Ballistic electron transport in low dimensional nanostructures

OTKA-FK 123894

Összefoglaló

A projekt nagy mobilitású grafén heterostruktúrák fejlesztését célozta meg. Míg korábbi tanulmányainkban felfüggesztett grafénre összpontosítottunk, itt a fő hangsúlyt a más 2D anyagok közé szendvicselt grafénre helyeztük. Ez a technika sokféle minta-architektúrát megeged és a grafén tulajdonságainak atomi szinten történő módosítását teszi lehetővé közelségi kölcsönhatások segítségével. A projekt kifejezetten sikeres volt a következő kutatási irányokban: i) a ballisztikus elektron transzport és az ezen alapuló elektronoptikai elemek tanulmányozása, ii) spináramok keltése grafénben, és a grafén sávszerkezetének módosítása a spin pálya kölcsönhatásának létrehozásának érdekében, és iii) egy olyan platform kifejlesztése, amely van der Waals heterostruktúrák mechanikai megfeszítésére használható és amelyet grafén mintákon teszteltünk. A grafén mellett más 2D anyagokat is tanulmányoztunk, mint például a WSe2, a BiTeBr, amelyeket spintronikai alkalmazásokhoz használtunk, vagy a MoS2, ahol először mutattuk meg a ferromágneses rend kialakulását. Ezek a tanulmányok több kutatóintézettel együttműködésben készültek. Itt kiemeljük az együttműködést Christian Schönenberger által vezetett Nanoelectronics kutatócsoporttal a Bázeli egyetemen, ahol a vezető kutató a posztdoktori kutatásait végezte, és ahol a mérések egy jelentős részét végeztük. Kiemelném továbbá a Wigner-MFA intézettel való együttműködést, ahol a nanofabrikációs folyamatok egy része elkészült. A projekt során 4 TKD munka, 3 BSC és 3 MSC dolgozat született. Az eredményeket rangos nemzetközi folyóiratokban publikáltuk, összesen 20 cikk jelent meg (vagy került elfogadásra), amik között Phy. Rev. Lett., Nature Nanoelectronics és több Nano Letters cikk is található.

Hasznosulás/Utilization

Bár az általunk folytatott kutatás alapkutatás jellegű, és nem közvetlen ipari kapcsolatokon keresztül hasznosulnak, a grafén alapú elektronikai eszközökben komoly potenciál rejlik. Ezt jól mutatja a Graphene Flagship, az EU zászlóshajó projektje, ami a kutatási eredmények ipari alkalmazását tartja egyik fő céljának. Talán ebből a szempontból a spintronikai eredményeinket emelnénk ki, amelyek a grafén alapú spintronikai eszközökben játszhatnak fontos szerepet.

Though our project is a fundamental research project without direct interaction with industrial partners, there is a huge potential in graphene based electronic circuits. This is well demonstrated by the Graphene Flagship projects, where one of the main goals is to find industrial applications to graphene based electronic circuits. From this aspect, I would highlight our spintronics research results which might play important role in future graphene based spin valve devices.

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Final report

Summary

The project targeted the development of high quality graphene heterostructures. Whereas as in our previous studies we focused suspended graphene, here the main focus on graphene encapsulated between other 2D materials, mostly. This technique allows versatile device architectures and the modification of the properties of graphene on the atomic level using proximity effects. The project was successful in different research directs: i) Study of ballistic transport and fabrication of electron-optical elements, ii) injecting spin currents into graphene, and modification of its band structure to engineer spin orbit interaction and iii) development of a platform that can be used to strain van der Waals heterostructures, which was tested on graphene samples. Besides graphene, other 2D materials were studied, like WSe2, BiTeBr which we used for spintronics applications or MoS2, where we demonstrated for the first time the formation of a ferromagnetic order. These studies were done in collaboration with several research Institutes. Here we highlight the collaboration with the Nanoelectronics research group at the University of Basel, led by Prof. Christian Schönenberger, where the PI has sent his postdoc period, and where a significant part of these results were measured. I would also highlight the collaboration with Wigner-MFA institute, where some of the fabrication has been done.

The project resulted in 4 BSc and 3 MSc thesis and 3 two theses for the Hungarian Scientific Students' Associations competition (TDK). The results have resulted in the publication (or acceptance) of 20 research papers in leading journals, including a Phys. Rev. Lett., a Nature Nanotechnology and several Nano Letters papers.

Below, we give a short overview of the main results of the project.

Ballistic electron transport

During the project we managed to implement a stacking method that can be used to achieve graphene (or other 2D material) based van der Waals heterostructures with high mobility. With this method samples with mobility above 100’000 cm^2/Vs have been fabricated. This method allows the fabrication of ballistic devices, where the electrons can travel up to a few micrometers without scattering. Therefore, the trajectories of electrons than can be engineered using electric and magnetic fields and electron optical devices, like waveguides or interferometers can be fabricated.

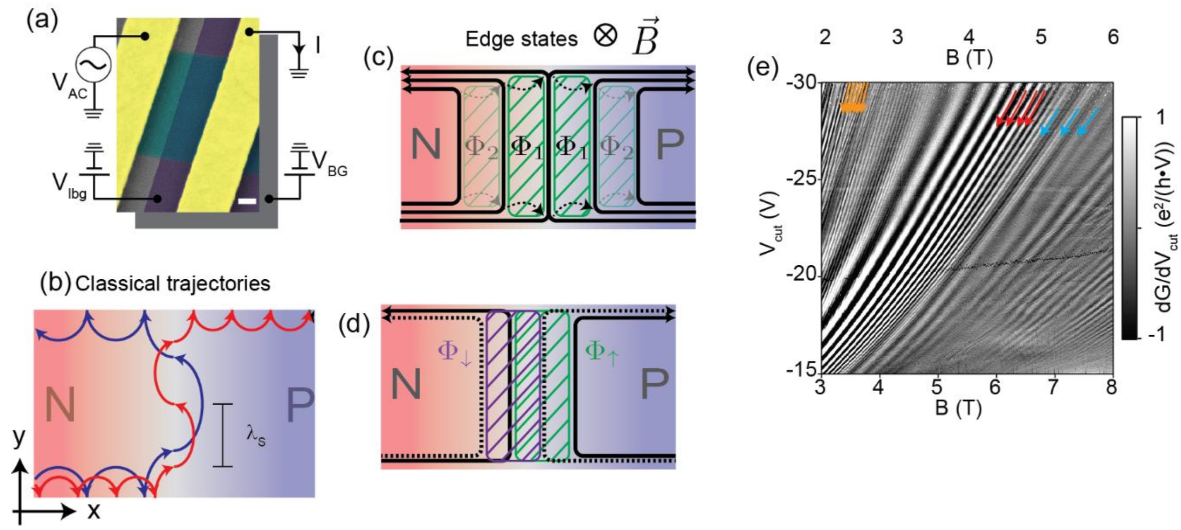

Figure 1. Magneto oscillations in high-mobility graphene pn junctions. a) False coloured SEM image of graphene pn junction. b) Sketch of classical snake states. c)-d) Mach Zender inferometers defined by edge states. e) Measurements on a p-n junction showing a wealth of magneto-oscillation effects.

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 pre-patterned graphite gates which resulted in ballistic devices and allowed the local gating of such devices. At low magnetic fields classical snake states formed, which resulted in magneto-oscillations as a function of magnetic field and gate voltage. 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 0th and 1st 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. [1].

We also started to investigate the formation of interferometers in bilayer graphene (BLG). In BLG a band gap can be opened in double-gate devices, and with special, split gate architectures quantum point contacts can be used to form semi-reflecting mirrors. Experiments on such devices are ongoing.

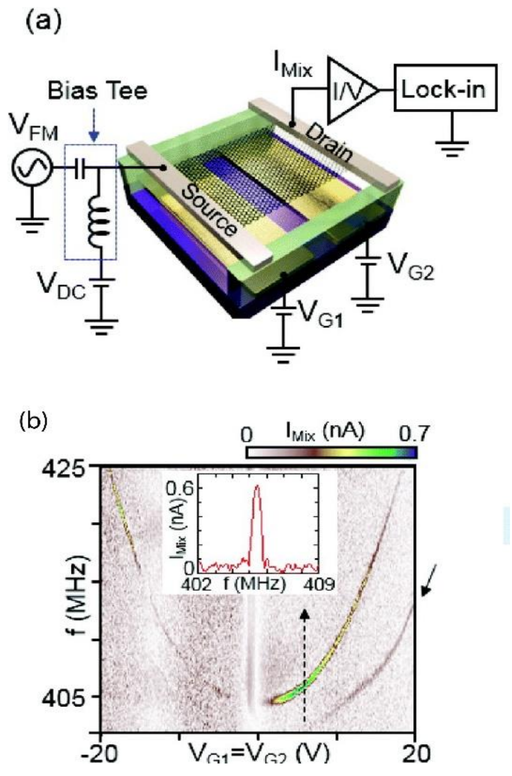

Figure 2: a) Schematics of suspended graphene resonator with the measurements circuit. b) Measurement of a lower frequency resonator. The plot shows the mixing current as a function of frequency and gate voltage with the large currents represent the resonance condition.

We have been measuring and analysing suspended graphene mechanical resonators. Here the PI was involved in the fabrication and measurement (this was done before the project) and in the analysis of the measurement (during the project). We have used graphene as a mechanical resonator, which was suspended using the LOR polymer technique. The driving was done via an RF excitation via the lead (or the gate). At well-defined frequencies this resulted in the oscillation of the graphene resonator (eigenmodes). We modelled the oscillatory motion via simple electrostatic and mechanical model. We also have investigated the effect of a pn junction formed in the middle of the sample on the mechanical motion, and we have found that the resonance signal is greatly enhanced in the bipolar regime. Finally, we have found an extremely high, above GHz eigenfrequency (first mode) of the resonator originating from the large built-in strain in the resonator. This is very promising for the investigation of quantum mechanical oscillators, since this oscillator can be cooled to the quantum mechanical ground state without the need of side-band cooling. These results were published in Nanoscale [2].

Finally, we also have used high mobility hetero-structures to realize novel moiré systems [13,17] and superconducting Josephson junctions [14,16].

Spintronics

A substantial part of the work was focussing on spintronics studies. The goal of spintronics is to use the spin of electrons to code information or to design devices with novel functionalities. Graphene is an ideal material from spintronics, since due to the relative absence of nuclear spins and to the small spin orbit interaction the spins have long spin relaxation times. This, combined with the large mobility enables to carry spin information to large distances. However, injecting spin currents into graphene is challenging. There are different approaches in the literature to deal with this problem.

In the first approach a tunnel barrier is fabricated between the ferromagnetic injector contacts (or detector) and graphene, which leads to larger injected spin currents. The PI has previously investigated hBN as tunnel barrier and found that it can be a good candidate to solve this problem. In parallel with this project these studies continued now concentrating on CVD hBN barrier together with the group of prof. Bart van Wees from Groningen. In the second approach we have used spin-pumping to inject spin polarization into graphene. 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

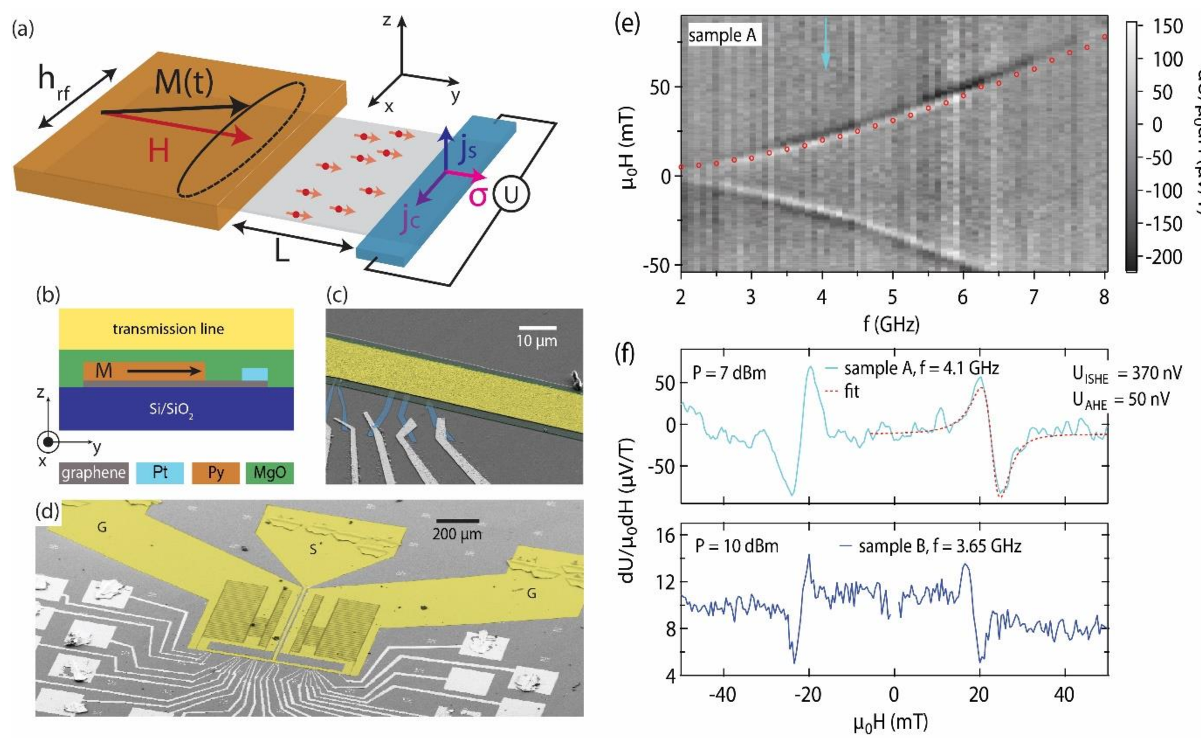

Figure 3. Spin pumping into graphene. a) sketch of the device with the precessing ferromagnet on the left, and the Pt electrode with the inverse spin Hall effect on the right. b) side view of the device c)-d) False coloured SEM images of the device. e) Spin hall voltage as a function of magnetic field and excitation energy. f) Cut around 4GHz, and the result for another device.

results in the injection of a spin current in the graphene. 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 work was done in collaboration with the group of prof. Christian Schönenberger in Basel. We have found 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 in good agreement with the measurements. The results were published in Phys. Rev. Appl. [3].

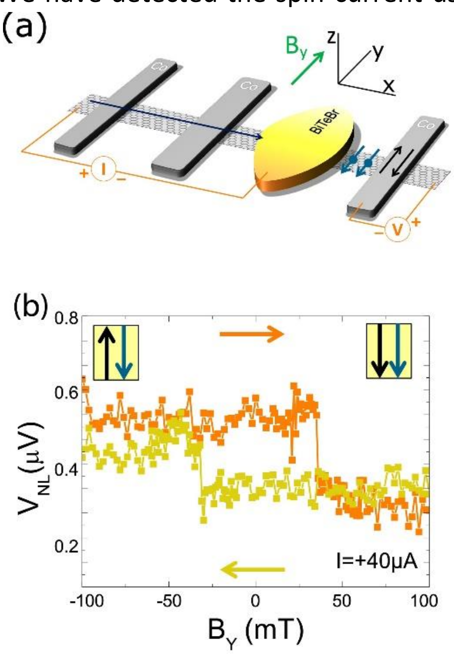

Figure 4. Spin injection using BiTeBr into graphene. a) Device sketch and a non-local measurement in b).

In the third approach we have investigated spin injection into graphene from a BiTeBr crystal, using the Rashba Edelstein effect. In a material with large SOC, like BiTeBr, the electric field leads to a finite spin polarization in the material, where the spin direction can be tuned by the direction of the electric field. This spin polarization can be injected into graphene where it can be detected with ferromagnetic electrodes using non-local measurements. The presence of spin polarization was also verified by Hanle measurements which is usually used to extract spin lifetimes in spin valve devices. The work was done in collaboration with the group of prof. S. Dash in Chalmers, and started as part of a FlagERA project. The analysis and publication was done within this OTKA project. The work has appeared in Nano Letters [4]. We have also used BiTeBr to investigate the gate tenability of a non-reciprocal transport process [15].

Whereas the lack of spin orbit coupling (SOC) in graphene allows long distance spin transport, several proposals suggested that the presence of SOC could allow electrical manipulation of spin currents or the engineering of topological states. We have investigated the engineering of spin-orbit interaction (SOI) in graphene by placing it on other 2D crystals with large SOI. We have measured single layer graphene placed on hBN. The measurements were done together with the group of prof. Christian Schönenberger in Basel. Weak anti-localization measurements showed the presence of spin orbit interaction. Further analysis showed that the SOI is valley-Zeeman type. The results have been published with the lead of the PI in Phys. Rev. B. [5]. In further studies we have managed to show that the SOC coupling can be boosted by applying hydrostatic pressure. The pressure pushes the graphene closer to the WSe2 and increases the SOC. These studies were mostly part of another FlagERA project [6,7].

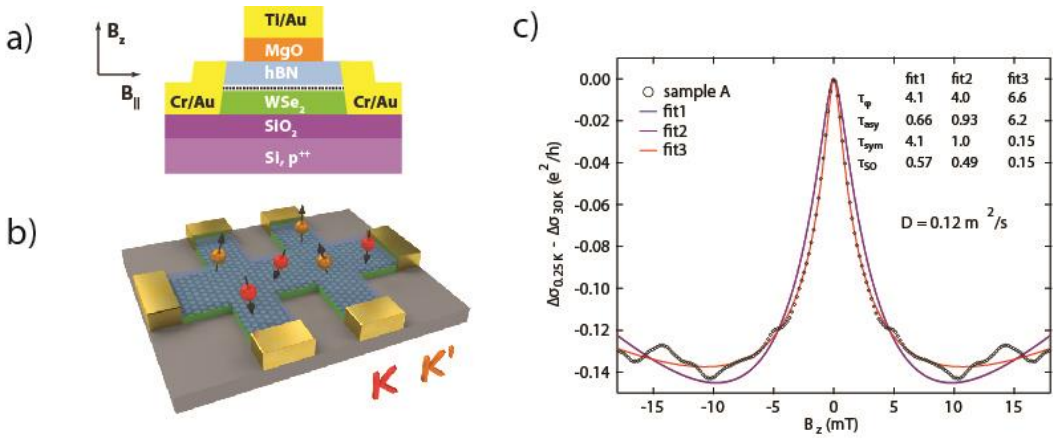

Figure 5. Induced spin orbit in graphene/WSe2 heterostructures. a) Sketch of the device under study. b) Artistic view of the Hall bar with the effect of valley Zeemann term on the spins. c) WAL measurement with the fit parameters shown in the legend.

The PI was involved in the fabrication and analysis of nano-optical measurements in encapsulated MoS2. More precisely, we have fabricated MoS2 samples, which were encapsulated between hBN crystals, contacted by graphene and could be also gated via a back-gate. We have studied optical absorption using a low temperature confocal microscopy setup, using circularly polarized excitations in different magnetic fields. In MoS2 (and other TMDCs also), valley selective excitations can be performed by using circularly polarized light. Also due to strong electronic correlations excitons and trions (excitations containing bound electron hole pairs) form with a large binding energy. We have investigated the different excitons and trions under different doping, polarization and magnetic fields and our studies pointed to the direction that at low doping the MoS2 gas becomes unstable towards a ferromagnetic ordering. This ferromagnetic state is broken down at high magnetic fields. These results were published in Nature Nanotechnology [8].

Strain engineering

Another large part of the work focused on strain engineering in graphene. The goal is to strain graphene controllably while measuring transport on it. It is predicted that certain strain patterns could lead to pseudo magnetic fields in graphene. The idea was to strain graphene using a so-called break junction setup, which the PI worked on during his PhD. First trials were on suspended graphene which we tried to strain. Raman measurements confirmed the straining, however, we could cur-rent anneal these samples which is needed for suspended graphene to achieve high mobility devices. Therefore, we combined break junction method with encapsulated devices. We have found using Raman measurements that we can generate uniaxial strain, while keeping the high mobility of the devices. We have also shown by Raman measurements, that strain patterns needed to realize pseudo magnetic fields can be realized. These results were published in Nano Letters [9].

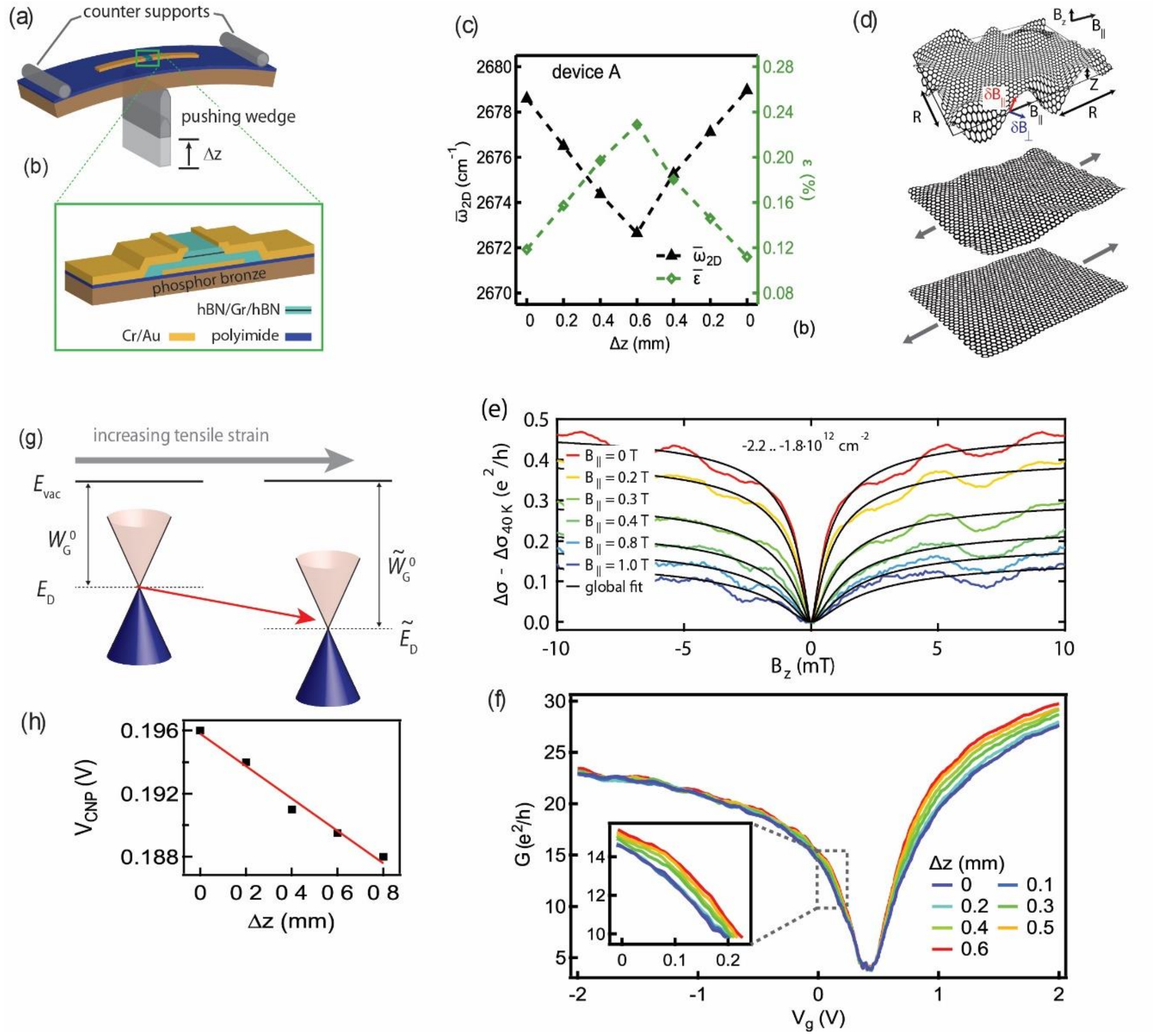

Fig. 6: Strain tuning of graphene samples: a)-b): Break junction setup for straining. The displacement Δz tunes the strain level. c): Position of the 2D peak position is shown vs. electrode displacement. d): Sketch of ironing strain fluctuations using strain. Dephasing due to ripples is also shown: in plane magnetic fields lead to random out of plane magnetic fields. e) Weak localization curves for different in plane magnetic fields. For larger fields the phase coherence time decreases. f) Bottom right: Conductance measurement as function of gate voltage for different strain levels. A clear increase of mobility is observed. g) Sketch of workfunction change with strain. h) Measurement of scalar potential on encapsulated graphene as a function of electrode displacement (strain).

The application of strain in graphene also leads to the appearance of a scalar potential, which renormalizes the work function of graphene. Recently we have managed to detect this using transport measurements. The work was published in Nat. Comm. Phys. [11].

We have investigated what limits the mobility of high-quality encapsulated graphene. One theory was, that it is limited by residual remote Coulomb scattering, whereas another theory suggested the role of strain fluctuations. By in-situ straining an encapsulated graphene and measuring its transport properties at low temperatures we have proven that indeed strain fluctuations result in additional scattering via locally varying scalar and vector potential. We have managed to increase the mobility of our samples with more than 30% by straining and confirmed our results using Raman measurements. The results have been published in Phys. Rev. Lett. [10].

Whereas our straining measurements have shown that the graphene structures have local strain fluctuations, if these strain fluctuations are in or out of plain were not clear. Another set of measurements have indicated that the strain fluctuations are out of plain: the graphene stack is corrugated. We have verified this using weak localization measurements and by using an additional in-plain magnetic field. In presence of random out of plane corrugations in graphene the in-plane magnetic fields lead to locally varying, random out-plane magnetic fields. This results in dephasing of the weak localization. The presence of out of plane corrugations was observed in several samples, even in samples with ultra-high quality. From simple modelling the corrugation volume can be also extracted and could be crossed check with high resolution AFM images. This study appeared in Phys. Rev. B. [12].

Major investements

During a project a larger investment was the purchase of a vector magnet system, which was combined with a low-loss helium dewar (purchased from another project), which allows the study of nanostructures in the 1.5-300K temperature range in magnetic fields 3/3/9T (x/y/z-direction), which is of utmost importance for spintronics studies. Two low temperature inserts were also developed during the project and the micromanipulator assembly used to fabricate heterostructures was also upgraded.

Parallel research

The running costs of this projects heavily exceeds the budget of the current proposal. The PI has received his salary from an OTKA PD project, then later from a Marie Curie and the Bolyai grant. Some of the research was funded by the Nanoelectronics momentum grant and some of the measurements were funded by the partners from abroad, where the measurements were done. Some of the work was started before the project, when the PI was a postdoc in Basel, as written above, also part of a FlagERA project IspinText. In parallel to this project the PI was the coordinator of a FlagERA network Topograph, which focused on the development of graphene based superconducting circuits and the role of SOC in superconducting correlations see e.g. [14,16-20].

Publications

Thesis

- Szentpéteri Bálint, TDK thesis - *Nem-lokális spintranszport mérések grafén/BiTeBr heteroszerkezetekben*
- Kocsis Matyas, TDK thesis- *Tuning the Rashba parameter in BiTeBr with ionic-liquid gating*
- Kedves Máté, TDK thesis - *Towards engineering topological states in graphene*
- Márffy Albin, BSc thesis- *Van der Waals heteroszerkezetek vizsgálata nyomás alatt*
- Márffy Albin, TDK thesis - *Kétdimenziós nanoáramkörök vizsgálata nyomás alatt*
- Szentpéteri Bálint, MSc thesis - *Spin fizika kétdimenziós heteroszerkezetekben*
- Kedves Máté, MSc thesis – Quantum effects in graphene
- Márffy Albin, MSc thesis - *Van der Waals heteroszerkezetek létrehozása és vizsgálata nyomás alatt*
- Pápai Tamás, BSc thesis - *Szupravezető áram-fázis reláció grafén heterostruktúrában*

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