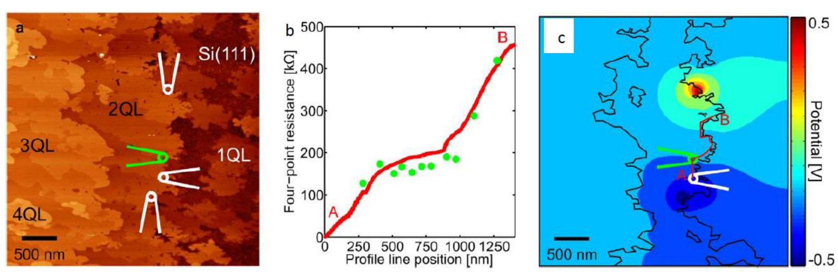


Figure 1: Scheme of the four-tip STM measurement setup.

Figure 2: (a) STM tips positioned at the 2QL step edge. The mobile voltage-probing tip which is moved along the step edge is indicated in green. (b) Measured 4-point resistance compared to FE calculations (red line) using the measured terrace conductivities. (c) Potential landscape from FE calculations.

[1] A. Leis et al., Adv. Quantum Technol. **4**, 2100083 (2021) https://doi.org/10.1002/qute.202100083.
[2] A. Leis et al., Adv. Quantum Technol. **5**, 2200043 (2022) https://doi.org/10.1002/qute.202200043.

+ Author for correspondence: jo.hofmann@fz-juelich.de

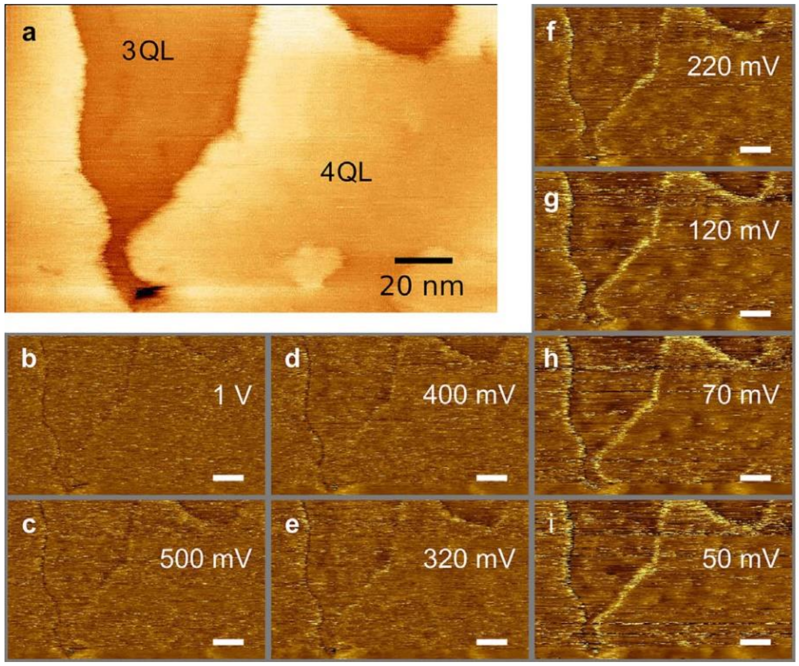


Figure 2: Differential conductance maps close to a step edge of the $(Bi_{0.16}Sb_{0.84})_2Te_3$ film. a) STM topography scan of the investigated area, including a step edge between a 3 QL terrace and a 4 QL terrace. b)-i) Corresponding spectroscopic $\mathrm{d}I/\mathrm{d}V$ maps, recorded in constant current mode at different sample bias voltages between 1 V and 50 mV. A pronounced feature in the $\mathrm{d}I/\mathrm{d}V$ signal along the step edge at voltages below 220 mV indicates an increased LDOS at the step edge, thus an edge state

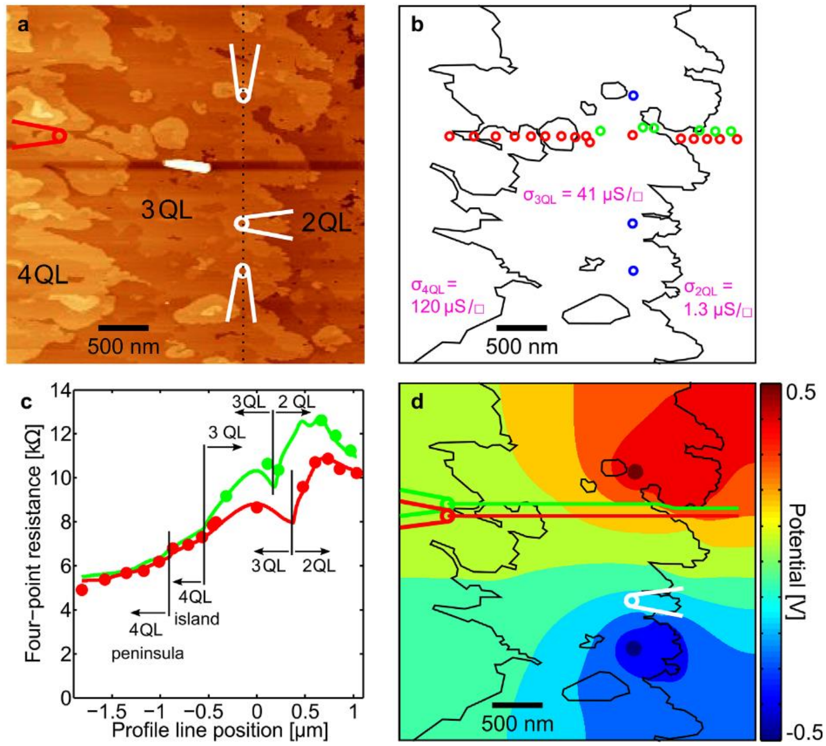


Figure 3:Four point resistance measurement perpendicular to a step edge. a) STM topography image of the investigated $(Bi_{0.16}Sb_{0.84})_2Te_3$ film. White symbols indicate the positions of the current injecting tips (top bottom) and the fixed voltage probing tip. The red tip symbol indicates the mobile voltage-probe tip. While the static STM tips are placed along the step edge between the 3 QL and the 2 QL terraces, the mobile voltage-probing tip is moved perpendicularly to the step edge. b) Outline of the step edges with terrace sheet conductivities indicated. Fixed tip positions are indicated by blue, mobile tip positions by red and green open circles. c) Measured four-point resistance R_{2D}^{4P} (red and green circles) versus position, in comparison with the results if a finite element simulation without a highly conductive edge channel (red and green curves). Characteristic positions along the profile line are marked. d) Color plot of the electric potential $\Phi(x,y)$ from the finite-element simulations without highly conductive edge channel. The step edges are highlighted as black lines. The white symbol indicates the fixed voltage-probing tip the green/red symbol the mobile voltage-probing tip at the first of the red data pints in (c). The trajectories of the mobile voltage-probing tips are indicated by the green/red lines.