Final report

OTKA PD121052 - Ballistic electron transport in hybrid nanostructures

The objective of the project was to harness the exceptional electronic properties of graphene, and construct **ballistic electron-optical and spintronics** devices. Although the project was terminated after one year it was successful in several fields: 1) investigation of edge states in graphene p-n junction, 2) study of spin-transport and spin-orbit proximity effects in graphene, 3) superconducting proximity effect in graphene.

The PI was a postdoctoral fellow in the University of Basel before the start of this project, and many of the results come from collaborations initiated there. Meanwhile he started to build up his own group in collaboration with prof. Szabolcs Csonka. The PI has two MSc students, works with 3 PhD students at the moment.

The OTKA PD project which covered the salary of the PI was postponed a year due to the extension of the PIs postdoc period in Basel. The project was terminated **after the first year** by the request of the PI, since he was awarded the Marie Curie fellowship. He will continue the project started within the OTKA PD project with an emphasis on superconducting proximity structures.

Below, we give a detailed description of the scientific result achieved within the project

1) Mach-Zehnder interferences and snake states – investigation of edge state transport and state equilibration along graphene p-n junctions

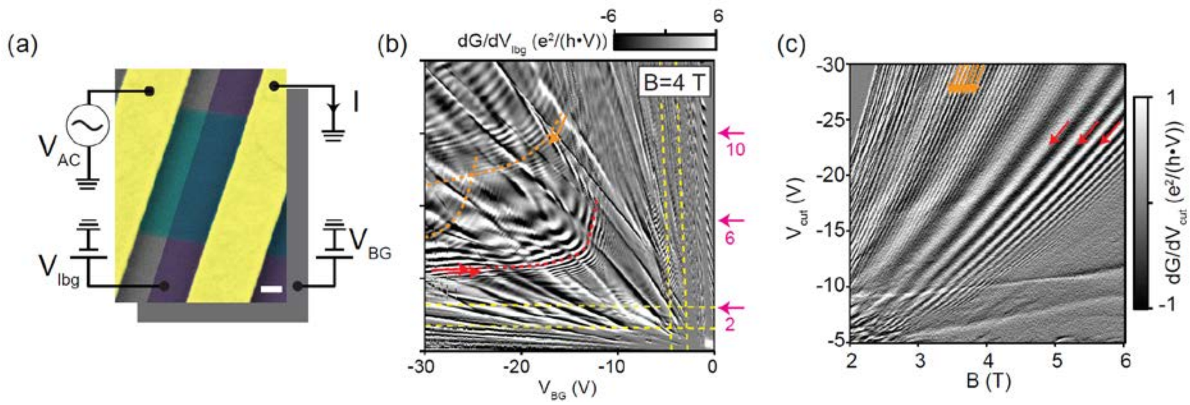

Figure 1: a) False colored SEM image of an ecapsulated graphene pn junction (contacts are yellow, graphene is colored green and the graphite bottomgate is shown by gray. b) Transconductance as a function of left and right gate voltages at 4T shown for the bipolar regime. The magneto conductance oscillations corresponding to snake states and Aharonov Bohm oscillations are shown by red and orange, respectively. c) Transconductance vs. magnetic field and gate voltage showing again the magneto-conductance oscillations.

We have engineered and investigated graphene p-n junction based Mach-Zehnder (or Aharonov-Bohm) type interferometers. For this we have used graphene encapsulated between hBN flakes, and prepatterned graphite gates (see Fig. 1a) which resulted in ballistic devices and allowed the local gating of such devices. The stacks were assembled using van der Waals dry stacking and the measurements were performed in Basel at temperatures of 230 mK-150K at the autumn of 2017 (by the PI and his former PhD student, C. Handschin). The analysis was done in Budapest together with Endre Tovari and the Basel collaborators.

At low magnetic fields classical snake states formed, which resulted in magneto-oscillations as a function of magnetic field and gate voltage (Fig. 1b-c.). At higher fields Landau levels developed and different oscillations appeared. We attributed these oscillations to the Aharonov Bohm oscillations of an edge state interferometer formed by edge state along the p-n junction. We have investigated different regimes, where the interferometer was formed by the 0^{th} and 1^{st} Landau level and a regime where the interferomemeter was formed by spin and valley splitted edge states. We extensively studied the bias, gate voltage, magnetic field and temperature dependence of these oscillations, and investigated the role of the electric field at the pn junction. Finally, we have managed to describe both the low field classical regime and the high field quantum Hall regime using a coherent quantum picture. This also showed, that in several previous reports the measurement results have been misinterpreted. The results were published in Phys. Rev. B. (P. Makk et al., PRB., Phys. Rev. B 98, 035413 (2018)).

2) Spin injection into graphene using spin-pumping

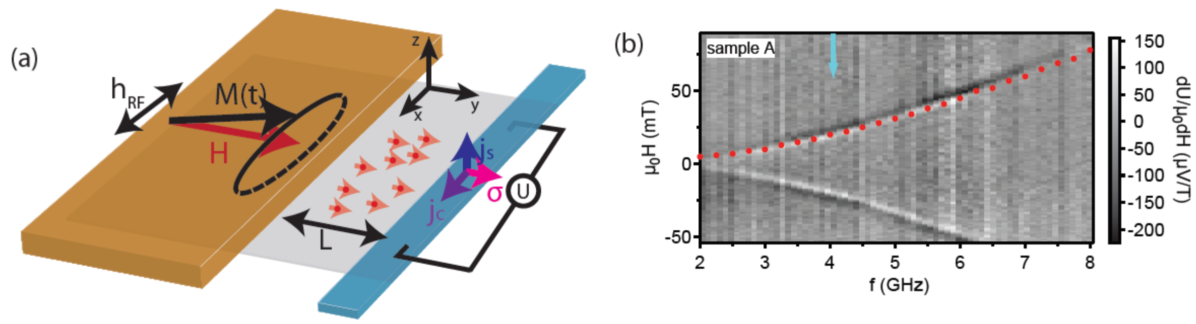

Figure 2: a) Sketch of the device used for spin-pumping (brown: Py island, blue Pt electrode). b) Inverse spin Hall signal measured on the Pt electrode as a function of the external magnetic field and RF frequency. The signal follows well the ferromagnetic resonance condition (dotted line).

Another way to inject spin polarization to nanostructures is using spin-pumping. Here a ferromagnetic island is driven into stable precession using a microwave RF field generated by a stripline (ferromagnetic resonance). The graphene attached to the ferromagnetic electrode opens a new damping channel for the precessing magnetization, which results in the injection of a spin current in the graphene (see Fig. 2a). We have detected the spin-current using inverse spin Hall effect in a Pt electrode. In this experiment no tunnel barrier is needed between the graphene and the ferromagnetic electrode.

The samples were prepared in the summer of 2017 in Basel, and were measured in 2017 autumn by D. Indolese (former student of the PI). The analysis and the modelling was done by the PI, S. Zihlmann and D. Indolese. We have found spin-currents similar to the ones injected by tunnel barriers and spin injection over a wide frequency range (1-8 GHz). Model calculations using literature values (e.g. spin Hall angle of Pt) gave spin-Hall voltages (Fig. 2b.) in good agreement with the measurements. The results are accepted to Phys. Rev. Appl. (D. Indolese et al., arXiv:1806.09356).

3) Induced spin-orbit interaction in graphene using WSe2 substrates

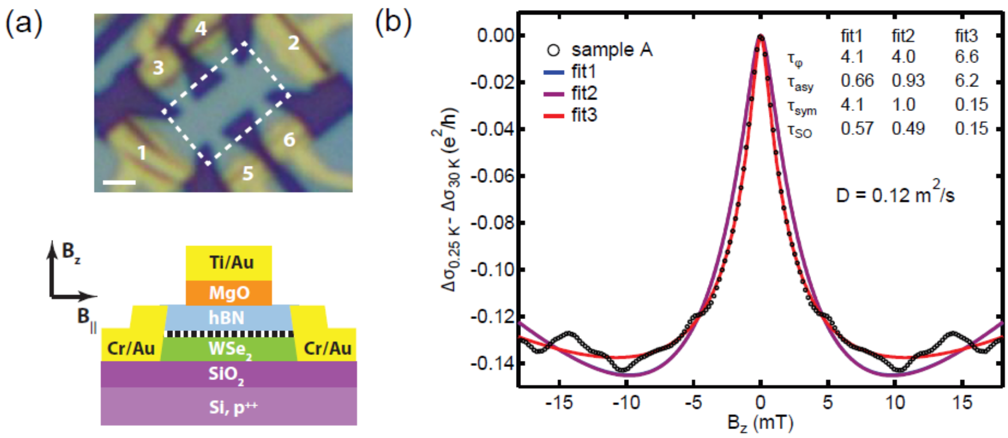

Figure 3: a) Optical micrograph of the sample (before the lithography of the top-gate) and side-sketch of the device. b) Weak anti-localization measurement and different fits and the corresponding spin-orbit parameters given.

We have investigated the engineering of spin-orbit interaction (SOI) in graphene by placing it on other 2D crystals with large SOI. An induced spin orbit interaction could be used for the electrical manipulation of the spin-signal or could result in interesting topological phases. We have measured single layer graphene placed on WSe2 (see Fig 3a). The measurements were done in Basel together with S. Zihlmann and Mate Kedves, the MSc student of the PI. Weak anti-localization measurements showed the presence of spin orbit interaction (Fig. 3b). Further analysis of the data showed that the SOI is valley-Zeeman type (density, in-plane magnetic field dependence). The results have been published with the lead of the PI in Phys. Rev. B. (S. Zihlmann et al., Phys. Rev. B 97, 075434 (2018)).

Since the appearance of the paper we have investigated bilayer graphene (BLG) encapsulated between hBN and WSe2. The difference compared to single layer graphene, that one side of the BLG is contact with the WSe2, which is expected to lead to induced spin orbit interaction present only in this layer. Due to the bandstructure of BLG this leads to spin-orbit interaction only present in the conduction band of graphene. Using electrostatic gating the spin-orbit interaction can be shifted to the valance band. First measurements showed induced spin orbit interaction, however the strength in different band and the gate tenability is still under investigation.

Meanwhile the PI was involved in the study of spin-orbit proximity effect of graphene-BiTeBr structures, where BiTeBr is a giant Rashba material. This is done within a FlagERA project, where localization and spin-valve measurements have been (and currently are) performed (e.g. by one of the master students of the PI, Balint Szentpeteri). Here if a spin-orbit interaction is induced in the graphene or not, is not clear for the moment.

4) Superconducting proximity effect in encapsulated graphene

During his postdoc period in Basel the PI started to work on superconducting (SC) contacts to graphene. First he investigated SC contacts on suspended graphene, later started to work on MoRe contacts to encapsulated graphene.

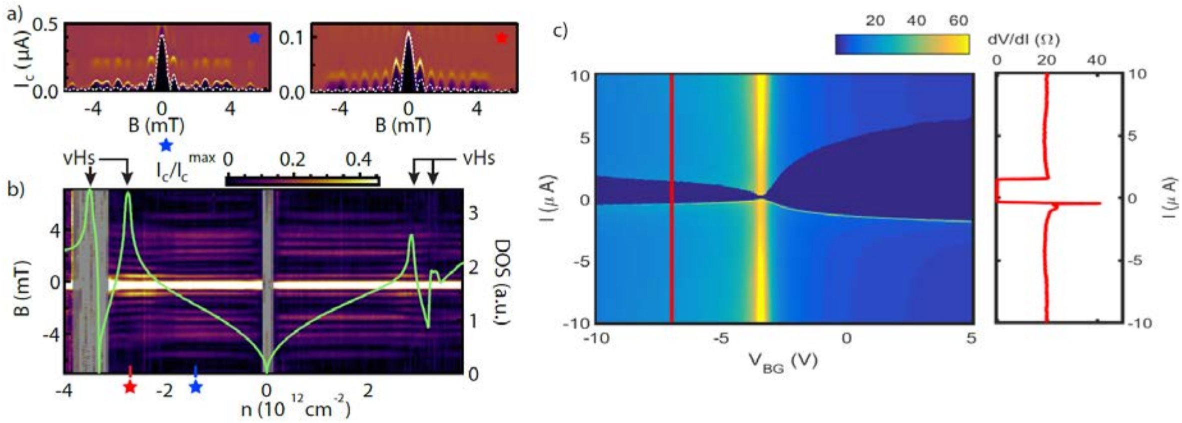

Figure 4. b) Switching current map fro a graphene superlattice as a function of gate voltage and magnetic field. The two stars mark the point where the interference maps of a) were measured. Close to the van Hove singularity (red star) the interference shows more SQUID like behaviour signalling the presence of edge states. c) Measurements on a graphene Josephson Junction made with MoRe electrodes. The color scale shows the differential resistance as a function of gate voltage and current bias. The dark blue state marks the superconducting region. To the right a cut at fixed backgate voltage is shown.

If the crystallographic axis of graphene is aligned with the one of hBN a Moiré superlattice is formed in graphene, and satellite Dirac points appear. By contacting such a structure to superconducting electrodes the band structure of the Moiré superlattice can be studied using supercurrent measurements. The measurements were done in Basel mainly by David Indolese and Raphaelle Delagrange. The analysis of the data was done during the granting period. It was found that the critical current depends strongly on the gate voltage and using this dependence, combined with the normal state resistance of the junction, the density of states of the superlattice could be obtained. This agreed well with theoretical calculations. We have also investigated the magnetic field dependence of the critical current ("interference pattern"), from which the current distribution can be obtained using inverse Fourier transform (see Fig. 4a-b). For one junction we have found a large edge state current at a special point of the bandstructure (van Hove singularity), however it likely has a trivial, non-topological origin (e.g. chemical edge modification during etching). These result were published in PRL (D. Indolese et al., Phys. Rev. Lett. 121, 137701 (2018)).

Since then, SC electrodes have been also tested in Budapest. Whereas NbTiN contacts still give quite large contact resistance (~5kOhm), measurements have just started on samples with MoRe junctions with low contact resistance. First measurements are shown in Fig. 4c.

5) Ferromagnetism in MoS_2 electron gas

MoS2 is a transition metal dichalcogenid, with a large spin orbit interaction. It can be easily exfoliated and localized. The single layer MoS2 has an inversion symmetry breaking and due its structure special selection rules appear for optical transitions. In particular, with a given polarization transitions in a given valley can be excited leading to valleytronics experiments. In these materials optical transitions usually lead to bound states of electrons and holes: excitons and trions. These excitons have extremely large binding energies (existing up to room temperature) and the reduced (2D) dimensionality also leads to enhanced electron-electron interactions. Whereas the band structure in the valence band is pretty well known (due to the large SO splitting), in the conduction band this is not clear yet, likely due to potential fluctuations in the order of the band splitting. However, most theories predicted an unpolarized ground state.

The PI was involved in fabrication of high quality encapsulated single layer MoS2 devices in the group of prof. Richard Warburton in Basel. The measurements analyzed the different excitons and trions formed in the presence and absence of magnetic field. Careful analysis of the data led to the conclusion that due to exchange interactions the MoS2 electron gas becomes spin-polarized even in zero magnetic field. The manuscript summarizing the findings is under review in Nature Nanotechnology (J.G. Roch et al., arXiv:1807.06636).

6) Parallel projects

Since the OTKA PD project only provides salary, some of experimental part of the work and travelling costs were funded by the MTA-Lendület program (PI: Szabolcs Csonka), the OTKA FK-123894 project (PI: Péter Makk). We also acknowledge the Bolyai fellowship. The work has been done in international collaboration, and hence quite substantial part was funded by the EU Commission (Flagship project), Swiss National Science Fund, Swiss National Science Institute and the Japanese MEXT grants.