Quantum transport in encapsulated graphene p-n junctions

Two dimensional electron gases (2DEGs) have been an exceptional platform and a constant source of new discoveries in quantum physics during the last decades. While for a long time 2DEGs fabricated by molecular beam epitaxy have been the working-horse of quantum transport measurements, with the discovery of graphene in 2004 a new, truly two-dimensional material entered the field. Within the few years since the experimental discovery of graphene it has risen from relative obscurity to the status of an exciting and promising model for 2D solids. The great interest in graphene can be attributed to its exceptional band structure which is described at low energies by the massless Dirac Hamiltonian, where the valence- and conduction-band touch each other at a single point (Dirac point). Being a zero-gap semi-conductor separates graphene from conventional metals and semi-conductors, making it unique of its kind. The ability to combine graphene with various 2D materials in so called Van der Waals heterostructures allows to taylor its properties almost at will. The nearly defect-free grapene lattice holds the potential for ballistic transport over long distances. Futhermore, the refraction index across an n-n' (unipolar) junction or p-n (bipolar) junction can be tuned seamlessly from positive to negative which is unique for graphene. Combining the ballistic transport with the tunability of the refraction index across an interface makes clean graphene an excellent platform for the investigation of various electron optical experiments.

This Thesis focuses on quantum transport phenomena in two-terminal graphene p-n junction, as this combines two bench-mark signatures in graphene, namely the observation of massless Dirac-fermions and the ability to establish gapless p-n junction. The Thesis starts with chapter 2 where important concepts related to the unique electronic band structure of graphene are introduced. This includes the ability to establish gapless p-n junctions, approaches how to characterize clean graphene, the possibility to form superlattices with other layered materials such as hexagonal boron-nitride (hBN) or the possibility to address additional degrees of freedom such as the valley-isospin. In chapter 3 a short comparison between suspension and encapsulation of graphene is given, since these two techniques are the most common ones to fabricate ultra-clean graphene. However, the fabricational details in chapter 4 are restricted to the encapsulation. Furthermore, details on how to fabricate local top- and bottom-gates, which are needed to establish p-n junctions, are given. The currently most common method to establish electrical contact with hBN/graphene/hBN heterostructures is via so called side-contacts. In chapter 5 an alternative approach is introduced to establish inner point contacts, being compatible with the encapsulation-technique. The latter might be of special interest if an isolated electrical contact has to be established in the middle of a hBN/graphene/hBN heterostructure. With chapter 6 the experimental part of the Thesis involving quantum transport in p-n junctions starts. In this chapter Fabry-Pérot resonances in a p-n-p device in the absence and presence of a Moiré superlattice are discussed. Fabry-Pérot resonances can be used to gain information about the exact position of the p-n junction as a function of charge carrier doping and on the yet not fully known band-reconstruction due to the Moirésuperlattice. In chapter 7 we report on three types of magnetoconductance oscillations which can occur along a graphene p-n junction. While several previous studies have tried to explain the observation of individual magnetoconductance oscillations, none of them describes all at the same time. On the contrary, we present experimental results where three different kinds of oscillations are observed within the same device/measurement. The latter allows for a more direct comparison between the different types of mangetoconductance oscillations and we can rule out differences in various device architectures. Finally, we can describe the underlying physics of the different types of magnetoconductance oscillations with a consistent model. Upon further increasing the magnetic field to very high values, the transport is governed by the lowest Landau level. In combination with a p-n junction, which is located perpendicular to the transport direction, conductance oscillations resulting from valley-isospin physics are expected. In chapter 8 experimental results are presented which show signatures of this effect for the first time. By tuning the position of the p-n junction this allows to locally probe the relative edge configuration, giving rise to conductance oscillations in the order of e^2/h. In the last chapter, chapter 9, preliminary experimental results and theoretical calculations on the electrical counterpart of the Michelson Morley interferometer are presented.

List of Publications

“Co-existence of classical snake states and Aharanov-Bohm oscillations along graphene p-n junctions”
P. Makk*, C. Handschin*, E. Tovari, K. Watanabe, T. Taniguchi, K. Richter, M.-H. Liu and C. Schönenberger
Submitted to PRX

“Giant valley-isospin conductance oscillations in ballistic graphene”
C. Handschin*, P. Makk*, P. Rickhaus*, R. Maurand, K. Watanabe, T. Taniguchi, K. Richter, M.-H. Liu and C. Schönenberger
Nano Letters **17**, 5389 (2017)

“Fabry-Pérot Resonances in a Graphene/hBN Moiré Superlattice”
C. Handschin, P. Makk, P. Rickhaus, M.-H. Liu, K. Watanabe, T. Taniguchi, K. Richter and C. Schönenberger
Nano Letters **17**, 328 (2016)

“Point contacts in encapsulated graphene”
C. Handschin, B. Fülöp, P. Makk, S. Blanter, M. Weiss, K. Watanabe,T. Taniguchi, S. Csonka and C. Schönenberger
Applied Physics Letters **107**, 183108 (2015)

“Fabrication of ballistic suspended graphene with local-gating”
R. Maurand, P. Rickhaus, P. Makk S. Hess, E. Tóvári, C. Handschin, M. Weiss and C. Schönenberger
Carbon **79**, 486 (2014)