One-Dimensional Systems for Quantum Technology

700. WE-Heraeus-Seminar

June 16 - 19, 2019
Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Subject to alterations!

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de.

Scope of the 700. WE-Heraeus-Seminar:

Historically, enhancing compute capability has meant integrating ever more and ever smaller devices into both, the memory and the processors. However, such scaling has become much more difficult recently because of physical scaling limits. Yet despite a lot of innovative technologies in materials, devices and architectures, the speed of increasing the density of transistors has slowed down. This raises the fundamental question of what technology is next to speed up computing? At the same time the progress in technologies important for quantum computing has increased significantly over recent years. This has resulted also in an ambitious European Flagship initiative in quantum technologies to ensure Europe's leading role in a technological revolution now under way. In that respect a large focus is put on qubit implementations based on superconducting Josephson junctions and ion traps based on their more advanced level of maturity for quantum computing. A big challenge is still to increase the number of gate operations or calculations possible until coherence is lost. In that regard topological quantum bits based on one dimensional (1D) systems are considered to play an important role in future quantum technology and the interest in those systems has significantly increased over the last five years. In particular Majorana fermions in nanowire hybrid systems as well as helical states are thought to be essential ingredients to future on-chip quantum information applications.

This seminar will concentrate on quantum transport in 1D systems and envisage to bring together the communities working on the hot and crucial topics of the field. Besides a focus on the topical Majorana fermions, a particular emphasis of the seminar will lie in correlations, which are especially strong in 1D and give rise to interesting effects like the mentioned helical phase, but also the famous 0.7-anomaly of short 1D constrictions (quantum point contacts), a transition from a Fermi- to a Luttinger liquid in clean and long wires, Wigner crystallization and more. These correlation effects are in competition with the formation of Majorana states where unambiguous proof is still a big focus of current research. The seminar will foster a lively discussion on the various 1D states of interest, their complex physics, their robustness and their suitability for on-chip quantum technology applications.

Introduction

Scientific Organizers:

Dr. Heike Riel	IBM Research Zurich Switzerland E-mail hei@zurich.ibm.com
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Registration:

Jutta Lang (WE-Heraeus Foundation)
at the Physikzentrum, reception office
Sunday (16:00 h – 21:00 h) and
Monday morning

Door Code:

(Key symbol button) 2 7 0 0 #
For entering the Physikzentrum
during the whole seminar

Program

Program

Sunday, 16 June 2019

16:00 – 21:00	Registration	
from 18:00	*BUFFET SUPPER / Informal get together*	
19:45 – 20:00	Scientific organizers	**Opening and welcome**

<u>**Chair: Heike Riel**</u>

20:00 – 21:00	Charles Bennett	**Quantum information's birth, growth, and significance**

Monday, 17 June 2019

07:45	*BREAKFAST*	

<u>**Chair: Katharina Franke**</u>

08.45 – 09:30	Werner Wegscheider	**Cleaved Edge Overgrowth – current status, perspectives and experimental challenges**
09:30 – 10:15	Jelena Klinovaja	**Andreev bound states and Majorana fermions in helical 1D systems**
10:15 – 10:45	*COFFEE BREAK*	

<u>**Chair: Stefan Ludwig**</u>

10:45 – 11:30	Dominik Zumbühl	**Edge state spectroscopy with a GaAs quantum wire**
11:30 – 12:30	**Poster flash presentations** (60 sec. each / 1 slide)	
12:30	*LUNCH*	

Program

Monday, 17 June 2019

<u>Chair: Jan von Delft</u>

14:00 – 14:45	Oleg Yevtushenko	**Helicity-protected transport in magnetically doped one-dimensional wires**
14:45 – 15:30	Fabrizio Nichele	**InAs/Al two-dimensional electron gases**
15:30 – 16:15	Hongqi Xu	**Semiconductor InSb nanolayers: A new platform for developments of quantum and topological devices**
16:15 – 17:00	Yuval Oreg	**Insulating phases of topological superconductors – the super-symmetric Majorana-zero modes point of view**
17:00 – 17:30	*COFFEE BREAK*	
17:30 – 18:30	**Poster session I**	
18:30	*DINNER*	

<u>Chair: Christian Schönenberger</u>

20:00 – 21:00	Leo Kouwenhoven	**1D hybrid nanowires of superconducting and semiconducting materials as a scalable platform for qubit circuits**

Program

Tuesday, 18 June 2019

07:45	*BREAKFAST*	

<u>Chair: Thomas Schäpers</u>

08:45 – 09:00	Stefan Jorda	**About the Wilhelm and Else Heraeus-Foundation**
09:00 – 09:45	Koji Ishibashi	**Quantum structures with carbon nanotubes**
09:45 – 10:30	Jan von Delft	**Multiloop functional renormalization group: Computing finite-temperature transport through inhomogeneous quantum wires**
10:30 – 11:00	*COFFEE BREAK*	

<u>Chair: Charles Marcus</u>

11:00 – 11:45	Katharina Franke	**From single magnetic adatoms on superconductors to coupled spin chains**
11:45 – 12:30	Erik Bakkers	**Bottom-up grown nanowire quantum devices**
12:30	**Conference Photo**	
12:40	*LUNCH*	

Tuesday, 18 June 2019

Chair: Piet Brouwer

14:00 – 14:45	Peter Krogstrup	**Engineering electronic hybridization in epitaxial materials**
14:45 – 15:30	Eduardo Lee	**Andreev bound states in hybrid superconductor-semiconductor nanowire devices**
15:30 – 16:15	Vadim Khrapai	**Heat conductance of an InAs nanowire proximitized by a superconductor**
16:15 – 16:45	*COFFEE BREAK*	

Chair: Heike Riel

16:45 – 17:30	Julia Meyer	**Multiterminal Josephson junctions based on helical states**
17:30 – 18:15	**Panel discussion**	
18:15	*HERAEUS DINNER at the Physikzentrum (cold & warm buffet, free beverages)*	
20:00	**Poster session II**	

Wednesday, 19 June 2019

08:00	*BREAKFAST*	

Chair: Julia Meyer

09:00 – 09:45	Piet Brouwer	**Quantum tomography of solitary electrons**
09:45 – 10:30	Floris Zwanenburg	**Quantum dots and superconductivity in GeSi nanowires**
10:30 – 11:00	*COFFEE BREAK*	

Chair: Eduardo Lee

11:00 – 11:45	Thomas Schäpers	**In-situ prepared nanowire-based Josephson junctions for qubit applications**
11:45 – 12:30	Martin Stehno	**Topological superconductivity in HgTe-based topological materials**
12:30	*LUNCH*	

Chair: Koji Ishibashi

14:00 – 14:45	Anton Akhmerov	**Majoranas in zigzag devices: Why shape matters**
14:45 – 15:30	Charles Marcus	**Vortices, Majorana zero modes, and quantum phase transitions in full-shell hybrid nanowires**
15:30 – 15:45	Scientific organizers	**Poster awards and closing remarks**

End of the seminar *and FAREWELL COFFEE* ***/ Departure***

Please note that there will be ***no*** *dinner at the Physikzentrum on Wednesday evening for participants leaving the next morning.*

Posters

Program

1.	Luca Alt	**Quantum wires defined by Cleaved Edge Overgrowth – Challenges & future goals**
2.	Ghada Badawy	**InSb nanowires for advanced quantum devices**
3.	Christian Bäuml	**Quantum transport through carbon nanotube $NbSe_2$ hybrid devices for Majorana Fermion detection**
4.	Jonathan Becker	**Low-dimensional transport properties of InAs-based nanowires**
5.	Arunav Bordoloi	**Double quantum dot tunneling magnetoresistance without ferromagnetic contacts**
6.	Erik Cheah / Clemens Todt	**Merging MBE grown semiconductor heterostructures with in-situ deposited thin film superconductors towards top-down topological quantum computation**
7.	Olivier Faist	**Parallel semiconductor nanowire based electronic devices**
8.	Felix Friedrich	**On the preparation and electronic properties of clean superconducting Nb(110) surfaces**
9.	Sergej Fust	**Advanced thermoelectric properties in high-mobility GaAs/AlGaAs core-shell nanowires**
10.	Max Geier	**Second-order topological insulators and superconductors with an order-two crystalline symmetry**
11.	Max Hoskam	**One-dimensional helical states in SnTe topological crystalline insulator nanowires: Modelling and growth**
12.	Andreas K. Hüttel	**Shaping electron wave functions in a nanotube tubewith a parallel magnetic field**
13.	Niklas Hüttner	**Coulomb blockade enhanced carbon nanotube optomechanics**
14.	Felix Jekat	**Electron pair charging in gate-defined quantum dots in indium antimonide nanowires**
15.	Jason Jung	**Selective area semiconductor-superconductor networks**

16.	Christoph Kastl	**Quantized conductance in topological insulators revealed by the Shockley-Ramo theorem**
17.	Chung-Ting Ke	**Ballistic superconductivity and tunable π-junctions in InSb quantum wells**
18.	Sabbir Khan	**Ballistic superconductor/semiconductor nanowire junctions**
19.	Anders Kringhøj	**Correlating transport and spectroscopy measurements of the Little-Parks effect in a gatemon qubit**
20.	Lucca Kühner	**Majorana fermions in tungsten ditelluride**
21.	Gunta Kunakova	**Ballistic topological insulator Bi_2Se_3 nanoribbon Josephson junctions**
22.	Chun-Xiao Liu	**Proposal for measuring the parity anomaly in a topological superconductor ring**
23.	Yu Liu	**InAs – EuS – Al hybrid nanowires**
24.	Emma Minarelli	**Improved quantum transport calculations using the numerical renormalization group**
25.	Wolfgang Möckel	**Transport spectroscopy of MoS_2 nanotubes**
26.	Filipp Müller	**Engineering electron-phonon interaction in quasi-one-dimensional systems**
27.	Roy Op het Veld	**In-plane InSb networks for quantum devices**
28.	Alessia Pally	**Tunnel spectroscopy of superconducting proximity effect in InAs nanowires using aligned crystal-phase quantum dots**
29.	Taras Patlatiuk	**Wave functions and velocities of quantum Hall edge states**
30.	Sreekoti Subha Pujitha Perla	**In-situ grown superconducting contacts on InAs nanowires**
31.	Michael Randle	**Gate-controlled metal-insulator transition in TiS_3 nanowire field-effect transistors**
32.	Stefan Rex	**Majorana bound states in magnetic skyrmions imposed onto a superconductor**

Posters

33.	Elisabeth Richter	**Spin helical surface states in mesoscopic topological HgTe structures**
34.	Jonas Rigo	**Generative model learning**
35.	Markus Ritter	**Building blocks for Majorana modes devices - Growth and gating of encapsulated high quality InAs nanowires**
36.	Marco Rossi	**Versatile platform for in-situ fabrication of InSb nanowire Majorana devices**
37.	Younghun Ryu	**Aluminum-InAs nanowire hybrid devices for observing Majorana zero modes**
38.	Deividas Sabonis	**Microwave induced single electron transitions between Majorana zero modes in hybrid superconducting-semiconducting islands**
39.	Vanessa Schaller	**Andreev oscillations in selective area InSb-Al Majorana nanowires**
40.	Sander Schellingerhout	**MBE growth and characterization of PbTe nanowires**
41.	Wei Tang	**Quantized thermal Hall conductance from edge currents in lattice models**
42.	Saulius Vaitiekenas	**Quantum phase transitions and topological superconductivity in full-shell nanowires**
43.	Pedro Vianez	**Observing a hierarchy of modes in a 1D strongly correlated liquid beyond the Luttinger regime**
44.	Guanzhong Wang	**Backbones of a topological qubit – High quality selective-area grown InSb nanowire networks using MBE**
45.	Qingzhen Wang	**Electronic transport in phase-biased zigzag Josephson junction**
46.	Alexander Whiticar	**Evidence of topological superconductivity in planar Josephson junctions**
47.	Di Xu	**Quantum transport in in-plane selective area InSb nanowire networks**

Abstracts of Lectures

(in chronological order)

Quantum Information's birth, growth, and significance

Charles H. Bennett[1]

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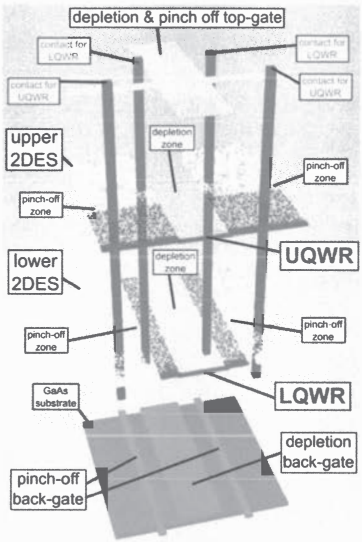
Beginning in the late 1960's quantum effects in information processing progressed from being viewed as a nuisance to be overcome, to the enabler of new kinds of practical cryptography and computation. Today quantum information has become an elegant new foundation from which the classical information processing of Turing and Shannon emerges as a useful special case, and a source of insights into fundamental questions like nature of black holes and the origin of spacetime.

Cleaved Edge Overgrowth – current status, perspectives and experimental challenges

W. Wegscheider, M. Berl and L. Alt

Laboratory for Solid State Physics, ETH Zürich, Switzerland

Since the invention of the cleaved edge overgrowth (CEO) technique [1], which combines molecular beam epitaxial growth along two or more crystal directions and, thus, can provide 2D or 3D quantum confinement [2], only very few laboratories succeeded in its implementation. Despite a large number of fascinating results on transport and optical spectroscopy of quantum wires and dots fabricated by this method, the realization of 1D ballistic channels remains still an experimental challenge. In this talk I will give an introduction to the CEO method applied to the GaAs/AlGaAs material system. After a short review on the different structures which have been successfully produced in this way, I will concentrate in more detail on these suitable for 1D transport spectroscopy. As it turns out this requires, in addition to solving the technological challenges, careful heterostructure design to ensure coupling of the 2D modes in the contact regions to the 1D modes in the ballistic channel.



The recent development of an ion implantation technique, which allows for the preparation of pre-structured, buried back-gates, represents a powerful tool and if combined with CEO opens the possibility to prepare and study much more sophisticated devices. In the example sketched to the left, two CEO quantum wires are formed. By means of appropriately biasing the different top- and back-gates, individual contacting of the two wires should be possible. These two independent transport paths are necessary to investigate Coulomb drag between Luttinger liquids, a topic studied theoretically because of its relevance with respect to electron-electron interactions.

References

[1] L. Pfeiffer, J. Cryst. Growth **127**, 849 (1993)
[2] W. Wegscheider, Phys. Rev. Lett. **79**, 1917 (1997)

Andreev Bound States and Majorana fermions in helical 1D systems

Jelena Klinovaja

Department of Physics, University of Basel, 4056 Basel, Switzerland

In my talk, I will discuss low-dimensional condensed matter systems, in which topological properties could be engineered per demand. Majorana fermions can emerge in hybrid systems with proximity-induced superconducting pairing. I will present our numerical and analytical studies of such geometries with proximity effects [1-3]. In the second part of the talk, I will discuss an analytical model of a Rashba nanowire that is partially covered by and coupled to a thin superconducting layer, where the uncovered region of the nanowire forms a quantum dot [4,5]. Even if there is no topological superconducting phase possible, there is a trivial Andreev bound state that becomes pinned exponentially close to zero energy as a function of magnetic field strength when the length of the quantum dot is tuned with respect to its spin-orbit length such that a resonance condition of Fabry-Perot type is satisfied. In this case, the Andreev bound state remains pinned near zero energy for Zeeman energies that exceed the characteristic spacing between Andreev bound state levels but that are smaller than the spin-orbit energy of the quantum dot. Importantly, as the pinning of the Andreev bound state depends only on properties of the quantum dot, this behavior is unrelated to topological superconductivity.

References

[1] C. Reeg, D. Loss, and J. Klinovaja, Phys. Rev. B **97**, 165425 (2018).
[2] C. Reeg, D. Loss, and J. Klinovaja, Phys. Rev. B **96**, 125426 (2017).
[3] C. Reeg, J. Klinovaja, and D. Loss, Phys. Rev. B **96**, 081301 (2017).
[4] C. Reeg, O. Dmytruk, D. Chevallier, D. Loss, and J. Klinovaja, Phys. Rev. B **98**, 245407 (2018).
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Edge State Spectroscopy with a GaAs Quantum Wire

D. Zumbühl

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GaAs cleaved edge overgrowth wires are among the cleanest realizations of quantum 1D systems, displaying conductance quantization as well as salient Luttinger liquid features arising from strong interactions. As the temperature of the wire is lowered, the conductance of the first mode drops from 2 e^2/h to 1 e^2/h and remains fixed at $1e^2/h$ below 100 mK, suggesting a spontaneous lifting of the spin degeneracy in absence of magnetic field in a novel type of quantum state of matter [1]. This behavior is consistent with helical nuclear spin order and an associated helical Luttinger liquid featuring a spin-resolved gap which is pinned at the chemical potential [2]. This is similar to a Rashba nanowire in a magnetic field, with key difference that the helical gap energy in the Rashba wire is set by the spin-orbit coupling, not the chemical potential.

To investigate this novel state, we have performed tunneling spectroscopy to probe the electronic dispersions of the quantum wire [3]. Within the model [2], a partial, spin-resolved gap at the Fermi momenta is expected. However, the dispersions are obliterated by additional features due to finite size effects, quantum interference and quantum Hall edge states. The tunneling spectroscopy can be employed to track momentum and position of the quantum Hall edge states with unprecedented precision and shows the evolution from very low magnetic fields all the way to high fields where depopulation occurs [4]. We present consistent analytical and numerical models, inferring the edge states from the well-known bulk spectrum, finding excellent agreement with the experiment—thus providing direct evidence for the bulk to edge correspondence. In addition, we observe various features beyond the single-particle picture, such as Fermi level pinning, exchange-enhanced spin splitting and signatures of edge-state reconstruction.

References

[1] *Possible Evidence for Helical Nuclear Spin Order in GaAs Quantum Wires,* C. P. Scheller, T.-M. Liu, G. Barak, A. Yacoby, L. N. Pfeiffer, K. W. West, and D. M. Zumbühl, Phys. Rev. Lett. **112**, 066801 (2014).

[2] *Nuclear magnetism and electron order in interacting one-dimensional conductors*, B. Braunecker, P. Simon, and D. Loss, Phys. Rev. **B80**, 165119 (2009); *NMR response of nuclear-spin helix in quantum wires with hyperfine and spin-orbit interaction*, P. Stano, and D. Loss, Phys. Rev. **B90**, 195312 (2014).

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[4] *Evolution of the quantum Hall bulk spectrum into chiral edge states*, T. Patlatiuk, C.P. Scheller, D. Hill, Y. Tserkovnyak, G. Barak, A. Yacoby, L. N. Pfeiffer, K. W. West, and D. M. Zumbühl, Nature Communications **9**, 3692 (2018).

Helicity-protected Transport in Magnetically Doped One-Dimensional Wires

A. M. Tsvelik[1] and O. M. Yevtushenko[2]

[1]BNL, Upton, USA
[2] LMU, Munich, Germany

We address the phase diagram and transport properties of one-dimensional quantum wires functionalized by magnetic ad-atoms with a high density. The appropriate theoretical model for these systems is a one-dimensional Kondo Lattice (KL) which consists of itinerant electrons interacting with Kondo impurities (KI) - localized quantum magnetic moments. We focus on dense KLs with isotropic exchange interaction between electrons and KI. We present a first-ever comprehensive study of such KLs at an arbitrary doping and predict a variety of regimes with different electronic phases [1]. Our most important finding is the exotic phase of the helical metal where transport is protected from a destructive influence of material imperfections [2]. We find conditions under which such a protection can emerge in the presence of the spin-rotation symmetry (cf. prediction reported in Refs. [3,4]) and discuss possible experiments where the theory could be tested. Our results could serve as a solid basis for realization of an emergent protection of the ballistic transport in the quantum wires.

References

[1] A. M. Tsvelik, and O. M. Yevtushenko, arXiv:1812.11507 (2018)
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[3] A. M. Tsvelik, and O. M. Yevtushenko, Phys. Rev. Lett. **115**, 216402 (2015)
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InAs/Al two-dimensional electron gases

Antonio Fornieri[1], Alexander M. Whiticar[1], F. Setiawan[2], Elias Portoles Marin[1], Asbjørn C. C. Drachmann[1], Anna Keselman[3], Sergei Gronin[4,5], Candice Thomas[4,5], Tian Wang[4,5], Ray Kallaher[4,5], Geoffrey C. Gardner[4,5], Erez Berg[2,6], Michael J. Manfra[4,5,7,8], Ady Stern[6], Charles M. Marcus[1] and Fabrizio Nichele[1]

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There is growing interest in material systems that both support Majorana zero modes (MZMs), relevant for quantum computing, and can be fabricated into complex and scalable geometries. So far, MZMs have been tentatively identified in individual InSb or InAs nanowires with induced superconductivity. Future tests of non-Abelian statistics will likely involve braiding or interferometric measurement, requiring branched or looped geometries, challenging to realize using individual nanowires.

I will present investigations of hybrid superconductor/semiconductor devices performed at the University of Copenhagen. Devices are based on a planar InAs heterostructure strongly coupled to a thin layer of epitaxial Al. By top-down lithography, we defined one-dimensional wires characterized by a hard superconducting gap, ballistic tunneling probes and in-plane critical fields up to 3 T. In the presence of an in-plane magnetic field, zero energy states robust in field emerge and show a behavior consistent with theory for MZMs, including low temperature saturation at the conductance quantum. Finally, I will show how a new generation of Majorana devices could be realized by taking advantage of phase control in planar Josephson junction geometries.

Semiconductor InSb nanolayers: A new platform for developments of quantum and topological devices

Hongqi Xu

Beijing Key Laboratory for Quantum Devices, Key laboratory for the Physics and Chemistry of nanodevices, and Department of Electronics, Peking University, Beijing 100871, China

Semiconductor InSb nanowires have been demonstrated as one of the most promising materials systems for realizing topological superconducting structures in which Majorana bound states can be created and manipulated [1-3]. For achieving quantum computing with Majorana bound states, an efficient scheme for braiding Majorana bound state needs to be developed. In this respect, proposals of using branched InSb nanowires and two-dimensional InSb planar structures have been envisioned [4,5]. In this talk, I will report on our recent developments in epitaxial growth of free-standing InSb nanoplates and in building quantum devices and superconducting Josephson junction devices with these InSb nanoplates [6-8]. These InSb nanoplates were grown by molecular beam epitaxy (MBE) and exhibits excellent structural and transport properties [6]. The advantages of employing these InSb nanoplates include flexibilities of transferring them to desired substrates for device fabrication and of directly contacting them with different metals and superconductors. Several quantum devices have been fabricated using our MBE-grown InSb nanoplates and have been studied by transport measurements. In particular, we will demonstrate realizations of first InSb nanoplate quantum dot devices [7] and first Al-InSb nanoplate-Al Josephson junction devices [8]. Perspectives of achieving topological quantum devices will also be presented and discussed.

References

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[6] D. Pan *et al.*, **16**, 834 (2016).
[7] J. H. Xue *et al.*, Appl. Phys. Lett. **114**, 023108 (2019).
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Insulating phases of topological superconductors - the super-symmetric Majorana-Zero Modes point of view

Yuval Oreg

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Strong Coulomb interactions may induce a phase transition between a topological superconductor and an insulator. We find that there are several possible insulating phases of topological superconductors, dual (equivalent) to certain spin liquid phases. They include phases with non Abelian particles that may support universal quantum computation. We will discuss possible way to stabilize these exotic phases by interactions between Majorana-zero modes in a Cooper box. In particular we will show how a critical super-symmetric state emerges.

1D hybrid nanowires of superconducting and semiconducting materials as a scalable platform for qubit circuits

Leo Kouwenhoven

Microsoft Quantum Labs and QuTech, Delft, The Netherlands

The materials quality of combinations of semiconductors and superconductors has improved enormously with the innovation of hybrid epitaxial growth realizing interfaces at the atomic scale. The resulting devices combine the best of both worlds with hard-gapped superconductivity and full flexibility in gate-defined field-effect control. A large diversity of devices have been realized such as superconducting islands, Majorana islands, nanowire-transmon and -fluxonium qubits, etc. An overview will be presented including a way forward towards a scalable platform for qubit circuits.

Quantum structures with carbon nanotubes

K. Ishibashi[1,2] and A. Hida[1]

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Single-wall carbon nanotubes (SWCNTs) are an ideal one-dimensional material with a diameter about ~1nm, and are a natural choice for the building block of the quantum devices [1]. A single quantum dot is easily fabricated just by depositing metallic contacts on the individual SWCNT [2,3], but a challenge is to develop methods to fabricate more complex and functional structures. We are developing a technique to use chemical bindings or molecules to fabricate such structures [4,5]. In this talk, we will demonstrate a formation of the single and double quantum dots by binding molecules at the ends of the individual SWCNT. A conditional gate operation of the exciton qubits will be shown in the double quantum dots. As another example, the Aharonov-Bohm ring structure will be shown, where the ballistic electron wave interference effects are demonstrated.

References

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Multiloop Functional Renormalization Group: Computing Finite-Temperature Transport through Inhomogeneous Quantum Wires

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The interplay of interactions and inhomogeneities in one-dimensional systems can give rise to intricate correlation effects. A much-studied example is the 0.7-anomaly in quantum point contacts, which arises when a smooth potential barrier in a one-dimensional transport channel causes an enhancement of the local density of states, thereby amplifying interaction effects. Another example of great current interest is many-body localization in a disordered quantum wire. The theoretical description of such systems calls for a tool capable of treating fairly strong interactions without relying on translational invariance. I will argue that the functional renormalization group (fRG) is such a tool. I will illustrate its potential by showing how an fRG treatment of an interacting quantum point contact elucidates the origin of the 0.7-anomaly [1,2]. However, I will also explain why traditional formulations of fRG are not suitable for computing the nonlinear conductance at finite source-drain bias. Finally, I will argue that this limitation can be overcome by employing a recently developed *multiloop* fRG approach [3-5].

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From single magnetic adatoms on superconductors to coupled spin chains

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Magnetic adsorbates on conventional s-wave superconductors lead to exchange interactions that can induce bound states inside the superconducting energy gap. These states are known as Yu-Shiba-Rusinov (YSR) states and can be resolved by scanning tunneling spectroscopy as a pair of resonances at positive and negative bias voltages in the superconducting gap. Recently, it has been suggested that proximity-coupled magnetic adsorbates induce a non-trivial superconducting state, which allows for the formation of Majorana bound states [1].

Here, we employ tunneling spectroscopy at 1.1 K to investigate magnetic atoms and chains on superconducting Pb surfaces. We show that individual Manganese (Mn) atoms give rise to a distinct number of YSR-states, depending on the crystal field imposed by the adsorption site. The spatial extension of these states directly reflects their origin as the singly occupied d-states [2].

When the atoms are brought into sufficiently close distance, the Shiba states hybridize, thus giving rise to states with bonding and anti-bonding character [3]. It has been shown that the Pb(110) surface supports the self-assembly of Fe chains, which exhibit fingerprints of Majorana bound states [1]. Using superconducting tips, we resolve a rich subgap structure including peaks at zero energy and low-energy resonances, which overlap with the putative Majorana states [4]. We also test, if Co chains on Pb(110) exhibit similar characteristics of ferromagnetic coupling and zero-energy states [5].

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Bottom-up grown nanowire quantum devices

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First signatures of MZM have been obtained in InSb nanowires [1]. Recently, different schemes for performing logical operations and uncovering the properties of Majorana states are proposed. For such a universal computational architecture the realization of a near-perfect nanowire network assembly is needed in which Majorana states are coherently coupled. Here, we demonstrate a generic process by which we can design any proposed braiding device by manipulating an InP substrate and thereby the nanowire growth position and orientation [2]. Our method leads to highly controlled growth of InSb nanowire networks with single crystalline wire-wire junctions. Additionally, nanowire "hashtag" structures are grown with a high yield and contacted. In these devices, the Aharonov–Bohm (AB) effect is observed, demonstrating phase coherent transport. These measurements reveal the high quality of these structures. Furthermore, this platform is used for in-situ epitaxial shadow growth of a superconductor on the nanowire facets, resulting in transport contacts. With this new generation devices we have observed quantized MZM [3].

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Engineering electronic hybridization in epitaxial materials

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Hybrid epitaxial materials are promising candidates for realizing topologically protected majorana bound states. I will present crystal growth and characterization of superconductors and ferromagnetic insulators grown on different III-V semiconducting platforms such as planar 2DEGs, Vapor-Liquid-Solid and Selective Area Grown nanowire networks [1].

I will discuss the mechanisms of hybrid epitaxy that leads to materials with well defined band alignments, a key reqiurement for engineering desired electronic hybridization.

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Andreev bound states in hybrid superconductor-semiconductor nanowire devices

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We perform tunneling measurements to study the low-energy states of quantum dots formed in semiconductor nanowires and coupled strongly to a superconductor. Although non-topological in nature, these states, commonly known as Andreev bound states (ABSs) or Yu-Shiba-Rusinov states, hold relevance in the context of topological superconductivity. Indeed, ABSs are expected to evolve towards Majorana modes across a topological phase transition when in the long wire limit [1, 2]. In addition, understanding the ABS spectra of hybrid nanowire devices is important for the interpretation of experiments directed at the observation of Majorana modes. In this work, we perform a detailed study of the sub-gap states of a tunable spin-½ quantum dot. We first exploit the ability to control the coupling between the dot and the superconductor to explore the phase diagram of the possible ground states of the system: a spin singlet or a magnetic doublet [3]. By applying external magnetic fields, we study the spin texture of the Andreev states and demonstrate zero-bias crossings resulting from parity-changing phase transitions [4]. Finally, we evaluate the impact of mesoscopic tunnel probes in the detection of ABSs. We show that the non-trivial density of states of such probes yields numerous replicas of the sub-gap states, thereby leading to crowded Andreev spectra [5].

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Heat conductance of an InAs nanowire proximitized by a superconductor

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Andreev reflection at the interface of a normal conductor with a superconductor is a fundamental example of a separation of charge and heat fluxes in an electronic system [1]. Recently, such an understanding of the Andreev reflection emerged in the context of research on proximity-induced topologically-nontrivial superconductivity in nanostructures. For example, one can think of a quantized heat-conductance predicted for Majorana nanowires at the topological phase transition [2].

In this talk, I will share the results of recent experiments in individual diffusive InAs nanowires with normal (N, gold) and superconducting (S, aluminum) contacts. The measurements were performed by means of transport and noise approaches in a $^3He/^4He$ dilution refrigerator at temperatures ~100 mK, well below the Al critical temperature. The high quality of the Al/InAs interface is supported by the observations of (i) the reentrance effect and excess current [3], (ii) the universal shot noise value in normal state [4] and (iii) the Josephson supercurrent.

The possibility of quasiparticle transport along the interface with a superconductor manifests in non-local transport and noise signals. In the first case, the non-equilibrium flux of quasiparticle excitations is detected by a shift and smearing of the Josephson *I-V* characteristics in presence of the non-local dc excitation. Most informative is the observation of non-local noise signals. In a 3-terminal setup N/InAs/S/InAs/N [2] we observed non-equilibrium heat flux along the 100-300 nm long InAs nanowire segments proximitized by the S-contacts. This heat transport channel is opened within the range of energies bounded by the superconducting gap of Al, when its heat conduction is suppressed, in contrast to the above-the-gap energies and the case of normal state in a magnetic field.

The measurement of a non-local noise temperature in dependence of the bias voltage is equivalent to a measurement of the heat conductance of the proximitized InAs nanowire. Therefore, these experiments can be relevant for the detection of non-locality of the Majorana states in such systems.

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Multiterminal Josephson Junctions based on Helical States

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Multiterminal Josephson junctions have been shown to provide a straightforward realization of tunable topological materials in synthetic dimensions, the independent superconducting phases playing the role of quasi-momenta. Here we analyze the Andreev spectrum in a four-terminal Josephson junction between one-dimensional topological superconductors in class D. In that case, the interplay of the topological nature of the superconductors and the topological properties one may attribute to the junction leads to interesting non-equilibrium effects. Namely, topologically protected crossings in the space of three superconducting phase differences may occur between a 2π-periodic and a 4π-periodic Andreev bound state. Such crossings can be detected through a transconductance quantization, in units of 2e2/h, between two voltage-biased terminals. It is important to note that, due to the presence of the 4π-periodic state, any applied voltage will drive the system out of equilibrium, as it does not possess a gap at the Fermi level. We show that such non-equilibrium conditions are in fact necessary to observe the transconductance quantization, which distinguishes this system from previous setups.

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Quantum Tomography of Solitary Electrons

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Initializing and measuring the wave-function of single freely-propagating particles are challenging but fundamental tasks for applications in quantum information processing and enhanced sensing. Recently, continuous-variable quantum tomography techniques developed for atomic beams and photonic modes have been adapted for on-demand electronic excitations but are limited to the region in energy-time phase space immediately around the Fermi level. Here we present a general, broad-band method for mapping the single-particle phase space Wigner distribution. We reconstruct the Wigner representation of the mixed-state density matrix for *solitary* electrons emitted by an on-demand source. This reveals highly localised distributions isolated from the Fermi sea.

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Quantum dots and superconductivity in GeSi nanowires

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Ge/Si core/shell nanowires are suitable candidates for electrically driven spin qubits, and for the creation of Majorana fermions [1]. In highly tuneable hole quantum dots [2, 3], we observe shell filling of new orbitals and corresponding Pauli spin blockade [4]. In nanowires with superconducting Al leads we create a Josephson junction via proximity-induced superconductivity [5]. A gate-tuneable supercurrent is observed with a maximum of ~60 nA, see Figure 1. We identify two different regimes: Cooper pair tunnelling via multiple subbands in the open regime the device [6], while near depletion the supercurrent is carried by single-particle levels of a quantum dot operating in the few-hole regime [5].

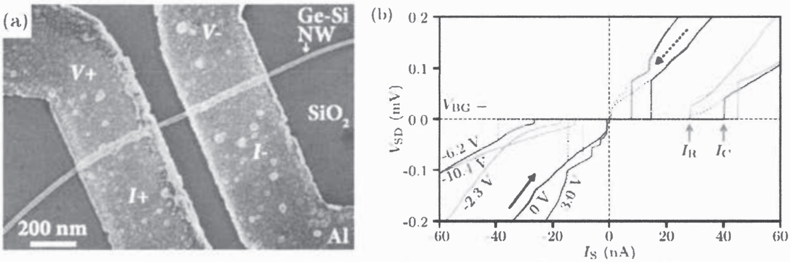

Figure 1. Josephson field-effect transistor. (a) False-color SEM image of the device. A nanowire with a 20 nm diameter (yellow) lies on top of SiO_2. Al source and drain contacts (green) define a 150 nm long nanowire channel. (b) Source-drain voltage V_{SD} versus I_S for five different back gate voltages V_{BG}. Solid lines are taken in positive sweep direction while the dotted lines are measured in negative sweep direction. Switching currents I_C and retrapping current I_R are indicated for the pink curve.

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In-situ prepared nanowire-based Josephson junctions for qubit applications

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Currently, the field of solid-state qubits is divided into two independent sections: On the one hand side, there are the well-established superconducting quantum bits (qubits), like the transmon, which provide stable and long-living quantum states due to the build-in coherence of the Cooper pair condensate. On the other hand, there are the semiconductor-based systems, where the two-level system is realized by means of strong confinement, i.e. quantum dots, and spin-orbit coupling. However, recently, a growing number of superconductor/semiconductor hybrid systems were proposed, all of them aiming to combine the main advantages of both concepts, i.e. robustness, small footprints, and electrical tunability. Typical examples are Andreev or gatemon qubits. The key element of these approaches is a gate-tunable Josephson junction. For conventional Josephson junctions, where the two superconducting electrodes are separated by a thin insulating barrier, the transport is based on the tunneling of Cooper pairs. If a semiconductor nanowire is used instead as a link between the superconducting electrodes, the Josephson supercurrent is determined by Andreev reflection processes. For qubit applications it is essential that the Andreev reflection contribution is as large as possible, which requests that the superconductor/semiconductors is as clean as possible. A suitable approach is to fabricate the nanowire-based Josephson junctions by an in-situ approach. In my presentation I will give a review of superconducting qubits based on semiconductor nanowires. I will introduce different approaches how in-situ junctions are prepared and will discuss their electrical transport properties.

Work done in collaboration with Patrick Zellekens[1,2], Russell Deacon[4,5], Steffen Schlör[3], Pujitha Perla[1,2], Patrick Liebisch[1,2], Benjamin Bennemann[1,2], Mihail Lepsa[1,2], Martin Weides[3], Koji Ishibashi[4,5], and Detlev Grützmacher[1,2], (1) Peter Grünberg Institute, Forschungszentrum Jülich, 52428 Jülich, Germany, (2) JARA-FIT, Fundamentals of Future Information Technology, (3) Karlsruhe Institute of Technology, 76131 Karlsruhe, Germany, (4) RIKEN Center for Emergent Matter Science, 351-0198 Saitama, Japan, (5) Advanced Device Laboratory, RIKEN, 351-0198 Saitama, Japan

Topological superconductivity in HgTe-based topological materials

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Edge channels in HgTe quantum wells are one-dimensional systems with manifest topological properties. In the decade since the seminal discovery, progress in strain engineering has revealed that the material HgTe harbors a much richer phase diagram of topological states: a 3D topological insulator (3D TI), a Dirac/Weyl semimetal, and a candidate system for quasi-one dimensional transport with tunable topological dispersion, the HgTe-CdTe core-shell nanowire. I will discuss the exciting physics that emerges when we couple this unique material with conventional superconductors and our next steps towards the manipulation of topological excitations in HgTe topological insulators.

Majoranas in zigzag devices: why shape matters

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High density superconductor-semiconductor-superconductor junctions have a small induced superconducting gap due to the quasiparticle trajectories with a large momentum parallel to the junction having a very long flight time. Because a large induced gap protects Majorana modes, these long trajectories constrain Majorana devices to a low electron density. We show that a zigzag-shaped geometry eliminates these trajectories, allowing the robust creation of Majorana states with both the induced gap and the Majorana size improved by more than an order of magnitude for realistic parameters. In addition to the improved robustness of Majoranas, this new zigzag geometry is insensitive to the geometric details and the device tuning.

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Abstracts of Posters

(in alphabetical order)

Quantum Wires defined by Cleaved Edge Overgrowth – Challenges & Future Goals

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We investigate the one dimensional (1D) physics of Cleaved Edge Overgrowth (CEO) Quantum Wires (QWRs) using AlGaAs/GaAs Molecular Beam Epitaxy (MBE). These very pure and atomically precise quantum systems are expected to reveal new physics of 1D Luttinger Liquids. Especially we are interested in the creation of separately gatable coupled QWRs and experiments inducing topological superconductivity in a wire due to the proximity effect and the influence of a magnetic field.

For the quantum wire fabrication using the CEO technique we start with a AlGaAs/GaAs heterostruture growth along the (001) direction. Then we define top gate structures on top of our sample by standard optical lithography and metal deposition, before we reintroduce the sample into the MBE chamber. The sample is cleaved along the (110) direction in the ultra high vacuum environment of the MBE chamber, followed by a second MBE growth along the cleaved (110) plane. Thus we can grow heterostructures along two crystal directions without contaminating the interface in between. The quantum wire forms at the interface between the heterostructures by gate depletion of the 2DEG. The length of the quantum wire is given by the width of the top gate.

Our first goal is to build a wire in an high mobility AlGaAs/GaAs system. Once this is achieved the development of separately gateable AlGaAs/GaAs quantum wires will be of interest. Within the first MBE growth a second AlGaAs/GaAs/AlGaAs stack will be grown. This will create a second wire which will be gated using structured back gates created by oxygen ion implantation [1]. With this setup the coupling between two separately tuned wires can be studied and Coulombdrag can be seen. For stronger spin-orbit interactions, InAs wires would also be of interest in the future. Another future project is the creation of a topological superconducting state. The basic setup needed is a 1D wire with spin-orbit coupling, a s-wave superconductor deposited on the cleaved edge and a magnetic field to break time-reversal symmetry [2]. Near the ends of the wire at the interface between the topological superconducting state and the trivial state, Majorana Fermions are predicted [3].

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InSb Nanowires for Advanced Quantum Devices

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Indium-antimonide (InSb) nanowires (NWs) have thus far contributed to the quest for topological states, such as Majorana zero modes, key components for fault-tolerant quantum computing. Their unique properties, such as their strong spin-orbit coupling and high electron mobility grant InSb NWs with the required ingredients for bearing topological phases when combined with a superconductor.

The synthesis of this superior material is rather challenging, requiring a nanowire "stem" of a foreign material for its nucleation. The use of a stem, however, poses two main drawbacks; it introduces material impurities to the InSb NW and limits its length to a maximum of about 4 µm. Longer InSb NWs are, however, preferred as they could minimize the overlap between the Majorana wavefunctions at the nanowire ends, by spatial separation. Furthermore, longer NWs are able to host multiple superconducting islands, giving rise to novel device configurations.

Here, we show the growth of pure zinc blende InSb NWs reaching tens of microns in length. Our technique involves the use of a selective-area mask, thereby allowing the complete omission of the foreign stem. The high chemical purity of these NWs is reflected in the significantly higher electron mobility values as compared to InSb NWs on stems.

To benefit from the high quality of these wires, we envision complete device fabrication, with predefined contacts *in-situ.* This relies on 2-dimensional InSb nanostructures synthesized in close proximity to the NWs to act as shadowing objects. In particular, by tuning patterning parameters, we can within statistical uncertainty locally choose whether a stemless NW or 2D structure are formed.

Quantum transport through carbon nanotube $NbSe_2$ hybrid devices for Majorana Fermion detection

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Recently, it was suggested that Majorana Fermions can also occur in carbon nanotubes (CNTs) in proximity to an ultrathin superconductor (SC) in large parallel fields [1,2]. We demonstrate first building blocks of the device following this proposal. As a SC we chose a bilayer $NbSe_2$ crystal, which is so thin that its electron density and chemical potential can be tuned by a gate. Such tunability is crucial to enter the topological phase of the proximitized CNT. We show that the $NbSe_2$-CNT contact transparency can be drastically improved by exfoliating and stamping the flake in N_2 atmosphere and by making use of edge contacts to both CNT and $NbSe_2$. We present a first proof-of-principle device, whose transport characteristics are measured as a function of temperature and magnetic field.

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Low-dimensional transport properties of InAs-based Nanowires

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One-dimensional (1D) InAs semiconductor nanowires (Nws) have attracted considerable attention in recent years, due to their high spin-orbit coupling as well as strong quantization and large subband-spacing for sub-50 nm diameter NWs. As such they play a prominent role for realizing ballistic transport and topological nanowire-superconductor systems. To understand the properties of these systems a precise knowledge of the underlying scattering mechanisms [1] and length-scales for phase coherent transport is indispensable.

In this contribution, we explore the one-dimensional electrical transport properties of radially strongly confined InAs NWs and surface-passivated InAs/InAlAs NWs. Planar NW field effect transistor (NWFET) devices were fabricated onto SiOx/n++ Si substrates, and in consecutive temperature dependent measurements (4.2 K – 77 K) conductance quantization was observed with plateaus of different shapes and sizes depending on the channel diameter. To elucidate the underlying regimes of transport, low-field magnetotransport measurements at temperatues between 2.4 K and 4.2 K reveal weak localization (WL) and weak antilocalization (WAL) tunable by the applied backgate voltage (as also observed in [2]) and NW diameter. Within this phase coherent transport, we extract useful metrics such as the phase coherence lengths and spin-orbit relaxation lengths which exhibit lengths of l_Φ , l_{SO} of ~40-100 nm, depending on channel diameter/length and temperature. Additional experiments performed on surface-passivated InAs-InAlAs (30-nm/8-nm) core-shell NWs exhibit very pronounced conductance peaks with equidistant peak separation of ~80 mV as revealed in detailed bias spectroscopy measurements near pinch-off. In this disordered system, where transport is dominated by Coulomb blockade, we further analyzed the measured gate capacitance and single electron charging energy of these devices, and found a quantum dot length which approximates almost the entire gated NW length.

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Double Quantum Dot Tunneling Magnetoresistance without Ferromagnetic Contacts

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Abstract: Semiconducting InAs nanowires (NWs) provide an ideal system for electron spin control due to their large g-factors and spin-orbit coupling. Short confined InAs nanowire segments with a single pair of ferromagnetic side gates (FSGs) exhibit a strong magnetoresistance (MR) [1], which depends on the magnetic stray field of the FSGs [2]. Here we investigate a weakly-coupled double quantum dot (DQD) with two pairs of FSGs to demonstrate tunneling magnetoresistance (TMR) without any ferromagnetic contacts.

The FSG pairs electrically tune the individual quantum dots and provide local magnetic fields, which can be oriented independently by characteristic values of the external magnetic field. We identify the four possible magnetization states of the two FSG pairs, corresponding to four different DQD conductance characteristics: two states with parallel (P) and two with anti-parallel (AP) magnetizations. The anti-parallel states result in a suppression of the maximum current by about $\Delta I/I \approx 14\%$ at zero external magnetic field, leading to single dot spin polarization of ~30% at the Fermi energy on resonance. Simple modeling also reproduces experiments at small external fields, suggesting gate tunable individual QD polarizations of up to 80%. At finite bias, we observe an unconventional shell filling in the DQD honeycomb pattern, leading to neighboring Pauli Spin Blockade (PSB) bias triangles [3], and inverted PSB at large magnetic fields [4]. The standard PSB triangles exhibit only one switching due to inversion in the FSG orientation, possibly related to the specific involved spin states. The demonstrated ability to engineer complex TMR devices without ferromagnetic contacts might enable nanometer scale spin injection and detection experiments, as well as the fabrication of larger FSG arrays to generate synthetic spin-orbit interactions [5].

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Merging MBE grown semiconductor heterostructures with in-situ deposited thin film superconductors towards top-down topological quantum computation

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Majorana fermions have become a hot contender for fault tolerant quantum computation based on non-Abelian exchange statistics [1]. The interest in the field has been fueled by the announcement of a possible realization of Majorana fermions in hybrid superconductor-semiconductor nanowire devices [2]. Although yielding promising results when looking for Majorana states, vapor liquid solid grown nanowires do not easily allow for intricate designs required for braiding operations. Hence top down integration of superconductor-semiconductor hybrid channels is an active field of research [3].

Semiconductor heterostructures of the 6.1 Å family, such as InAs, AlSb, InSb and GaSb, with their wide range of energy gaps and large spin-orbit interaction are prime candidates. Here, we present MBE grown InAs and InSb surface quantum wells. The crystalline quality and its impact on the electronic transport properties at cryogenic temperatures were analyzed and optimized [4, 5]. In a further step, in-situ deposited aluminum thin-films [6] were investigated by AFM and TEM.

Furthermore, superconductors beyond aluminum are of interest for us. Ongoing work is focusing on deposition of elemental and A15 phase superconductors in-situ after MBE growth. Issues such as Schottky barrier formation and coupling efficiency [6], as well as thin film effects are to be addressed. Ultimately, our goal is to achieve a platform which allows Majorana braiding.

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Parallel semiconductor nanowire based electronic devices

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Recent advances in semiconductor nanowire (NW) device fabrication have resulted in a new family of electronic and superconducting devices which are based on two (or more) parallel NWs in close proximity. In a first step, the application of such double NWs for the realization of a Cooper pair splitter with an efficiency of 20% was demonstrated [1]. Theoretical work predicts that a device consisting of a double NW with a strong interwire coupling set by a superconductor can host fractional Majorana bound states called parafermions [2]. These are of particular interest for topological quantum computing, since parafermions allow a wider set of operations than Majorana bound states [2].

Here we present two new experiments using a double NW geometry: in the first, we measure the current through a Josephson junction, in which two superconducting contacts are coupled by two NWs in parallel, which can selectively be tuned and depleted, similarly as reported in [3].

In the second experiment we use two individually contacted parallel NWs and measure the response in one NW while driving a current through the other. We find two contributions to the induced current on the second NW, one that scales linearly and one that scales with the square of the drive current in the first NW. We tentatively attribute the former to Coulomb drag resulting from gate-tunable electron-electron interactions between the parallel NWs [4], while the latter effects probably originate from a thermoelectric coupling between the NWs.

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On the preparation and electronic properties of clean superconducting Nb(110) surfaces

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We have studied cleaning procedures of Nb(110) by verifying the surface quality with low-energy electron diffraction, Auger electron spectroscopy, and scanning tunneling microscopy and spectroscopy [1]. Our results show that the formation of a surface-near impurity depletion zone is inhibited by the very high diffusivity of oxygen in the Nb host crystal which kicks in at annealing temperatures as low as a few hundred degree Celsius. Oxygen can be removed from the surface by heating the crystal up to 2400°C. Tunneling spectra measured on the clean Nb(110) surface exhibit a sharp conductance peak in the occupied states at an energy of about -450 meV, originating from a d_{z^2}-like surface resonance band at the $\bar{\Gamma}$ point of the Brillouin zone, as shown by density functional theory calculations. The clean Nb(110) surface is superconducting with a gap width and a critical magnetic field strength in good agreement to the bulk. In an external magnetic field, we observe the Abrikosov lattice of flux quanta (vortices). Spatially resolved spectra show a zero-bias anomaly in the vortex core. If imaged at bias voltages corresponding to energies inside the superconducting gap, a pronounced asymmetry of the vortex is observed. Possible explanations for this asymmetry will be discussed.

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Advanced thermoelectric properties in high-mobility GaAs/AlGaAs core-shell nanowires

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Semiconductor nanowires (NW) are promising one-dimensional (1D) systems for thermoelectric power conversion applications. A particularly appealing feature of 1D-NWs is that electrical and thermal effects can be theoretically decoupled. By working in the ballistic transport regime, high electrical conductivity and large Seebeck coefficients may thus be achieved. However, the simultaneous realization of low thermal conductivity is a challenge, since the large surface-to-volume ratio responsible for high phonon scattering also usually increases electron scattering thus preventing ballistic 1D transport. This encourages the development of completely new approaches for designing efficient nanowire thermoelectrics.

A suitable platform to circumvent this problem is presented in this work. Our studies are based on high-mobility Si-delta doped GaAs/AlGaAs core-shell NW heterostructures, which hold the potential for both high-performance steep-slope NW-field effect transistors (NWFET) [1] and for in-depth investigations of low-temperature quantum transport [2]. Top-gated NW-FETs were used to study the quantum transport characteristics at low temperature (4-7 K). During pinch-off we observe clear plateau-like signatures, consistent with the depopulation of quasi-1D subbands as confirmed by correlated simulations [2]. Subsequent Seebeck effect measurements show distinct spikes in the Seebeck voltage as a function of applied gate voltage and different heater powers which correspond to the 1D-like plateaus in conductivity [3]. Furthermore, thermal conductivity measurements were carried out on suspended NWs using Raman spectroscopy [4], to probe the effect of the AlGaAs barrier on phonon scattering.

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Second-order topological insulators and superconductors with an order-two crystalline symmetry

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Second-order topological insulators and superconductors have a gapped excitation spectrum in bulk and along boundaries, but protected zero modes at corners of a two -dimensional crystal or protected anomalous gapless modes at hinges of a three-dimensional crystal [1]. A second-order topological phase can be induced by the presence of a bulk crystalline symmetry. Protected gapless boundary states that are induced by the presence of a bulk second order topological phase are termed intrinsic boundary signatures. This is in contrast to extrinsic boundary signatures that can be induced and removed by a change of crystal termination. The poster will emphasize the difference of those boundary signatures and discuss the anomalies of the possible boundary signatures. We show how boundary signatures and the corresponding second order topological phases can be systematically classified in crystals with an order two crystalline symmetry such as mirror, twofold rotation or inversion symmetry.

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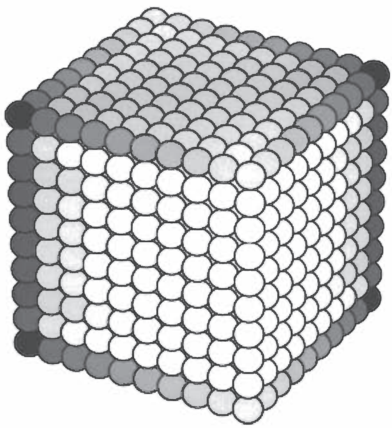

One-dimensional helical states in SnTe topological crystalline insulator nanowires: Modelling and growth

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Tin telluride (SnTe) is a topological crystalline insulator (TCI) with gapless surface states protected by mirror symmetry [1]. We have grown SnTe nanowires for the first time in MBE with and without metal catalyst particles. We can grow nanowires with either $\{100\}$ or $\{111\}$ facets. A layer of Al_2O_3 is deposited in ALD to protect the nanowires against oxidation, so that the SnTe surface facets remain pristine. The promise of MBE growth of SnTe nanowires is to solve the p-type doping problem [2], by growing in out-of-equilibrium conditions. Therefore, charge carrier densities are measured in transport measurements.
By modelling superconducting SnTe thin films we showed the realization of 2 and 4 Majorana fermions at each end of a superconducting π-junction for the $\{111\}$ and $\{001\}$ surface facets respectively. Besides that for nanowire energy dispersions indications of Dirac physics appear, but Dirac cones seem to be buried in the bulk bands for practical nanowire diameters. Furthermore, we investigate symmetry breaking by strain, substrates and electric fields for the purpose of SnTe HOTIs.

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Shaping electron wave functions in a nanotube with a parallel magnetic field[1]

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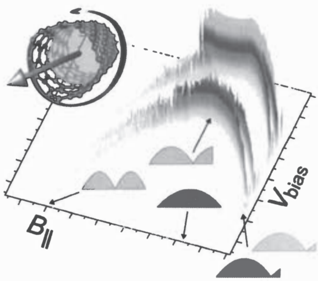

The motion and distribution of charges in almost all known systems is affected only by the transverse components of the magnetic field. Classically, the Lorentz force is perpendicular to *B*. Quantum mechanically, the parallel component of the vector potential can be gauged away. In carbon nanotubes, however, the common intuition fails: the electron's motion is not immune to the parallel component of the magnetic field. Due to the nanotube's cylindrical topology and bipartite hexagonal lattice, the boundary conditions couple the transverse and longitudinal components of the electronic wave vector. By tuning the former via the Aharonov-Bohm effect, we also affect the latter.

The high fields (up to 17 T) in our experiment are sufficient to reshape the electronic wave function from a “quarter-wave resonator” profile with an antinode at one end all the way to a “half-wave resonator” profile with nodes at both ends. These changes cause a distinct dependence of the conductance through our device on the magnetic field. Using the non-trivial lattice and topology of carbon nanotubes we have discovered a new strategy for the control of the wave functions, using an unexpected agent – the parallel magnetic field.

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Coulomb blockade enhanced carbon nanotube optomechanics[1]

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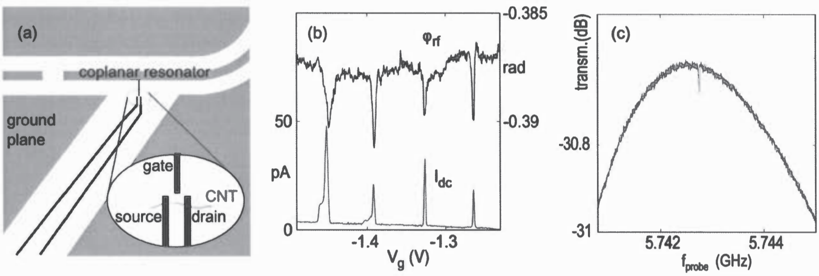
A clean, suspended single wall carbon nanotube is the ultimate limit of a nanomechanical beam resonator, where the fundamental transversal vibration mode reaches resonance frequencies on the order of 100MHz – 1GHz and mechanical quality factors up to 10^6. However, small vibrational deflection and length have made the optomechanical coupling of a nanotube to microwave fields, as used in solid state cavity quantum electrodynamics or quantum information experiments, so far impossible.

Here, we present first results on optomechanical coupling of a suspended carbon nanotube quantum dot and a microwave cavity at millikelvin temperatures. With an optomechanically induced transparency (OMIT) experiment [2], we demonstrate that the intrinsic nonlinearity of Coulomb blockade enhances the coupling by several orders of magnitude, reaching outstanding single-photon couplings of up to $g_0 = 2\pi \cdot 88$Hz.

This indicates that the strong optomechanical coupling limit and full quantum control of the nanotube vibration is feasible in the near future. The carbon nanotube – coplanar waveguide resonator system lends itself for manifold nano-electro-mechanical experiments, integrating the research areas of optomechanics and quantum transport.



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Electron pair charging in gate-defined quantum dots in indium antimonide nanowires

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Indium antimonide (InSb) nanowires can be grown in high quality and offer, due to their locally tunable charge carrier density, the possibility to study low-dimensional quantum systems such as quantum wires, quantum dots, and quantum point contacts. They also feature a strong Rashba spin-orbit interaction. In conjunction with superconductors, they are promising building blocks for quantum information technology.

We investigate InSb nanowires placed on bottom gates with mechanically exfoliated hexagonal boron nitride (h-BN) as a dielectric. The sample consists of five 50 nm wide finger gates with a spacing of 30 nm. The h-BN is placed on top of the finger gates. The nanowires are then placed mechanically onto h-BN [1].

We present transport measurements on gate-defined quantum dots at temperatures down to 300 mK. Due to the dielectric, the time stability of our device improved to around 5 µeV/h. The charge stability diagram shows Coulomb diamonds with a charging energy of 1.24 meV and an orbital energy of 0.33 meV. From the magnetic field dependence of the excited states we extract a g-factor of about 75.

In a perpendicular magnetic field, the zero bias state splits at around 380 mT with a doubling of the gate-periodicity below and above the transition field. This splitting resembles the one reported by Shen *et al.* on nanowires partially covered by superconductors [2]. But since in our sample there is no superconductor involved, the doubling is of unknown origin. However, the change in periodicity implies a change of the pairing mechanism, possibly triggered by electron-electron interaction.

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Selective area semiconductor-superconductor networks

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Proximitized hybrid semiconductor-superconductor nanowires are a promising candidate for future applications in quantum information processing [1]. A major contribution to their importance is the theoretically predicted existence of non-abelian states in the form of Majorana bound states. These states are topologically protected against local perturbations, which provides a basis for naturally fault tolerant quantum computing. This project entails the development of in-plane selective area grown semiconductor nanowires with an epitaxially grown superconductor. Transport measurements on the resulting wires showed a hard gap induced by the proximity effect as well as the characteristic transition from Cooper pair to a single-electron tunneling process. These properties show the potential of the hybrid system as a basis for topological networks.

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Quantized conductance in topological insulators revealed by the Shockley-Ramo theorem

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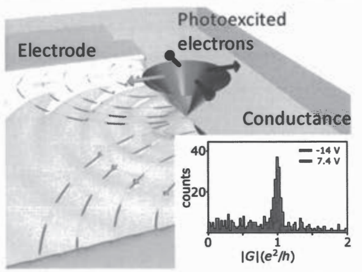
Crystals with symmetry-protected topological order, such as topological insulators, promise coherent spin and charge transport phenomena even in the presence of disorder at room temperature. Here, we demonstrate how to image and read-out the local conductance of helical surface modes in the prototypical topological insulators Bi_2Se_3 and $BiSbTe_3$. We apply the so-called Shockley-Ramo theorem to design an optoelectronic probe circuit for the gapless surface states, and find a well-defined conductance quantization at $1e^2/h$ within the experimental error without any external magnetic field. The unprecedented response is a clear signature of local spin-polarized transport, and it can be switched on and off via an electrostatic field effect. The macroscopic, global read-out scheme is based on an electrostatic coupling from the local excitation spot to the read-out electrodes, and it does not require coherent transport between electrodes in contrast to the conventional Landauer-Büttiker description. It provides a generalizable platform for studying further non-trivial gapless systems such as Weyl-semimetals and quantum spin-Hall insulators.



Switchable detection of a quantized conductance in a topological insulator field effect device.

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Ballistic superconductivity and tunable π-junctions in InSb quantum wells

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Two-dimensional electron gases(2DEGs) coupled to superconductors offer the opportunity to explore a variety of quantum phenomena. These include the study of novel Josephson effects, superconducting correlations in quantum (spin) Hall systems, hybrid superconducting qubits and emergent topological states in semiconductors with spin-orbit interaction (SOI). In particular, there has been a recent interest in realizing topological superconductivity in planar Josephson junctions (JJs) in 2DEGs. A topological phase transition is predicted when a Zeeman field alters the ground state of the JJ from 0 to π[1]. The exceptional electronic properties of InSb 2DEGs make it a perfect material to realize this π- junction. However, so far, material challenges have prevented the study of hybrid superconducting devices in InSb 2DEGs. Here, we interface InSb 2DEGs with a superconductor (NbTiN) to create Josephson junctions, thus providing the first evidence of induced superconductivity in high-quality InSb 2DEGs[2]. The JJs support supercurrent transport over several microns and display clear signatures of ballistic superconductivity. Furthermore, we exploit the large Lande g-factor and gate tunability of the junctions to control the current-phase relation and drive transitions between the 0 and π states. The transition is determined by a simple resonance condition, where the Zeeman energy and Thouless energy become comparable. We demonstrate that both electric and magnetic fields control of 0-π transitions. This control over the free energy landscape allows us to construct a phase diagram identifying the 0 and π regions, in agreement with theory. Our results establish InSb 2DEGs as a promising new material platform to study the interplay between superconductivity, SOI and magnetism. The exceptionally large π-regions in the parameter space is ideal to study topological superconductivity in InSb 2DEGs.

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Ballistic superconductor/semiconductor nanowire junctions

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Quantum Computing (QC) promises exponential leap in computation for certain challenging problems. Realizing QC largely depends on the coherence times of the qubits which again depends on the level of quantum state isolation. One proposal is the topological protected Majorana fermion-based quantum bits which has the potential of isolation from local perturbations leading to a stable quantum state. One-dimensional hybrid superconductor/semiconductor nanowires are promising material platforms to host Majorana bound states [1][2]. Requirements for the formation of such nanowires are many, on both choice of materials, morphology and crystal quality. Because of the requirements of tunability, strong spin-orbit coupling, large landé g-factor factor and superconductivity we grow single crystalline InAs, InSb and $InAs_{0.3}Sb_{0.7}$ nanowire networks with epitaxial Al shadow junctions in a single-step molecular beam epitaxy growth process. We compare and discuss pros and cons associated with the different material systems. The InAs/InSb/$InAs_{0.3}Sb_{0.7}$ nanowires are grown from InAs <111>B facets in etched trenches and Al is grown on selected nanowire facets at liquid Nitrogen cooled temperatures. We characterize both in-situ and post-growth etched junctions and demonstrate in-situ junctions exhibit clean surface morphology and better electrical transport with sharp pinch-off and quantized conductance for all types of wires.

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Correlating transport and spectroscopy measurements of the Little-Parks effect in a gatemon qubit

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Proximitized semiconducting nanowires serve as a promising platform for both superconducting qubits [1] and topological qubits based on Majorana zero modes (MZM) [2,3]. Here we demonstrate *in-situ* switching between coherent cQED measurements and transport measurements based on a full-shell nanowire using a Josephson junction as a gate tuneable switch. These field-compatible devices show flux-dependent lobe spectra in both transport and cQED measurements associated with the Little-Parks effect. Coherent operation is performed both around zero applied field and around 90 mT, corresponding to one flux quantum being threaded through the wire, with a destructive regime in between.
This opens the possibility of detecting the presence of MZMs in one-flux-quantum regime by cQED measurements.

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Majorana fermions in tungsten ditelluride

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Topological superconductors give rise to a variety of extraordinary phenomena, such as fractionalization of particles or non-Abelian exchange statistics [1]. In fact, these novel quantum properties originate from exotic states in topological superconductors, related to so-called Majorana modes [2]. Creating and controlling them, therefore, is of utmost interest and would herald a new era of quantum computation. Fortunately, these modes are insensitive to external noise and hence are ideally suited as quantum bits. In solid state systems, Majorana modes can be artificially created by proximity-coupling a superconductor to a quantum spin Hall insulator which are both subject to an incident magnetic field [3]. So far, the existence of Majorana fermions is mainly hampered by the poor interface quality between the superconductor and quantum spin Hall insulator. Beneficially, monolayer tungsten ditelluride (WTe_2) was recently shown to exhibit a superconducting and a quantum spin Hall insulator phase at the same temperature [4,5]. These phases can be accessed solely by electrostatic gating of the flake and thus be brought into close proximity without the need of interface engineering. Within the poster session, I will introduce the topic of Majorana fermions and explain how we plan to create these modes in a monolayer of tungsten ditelluride (WTe_2).

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Ballistic topological insulator Bi_2Se_3 nanoribbon Josephson junctions

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Topological Insulators (TI) are materials with topologically protected surface states, where the carriers are Dirac electrons characterized by a linear energy momentum dispersion. The realization of hybrid devices by coupling a TI and an s – wave superconductor (SC) is a prospective platform for inducing topological superconductivity essential to generate Majorana bound states (MBS) of relevance for topological quantum computing.

Josephson junctions made of TIs as a barrier can be used to experimentally probe MBS. However, limitations are set by the fact, that the induced MBS is only one of many trivial channels. So far, most of the TIs Josephson junctions have been characterized by low transparency SC/TI interfaces and a diffusive transport through the topological surface states.

Here we study topological insulator Al - Bi_2Se_3 nanoribbon - Al hybrid Josephson junctions. The characteristic parameter - I_cR_n product of the fabricated devices is close to the value of superconducting gap of Al and the conductance spectra (*dI/dV*) indicates very well resolved multiple Andreev Reflections (MAR). The analysis of the conductance spectra confirms a highly transparent interface between Al and the topological insulator. The gate dependent transport in our devices reveal Fabry - Pérot interferences induced oscillations of the normal resistance and the critical current, pointing to the ballistic transport via the topological surface states.

Proposal for Measuring the Parity Anomaly in a Topological Superconductor Ring

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A topological superconductor ring is uniquely characterized by a switch in the ground state fermion number parity upon insertion of one superconducting flux quantum—a direct consequence of the topological “parity anomaly.” Despite the many other tantalizing signatures and applications of topological superconductors, this fundamental, defining property remains to be observed experimentally. Here we propose definitive detection of the fermion parity switch from the charging energy, temperature, and tunnel barrier dependence of the flux periodicity of two-terminal conductance of a floating superconductor ring. We extend the Ambegaokar-Eckern-Schön formalism for superconductors with a Coulomb charging energy to establish new explicit relationships between thermodynamic and transport properties of such a ring and the topological invariant of the superconductor. Crucially, we show that the topological contribution to the conductance oscillations can be isolated from Aharonov-Bohm oscillations of nontopological origin by their different dependence on the charging energy or barrier transparency.

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InAs – EuS – Al hybrid nanowires

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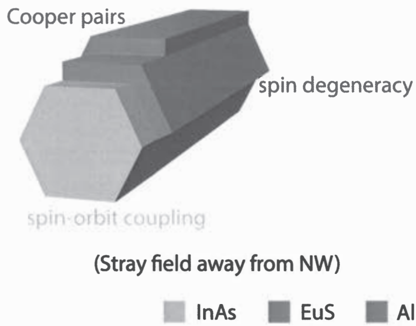
Material development holds promise as the basis of topological quantum computing with Majorana fermions. These quasiparticles have been predicted to be formed in semiconductor nanowires coupled to conventional superconductors.[1-2] This prediction was followed by a series of experiments providing strong evidence.[3-4] However, in the current system, an external magnetic field along the NW axis is always needed to realize Majorana states. Therefore, in order to integrate and scale up qubit devices, it is aimed to induce a self-sustaining parallel magnetic field on semiconductor–superconductor hybrid NWs. Composite materials using ferromagnetic insulators (FMIs) in close proximity to a semiconductor – superconductor structure have been proposed as a solution to reach a zero-field topological state[5], where the effective Zeeman splitting is induced by an magnetic exchange coupling by the FMI. In this work, we grow epitaxial semiconductor – ferromagnetic insulator – superconductor InAs-EuS-Al hybrid nanowires in-situ in the molecular beam epitaxy system. The results show the superconducting hard gap, the transport hysteresis and the shape-defined magnetic single domain structures based on well-controlled epitaxy, which suggests that this highly ordered material system is a promising platform for scalable topological quantum computing.



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Improved quantum transport calculations using the Numerical Renormalization Group

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Considering the two most effective formulae to calculate the conductance in Mesoscopic Quantum Systems, i.e. Meir-Wingreen in Non-Equilibrium Theory [1] and Kubo in Linear Response Theory [2], we will introduce their limiting features.
Motivated by those, we will show some alternative analytical expressions we have derived in both formalism, stressing their advantages with respect to the existing formulae.
Next, we will introduce the 1-Channel Charge-Kondo Model [3] and implement the improved version of Kubo conductance formula in it. Using Numerical Renormalization Group technique, the outcome for both single-channel and spin-flip conductance shows advance with respects to current literature results [4].

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Transport spectroscopy of MoS_2 nanotubes[1]

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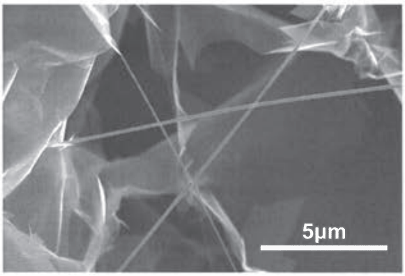
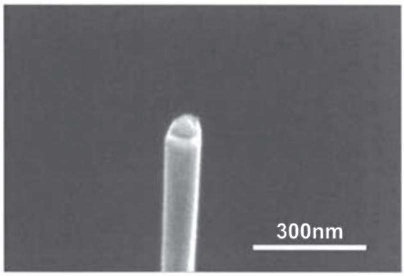
While synthesis procedures for nanotubes based on layered materials other than graphene are well-known [2, 3, 4], their transport properties are so far largely unexplored [5, 6]. Here, we introduce transition metal dichalcogenide (TMDC) nanotubes as a new material platform for transport spectroscopy. We present results on optimized nanotube synthesis, first device fabrication, and demonstrate low-temperature transport spectroscopy measurements on quantum dots lithographically defined in multiwall MoS_2 nanotubes [1]. At T=300mK, clear Coulomb blockade is observed, with charging energies in the range of 1meV. In single electron tunneling, discrete conductance resonances are observed. Additionally, a magnetic field perpendicular to the nanotube axis reveals a rich spectrum of transport phenomena.





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Engineering electron-phonon interaction in quasi-one-dimensional systems

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Although phonons are amongst the most fundamental excitations in condensed matter, in quantum technology applications they have a bad reputation because they are mainly seen as a source of decoherence mediated by electron-phonon interaction. However, coherent phonons have their own advantages, mainly because their wavelength can be matched to the size of nanostructures. Therefore, phonons interact stronger with electrons confined in nanostructures than photons. In analogy to cavity QED, we use focusing Bragg reflectors for the confinement of surface acoustic waves coupled to a few electron double QD. The Bragg reflectors are defined by the mass load of curved-shape surface gates.They form a high-Q phonon cavity resulting in an enhanced coupling between the cavity phonons and confined electrons. Here, we present preliminary results aiming at the strong electron-phonon coupling regime. Further, we discuss the feasibility of transferring the phonon cavities to intrinsically one-dimensional structures such as semiconductor nanowires, which could enhance the electron-phonon coupling further.

In-plane InSb Networks for quantum devices

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Keywords: InSb, Indium Antimonide, selective area growth

Growth of In-plane Selective Area Networks (InSANe) of InSb nanowires with a high crystal quality. Although InSb has a large lattice mismatch with Indium Phosphide (InP) (high bandgap substrate material), we manage to synthesize single crystal nanowire networks. We investigate the nucleation and growth kinetics in different crystal orientations and show that the surface diffusion length of precursors is key to grow single crystalline networks. Transmission electron microscopy (TEM) analysis shows a zincblende InSb nanowire with a single twin defect a few nanometers above the interface with the underlying substrate. Low temperature transport measurements (e.g. Aharonov-Bohm interference) demonstrate a large electron coherence length of up to 10 μm confirming the high quality of the InSb nanowire networks. Our system holds great promise for Majorana topological quantum computing.

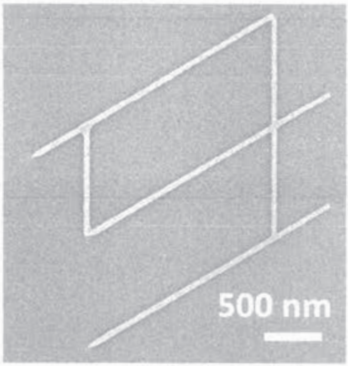

Figure 1. *Scanning electron micrograph of an in-plane InSb nanowire network designed for measuring one Majorana qubit[1]. The structure is selectively grown on an InP substrate.*

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Tunnel spectroscopy of superconducting proximity effect in InAs nanowires using aligned crystal-phase quantum dots

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Superconductor-semiconductor hybrid nanowires devices (NWs) are a promising platform to study proximity-induced low-dimensional quantum transport phenomena such as Andreev bound states and Majorana bound states (ABS/MBSs). ABSs are predicted to evolve into topological protected MBSs with increasing magnetic field in a system where a s-wave superconductor is coupled to a NW with strong spin-orbit coupling. This results in a proximitized superconducting region with p-wave character [1]. A suitable investigation tool for such systems is tunnel spectroscopy using a well-defined, weakly coupled quantum dot (QD) in a NW. So far, it has not been possible to combine a proximity-induced hard gap with such a QD. On the one hand, in NWs with epitaxially grown aluminium (Al) shell, a hard superconducting gap has been reported [2]; however, the QD was only defined by relying on electrostatic gating and/or spontaneous formation. On the other hand, evaporated Al contacts can be combined with build-in well-defined QDs [3], but only a soft superconducting gap has been achieved so far. We aim to study the proximity induced gap with evaporated Al contacts in InAs NWs with built-in crystal-phase defined QDs. Additionally, a selectively grown GaSb-shell [4] allows us to accurately locate the QD and use this information to investigate the behaviour of the induced gap in dependence of the distance of the superconductor to the QD. This in turn will allow us to reliably investigate the induced superconducting behaviour of the NW directly underneath the superconducting contact. So far, we have shown that we can reproduce data measured in crystal-phase defined QD NWs without GaSb-shell. Therefore, we have shown that we can etch the GaSb-shell and couple the superconducting Al to the InAs NW resulting in a soft superconducting gap.

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Wave Functions and Velocities of Quantum Hall edge states

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GaAs cleaved edge overgrowth wires are among the cleanest realizations of quantum 1D systems, displaying conductance quantization as well as salient Luttinger liquid features such interaction enhanced charge velocity, spin charge separation or helical nuclear spin order [1] induced by the strongly interacting electronic system.

Tunneling spectroscopy between two parallel wires is proven to be a powerful tool to probe the electronic dispersions of the quantum wires themselves [2], as well as the adjacent integer quantum Hall edge states that form in presence of a perpendicular magnetic field [3]. The momenta of the edge states can be obtained from the values of the in-plane magnetic field where the tunneling resonances appear for energy and momentum conservation. To determine the wave functions of the edge states, we solve the Poisson and Schrödinger equations self-consistently and calculate the brightness of the tunneling resonance between these edge states and wire modes. The brightness of the resonances is in a good agreement with the values predicted theoretically, confirming validity of the calculated wave functions.

The edge states velocities are another set of important quantities subject to renormalization in the presence of electron-electron interactions. Using bias tunneling spectroscopy we are able to measure the velocities of the lowest two Landau level edge states as a function of the filling factor (out-of-plane magnetic field). In order to do this, we developed a four terminal measurement configuration that allows us to directly determine the voltage drop across the involved tunnel junction and therefore infer the velocities witout additional assumptions, finding good agreement with the unrenormalized velocities for the integer modes.

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In-situ grown superconducting contacts on InAs nanowires

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In the last few years superconducting heterostructures have taken a prominent position in the research area of topological superconductivity. A greatly favored way to realize such a system is the combination of a semiconductor with superconducting electrodes, which effectively leads to an electrically tunable Josephson junction. Especially semiconducting nanowires, like InAs or InSb, have shown a great potential as building blocks for hybrid qubit devices.
we have epitaxially grown aluminum and niobium superconductors on the semiconductor surface done in-situ. This method is based on a molecular beam epitaxy (MBE) growth of an InAs nanowire core and either a metallic aluminum (Al) nanowire full or half shell, or a Niobium (Nb) shell. Because of the ultra-high vacuum (*UHV*) of the MBE reactor the interface is highly uniform along the length of the wire.
The InAs nanowires were grown on (111) B Silicon substrates by the vapor-liquid-solid method in a solid-source MBE system. The wires grow in the [0001] B wurtzite crystal direction, perpendicular to the substrate. After the wire growth the substrate is then transferred to the so-called preparation chamber, by maintaining the UHV conditions, and is further heated for arsenic desorption to avoid the formation of a large bandgap AlAs interface barrier.
Later the substrate is cooled down in the metal MBE and the growth is terminated with an aluminum layer of 25 nm. At such low temperatures, the surface diffusion length of aluminum is only a few nanometers and the aluminum crystals are formed uniformly along the side facets of the InAs nanowire. Here, we have performed two different kind of depositions to achieve a full shell and a half shell configuration. The analysis by means of scanning and transmission electron microscopy show a smooth superconducting contact on the semiconductor and a barrier free interface.
We have also adapted a totally different approach in order to deposit niobium contacts in-situ on InAs nanowires. The nanowires in this case are oriented to have the desired side-facets facing the niobium source. The contacts deposited in this case are very smooth and uniformly covered and do not cause any physical strain to the nanowire. The nanowires are grown on pre-patterned Silicon (100) substrates, which were etched with TMAH solution to reveal the (111) B facets. In a second step, we introduced growth windows into the previously revealed Si (111)B facets, which were geometrically placed to cause shadowing effect of one wire on the other during the metal contact deposition leading to clean in-situ Josephson junctions.

Gate-Controlled Metal-Insulator Transition in TiS_3 Nanowire Field-Effect Transistors

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TiS_3 is an n-type 2D transition metal trichalcogenide that exhibits highly anisotropic, quasi-1D carrier transport. We report extensive electrical characterization of this nanomaterial as a field-effect transistor when it is exfoliated onto and gated through a SiO_2/Si substrate [1]. The transfer curves of this material, measured at temperatures below 100 K, reveal mesoscopic conductance fluctuations in its disordered conductor state that are modulated by both gate-voltage and temperature in a non-monotonic manner; this unusual temperature-dependent behavior is atypical for nanomaterials, and may be related to the formation of a novel charge-density-wave state. Additionally, the metal-insulator transition in TiS_3 is demonstrated to be gate-voltage dependent. Observations over a wide temperature range (3-350 K) allow us to extract a gate-voltage dependent mobility utilizing a modified square-law model. We obtain values as large as 20 cm^2/Vs at room temperature and ON/OFF ratios as large as 10^4. Transistor measurements far from the FET cutoff region reveal marked nonlinear behavior at low applied source-drain voltages, which may again be related to the emergent charge-density-wave state. With increasing temperature, this behavior becomes less pronounced, and disappears entirely near room temperature. Calculations of the transfer- and transistor-curves for these devices, utilizing standard transistor models and semiclassical Boltzmann transport theory, give further insight into the microscopic origins of these results. Schottky-barrier analysis reveals a small effective barrier height (11 meV.) that monotonically decreases with gate bias. This demonstrates the minimal influence of contact resistance on the nonlinearity observed in low-field measurements. These results not only demonstrate that TiS_3 is a testbed for a variety of interesting physics, but show it is viable as a channel-replacement material for use in scaled transistors in future technology generations.

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Majorana bound states in magnetic skyrmions imposed onto a superconductor

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We consider a superconducting film exchange-coupled to a close-by chiral magnetic layer and study how magnetic skyrmions can induce the formation of Majorana bound states (MBS) in the superconductor. Inspired by a proposal by Yang *et al.* [2], which suggested MBS in skyrmions of even winding number, we explore whether such skyrmions could result from a merger of ordinary skyrmions. We conclude that the formation of higher-winding skyrmions is not realistic in chiral magnets. Subsequently, we present a possibility to obtain MBS from realistic skyrmions of winding number one, if a skyrmion-vortex pair is formed instead of a bare skyrmion. Specifically, we show that MBS are supported in a pair of a circular skyrmion and a vortex which both have a winding number of one. We back up our analytical prediction with results from numerical diagonalization and obtain the spatial profile of the MBS. In light of recent experimental progress on the manipulation of skyrmions, such systems are promising candidates to achieve direct spatial control of MBS.

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Spin helical surface states in mesoscopic topological HgTe structures

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Dirac-like surface states of an ideal topological insulator nanowire form a conducting cylinder around the insulating bulk. A magnetic field B aligned along the wire axis results in h/e-periodic oscillations, which reflect the nanowire band structure [1-3]. The latter exhibits a gap for zero magnetic flux $\phi = 0$, but gapless states when half a flux quantum $\phi_0 = h/e$ passes through the cross section. At $\phi = \phi_0/2$, the flux cancels the Berry phase, the gap closes and non-degenerate, perfectly transmitted modes form [4].

Previously, we have shown that a gate voltage applied to the nanowire allows to tune the Fermi level E_F through the wires' subband structure and the magnetoresistance shows *h/e*-periodic Aharonov-Bohm oscillations and a switching of their phase with varying E_F, expected from the wires' band structure.

In the present work, we focus on wires with varying cross sections, or non-simply connected structures, e.g. with an additional hole in the center. The presented geometry aims to probe the effect of varying cross sections on the quantum oscillations, the second one to probe Aharonov-Bohm driven interference effects in quantizing magnetic fields.

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Generative Model Learning

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The theoretical investigation of molecular transistors calls for a deeper understanding of highly non-trivial quantum impurity type Hamiltonians, comprising both molecular orbital complexity and also strong electron interactions. To overcome this problem, we use a generative machine learning [1] scheme to create an effective quantum impurity Hamiltonian that is simple enough to be treated exactly in a second step by methods such as the Numerical Renormalization Group. The effective Hamiltonian is based on the configuration distribution obtained by performing Continuous-Time Hybridization [2] expansion with the original Hamiltonian.

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Building Blocks for Majorana Modes Devices - Growth and Gating of Encapsulated High Quality InAs Nanowires

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Semiconductor nanowires with strong spin-orbit interaction are attracting considerable interest as potential platform for spintronic and topological quantum computing applications. However, future progress will require scalability and integration concepts that go well beyond the single nanowire level.

We will present the low temperature characterization of InAs nanowires obtained via the template assisted selective epitaxy (TASE) technique [1]. The TASE approach allows for the deterministic growth of semiconducting nanowires, nanowire networks and complex branched geometries on a two-dimensional silicon platform. Furthermore, structures grow encapsulated into a silicon oxide shell, which protects them from the environment and preserves them from undesirable doping and surface oxidation. The high quality of TASE grown InAs nanowires was recently demonstrated by the observation of ballistic electron transport over length scales approaching one micrometer [2, 3]. In this work we additionally show quantized conductance measurements in a magnetic field and transport spectroscopy of Coulomb island devices, for characterization of Lande' g-factor and spin-orbit coupling strength.

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Versatile platform for *in-situ* fabrication of InSb nanowire Majorana devices

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InSb nanowires combined with a superconductor have recently gained a lot of attention because the first signatures of Majorana fermions have been detected in 2012 on a superconductor-semiconductor nanowire platform[1]. These first experiments suffered from device fabrication limitations, which compromised the quality of the nanowire, making the measurements somewhat noisy. On that account, the aim of our research is to tackle these fabrication issues to obtain high quality devices.

In order to ensure a clean and smooth superconductor-semiconductor interface, that is crucial to detect Majoranas, we developed a unique substrate fabrication process. With this technique we are able to grow InSb nanowires and InSb nanoflakes on the substrate and place them in pre-determined positions. In particular, every InSb nanoflake is positioned in such a way that it shadows a large area of a rear InSb nanowire during a directional MBE deposition of superconducting material, thus selectively depositing the superconductor on only one part of the nanowire. Through this technique the Majorana device is fabricated *in-situ* with just a single MBE deposition, therefore it is possible to avoid using etchants to remove the superconductor from the other part of the wire (where it is not needed), which tends to be a rather harsh fabrication step, possibly damaging the nanowire surface.

The unique platform fabrication alongside with the new shadowing technique represents a new possibility to fabricate different and more complex InSb-based devices with high crystallinity and clean and smooth interfaces. The technique can be adapted to many different situations, for example a 4-terminal Josephson junction can be fabricated with the shadowing of the nanoflakes on a rear crossed nanowire structure. This device could lead to further understanding of the behaviour of topological matter and Majorana fermions.

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Aluminum-InAs nanowire hybrid devices for observing Majorana zero modes

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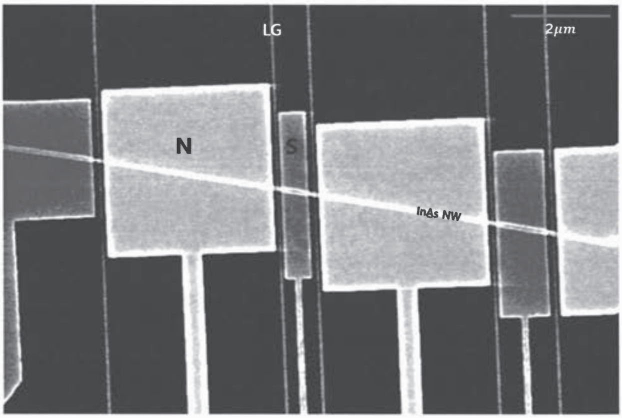
Superconductivity with strong spin-orbit coupling and broken time reversal symmetry provide a basis for generating Majorana zero modes (MZM). Hybrid systems of 1D InAs channel in contact to superconducting aluminum satisfy such property [1]. Since their realization rely heavily on transparent and reliable metal-InAs contacts, we focused on the InAs surface preparation step before metal deposition, and found an optimal protocol of etching the surface of InAs nanowires in NH_4S solution. Resulting devices with normal metal contacts reveal clear signatures of quantized 1D electron transport channels through InAs nanowires. Devices with different lengths of aluminum covering InAs nanowires are currently prepared in order to observe MZM interference effects.



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Microwave induced single electron transitions between Majorana zero modes in hybrid superconducting-semiconducting islands

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Superconductor-semiconductor structures can be driven into a topological regime by application of an external magnetic field, in which Majorana zero modes emerge. Our contribution extends previous work on Majorana modes in superconducting structures [1-5], by developing nanowire-based double-island devices where both the Josephson coupling as well as Majorana coupling between islands can be manipulated using gate electrodes, whereas the charge of islands can be measured with high-bandwidth proximal charge sensors [6].

We experimentally study microwave induced transitions between two superconducting islands when the magnetic field along the nanowire axis is applied [7]. At higher magnetic fields we observe a change in gate space periodicity of the microwave induced transitions. Results are compatible with single electron transitions between zero modes on both sides of the junction. From microwave spectroscopy extracted energy scales for Josephson and single electron coupling are fundamentally important quantities for future developments of topologicaly protected qubits.

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Andreev Oscillations in Selective Area InSb-Al Majorana Nanowires

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Hybrid superconductor-semiconductor nanowires are predicted to host Majorana zero modes, the building block of a topological quantum computer [1, 2]. In this work, we study the transport properties of an InSb nanowire with an epitaxial Al superconductor, where the nanowire was grown from an in-plane structure. These selective area grown (SAG) wires can easily scale up to complicated networks for future braiding experiments [3]. In a tunnelling spectroscopy experiment we observe a hard induced superconducting gap and oscillating Andreev bound states that can transform into a zero bias peak sticking over a magnetic field range of 500mT. By tuning the chemical potential this zero bias peak shows a crossing instead of robustness confirming its trivial nature [4]. Our observation provides a guidance for the detection and correct interpretation of Majorana signatures in SAG InSb-Al wires.

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MBE growth and characterization of PbTe nanowires

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PbTe is a promising material for future quantum transport devices due to its large spin-orbit coupling, high mobility [1] and small effective mass. One dimensional transport may be realized in the nanowire geometry, and since the material can be easily combined with lead as superconductor, exciting possibilities for Majorana devices arise. Additionally, it has been demonstrated that the background carrier concentration and type of carriers can be controlled using the IV/VI ratio during growth [2]. Here we demonstrate the growth of defect-free PbTe nanowires on a silicon substrate, using molecular beam epitaxy. The nanowires show a clearly defined rock salt crystal structure, with {100} side facets and a <100> growth direction. A length of several microns is achieved with diameters of 60 to 100 nm. Initial carrier mobility, carrier density and gate response measurements are performed on single nanowires, and show promising results for future experiments.

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Quantized thermal Hall conductance from edge currents in lattice models

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The quantized thermal Hall effect is an important probe for detecting chiral topological order and revealing the nature of chiral gapless edge states. The standard method for calculating the thermal Hall conductance κ_{xy} is based on the linear-response theory (Kubo formula), the application of which is confronted with big challenges due to the lack of a reliable numerical method for calculating dynamical quantities in microscopic models. In this work, we propose a new approach for calculating κ_{xy} in two-dimensional lattices models displaying chiral topological order. Our approach targets at the edge current localized at the boundary and involves only thermal averages of local operators in equilibrium, thus drastically lowering the barrier for the calculation of κ_{xy}. We use the chiral p-wave superconductor (with and without disorder) and the Hofstadter model as benchmark examples to illustrate several sources of finite-size effects and suggest the long (or infinite) strip as the best geometry for carrying out numerical simulations.

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Quantum Phase Transitions and Topological Superconductivity in Full-shell Nanowires

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Fluxoid quantization in hybrid semiconducting wires with full superconducting shell gives rise to numerous exciting condensed matter phenomena. Here, we experimentally investigate InAs nanowire with Al shell. Resistance measurements of the shell reveal destructive Little-Parks regime that leads to a flux-tuned quantum phase transition. The measured flux, temperature, and current-bias phase diagrams are well described by the Ginzuburg-Landau theory with no free fit parameters. We observe quantum tunneling between two fluxoid states, that can be tuned by a perpendicular magnetic field. Tunneling spectroscopy at the end of the wire shows that the proximity-induced superconductivity with a quantized number of phase windings can host Majorana modes around one applied flux quantum. The presence of the topological phase is further supported by the exponential length dependence of the hybridization energy in Coulomb islands.

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Observing a Hierarchy of Modes in a 1D Strongly Correlated Liquid beyond the Luttinger Regime

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It is notoriously hard to study theoretically interacting quantum systems outside the Luttinger-liquid regime, particularly when considering higher-energy excitations in finite-length 1D systems, as its key assumptions no longer hold [1]. Recent theoretical work has focused on extending this theory to include such regimes [2]. It is predicted that, for higher-order excitations, 'replica' parabolic dispersions with higher momenta or negative effective mass should be observed, in addition to the simple parabolic dispersion, and that a hierarchy of modes should therefore emerge [3,4], controlled by system length and separated in amplitude by powers of R^2/L^2, where R is the interaction length-scale and L is the length of the system.

Our work focuses on the experimental detection and quantification of these higher-order excitations. We measure momentum-resolved tunnelling of electrons to and from an array of wires formed within a GaAs heterostructure, and map the dispersion of the system both in the equilibrium and nonequilibrium regimes. We will present recent experimental data obtained at 300mK for systems ranging from 1-5 µm where both first- and second-order replica modes, in addition to the lowest 1D subband itself, can be seen. The momentum dependence of the observed structure will also be discussed and compared to what is predicted by theory. Independent interaction parameters are obtained from other well-known 1D features observed at low energy, such as the spin-charge separation and the zero-bias anomaly [5].

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Backbones of a Topological Qubit – High Quality Selective-Area Grown InSb Nanowire Networks using MBE

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Nanowires made from III-V compound semiconductors are arguably the most mature platform for studying topological superconductivity and realizing Majorana bound states (MBSs). So far, progress on this front have been restricted to single nanowires grown with conventional vapor-liquid-solid (VLS) method. Although it is able to produce nanowire crosses and hashtag structures, the realization of more complex networks calls for a planar approach. Here, we implement such planar synthesis of InSb by employing a selective area growth (SAG) technique by molecular-beam epitaxy (MBE). We perform structural characterization to assess the crystal quality and basic transport characterizations to demonstrate the electronic properties. The high quality of electron transport in bare InSb nanowires and cross junctions are verified by both classical mobility and quantum transport measurements with Hall mobility reaching 17,000 cm2/(V*s) and quantum point contact (QPC) plateaus at finite magnetic field. We also demonstrate phase coherent transport by studying Aharonov-Bohm interference in loops and induced superconductivity in an Al-covered sample. These results combined make InSb SAG a promising material platform for realizing a topological qubit.

Electronic transport in phase-biased zigzag Josephson junction

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Majorana zero-modes are leading candidates for realizing topological quantum computation and have been intensively studied over the past few years in semiconductor-superconductor hybrid systems. Two-dimensional electron gases with induced superconductivity not only provide the opportunity to create scalable Majorana networks, but also offers an alternative approach to create Majoranas using planar Josephson junctions. By controlling the phase difference across the junction it has been predicted that the system can be driven into the topological regime at ideally zero magnetic field [2]. In comparison to a conventional straight junction geometry, latest theoretical work also points out that a zigzag-shaped junction enhances the superconducting gap, by eliminating the quasi-particle trajectories with large momentum parallel to the junction [3]. This allows for the robust creation of Majorana states with a much larger topological gap Δ which isolates these zero-energy modes from the local perturbation. Here we report the electronic transport measurements performed on such zigzag Josephson junctions formed in an InAs 2DEG with epitaxially grown aluminum. Tunneling spectroscopy is performed at the end of the junction and a hard induced superconducting gap is observed. Furthermore we investigate the junction behaviour in an RF SQUID geometry where the phase is well controlled, and demonstrate flux-periodic oscillations of the gap. We have also investigated the evolution of the superconducting gap with increased in-plane magnetic field. By performing similar measurements on a straight (i.e. non-zigzag) junction, we are able to compare properties like the superconducting gap and its magnetic evolution. So far no significant differences between devices with different junctions have been observed, but it can arise from the non-ideal zigzag geometry and small critical field of the hybrid devices. These problems can be tackled by improvements in fabrication, which helps demonstrate the non-locality of zero-energy states predicted in this system.

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Evidence of topological superconductivity in planar Josephson junctions

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Majorana zero modes are quasiparticle states localized at the boundaries of topological superconductors that are expected to be ideal building blocks for fault-tolerant quantum computing. Here, we introduce a new two-dimensional platform for realizing Majorana zero modes based on a phase-biased planar Josephson junction [1,2,3]. We observe phase-dependent zero-bias conductance peaks measured by tunneling spectroscopy at the end of Josephson junctions realized on an InAs/Al heterostructure. Phase biasing the junction to $\phi \sim \pi$ significantly reduces the critical field at which the zero-bias peak appears, with respect to $\phi = 0$. The phase, magnetic field, and chemical potential dependence of the zero-energy states is consistent with a model of Majorana zero modes in a finite-size Josephson junction.

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Quantum transport in in-plane selective area InSb nanowire networks

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Semiconductor-superconductor hybrid nanowires are the leading candidate for topological quantum computation with Majorana zero modes [1,2]. For qubit operation, it is necessary to scale this system to complex nanowire network-based architectures [3]. We realize these nanowire networks through in-plane selective area growth of InSb using metalorganic vapour-phase epitaxy (MOVPE). The capability of this new platform based on MOVPE is investigated by characterizing the transport properties. Magnetoconductance measurements in nanowire loops reveal phase coherent transport through the Aharonov-Bohm effect. Detailed study of the Aharonov-Bohm interference including temperature dependence shows up to 5 harmonics, With an estimated phase coherence length of 10 μm at 20 mK. On Hybrid semiconductor-superconductor InSb-Al nanowires, Coulomb blockade spectroscopy of a superconducting island is 2*e* periodic in gate charge, which indicates negligible quasi-particle poisoning. This 2*e* periodicity is reduced to 1*e* upon the application of an in-plane magnetic field, which could be related to the appearance of Majorana zero modes in the system. Our results confirm the high quality of the in-plane selective area grown InSb nanowire networks, showing its promise as a platform for topological qubit architectures.

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