Publications

In this project 1 article has been published in Nature and 2 in Phys. Rev. Letters. The **cumulative impact factor** of the publications is **49.14.**

[1] L. Hofstetter, S. Csonka, J. Nygard, and C. Schönenberger, *Cooper pair splitter realized in a two-quantum-dot Y-junction*, Nature 460, 906 (2009).
[2] Hofstetter L, Geresdi A, Aagesen M, Nygarid J, Schonenberger C, Csonka S *Ferromagnetic Proximity Effect in a Ferromagnet–Quantum-Dot–Superconductor Device.* Phys. Rev. Lett., 104, 246804. (2010)
[3] I. Weymann, G. Zaránd, S. Csonka *Gate tunable spin current amplifier, under preparation* (2011)
[4] A Halbritter, P Makk, Sz Mackowiak, Sz Csonka, M Wawrzyniak, J Martinek *Regular Atomic Narrowing of Ni, Fe, and V Nanowires Resolved by Two-Dimensional Correlation Analysis.* Phys. Rev. Lett. 105, 266805. (2010)

[d1] G. Fülöp, BSc Thesis, *Fabrication of Nanostructures with e-beam lithography*, BME TTK (2009).
[d2] A. Márton, BSc Thesis, *Investigation of nanoscale circuits at low temperature*, BME TTK (2010).
[d3] G. Fülöp, TDK work, *Improvement of Cooper pair splitter nanocircuits*, BME TTK (2010).
[d4] E. Tóvári, TDK dolgozat, *Fabrication of graphene nanoribbons*, BME TTK (2010).

Conference contributions, talks

- Fifth International School and Conference on Spintronics and Quantum Information Technology, SPINTECH V, Kraków, Poland, 07/07/2009 . „Two Quantum Dots Cooper Pair Splitter based on InAs Nanowire" talk
- International Conference on Quantum Phenomena at Nanoscale, Montenegro, Aug. 30 - Sep.45, 2009. „Crossed Andreev Reflection in Metallic and Semiconducting Nanowire Based Hybrid Devices" talk
- Seminar at Quantronics Group, CEA Saclay, France, 04/2009 „Quantum electronics devices based on InAs NWs" talk
- Condensed Matter Theory Seminar, University Basel, Switzerland, 25/06/2009, „Two Quantum Dots Cooper Pair Splitter based on InAs Nanowire" talk
- 24th International Winteschool on Electronic Properties of Novel Materials: "Molecular nanostructures", Kirchberg/Tirol, Austria, 7/03-12/03/2010 "Cooper pair splitter realized in a two-quantum-dot Y-junction" poster presentation
- Seminar at Kavli Institute of Nanoscience at Delft University of Technology, Delft, the Nederlands , 04/2010 "Cooper-pair splitter realized in a two-quantum-dot Y-junction", Talk

- Ortvay Seminar Series, Eotvos University Budapest, Hungary 10/05/2010 “Cooper-pair splitter realized in a two-quantum-dot Y-junction", Talk
- ESF network INSTANS workshop ,Time-dependent dynamics and non-equilibrium quantum systems, Budapest, Hungary", 05/2010 "Cooper pair splitter realized in a two-quantum-dot Y-junction", Talk
- Swiss Physical Society Meeting, Basel, CH, 10-12/06/2010 "Cooper pair splitter realized in a two-quantum-dot Y-junction",Talk
- Spin-based quantum information processing, Konstanz, DE 16-20/08/2010 G. Fulop, A. Geresdi, C. Urbina, L. Hofstetter, C. Schonenberger, J. Nygard, G. Mihaly, S. Csonka “Electron distribution function in InAs Nanowires”, Poster
- Theoretical Physics seminar, BME, Budapest, Hungary 26/11/2010, ’Transport in InAs nanowire hybrid structures’, Talk
- Seminar at CEA Saclay, France, 12/2010 „Quantum electronics devices based on InAs NWs” talk
- MAFIHE Winterschool, Budapest, 02/2011, ’Electron transport in graphene’ talk
- Moriond 2011, Quantum Mesoscopic Physics, La Thule, Italy, 03/2011, “Cooper pair splitter realized in a two-quantum-dot Y-junction” poster presentation

Fabrication and Electron Transport Study of Nanowire based Quantum Devices

1. Introduction, goals

During the last four decades an enormous development has been archived in the computer hardware, which has dramatically increased the usefulness of digital electronics in every segment of science, economy and daily life and significantly contributed to the social and technological changes of the last half century. The continuous miniaturization of the electric circuit elements has given the driving force of this development. However, in the present days we are reaching the physical limits of the applied technologies and new alternatives are required for further improvements. Overcoming this technological challenge is a central issue of nowadays NanoScinece and Technology and has a high impact on **sustainable development** and on our future society as well. Based on the International Technological Roadmap for Semiconductors (ITNS, 2007), nanowires are one of the promising materials that could provide potential solution for these future technological needs. The present proposal contributes to this field with focusing on the fabrication and electron transport study of novel semiconductor nanowire based devices.

When the size of an object reaches the nanoscale, quantum mechanical effects start to manifest in its transport properties. The field focusing on these quantum effects - often called **quantum electronics** - has achieved enormous progress in recent years to reach a full control of the charge and spin at the single electron level, which is essential for future quantum information processing and spintronics applications.
Quantum dot (QDot) [1] is one of the central objects of quantum electronics. It is a small region of space (e.g. metallic grain, molecule, nanotube, confined region in 2DEG) connected to a source and a drain electrode. Due to the quantization of the electron charge and the discrete states of the confinement, a dot can only be filled sequentially with electrons. The fascinating feature of this zero dimensional object is that the charge transport can be controlled at the single electron level. It behaves as an artificial atom with the possibility to analyze atomic states by electron transport through the attached leads. The study of QDots has contributed to understand fundamental questions of physics, like the many-body Kondo-effect [2].

Semiconducting nanowires (NW) provide a new class of building blocks to fabricate quantum electronic devices. Due to the recent development in growth technologies, a high level of control over the structure of these single-crystalline objects was achieved: several compositions, heterostructures and different dimensions (e.g. for InAs diameters >40nm, lengths up to 4 - 8µm) are available [3]. Fabricating metallic leads to NWs electric devices can be produced. Since the electron density of the NW can be strongly varied by gate electrodes, the transport behavior can be explored from the quasi-ballistic to the QDot regime. Despite the young age of NW research several exciting transport experiments have been performed [4-9], and due to their exceptional properties (e.g. band structure engineering, possibility to contact them with ferromagnetic, superconducting leads, local gating) NW based devices are expected to open a new horizon in quantum transport.

The **main goal of the present work** is to establish the e-beam lithography-based fabrication of nanoelectronic devices, which is the missing piece of the experimental quantum electronics investigations at the national environment. In the framework of this project, it is also planned to build up a new measurement system for cryogenic transport studies. With this infrastructure the applicants mainly intend to fabricate and investigate InAs Nanowire based devices, but it will also support the ongoing molecular electronics and Andreev-spectroscopy experiments.

2. Results

2.1 E-beam lithography system, low-T transport measurement setup[d1&2]

In the first year of the project a Jeol 848 Electron Microscope has been installed in the joint laboratory of the Physics Department of the BME (Budapest Unniversity of Technology and Economics) and MFA (Research Institute for Technical Physics and Material Science). The optics has been cleaned and the column has been optimized for lithography purposes. All the fabrication steps related to the lithography (spinning, oxygen plasma cleaning, thickness measurement, baking) have been worked out and tested. Currently, writing precision bellow 50nm can be routinely achieved using 300nm thick standard PMMA resist. Typical nanostructures and electric circuits fabricated by the setup are presented in Fig. 1. Presently, several research groups use our electron beam lithography facility for various nanostructuring purposes, which demonstrates most the need and success of its establishment.
In addition a transport measurement system was also developed, which allows the characterization of the nanoelectric circuits at cryogenic temperature. Measurement system consist a self developed sample holder, which suitable to electrically access the nanocircuits hosted in ceramic chip carriers (see Fig. 1d), and a flexible computer controlled data acquisition unit, which is capable to carry out quantum dot spectroscopy measurements and data analysis.

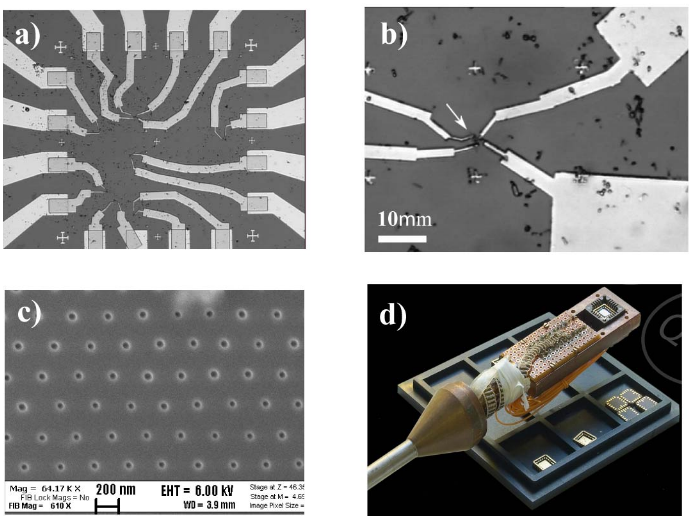

Fig. 1. *Fabrication and characterization of quantum electronic devices. Nanostructures are fabricated by the lithography setup. a) Wiring of several quantum circuits based on InAs nanowires. b) Enlarged view of one of these devices. c) Network of holes defined in a PMMA resist. The diameter of a hole is in the range of 50nm.d) Sample holder which allows the transport characterization of nanocircuits at cryogenic temperature. The devices are built into chip sockets.*

2.2 Cooper-pair splitter realized in a two-quantum-dot Y-junction[10]

We report here on the realization of a **source of spin-entangled electron pairs by Cooper-pair splitting** in NWs. In quantum mechanics the properties of two and more particles can be **entangled**. Pairs of entangled particles, so called Einstein-Podolsky-Rosen (EPR) pairs are toy objects in fundamental studies of quantum mechanics. They provide such things as "spooky interaction at distance" and enable through their entanglement secure encoding and teleportation. They are also the key resource for quantum information. Whereas EPR pairs of photons can be generated by parametric down conversion (PDC) in a crystal, a similar source for EPR pairs of electrons does not exists yet. In the solid-state, electrons can be entangled by interactions. In principle it is enough to overlap two electrons in separate quantum dots to form a molecular state similar to the bonding state of the H_2 molecule. This chemical bond is formed by a pair of electrons with opposite spin. Because nature cannot decide on whether the spin up electron should sit on atom A and the spin down one on atom B, it opts for a compromise, which is a symmetric superposition. This superposition is an entangled state, an EPR pair of electrons.

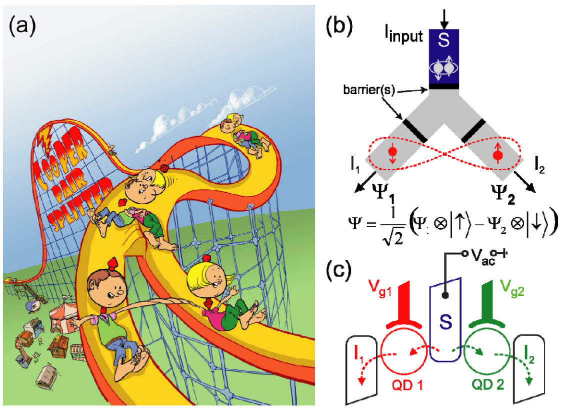

Fig. 2: (a) illustration of Cooper pair splitting in a Y-junction (b) and realization (c) using two quantum dots.

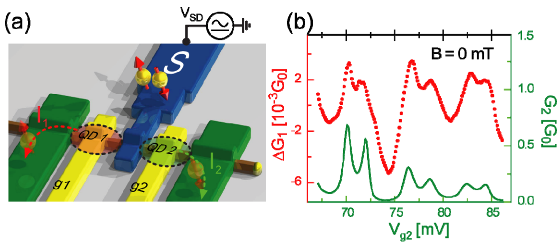

Fig. 3: (a) Realization of the two quantum dot Cooper pair splitter using an InAs semiconducting nanowire. The measurement in (b) shows that the cross-conductance (red) is positive correlated to the direct conductance (green) proofing Cooper-pair splitting. [10]

There is another system where entangled EPR pairs of electrons come almost for free. The superconducting ground state is formed by a condensate of so-called Cooper-pairs which are electron pairs in a spin-singlet state. Since there are many Cooper pairs in a metallic superconductor like Al, the main task is to extract Cooper pairs one by one and to split them into different arms. We have recently demonstrated that this is possible with a remarkably high efficiency [10]. Whereas the optical PDC has an efficiency of only $< 10^{-6}$, Cooper pair splitting with an efficiency in the 10% range could be demonstrated [10,11]. Theory shows in addition, that a fidelity near 100% should be possible if the device is operated in the ideal parameter regime [12].

The first step in the source of EPR electrons is the extraction of single Cooper pairs one-be-one. This is well known and works by tunneling. If the tunneling barrier is sufficiently opaque (the tunnel rate should be much larger than the superconducting gap parameter Δ) and quasiparticle tunneling is prohibited (low enough temperatures and an applied bias $eV << \Delta$), only Cooper pairs tunnel and they tunnel well separated in time.

The real challenge lies in the separation of the two electrons that make up a Cooper pair. The desired process is schematically shown in Fig. 2a,b. When a Cooper pair is approaching the Y branch, the two particles can stay together emanating at the left or at the right arm or they can split. In a mesoscopic device with many channels the desired Cooper-pair splitting has in general a weight comparable to the other undesired processes.

The slide in the illustration of Fig. 2a already emphasizes what is needed to efficiently split the pairs. If the slide is narrow enough so that only one person fits into it, splitting must occur with unit efficiency. Hence, interaction is the key. With electrons we employ the Coulomb interaction to do exactly this [12]. The concept is sketched in the bottom right part of Fig. 2c. The superconducting source (S) is connected to two quantum dots (QD1 and QD2). The transfer of the Cooper pair through a single QD cost twice as much charging energy than the transfer of two split electrons transferring the two arms separately. At low temperatures, this selection rule can lead to a 100% efficient Cooper pair splitter. The driving force of the selection rule can be infiltrated if the two electrons of a single Cooper pair tunnel sequentially, one after the other through the same QD. This unwanted channel can be suppressed if Δ is chosen sufficiently larger than the coupling of the QDs to the S contact.

We have used an InAs NW to define the two QDs. This is schematically shown in Fig. 3 together with one of the key cross-signal measurement proofing Cooper-pair splitting. The change of the current through QD1 (red) is measured while the gate V_{g2} of QD2 is changed. If the source is a voltage terminal and both arms are independent, no cross-signal is expected. However, Cooper pair splitting induces a correlation in the current through the two QDs, leading to a positive cross-signal, i.e. the current I_1 increases in synchrony with the transmission probability through QD2. This expected correlation is nicely seen in the measured data. It disappears if superconductivity is suppressed by either temperature or a magnetic field.

This experiment is an important milestone for future solid-state experiments aiming at properties beyond single electron physics. Our devices show controlled Cooper pair splitting with a surprisingly large efficiency in a tunable double quantum-dot system. The next challenge is to proof entanglement. Ferromagnetic contacts with well defined domain patterns will be one important ingredient enabling spin-projection measurement. In addition collision experiments on an added beam splitter will provide further insight.

2.3 Local etching of InAs Nanowires [d3]

The characterization of Cooper-pair splitters pointed out that our devices are not in the ideal parameter range. Based on the theoretical proposal [12] the maximal pair splitting can be gained if the charging energy (E_C) of the quantum dot and the superconducting gap (Δ) are much larger than the tunnel coupling (Γ) between the dot and the electrodes. In our case the first condition is fulfilled, however $\Delta \approx \Gamma$, thus by decreasing the tunnel coupling enhancement of the splitting efficiency is expected. We tried to decrease Γ by changing the native oxide layer thickness on the nanowire surface under the contacting electrode. However the device characteristics did not show systematic improvement, the tunnel coupling still remained in the 100microV range. Therefore we started to test and develop other fabrication techniques.

It is known from the literature that InAs nanowires get insulating under a critical diameter (approx. 35nm), thus **local thinning of the wire** could lead to the formation of robust tunnel barriers. We worked out a new etching method (see Fig. 4) which based on **sulfur passivation** of the NW surface and subsequent **piranha etching**. We demonstrated that proper sulfur based covering layer on the nanowire surface protects the nanowire against piranha etching. Thus locally patterned sulfur passivated nanowire surface allows selective thinning of the diameter in predefined location. The method requires one lithography step, the same mask is used for evaporation of the contacts and etching of the NW, which guarantees a **precise alignment** of the contacting electrodes and etched segments.

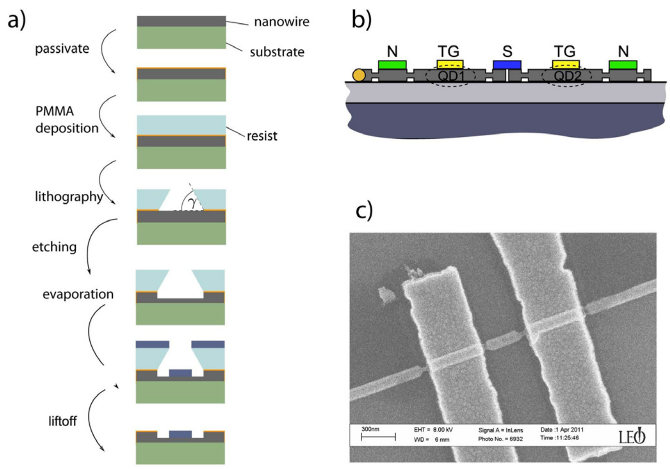

Fig. 4 *New etching technique of InAs Nanowires.*
b)New Cooper pair splitter geometry, where the coupling between QDots and superconducting is decreased. a) Developed new etching technique, which allows the thinning of the NW next to the contact. c) Scanning electron microscope picture of a realized device, where the InAs nanowire is thinned in the barrier regions, due to the applied self-aligned etching method.

2.4 Ferromagnetic Proximity Effect in an F–QuantumDot–S Device[13]

We could successfully contact NWs with various ferromagnetic (Ni, Co, Fe) contacts. We have investigated the influence of the ferromagnetic correlations on the transport behavior of InAs NW based quantum dot between one ferromagnetic and one superconducting leads (see Fig. 5). It turned out that the ferromagnetic contacts induce a strong **ferromagnetic proximity effect** on the quantum dots. The influence of the F lead is detected through the splitting of the spin-1/2 Kondo resonance (see Fig. 6). We show that the F lead induces a **local exchange field** on the QD, which has varying amplitude and sign depending on the charge states. Furthermore, we have shown that the exchange field even **changes sign for a single charge state**, allowing electric gate controlled reversal of the spin ground state. The interplay of the F and S correlations generates an exchange field related supgap feature. This novel mini-gap allows the visualization of the exchange field also in even charge states.

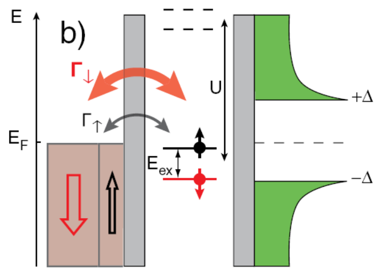

Fig. 5 Energy diagram of a Ferromagnet- QuantumDot – Superconductor junction. The coupling to a ferromagnetic lead generates a local exchange field on the dot.

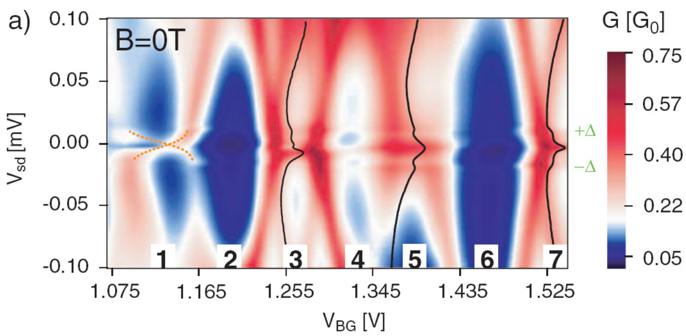

Fig. 6 *Analysis of the local exchange field by Kondo resonance. As the number of electrons is increased one by one (see numbers) the splitting of the Kondo resonance is changing demonstrating a charge state dependent exchange filed.*

2.5 Gate tunable spin current amplifier[14]

Our experiments on ferromagnetic proximity effect raised a very natural question, whether the ferromagnetic lead induced local exchange on the quantum dot could be used to generate spin polarized current. In cooperation with theoreticians of our Institute (G. Zarand and I. Weymann) we have analyzed this problem. It turned out that an F-QDot –N device (see Fig. 7) could act as a very efficient spin current source. Based on the performed NRG calculations, in the presence of a strongly coupled ferromagnetic lead not only the Kondo resonance splits into spin polarized peaks but the two Hubbard peaks also become almost fully spin polarized. Weakly coupling such an F-QDot unit to another lead, the spin polarization of the current follows the polarization of the density of states of the dot. Such an F- QDot - N system is very attractive for spintronic applications: a) it amplifies the spin polarization of F lead b) it allows the reverse of the spin polarization direction with high speed by gate voltage c) it can be scaled down to molecular level, which would allow room temperature operation as well.

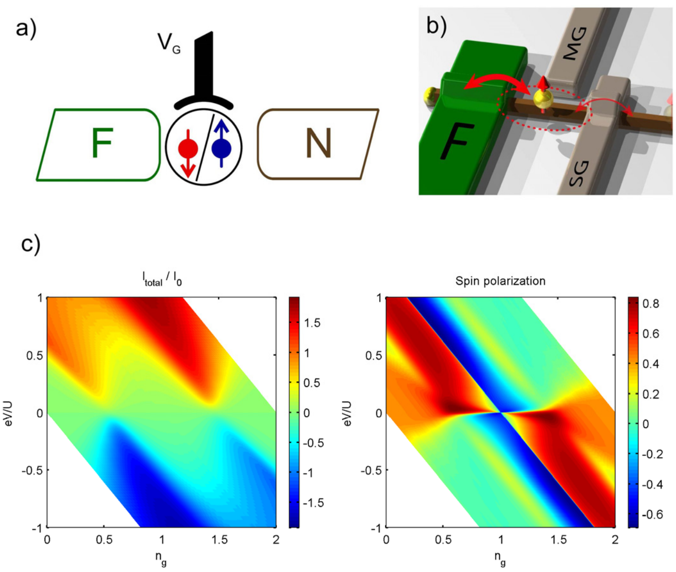

Fig. 7*: Concept of spin current amplifier.*
a) The device contains a quantum dot strongly coupled to a ferromagnetic lead (F) and weakly to another electrode (N).Due to induced local exchange field the the F lead polarizes electron states on the dot. The direction of the polarization can be varied by gate voltage. b) Possible implementation of concept in NW or carbon nanotube devices. c) Transport properties of this device calculated by NRG technique. Left panel shows a coulomb diamond, while the left panel demonstrates the spin polarization for the same parameters. By gate voltage (n_g) or bias (V) the spin polarization can be reversed.

2.6 Other contributions

Beside the investigation of the InAs nanowire based devices the established infrastructure allowed to contribute to other research projects as well. We have started to fabricate graphene based electric circuits by the e-beam lithography system [d4]. Since **graphene** can be contacted by ferromagnetic and superconducting electrodes as well, it is also suitable material platform to produce hybrid quantum electronic devices. In addition, **ferromagnetic normal nanostructures** have also been produced e.g. for the calibration of Andreev spectrometer. Furthermore, dynamics of nanoscale ferromagnetic junctions were also investigated [15].

In addition to the published scientific results and the established infrastructure, the present project allowed dedicated **nanofabrication training for young scientists and students**. During the two-years of the project, 3 phd and diploma students spent more than 9 months in the Nanocenter of Basel, where they had the opportunity to learn various experimental techniques in a world leading laboratory. Furthermore, additional 4 phd and master students acquired e-beam lithography technique and produced their own nanocircuits here in Budapest.

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Publications of the present project are written in bold.

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