Transport Studies on Ultrathin Epitaxial Bi_2Se_3 Topological Insulator Epilayers

Y. Arango, J. Kampmeier, T. Merzenich, C. Weyrich, G. Mussler, D. Grützmacher, and T. Schäpers

Peter Grünberg Institute - 9, Forschungszentrum Jülich
52425 Jülich, Germany

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Introduction

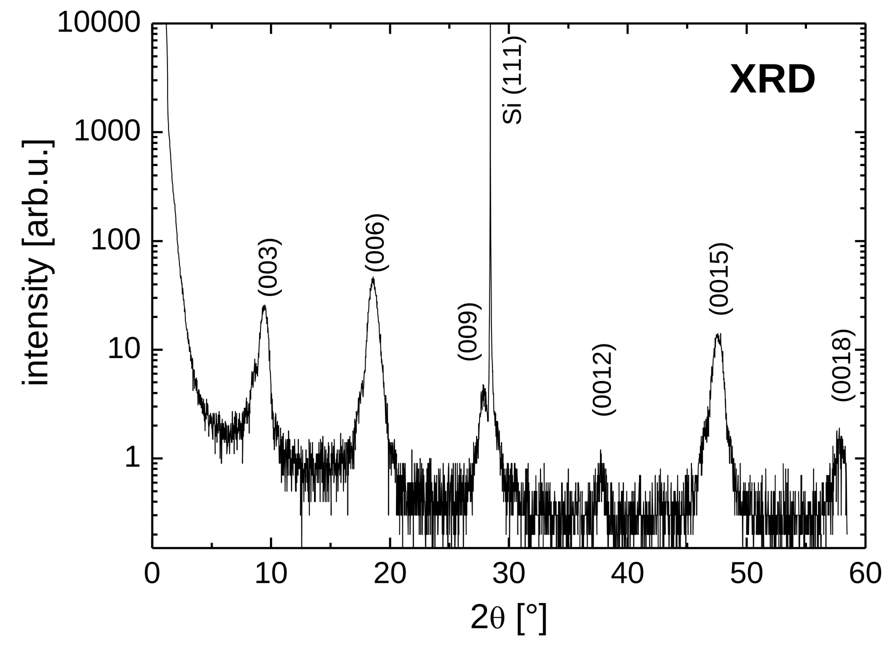
The surface state electronic transport is a key tool for exploring the predicted novel phenomena and feasible applications of the so-called "*next generation*" of 3D topological insulator (TI) materials including Bi_2Se_3, Bi_2Te_3, and Sb_2Te_3. Despite considerable advances, the suppression or at least decoupling of the residual bulk states from the surface states as well as the ability to tune the carrier density remains an experimental challenge. Thin film technology potentially offers pathways to achieve these goals. Hence, in the present study molecular beam epitaxy (MBE) is being employed to grow Bi_2Se_3 films on Si (111) substrates with thickness down to 10 nm. The transport studies from Hall bar structure based devices in the micrometer scale allow to estimate the contribution from surface states and the remaining bulk carriers. In order to reduce the effect of the high bulk electronic concentration and enhance the surface state signal in the Bi_2Se_3 thin films, the proper tuning of the carrier densities through the top-gate voltage is evaluated by testing $LaLuO_3$ as dielectric material.

MBE grown epilayers

Substrate: Si (111) **Growth rate: 4.5 nm/h**

Growth parameters: T_{Sub}: 300 °C, T_{Bi}: 470 °C, T_{Se}: 110 °C

(001) oriented Bi_2Se_3 epilayer on Si (111) substrate



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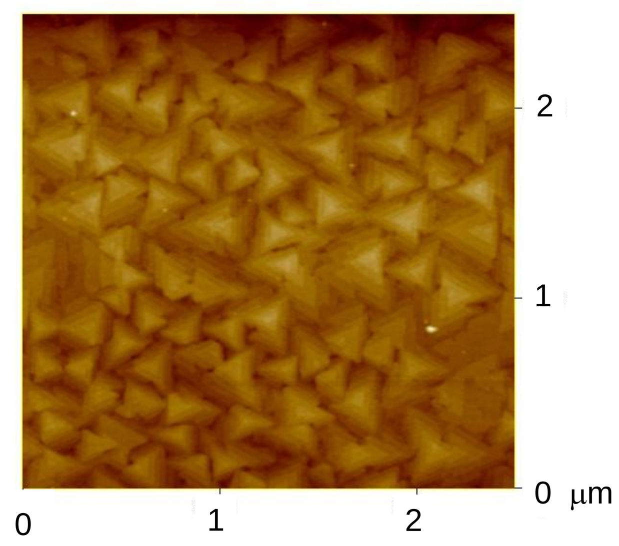
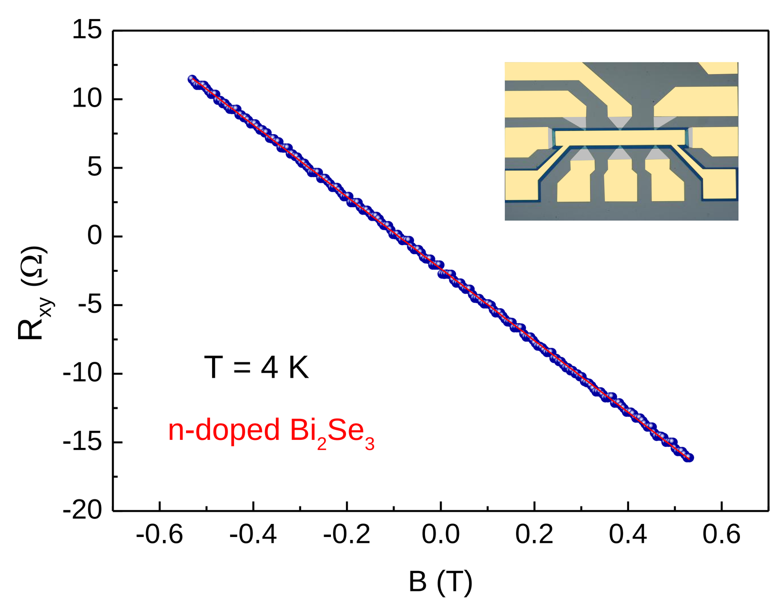


Electronic Transport

Magnetotransport of an uncapped Bi_2Se_3 Hall bar device at low magnetic field

Bi_2Se_3 thickness: 14 nm   Metal contacts : 20 nm Ti / 80 nm Au

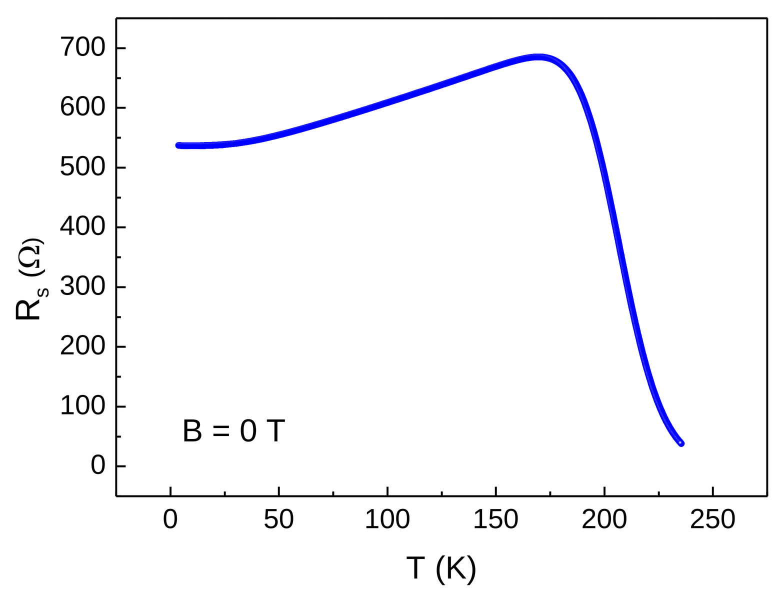
Hall Resistance (R_{xy} vs B)



Carrier density: n_{2D} = 2.385 x 10^{13} cm^{-2}, n_{3D} = 1.7 x 10^{19} cm^{-3}

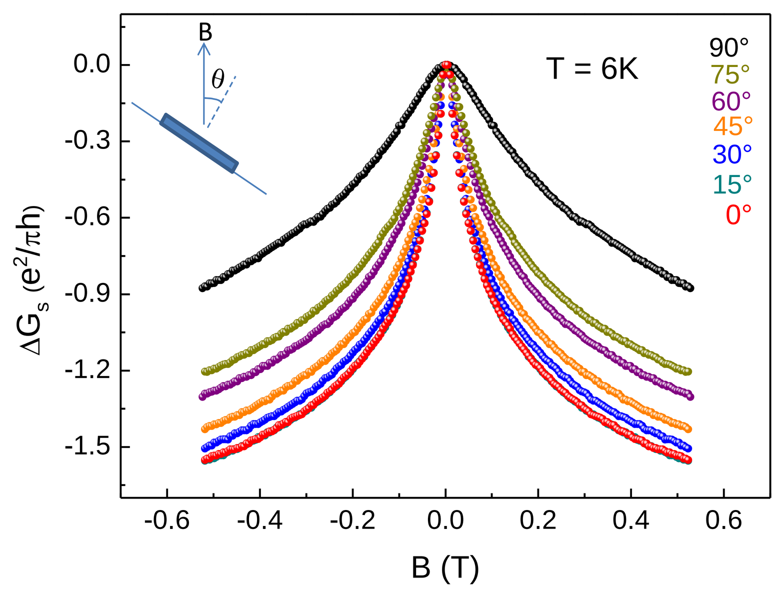
Carrier mobility: μ_H= 479 cm^2/(V s)

Sheet Resistance (R_s vs T)



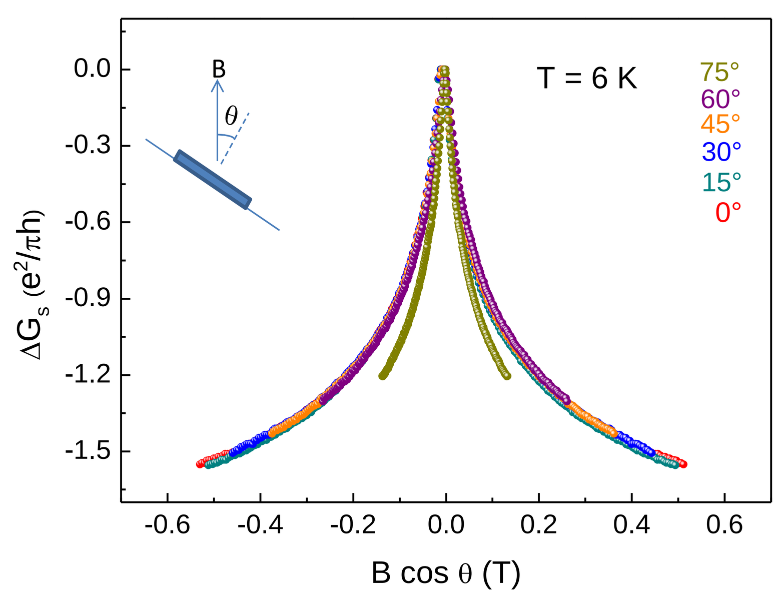
The saturation of R_s at low temperature points out a finite metallic conductivity at T = 0 K.

Weak Antilocalization (WAL)



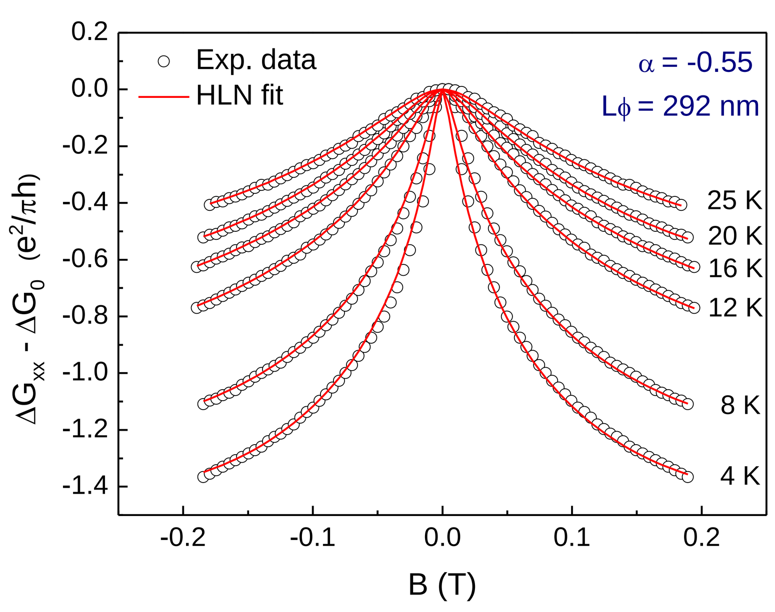
At low field the absence to localization can be attributed to both the bulk spin orbit coupling (3D) and helicity of the surface states (2D).

2D contribution to WAL

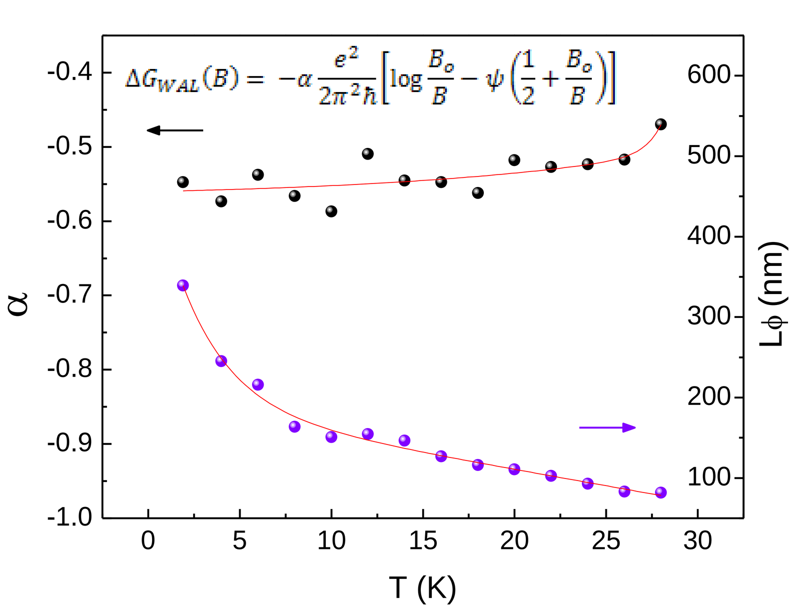


The single trace in the angular dependence of the WAL feature renders immunity to localization caused by the transport of non trivial 2D metallic states.

Hikami-Larkin-Nagaoka (HLN) model for 2D magnetoconductivity



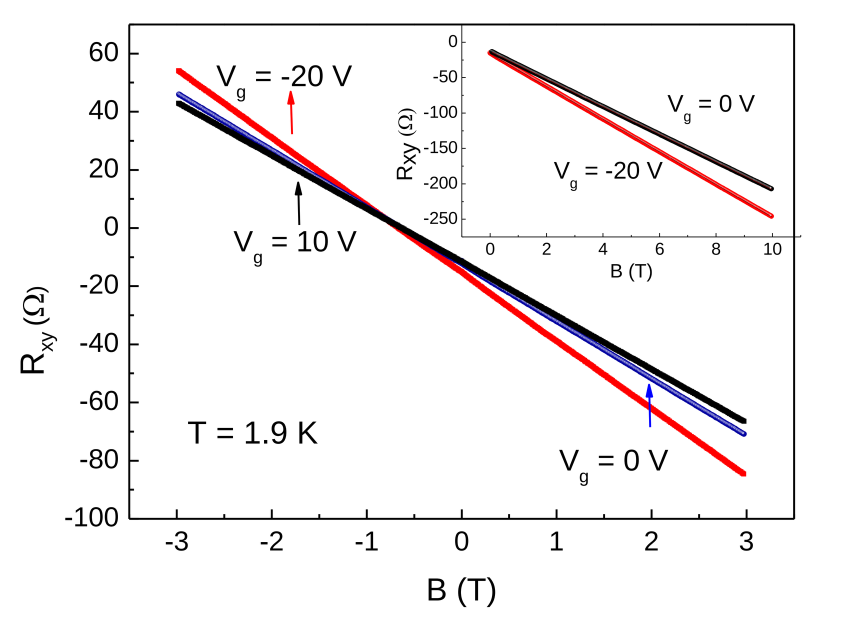
Fit to the low field HLN model: The coherence length is larger than the epilayer thickness, which indicates that the bulk SO coupling contribution is in the 2D limit.



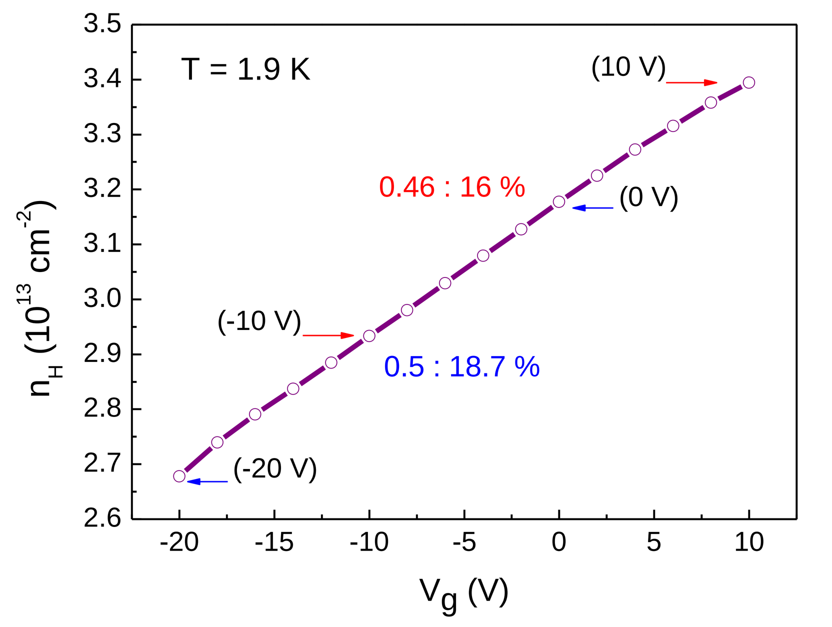
The estimated value α ≅ 0.5 at low temperature suggests a strong coupling of surface states and bulk carriers in a single conductive channel. This is typical for highly doped samples.

Gate-voltage dependence (Top gate: deposited on $LaLuO_3$)

Tunability of the 2D carrier density

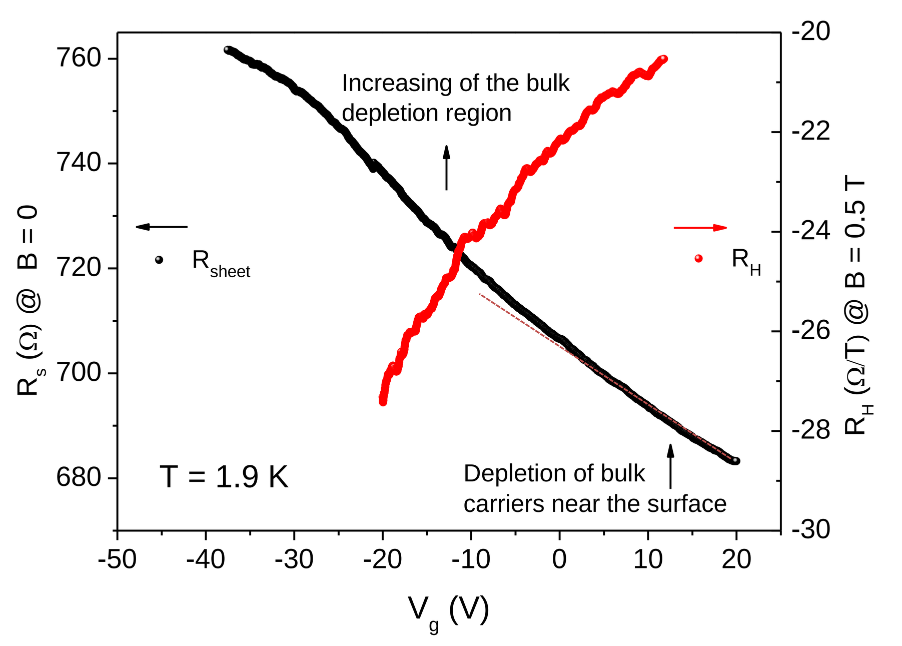


The linear dependence in R_{xy} vs B, indicative of a single type of charge carriers, would reflect the intermixing of bulk and surface states contributions, even at V_g = -20 V.

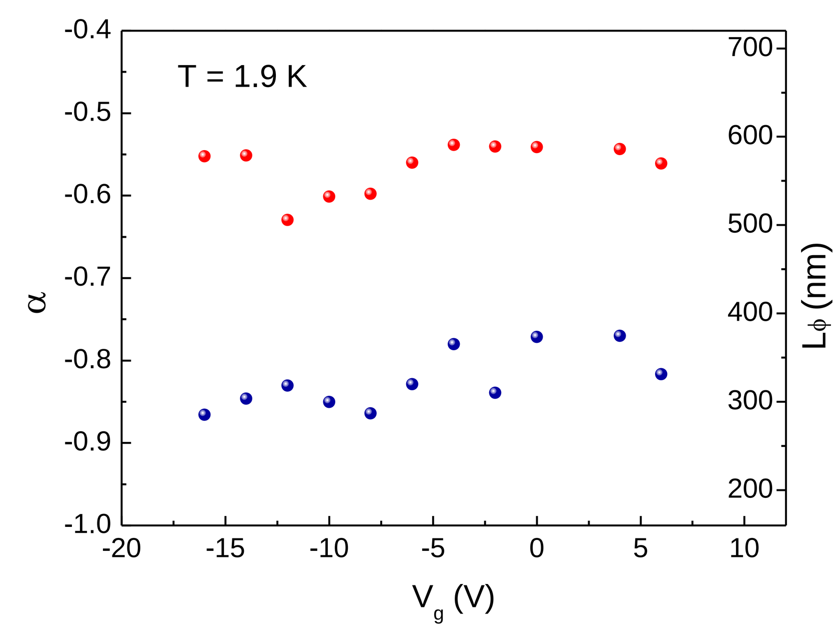


The data show a typical tuning of the 2D carrier density (~16 %) from -10 to +10 V in uncapped Bi_2Se_3 thin films grown by MBE.

Coexistance of bulk and surface state (SS) channels



The carrier type modulation is only partially developed and a higher V_g is required in order to form a bulk depletion region.

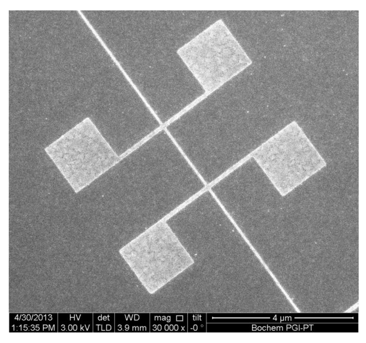


As deduced from the α value (α < |1|), the depletion region at V_g = -20 V is insufficient to coherently decouple the SS from the bulk states at low T (indept. coherent channels).

Summary / Outlook

Bi_2Se_3 epilayers grown by MBE, without a passivation layer, have shown a significant bulk contribution of charge carriers next to the surface state transport. These presumably non trivial metallic states at the surface are strongly coupled to the bulk forming a single transport channel. The attempt for reduction of the bulk carrier density and the effective decoupling of the surface states is currently approached by means of:

- ✓ In-situ Al passivation layer
- ✓ Sb doped Bi_2Se_3 – $(Bi_xSb_{1-x})_2Se_3$
- ✓ Larger electrostatic gating – Testing materials with a high dielectric constant: ZrO_2 and HfO_2
- ✓ Nanostructure fabrication: increase of the effective area of the single domains in the Hall structure for transport measurements



SEM image from a 50 nm linewidth nanostructure (Hall bar)

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