CONDUCTING CHANNELS AND LOCALIZATION IN GRAPHENE IN A MAGNETIC FIELD

PhD Thesis booklet

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Introduction

Electromagnetic waves are capable of interference, similarly to waves in water. But the energy they carry is absorbed in matter not in arbitrarily small but well-defined, discrete quantities, meaning light can behave like a particle [Planck 1900a; Planck 1900b; Einstein 1905]. Nowadays the wave-like and particle-like properties of light are exploited simultaneously in lasers and LEDs in countless areas of electronics and photonics. On the other hand, particles such as electrons [Thomson et al. 1927; Davisson et al. 1928] are capable of interference, a definitive wavelike property. It is also possible to perform other types of optical experiments with electrons, to create lenses, mirrors and waveguides using electric and magnetic fields. This can be exploited to design solid state electronic devices - most easily in two dimensions - that operate according to the principles of optics, offering new functionalities.

Electron optics devices require ballistic transport, which calls for materials of very high purity. This has been achieved in defect-free semiconductor heterostructures that host a conducting, quasi two-dimensional (2D) electron or hole layer called a 2D electron/hole gas (2DEG/2DHG). The mean free path at low temperature can be well above 100 μm [Kumar et al. 2010]; in comparison, in most metals it is on the scale of nanometers. Charge carrier mobility μ is often used to characterize the quality of semiconducting devices: $\mu \sim 10^5$-10^7 cm^2/Vs corresponds to micron-scale or larger mean free paths.

The discovery of graphene, the first freestanding 2D material [Novoselov et al. 2004], was a surprise to solid state physicists since 2D crystals were assumed to be unstable [Mermin et al. 1966; Fasolino et al. 2007]. As electrons in graphene are naturally confined to a plane, and their mobility even in early samples was found to be several thousand cm^2/Vs, it showed promise in electron optics. Moreover, charge carriers behave as massless Dirac particles, and exhibit a solid state analogue of a relativistic phenomenon called Klein tunnelling [Katsnelson et al. 2006], where the transmission probability through a potential barrier higher than the energy of the particle is unity at normal incidence. Lack of a band gap enables setting up non-uniform doping with capacitively coupled local gate electrodes, even the creation of p-n junctions. These expand the range of possibilities in electron optics compared to 2DEGs: for example, snake states can be created. In addition, 2D Dirac fermions in a magnetic field produce an anomalous integer quantum Hall effect (QHE) [Novoselov et al. 2005; Zhang et al. 2005] which is observable at room temperature [Novoselov et al. 2007]. In addition, quantum Hall propagating states may appear below $B = 100$ mT in high-quality graphene, which would allow their coexistence with Cooper pairs injected from superconducting electrodes, making possible experiments on quantum entanglement in the quantum Hall regime, or the realization of exotic superconducting topological states like parafermions. By electrostatically controlling their trajectories, we may study fractional quantum Hall states via interference, and valley-polarized channels from broken-symmetry Landau levels or induced by strain engineering.

Graphene is a promising material for designing future spintronic devices, as well: due to a low spin-orbit coupling[Gmitra et al. 2009] and low concentration of ^{13}C nuclear spins, the spin state is retained over relatively long distances and time scales [Drögeler et al. 2016]. The spin of charges localized to potential wells called quantum dots (QDs) can serve as so-called quantum bits or qubits [Loss et al. 1998; Trauzettel et al. 2007], which are the would-be building blocks of quantum computers: proposed computation systems able to efficiently solve certain kinds of difficult calculations by exploiting the laws of quantum mechanics [DiVincenzo 2000; Ladd et al. 2010]. Moreover, graphene nanoribbons of a certain edge type may serve as spin-filters [Son et al. 2006] or thin conducting channels in future nanoelectronic devices.

Objectives

The charge carrier mobility of the first graphene devices fabricated on a SiO_2 gate dielectric was on the order of 10^4 cm^2/Vs in the 10^{12} cm^{-2} density range [Checkelsky et al. 2008], corresponding to a mean free path on the order of a hundred nanometers. However, electron optics require ballistic transport on the scale of the device dimensions (typically micrometers), while lack of a band gap in single-layer graphene (SLG) prevents the confinement of charges to QDs via electrostatic depletion. Although beamsplitters and waveguides can be fabricated using p–n junctions, the confinement offered by the p–n transition is imperfect and electrons can leak out. The goal of this PhD work was to investigate the possibilities of fabricating graphene electron optic and quantum electronic devices, from highly conducting channels to quantum dots.

As common graphene nanoribbon (GNR) fabrication techniques produce ribbons with large edge roughness and low conductance [Stampfer et al. 2009; Han et al. 2010], our first objective was to test novel techniques such as carbothermal etching [Nemes-Incze et al. 2010] to create high-quality nanoribbons with well-defined edges. Since transport in bulk graphene samples on SiO_2 is diffusive due to the substrate itself - which is a significant limiting factor for nanoribbons, as well - the second goal was to investigate whether SiN_x is a better substitute. Ultimately, the highest quality can be achieved by suspending and annealing graphene [Bolotin et al. 2008; Tombros et al. 2011]. The mobility of these devices surpasses that of all supported samples: it is on the scale of 10^6 cm^2/Vs, corresponding to mean free paths of several microns. We combined a polymer-based suspension technique with local gates with the aim to study the controllability of ballistic quasi-classical trajectories and quantum Hall propagating states (quantum Hall channels, QHCs) with gate-defined potentials, and to exploit the gaps between Landau levels for electrostatic formation of QDs in SLG.

Thesis points

1 Properties of graphene on SiN_x I investigated the properties of graphene on SiN_x. In order to achieve good visibility for fabrication, first I simulated the optical properties of a $Si/SiO_2/SiN_x$ heterostructure with and without graphene; the oxide layer was included to provide an extra degree of freedom. I fabricated graphene devices on such substrates with dielectric thicknesses close to the optimal values regarding contrast. Using atomic force microscopy, optical microscopy and Raman spectroscopy, I ascertained that the optical visibility and Raman signature of few-layer flakes are adequate for localizing them on a wafer, and for determining their thickness, respectively. After etching and contacting, I performed magnetotransport measurements at 4 K both in the classical and the quantum Hall regimes, and determined the charge carrier mobility. Its maximum value of 4500 cm^2/Vs, and the onset field of the QHE around 4 T, are comparable to values of graphene samples on SiO_2. This demonstrates that SiN_x serves as a similarly good substrate for graphene circuits, and - due to its better chemical stability and its mechanical characteristics - especially for nanoelectromechanical systems.

Related publication: 1.

2 Fabrication of suspended devices with bottom gates I took part in the development of the fabrication process of suspended graphene samples complemented with bottom gate electrodes. The technique consists of predefining gates on an insulating substrate, covering them with a lift-off resist (LOR), transferring graphene - prepared on a sacrificial wafer - on top, fabricating contact leads, and removing LOR from beneath graphene via e-beam exposure. I demonstrated that reactive ion etching does not reduce the stability of a suspended junction. I fabricated and suspended holey devices for the first time. I improved the current annealing technique used to clean suspended graphene to achieve high quality. I performed low-temperature measurements on holey junctions with two bottom gates. Based on the observed quantum Hall plateaus, I have shown the two sides of the hole conduct as two separate nanoribbons that can be switched on and off due to the exchange interaction induced splitting of the zero-energy Landau level above 3 T.

Related publications: 2., 4.

3 Controlling Quantum Hall channels I fabricated and annealed suspended graphene samples with holey bottom gates. Here the density in the center of the device, above the hole is tuned by the Si backgate, while in the outer regions, by the bottom gate. By evaluating low-temperature conductance measurements in the quantum Hall regime, I proposed that for bipolar doping - when the sign of the inner and outer densities is opposite and a circular p-n junction is formed, propagating channels circulate in the center of the device, whose size and coupling to electrodes is controlled by gate voltages. Based on calculations of the position-dependent capacitances, I simulated the trajectories of quantum Hall channels (QHCs), and estimated their conductance contribution using realistic assumptions, which agrees with the transport data.

Related publication: 3.

4 Electrostatic confinement in single-layer graphene in the quantum Hall regime I investigated the transport properties of suspended graphene nanoribbons with a width of 200 nm in high magnetic fields. I observed regular conductance oscillations near the edges of quantum Hall plateaus. Based on their density and magnetic field dependence, I concluded that these are caused by charge transport through single QDs: confinement is enabled due to the interplay of the field-induced Landau gap, a disorder potential from fabrication residues, and electrostatic screening. Their conductance signature is observable because of their forward or backscattering effect between QHCs or contacts, while the dominance of a single QD is the result of the narrowness of the devices. I performed measurements on wide, double-gated junctions, as well, and observed that the conductance fluctuations here - originating in a network of several dots - often show avoided crossings as a function of the two gate voltages, demonstrating double dot formation. My results show a proof of principle on how to define quantum dots in an otherwise gapless SLG in the quantum Hall regime.

Related publication: 4.

5 Ballistic trajectories in a magnetic field I fabricated a suspended graphene sample with double bottom gates in parallel with the two contacts, and through annealing achieved excellent mobility and a record-low onset field (60 mT) of the QHE in SLG. I performed measurements in low magnetic field B, and observed conductance oscillations as a function of the two gate voltages, as well as B, that originated in Fabry-Pérot interference of ballistic trajectories bent by the Lorentz force. At antisymmetric doping, when the density n is opposite in the two halves of the device and thus a p-n junction forms across its width, fluctuations were observed along parabolic contours on $|n|-B$ maps while the quasiclassical description was still valid. Based on tight-binding simulations of conductance and current density, we concluded that they are caused by snake states. These are cyclotron orbits that propagate along the p-n interface, and at its end they scatter on the flake edge either to the source or to the drain contact, producing a switching effect in the current.

Related publication: 5.

Publications related to thesis points

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2. Romain Maurand, Peter Rickhaus, Péter Makk, Samuel Hess, Endre Tóvári, Clevin Handschin, Markus Weiss, Christian Schönenberger: Fabrication of ballistic suspended graphene with local-gating, **Carbon** 79, pp. 486-492 (2014)

3. Endre Tóvári, Péter Makk, Ming-Hao Liu, Peter Rickhaus, Zoltán Kovács-Krausz, Klaus Richter, Christian Schönenberger, Szabolcs Csonka: Gate-controlled conductance enhancement from quantum Hall channels along graphene p-n junctions, **Nanoscale** 8, 19910 (2016)

4. Endre Tóvári, Péter Makk, Peter Rickhaus, Christian Schönenberger, Szabolcs Csonka: Signatures of single quantum dots in graphene nanoribbons within the quantum Hall regime, **Nanoscale** 8, 11480 (2016)

5. Peter Rickhaus, Péter Makk, Ming-Hao Liu, Endre Tóvári, Markus Weiss, Romain Maurand, Klaus Richter, Christian Schönenberger: Snake trajectories in ultraclean graphene p-n junctions, **Nature Communications** 6, 6470 (2015)

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