MSc project proposal: Development of resistive gate electrodes / determining the plasmon velocities of QAH edge states

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Summary

Charges within mesoscopic conductors interact via Coulomb repulsion and attraction forces in between individual charges and in between charges and the periodic lattice potential, respectively. Within two- as well as three-dimensional conductive systems the Fermi liquid theory describes these interactions by introducing Landau quasiparticles. Compared to fermions within a non-interacting Fermi gas, the dynamic properties of these fermionic quasiparticles (e.g. mass) are renormalized, depending on their interaction strength. Within one-dimensional conductors, however, the interacting quasiparticle picture breaks down. In these systems charges interact only with their nearest neighbors and can therefore be described as collective excitations within the Tomonaga-Luttinger liquid formalism. Macroscopically, these one-dimensional plasmonic excitations appear as coherent electron density oscillations.

Your task will be to determine the dynamic properties of one-dimensional magnetoplasmons within quantum anomalous Hall (QAH) edge states of the magnetically doped topological insulator V-doped $(Bi_xSb_{1-x})_2Te_3$ (*1*). One edge plasmon can be excited using a voltage step applied through an injector gate. By determining the time-dependent current at an ohmic contact at some distance from the injector gate along the conductive sample edge, the plasmon velocity can be determined (*2*). For full conductance quantization along the one-dimensional edge channels without additional two-dimensional surface or three-dimensional bulk conductance contributions, the electrochemical potential within the channel has to be fine tuned. In order to change the relative position of the Fermi energy electrostatic gates using a parallel plate capacitor geometry are defined by covering the QAH insulator by a dielectric gate oxide onto which a metallic gate is deposited. The capacitive coupling of the plasmon to the gate electrode, however, dephases the high-frequent plasmonic excitations and has been found to lead to a reduction of the plasmons velocity. Therefore, at the beginning of your project you will optimize the deposition of Al-doped ZnO resistive gate electrodes (*3*), for which the coupling to the edge plasmon is reduced due to an increase in the gate electrodes RC charging time. For the definition of these highly resistive gate electrodes you will work at the newly purchased atomic layer deposition tool within the laboratory of the Bocquillon workgroup. Together with our PhD students and PostDoc you will then define devices based on thin films of V-BST, grown by molecular beam epitaxy, provided by the Ando group.

Keywords: **Topological Insulator, Quantum Anomalous Hall Insulator, Atomic Layer Deposition, Edge Magnetoplasmon, Mesoscopic Physics, Electrostatic Gating**

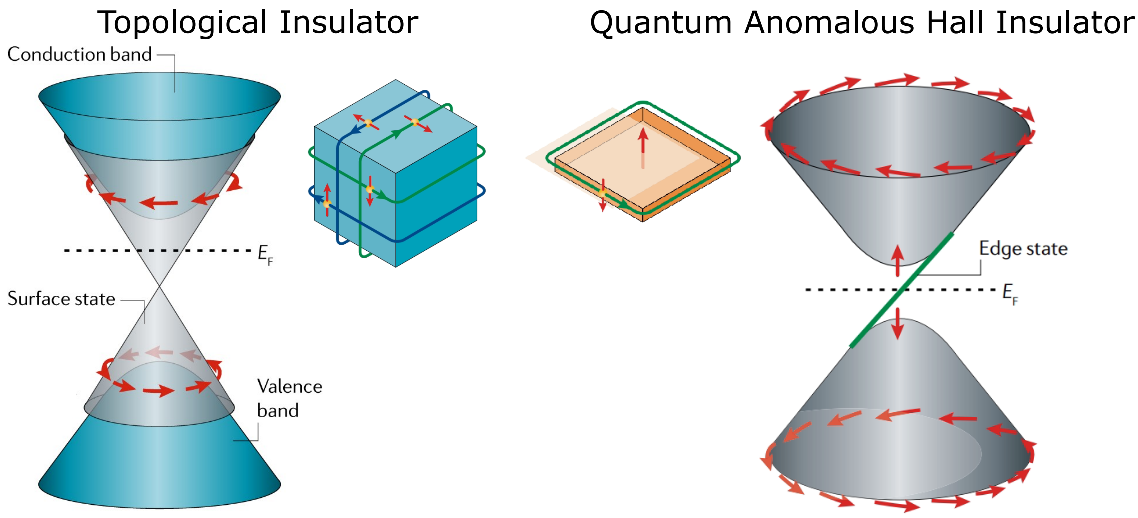

Figure 1: Schematic representation of the surface and bulk state dispersion in topological insulators (TI, left) and the surface and edge state dispersion in quantum anomalous Hall insulators (QAHI, right), adapted from (*6*). The surface state dispersion of the TI is represented by the Dirac cone shown in grey, highlighting the helical spin dispersion of surface charges. Due to a magnetic exchange interaction in magnetically doped TIs an energetic gap in the surface state spectrum around small momenta at the Dirac point established. Within the magnetic gap chiral QAH edge states arise (green).

Research Background

Topological insulators have, compared to trivial insulators, an inverted band structure due to a strong spin-orbit interaction of charges within p-orbitals energetically closest to the Fermi energy (*4*). Well-known examples are the heavy-element binary compounds Bi_2Te_3 (BT), Bi_2Se_3 (BS), Sb_2Te_3 (ST) as well as ternary $(Bi_xSb_{1-x})_2Te_3$ (BST) and quaternary $(Bi_xSb_{1-x})_2(Te_ySe_{1-y})_3$ (BSTS) alloys of these chalcogenide V-VI compounds. The topologically non-trivial band ordering evokes gapless surface states at the interface towards a topologically trivial insulator as bands of the same parity need to connect. This gives rise to metallic surface states with linear Dirac dispersion at the interface of a TI towards a trivial insulator. Due to the strong spin orbit interaction on atomic level, the spin of charges in TI thin-films is also found to be dependent on the charges momentum within the crystal. In three dimensions the band dispersion of the surface states resembles a Dirac cone as schematically depicted on the left side of Fig. 1.

One of the early experimental platforms for the observation of **one-dimensional edge magnetoplasmons** has been the quantum Hall state first discovered in the two dimensional electron gas of a silicon based metal-oxide-semiconductor field-effect transistor (*5*). Within the two-dimensional conducting sheet, a perpendicular magnetic field will give rise to Landau quantisation of circular cyclotron orbits of electronic charges. These Landau levels are bent near the sample edges such that at large enough magnetic fields only a few integer number ν of filled levels cross the Fermi energy at the sample edges, giving rise to a finite number of quantum Hall edge states.
Just recently the **quantum anomalous Hall state** (quantum Hall state with intrinsic magnetic moment) has been experimentally verified in magnetically doped topological insulator materials. These materials include Cr- and V-doped $(Bi,Sb)_2Te_3$ (BST). When magnetised below the Curie temperature (20-30 K) the magnetization of the magnetic dopants within Cr-/V-BST perpendicular to the surface will open an exchange gap around small momenta at the Dirac point of the topologial insulator surface states. Within the exchange gap chiral anomalous Hall edge states give rise to a quantized Hall resistance of h/e^2. The surface state dispersion including the magnetic exchange gap are schematically depicted in Fig 1 (right side).

References

1. G. Lippertz *et al.*, *Physical Review B* **106**, 045419 (2022).

2. N. Kumada *et al.*, *Physical Review B* **101**, 205205 (2020).

3. T. Tynell, R. Okazaki, I. Terasaki, H. Yamauchi, M. Karppinen, *Journal of Materials Science* **48**, 2806–2811 (2012).

4. H. Zhang *et al.*, *Nat. Phys.* **5**, 438–442 (2009).

5. K. von Klitzing, *Rev. Mod. Phys.* **58**, 519–531 (3 1986).

6. J. Wang, B. Lian, S.-C. Zhang, *Phys. Scr.* **T164**, 014003 (2015).