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Full Length Article

Electron transport in Bi_2Se_3 ultra thin films

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ABSTRACT

We studied the electronic transport properties of a 4 QL thin Bi_2Se_3 film in the hybridized phase on Si(111) by scanning tunneling potentiometry. When a transverse voltage is applied, the film exhibits a homogeneous electric field on the nm scale. In addition, thermovoltage signals with lateral nm variations are found which result from sample heating by the transverse current. The thermovoltage signals are directly correlated to morphological structures on the surface, i.e. step edges, and indicate a lateral variation of the local density of states at the Bi_2Se_3 surface. No discernible voltage drops appear at the surface so that the whole film serves as a current carrying medium and scattering at surface defects is less important.

1. Introduction

Bi_2Se_3 belongs to the class of 3D topological insulators (TI) [1]. These materials have unique electronic properties [2]: In its interior, an ideal 3D TI is insulating and a spin polarized surface state arises which does not allow for direct backscattering of electrons. This suggests a high conductivity of the TI surface. Both, the high conductivity and the spin polarization, make TIs interesting for prospective devices in (opto-) spintronics [3]. The surface states of TIs evolve due to the difference in the topology at the interface between the TI and an adjacent trivial material (e.g. the vacuum) and cannot be disturbed by weak nonmagnetic impurities or adsorbates [2]. Especially, direct backscattering of conduction electrons is forbidden.

Bi_2Se_3 is a promising 3D TI material which can be easily prepared by epitaxy on the technological important substrate silicon [4–6]. It has a band gap of 0.3 eV which is large enough to prevent intrinsic conductivity at room temperature [4]. This makes Bi_2Se_3 a good candidate for the use in electronic devices. Bi_2Se_3 is a layered material of quintuple layers (QL) [7] and grows in a QL-by-QL fashion [5]. However, for thin Bi_2Se_3 films [8] the surface state at the interface to the vacuum and the surface state at the interface to the substrate have a penetration depth of around 3 QL into the Bi_2Se_3 film. Both states have an opposite spin polarization. Therefore, for thicknesses smaller than 6 QL, both interface states overlap significantly and the direct backscattering in this so called hybridized state becomes possible. In this paper, we want to address the transport properties of such thin films.

The electronic properties of thin Bi_2Se_3 films have already been studied on a macroscopic scale [6,9,10–13]. Aside from conductance measurements there exist measurements of the local differential conductance (dI/dV) by scanning tunneling microscopy (STM) which show the lateral variation of the local density of states (LDOS) [14–17]. Very recently, we have shown that for Bi_2Se_3 films in the topological phase local voltage drops are found at individual 1 QL steps if a lateral current flows through the film [18]. In the case of ultra thin Bi_2Se_3 films in the hybridized phase (3 QL), Wang et al. [17] show lateral oscillations of the LDOS near step edges of the Bi_2Se_3 film which result from electron scattering.

In this work, we directly investigate the electron transport through a 4 QL thin Bi_2Se_3 film in the hybridized phase under realistic transport conditions, i. e. while a lateral current flows through the Bi_2Se_3 film. In particular, we study the electrochemical potential μ_{ec} of the Bi_2Se_3 film by scanning tunneling potentiometry [19], which gives us a detailed view into local transport phenomena.

Abbreviations: LDOS, local density of states; QL, quintuple layer; STM, scanning tunneling microscope/microscopy; STP, scanning tunneling potentiometry; TI, topological insulator.

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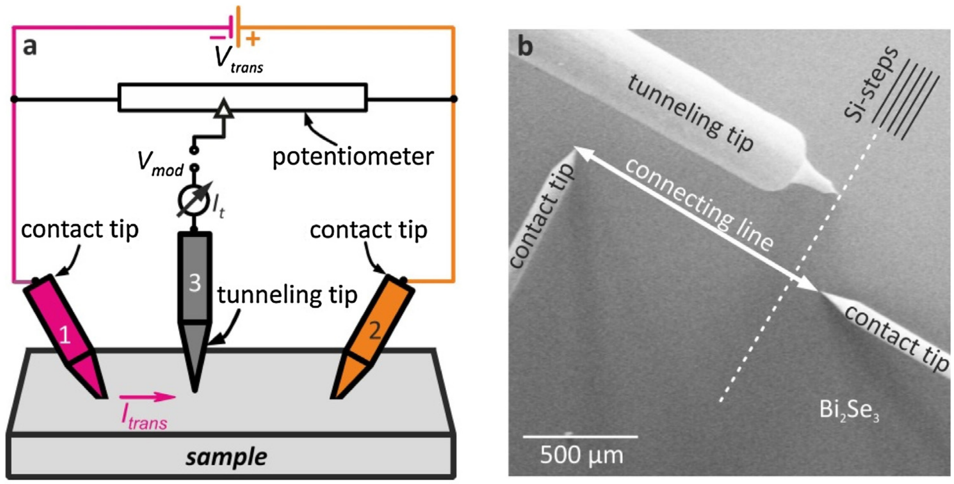

Fig. 1. STP setup. a, Scheme of the STP setup: A transverse voltage V_{trans} is applied by two tips (colored circuit) and leads to a transverse current I_{trans}. A potentiometer connects a tunneling tip to the two contact tips, forming a Wheatstone bridge circuit. The tunneling tip maps the topography and the local electrochemical potential of the sample simultaneously. b, SEM image of the contact geometry on the 4 QL thick Bi_2Se_3 film. The connecting line between the contact tips is perpendicular to the step edge direction of the Si substrate (marked by parallel line array). The distance between the contact tips is about 1200 μm. We measured the surface topography and the corresponding potential for different positions along the dashed line.

2. Experiment

2.1. Method

Scanning tunneling potentiometry (STP) [19] permits us to measure simultaneously the local topography and the local electrochemical potential μ_{ec} of the sample surface with atomic precision. We use a multiprobe STM setup to perform STP [20]. In brief (see Fig. 1a): Two tips contact the sample surface and apply a transverse voltage V_{trans} leading to a transverse current I_{trans}. A third tip is brought into tunneling contact in the area between both contact tips and is connected via a potentiometer to the contact tips. Basically, the system forms a Wheatstone bridge circuit. The bridge is adjusted such that the average DC tunneling current vanishes ($\langle I_t \rangle = 0$). Then the potential applied to the tip and the potential of the surface at the position of the tip are equal. During scanning, the bridge is automatically readjusted so that the lateral variation of the surface potential is probed. The readjusted potential of the tip is recorded and yields the lateral variation of μ_{ec} (for detail see Bannani et al. [21]). In our setup, a small alternating bias voltage V_{mod} is applied to the tunneling contact resulting in an AC tunneling current which is used for the distance control between tunneling tip and surface. Thus, the topography of the sample and its local electrochemical potential (from now on called potential) are recorded simultaneously by STP. The STP geometry is monitored by a scanning electron microscope (SEM, Staib nanofocus 50, see Fig. 1b). All transport measurements (macroscopic and microscopic) presented in this manuscript were performed at room temperature.

2.2. Preparation

The preparation was performed *in situ* under UHV conditions (base pressure < 5×10^{-10} mbar). The amount of deposited material was controlled and monitored by a quartz micro balance and a quadrupole mass spectrometer. The geometrical structure of the sample surface for the different steps of preparation was checked by low energy electron diffraction (LEED). The Si substrate stems from a wafer with a nominal thickness of about 300 μm and a low *n*-doping (phosphorus, conductivity of 7.7 mS/cm) and a miscut of 0.5° (ca. 30 Si-steps/μm).

We prepared thin Bi_2Se_3 films on Si(111) similar to Zhang et al. [9]: At first the (7×7) reconstruction of the Si(111) was formed by flash annealing of the Si wafer up to 1500 K. Bi (purity of 99.997% by Mateck) was deposited onto the (7×7) surface at 300 K (thickness ca. 10 ML) followed by annealing of the sample up to 720 K to form a Si(111)-$(\sqrt{3} \times \sqrt{3})$-Bi reconstruction [22]. This surface serves as template. Bi and Se (purity of 99.999% by Mateck) were then co-evaporated with a Bi:Se ratio of 1:2. The Bi_2Se_3 film was annealed to 420 K for 5 min (in front of a LEED) to ensure a flat and smooth film morphology. The nominal thickness of the prepared Bi_2Se_3 was about 4 QL, which is below the critical value of 6 QL for the TI phase and results in a hybridized phase of the film's electronic structure [8].

Fig. 2a shows an exemplary STM image of the Bi_2Se_3 film. The film appears flat and crystalline. The LEED image in Fig. 2b shows sharp LEED reflexes with a lattice constant of 410 ± 20 pm. The height of a Bi_2Se_3 layer determined by STM is 960 ± 50 pm and agrees well with the reported values from H. Okamato [23] (average value 960 pm, extracted from [23]). Beside Bi_2Se_3 islands, a domain boundary of the Bi_2Se_3 film is also observed (marked by a circle in Fig. 2a) which appears as a thin line of very small height (50 ± 20 pm) and width (150 ± 50 pm) in the STM image. Additionally, another topographic feature is observed, i.e. a large Si substrate step edge seems to cross the image from top to bottom with an apparent height of about 0.30 ± 0.05 nm. This agrees with the height of a Si step (0.31 nm), identifying this as a Si terrace which is covered by the Bi_2Se_3 film.

3. Results

3.1. Two point probe measurement

After preparation, the character of the macroscopic conduction of the Bi_2Se_3 film was measured *in situ* similar to Jaschinsky et al. [24] by our multi probe STM at room temperature. We contact two Au tips to the sample surface at different tip distances and measure the resistance between the tips as a function of probe spacing (see Fig. 3). Contact resistances of the tips only introduce an offset to the resistance data and are easy to handle without affecting the fitted values. The placing of the tips was monitored by SEM (see Fig. 3b).