Summary

Topological insulators have sparked ample interest in the condensed matter physics research community in recent years due to their theoretical research value for novel quantum phenomena and potential practical applications, like in spintronics. However, a long-standing problem in the branch of the transport research field is that the bulk conductivity overwhelms the charge transport and therefore hinders the access to the topological surface states in most current topological insulator materials. The first main topic of this thesis is to reduce the contribution of the bulk conductivity in the prototypical topological insulator material $Bi_{2-x}Sb_xTe_{3-y}Se_y$ (BSTS), then detect the topological surface states and investigate their transport properties. As the notion of topological insulators extends to topological superconductors, topological superconductors have become a hot topic as well, notably because they could harbor Majorana zero modes at the surface. Mojorana zero modes are predicted to provide a new route to fault tolerant quantum computation. Therefore, the search for topological superconductors and the determination of their intrinsic properties is a timely research topic. The second main topic of this thesis is to study two candidate topological superconductors ErPdBi and $Sr_xBi_2Se_3$.

In Chapter 2, we present the preparation and characterization of the crystals studied in this thesis, i.e. BSTS (Chapter 4, 5), ErPdBi (Chapter 6) and $Sr_xBi_2Se_3$ (Chapter 7). The BSTS and $Sr_xBi_2Se_3$ were grown by the Bridgman technique, while ErPdBi was prepared by the flux method. The phase homogeneity was investigated by X-ray diffraction and Electron Probe Micro Analysis. The single crystallinity was verified by back-scattering Laue diffraction. Besides we describe the experimental facilities used for investigation of the transport and magnetic properties of these crystals, especially, the Physical Property Measurement System (PPMS) Dynacool. Special attention is

given by the Resistivity option, Horizontal Rotator option, VSM option and ACMS II option are described.

In Chapter 3, we present the general theoretical background relevant to the thesis research. Topological insulators are distinguished by their $\mathbb{Z}_2$ topological invariant, which in centrosymmetric materials can be calculated from the parity of the occupied valence bands at the time-reversal invariant points in k space. Band inversion originating from strong spin-orbit coupling is the root-cause in topological insulators and gives rise to topological edge or surface states with unique properties such as spin-momentum locking and a π Berry phase. To examine their intrinsic insulating behavior in terms of electrical transport, simple criteria given by Mott and Ioffe-Regel with a critical value of the carrier density $N_{BD} = 3 \times 10^{14}$ cm^{-3} and $k_F \ell \sim 1$, respectively, are introduced. Also, band bending effects which affect the transport properties are briefly discussed. Next the theoretical background of the weak anti-localization effect (WAL) and the Shubnikov de Haas effect (SdH) are presented. WAL and SdH used to characterize the topological surface states in BSTS. Finally, the criterion for identification of time-reversal invariant topological superconductors with inversion symmetry is presented, that is, (i) the superconducting pair wave function has odd-parity symmetry and the superconducting gap is fully gapped; (ii) the Fermi surface encloses an odd number of timereversal invariant momenta.

In Chapter 4, an extensive investigation of the bulk-insulating properties of BSTS single crystals is presented. In order to obtain intrinsic bulk-insulating transport behavior, numerous $\mathrm{Bi}_{2-x}\mathrm{Sb}_x\mathrm{Te}_{3-y}\mathrm{Se}_y$ single crystals have been grown around $x = 0.5$ and $y = 1.3$ with composition steps in x of 0.02 and in y of 0.1. Through measurements of resistance and Hall effect, we show that the composition $\mathrm{Bi}_{1.46}\mathrm{Sb}_{0.54}\mathrm{Te}_{1.7}\mathrm{Se}_{1.3}$ has a record-high resistivity and a low carrier density. Since the bulk and surface channels connect in parallel, the surface transport can be enhanced by reducing the sample thickness. We performed resistivity measurements for crystals with different sample thickness and analyzed the measured resistivity at low temperature using a parallel resistor model. The analysis shows when the sample thickness is reduced to 1 μm the surface contribution to the electrical transport amounts to 97 %. Therefore, devices fabricated with submicrometer thickness are sufficiently bulk insulating to exploit the topological surface states by transport techniques. This is further examined by magnetoresistance measurements on an exfoliated BSTS nanoflake that show the weak antilocalization effect. The 2D nature of the weak antilocalization is confirmed by the collapse of the magnetoconductance data as a function of the perpendicular magnetic field component. The 2D weak antilocalization analyzed within the Hikami-Larkin-Nagaoka model yields the fit parameter $\alpha \simeq -1$ as expected for conduction via a pair of topological surface states. No Rashba-split non-topological surface states appear in our $Bi_{1.46}Sb_{0.54}Te_{1.7}Se_{1.3}$ crystals, which is in coincide with our ARPES data recorded under band-bent conditions.

In Chapter 5, we present a magnetotransport study on low-carrier crystals of the topological insulator $Bi_{2-x}Sb_xTe_{3-y}Se_y$ with $(x, y) = (0.50, 1.3)$ and $(x, y) = (0.54, 1.3)$. Shubnikov - de Haas oscillations with a frequency of 63 and 33 T for $(x, y) = (0.50, 1.3)$ and $(x, y) = (0.54, 1.3)$ respectively are observed in high magnetic fields. When tilting the sample with respect to the field, the oscillations collapse as a function of the perpendicular magnetic field component, which confirms their 2D origin. The oscillations are analyzed within the framework of the Lifshitz-Kosevich theory and important transport parameters, such as the cyclotron mass, the mean free path and the mobility are deduced. The Landau level plots are obtained and the resulting phase factors are extracted from the extrapolated x-axis crossing of the linear Landau level plot. The resulting phase factors deviate from the ideal value 0.5 as expected for topological surface states. The deviation is analyzed with a model incorporating a non-ideal Dirac dispersion that was measured directly using ARPES, and a Zeeman coupling-term with large g_s-factor for $(x, y) = (0.50, 1.3)$. Based on the band parameters deduced from ARPES measurements carried out on a sample prepared from the same single-crystalline batch, the SdH oscillations can be attributed to topological surface states with an electron spin g-factor $g_s = 70$ or -54 as fitting parameter in the LL plot model. To estimate the surface contribution, the Hall resistivity for $(x, y) = (0.50, 1.3)$ is fitted within a two-band (bulk + surface) model by combining the carrier density and mobility for the topological surface states from the SdH data. It shows that the surface contribution to the total electrical transport amounts to around 32 % in our $Bi_{1.5}Sb_{0.5}Te_{1.7}Se_{1.3}$ crystal with a thickness of 40 μm.

In Chapter 6, we present electrical transport, ac-susceptibility and dc-magnetization measurements that led to the discovery of superconductivity at T_c = 1.22 K and antiferromagnetic order at T_N = 1.06 K in the non-centrosymmetric half Heusler compound ErPdBi. Bulk superconductivity is inferred from a diamagnetic screening volume fraction of around 90%. The upper critical field, B_{c2}, has an unusual quasi-linear temperature variation which reaches a value of 1.6 T for $T \to 0$. Antiferromagnetic order sets in below T_c and is suppressed by a magnetic field at $B_M \sim 2.5$ T for $T \to 0$. The combination of superconductivity and AFM order is unusual. Possibly, the ordering phenomena occur in different electron subsystems: superconductivity in the low-carrier hole band and local moment magnetism due to Er $4f$-moments. However, since $T_N \simeq T_c$, and ErPdBi lacks inversion symmetry, the interplay of superconductivity and magnetism might give rise to a complex ground state. Moreover, ErPdBi has an inverted band order indicating its non-trivial topological nature from electronic structure calculations, together with the even and odd parity mixed superconducting states, its a promising candidate for topological superconductors.

In Chapter 7, we present the investigation of the upper critical field of superconducting $Sr_xBi_2Se_3$ crystals with T_c = 3 K. When the magnet field is rotated in the basal plane, the angular dependent magnetoresistance curves and the upper critical field B_{c2} both reveal a striking two-fold anisotropy. For $Sr_{0.15}Bi_2Se_3$, the upper critical fields B_{c2} along the two orthogonal directions in the basal plane are 7.4 T and 2.3 T respectively at T_c = 3 K. The effect of flux flow caused by the Lorentz force and the anisotropic effective mass Ginzburg-Landau model both fail to explain the large anisotropy. Two alternative explanations are addressed: (i) unconventional superconductivity with an odd-parity triplet Cooper-pair state (Δ_4 pairing), which recently has been proposed for the candidate topological superconductor $Cu_xBi_2Se_3$, and (ii) self-organized striped superconductivity due to preferential ordering of Sr atoms. The present experiments and results provide an important benchmark for further unravelling the superconducting properties of the new candidate topological superconductor $Sr_xBi_2Se_3$.