Lund-Tokyo-Copenhagen-Beijing Joint Workshop
on
Quantum Devices

March 24-25, 2013
Lund/Copenhagen
Organizers:

Hongqi Xu          Lund University & Peking University
Charles Marcus    University of Copenhagen
Seigo Tarucha     University of Tokyo
Akira Oiwa        University of Tokyo
Jess Martin        University of Copenhagen
Lund-Tokyo-Copenhagen-Beijing Joint Workshop on Quantum Devices
Lund/Copenhagen, March 24-25, 2013

List of speakers

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Giles Allison  
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Juergen Sailer  
a.c. Josephson effect in Niobium/InSb nanowire junctions
Yasushi Kanai  
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Spin induced subgap states in superconductor/quantum dot/superconductor junctions
Program

Sunday 24/3, k-Space, Division of Solid State Physics, Lund University

09:30-10.00  Registration and Coffee
10:00-10:10  Opening and General Information

Josephson Junction Devices I

Chair: Seigo Tarucha
10:10-10:45  Akira Oiwa, Cooper pair splitting in parallel quantum dot Josephson junctions
10:45-11:20  Martin Leijnse, Coupling Spin Qubits via Superconductors
11:20-11:55  Juergen Sailer, a.c. Josephson effect in Niobium/InSb nanowire junctions

12:00-13:30  Lunch

Coupling of Microwave to Quantum States

Chair: Andreas Wacker
13:30-14:05  Peter Samuelsson, Nonlocal electron transport through nanoscale conductors in microwave cavities
14:05-14:40  Giles Allison, Coupling a quantum dot in an InSb nanowire to a superconducting resonator
14:40-15:15  Johannes Beil, Microwave control of the exchange-only spin

15:15-15:45  Coffee

Thermoelectric, Magnetotransport and Interference

Chair: Akira Oiwa
15:45-16:20  Andreas Wacker, Two-level interference in nanosystems
16:20-16:55  Kristian Storm, Spatially resolved Hall measurements in core-shell InP nanowires
16:55-17:30  Heiner Linke, Reciprocity relations in thermoelectric transport

18:30  Dinner for all participants

Monday 25/3, Center for Quantum Devices, Niels Bohr Institute, Copenhagen University

09:30-10.00  Registration and Coffee
10:00-10:10  Practical information

Josephson Junction Devices II

Chair: Karsten Flensberg
10:10-10:45  Mingtang Deng, Zero-bias conductance peak in Josephson quantum dot junctions with and without Majorana fermions
10:45-11:20  Gediminas Kirsanskas, Spin induced subgap states in superconductor/quantum dot/superconductor junctions
11:20-11:55 Gunagyao Huang, Signatures of Majorana fermions in hybrid superconductor-semiconductor-superconductor Josephson nanowire devices

12:00-13:30 Lunch

**Hole States and Spin-Orbit Coupling**

Chair: Charlie Marcus

13:30-14:05 Ferdinand Kuemmeth, Hole spin physics in Ge-Si core-shell nanowires
14:05-14:40 Shaoyun Hunag, Si and Ge nanowire based quantum dots for spin qubits
14:40-15:15 Yasushi Kanai, Josephson current through an InSb nanowire with a strong spin-orbit interaction

15:15-15:25 Closing

15:30 Tour of Center for Quantum Devices with reception

18:00 Dinner by invitation
Abstracts
Cooper pair splitting in parallel quantum dot Josephson junctions

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Generation of non-local entanglement in solid state devices would allow one to study the phenomena governed by quantum mechanics and to construct on-chip quantum circuit. The quantum teleportation, which is one of the ingredients for such on-chip quantum circuits, can be realized using non-local entanglement of conducting electrons in the device. Cooper pair in BCS superconductor, which forms a spin-singlet state, provides a natural source of entanglement [1]. Though splitting of the Cooper pairs has been already demonstrated using the carbon nanotubes or InAs nanowires [2,3,4] the spin entanglement has not been fully proven yet. To tackle this intriguing subject, we develop the parallel double quantum dot Josephson junction and show the Josephson current due to the non-local tunneling process.

We fabricated the InAs self-assembled parallel double quantum dot (QD) coupled to two Aluminium superconductors. The electronic states of the two QDs can be tuned separately by the nearby surface sidegate electrodes. The Josephson energy of this system consists of local pair tunneling process through each dot and non-local tunneling process. Comparison of normal and superconducting state transport with careful tuning of electronic states of the two QDs allows one to discriminate these local and non-local processes. In the normal state, there is no signature of the inter-dot capacitive and tunnel couplings. We observe that the conductance when both QDs are resonance is reduced from the sum of conductance for each QD on-resonance with the other off-resonance. In the superconducting state, we identified the $\pi$-junction like behavior in one of the QDs with odd electron occupation, giving a negative contribution to the total Josephson current. The suppression of the supercurrent appears only when the other dots is near resonance. In addition the supercurrent is enhanced when both QDs are on resonance whereas the normal state conductance is suppressed at the same condition. These enhancement and suppression of the supercurrent arises from the non-local tunneling process.

References
Coupling spin qubits via superconductors

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I will discuss how superconductors can be used to couple, initialize, and read out spatially separated spin qubits in a setup similar to a so-called Cooper pair splitter. When two single-electron quantum dots are tunnel coupled to the same superconductor, the singlet component of the two-electron wavefunction partially leaks into the superconductor via crossed Andreev reflection. This induces a gate-controlled singlet-triplet splitting which, with an appropriate choice of superconductor geometry, remains large for dot separations within the superconducting coherence length. Furthermore, I will show that when two double-dot singlet-triplet qubits are tunnel coupled to a floating superconductor with a finite charging energy (Cooper pair box), crossed Andreev reflection enables a strong two-qubit coupling over distances much larger than the coherence length.

References
We will present preliminary results on the measurement of the supercurrent in Josephson junctions formed from InSb nanowires contacted with niobium source/drain leads. Our work is motivated by recent proposals for the realization of Majorana Fermions (MFs) in 1-D systems with strong spin-orbit interaction coupled to s-wave superconductors [1, 2] and encouraging experimental results which hint at the detection of MFs [3, 4]. We fabricate devices using both niobium deposited by electron beam evaporation and RF magnetron sputtering. Our devices show the signature of gate tunable switching current which persists to high magnetic fields (up to 3T). We are able to measure the ac-Josephson effect in this magnetic field range and observe the Shapiro step pattern. In addition we observe suppression and recovery of the switching current with increasing magnetic field indicating the influence of the Zeeman effect.

References
Non-local transport properties of nanoscale conductor-microwave cavity systems

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Recent experimental progress in coupling nanoscale conductors to superconducting microwave cavities has opened up for transport investigations of the deep quantum limit of light-matter interactions, with tunneling electrons strongly coupled to individual cavity photons. We have investigated theoretically the most basic cavity-conductor system with strong, single photon induced non-local transport effects; two spatially separated double quantum dots (DQD:s) resonantly coupled to the fundamental cavity mode [1]. The system, described by a generalized Tavis-Cummings model, is investigated within a quantum master equation formalism, allowing us to account for both the electronic transport properties through the DQD:s as well as the coherent, non-equilibrium cavity photon state. We find sizeable non-locally induced current and current cross-correlations mediated by individual photons. From a full statistical description of the electron transport we further reveal a dynamical channel blockade in one DQD lifted by photon emission due to tunneling through the other DQD. Moreover, large entanglement between the orbital states of electrons in the two DQD:s is found for small DQD-lead temperatures.

References

Coupling a quantum dot in an InSb nanowire to a superconducting resonator

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Cavity quantum electrodynamics (cQED) is a rapidly growing field in physics and engineering in which great progress has been made in recent years. The coupling of photons in cavities with various types of qubits is an intriguing prospect for quantum processing and quantum memories. So-called 'transmon' devices which utilize superconducting resonators and Josephson junctions are currently leading the field in this topic, for instance in recent work a compiled version of Shor's algorithm was performed [1], however, the relatively short coherence times of these devices make further progress challenging [2]. As a consequence several other systems have been realized, such as coupling to spins in diamond [3], and quantum dots in InAs [4], GaAs [5] and carbon nanotubes [6].

In this work we propose a system to, and give preliminary results for, coupling a quantum dot in an InSb nanowire to a niobium superconducting resonator. In theoretical work [7] it has been proposed to couple the electron spin in a quantum dot to a resonator via the spin-orbit interaction and the large spin-orbit energy of InSb nanowires [8] makes them ideal systems to reveal this coupling. In addition, because of the large electron and hole g-factors of InSb nanowires, only a modest magnetic field, over which little change in the resonator quality factor is observed, is required for the Zeeman energy to equal the energy of the photons in the cavity.

References
Microwave control of the exchange-only spin qubit


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We demonstrate two-axis control of an exchange-only spin qubit in a GaAs triple quantum dot using a resonant microwave excitation. The qubit is operated in a regime where two separate exchange interactions are active simultaneously, suppressing leakage out of the qubit subspace and providing some immunity to charge noise. Spectroscopic probes of the qubit reveal that the resonance frequency can be adjusted between 100 MHz and 1.5 GHz with a voltage applied to the middle quantum dot. We find a coherence time $T_2 \sim 20 \, \mu s$ for a 64 pulse Carr-Purcell-Meiboom-Gill dynamical decoupling sequence. Finally, analysis of the coherence time for multiple sequences reveals a power spectrum $S(\omega) \sim \omega^{-0.9}$, which suggests that the fluctuating Overhauser fields are not the dominant source of dephasing in this system.

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Two-Level Interference in Nanosystems

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Two-level systems constitute the most simple testing ground for the relevance of quantum interference between states on transport properties of nanosystems. Despite their simplicity they provide a rich wealth of effects, which is far from being fully exploited yet.

Interference between different paths through the sample in connection with electron-electron interaction, can provide a surprisingly strong effects if the levels cross each other. Here a canyon of conductance blockade can be observed, which constitutes a line of current suppression cutting both through the direct tunneling lines and the Coulomb blockade region, where still a significant cotunneling current is present [1]. The theoretical description requires to include both interaction and higher order tunneling, which is achieved by our second order von Neumann formalism [2]. We find that the phenomenon is rather robust and compare it to similar scenarios at high bias.

The coherent superposition of different paths allows furthermore to tailor the transmission function in a wide range, which allows for optimizing thermoelectric properties. A rather favorite situation occurs if both levels are either above or below the chemical potential and contribute with opposite tunnel couplings. Such a situation can, e.g., be realized with specially tailored porphine molecules. Our calculations show, that this configuration provides a good power performance in connection with high efficiency as demonstrated by ZT values well above two.[3]

References
Spatially resolved Hall effect measurements in core-shell InP nanowires

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Nanowires offer many benefits not readily available to bulk semiconductors. This enables applications and optimizations difficult to realize in classical semiconductor systems. The development of radial nanowire epitaxy allows growth along crystal directions difficult or expensive to realize in planar epitaxial growth, for example along the nonpolar m-plane of GaN [1]. This may enable higher efficiency solid state light emission from cheap nonpolar substrates. Furthermore, experiments have shown that nanowire arrays absorb light more efficiently than planar substrates [2], offering interesting opportunities in photovoltaic devices. Despite these advances, the ability to perform accurate electrical characterization of the material intended for devices remains in the development stage. The most common method to electrically determine doping concentration and carrier mobility is by field-mobility measurements, a method that has inherent shortcomings and is challenging to adapt to core-shell nanowires.

Here, it is demonstrated how Hall effect measurements were implemented on nanowires for the first time. Hall effect measurements are conventionally used as a routine characterization tool for planar samples, and provides detailed information on doping density and carrier mobility. In this study, the Hall effect was measured in core-shell p-n junction InP nanowires intended for solar cell applications by depositing multiple Hall probes along the length of the nanowire, see the figure. This enables Hall effect measurements to be performed with spatial resolution on the shell of the nanowire. Two-dimensional Poisson simulations were carried out to investigate the role of the p-n junction and three-dimensional current-continuity simulations were carried out to correlate the experimental data to carrier density in the nanowire. It was found that the nanowire shell exhibited a doping gradient along the length of the nanowire. The conclusion was corroborated by additional four-probe measurements as well as cathodo-luminescence measurements. This doping gradient is important to control and engineer to optimize nanowire LEDs and solar cell devices.

References
Experimental test of thermoelectric reciprocity relations

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Symmetry relationships such as the Onsager relations, which are based on the principle of microreversibility, are cornerstones of physics. In the context of mesoscopic physics, symmetries of the conductance in two-terminal and multiterminal devices have been explored in great detail [1,2,3]. Here, we extend these studies to the case where combined thermal and electric (thermoelectric) biases are present. Also for this case, symmetry relations have been predicted, but it has also been predicted that these relations break down at the transition from quantum to classical behavior. We have experimentally investigated the magnetic field dependence of thermoelectric transport properties in a four-terminal micro-junction, with heat and voltage reservoirs attached to each terminal [4,5]. The linear response thermoelectric coefficients are found to be symmetric under a simultaneous reversal of magnetic field and exchange of injection and emission terminals, confirming the generality of the magnetic-field symmetries. In the non-linear thermal bias regime we find signatures of a break-down of the symmetries, raising new fundamental questions about the mechanism of this breakdown.

References
Zero-bias conductance peaks in Superconductor-Semiconductor Hybrid Quantum Devices: with and without Majorana fermions

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Majorana zero-energy quasi-particle in solid state system, especially in superconductor coupled semiconductor nanowires with strong spin-orbit interaction, has attracted intense research recently [1-2]. In the tunneling spectrum of superconductor-semiconductor hybrid devices, Majorana zero-energy modes manifest themselves as emergences of zero-bias differential conductance peaks in a finite magnetic field, and these zero-bias peaks signatures were reported by several groups [3-6]. However, many other mechanisms could mimic the same zero-bias anomalies as Majorana fermions. Here, we discuss several different mechanisms in superconductor-quantum dot-superconductor (S-QD-S) hybrid devices, which may lead emergences of zero-bias peak in finite magnetic field, such as thermal activation [7], Kondo effect [10], normal Josephson supercurrent, and Andreev bound states [8-10]. We also compare these zero-bias peaks with the Majorana zero-energy modes caused zero-bias peaks in S-QD-S structure.

References
Spin induced subgap states in superconductor/quantum dot/superconductor junctions

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We examine the emergence of subgap states in a junction consisting of two superconducting leads coupled to spinful Coulomb blockaded quantum dot. The system is modeled by an effective Kondo model, which gives rise to so-called Yu-Shiba-Rusinov states inside the gap. We determine the dispersion of these states with an applied phase difference across the junction and study their dependence on an applied magnetic field. Also the effects of coupling asymmetry to the leads and deviation from the particle-hole symmetric point are addressed.

References
Signatures of Majorana Fermions in hybrid Superconductor-Semiconductor-Superconductor Josephson nanowire devices

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The main physics of Majorana fermions (MFs) in one-dimensional (1D) three-segment hybrid nanowire devices is studied and the signatures of MFs are fully revealed after a brief review of the concept of MF and in different 1D nanowire model. We establish the three-segment model of the devices containing the parameters of Zeeman energy, the coupling between the middle segment and both sides of superconductive segments, the length of middle segment and the phase difference of superconductive segments. The energy spectrum and differential conductance are detailed analysed in the case of symmetric coupling. Two pairs of MFs emerge in the ends of each superconductive segments after the transition from trivial superconductor phase to topological superconductor phase driven by Zeeman energy, two of which reside in the ends of the entire wire remain in zero energy while the other two are hybridized into quasi-state and -hole states in the middle segment. These zero energy MFs and hybridized MFs show ZBCP and side peaks through local Andreev reflection and crossed Andreev reflection, respectively. The combination of the two types of signals can be unique signatures of the existence of MFs. From symmetric coupling to asymmetric coupling and smoothly varying superconducting pair potential in middle segment, most of the MF physics keeps unchanged. In the case of smoothly varying superconducting pair potential and taking into account the superconductor pair potential-magnetic field relation, two different evolution paths are discovered when comparing the critical magnetic field in superconductive and middle segments. The effect of disorder on Zeeman energy and superconductor pair potential is simulated, in which we can confirm the signatures of both zero-energy and hybridized MFs are robust even in the present of weak disorder. Finally the nontrivial behavior of side peak structure induced by the quantum dot-intermediated interaction of MFs in Josephson junction devices, which is also a strong signatures of the MF in our devices.

References
Hole spin physics in Ge-Si core-shell nanowires

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Double quantum dots formed in Ge-Si core-shell nanowires offer an attractive route to realizing spin qubits with novel properties compared to “conventional” electron spin qubits in III-V materials. Our spin qubits are constructed from electrostatically confined hole states in the valence band of crystalline germanium nanowires, protected by an epitaxial silicon shell. Hence there are almost no nuclear spins that would dephase the qubit via hyperfine coupling. Furthermore, recent theory [1] identified a new type of spin-orbit coupling in the strained Ge core that can be tuned over a wide range by the thickness of the Si shell. The resulting spin-orbit coupling may be useful to coherently rotate individual spins via AC electric fields, but experiments are needed to demonstrate sufficiently long intrinsic spin life times and fast spin manipulation and readout techniques.

By confining holes in a gate-induced double quantum dot (Figure) at subkelvin temperatures, our devices allow the characterization of spin coherence of individual holes. Spin-selective tunneling events between the two quantum dots are induced by fast voltage pulses applied to the gate electrodes and subsequently detected either by a nearby quantum dot charge sensor or via LC tank circuits attached to the source and drain contacts [2]. Sufficiently long spin-relaxation times (approaching 1ms at zero magnetic field) have already been demonstrated when the dots are occupied by several holes [3]. I will discuss our most recent device fabrication, and present our progress towards measuring the inhomogeneous dephasing time $T_2^*$ in these devices.

Figure: Scanning electron micrograph of a Ge-Si core-shell nanowire that is contacted by source and drain contacts and runs across several isolated gate electrodes. Time dependent gate voltages are applied to electrostatically induce a double well potential that can be manipulated on a nanosecond time scale. Spin-selective tunneling between the right and left quantum well are detected by charge sensing techniques, and reveals information about spin coherence times.

References
Si and Ge nanowire based quantum dots for spin qubits

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Chemically self-assembling synthesized Si and Ge nanowires (SiNWs and GeNWs) with a diameter of a few tens of nanometers could be one of attracting candidates of electron-spin degree of freedom based quantum information devices due to their long electron-spin coherence time. [1] The 1D characteristic allows simple spin configurations even with many electrons confined, because the level degeneracy is constant, independent on the number of electrons. [2] The work aims to develop fabrication processes as well as to realize nanowire quantum dots (QDs) and to explore single-electron spectroscopie of the dots for implementations of quantum information processing technologies.

N-type monocrystalline SiNWs (GeNWs) with diameters ranging from 30 to 40 nm were synthesized via gold nano-catalysts mediated VLS mechanism in Silane (Germane)/Phosphine CVD. Source and drain contacts were fabricated on an individual nanowire by lithography techniques. With a 10 nm HfO2 thin film in between, the constricted nanowire was fully covered by an omega-shaped top-gate. The single-electron spectroscopes of the dots were probed by measuring the characteristics of single-electron transistors at cold temperatures.

The comparison shows that GeNW dots possess much more significant quantum effects in terms of considerable energy-level separations than Si counterparts, arising from smaller electron effective mass. [3] The electron number even-odd effect, alternate manipulation of electron spin between 0 and 1/2, happens in the GeNW dot. [4] This fact suggests the possible application to an electron-spin qubit even with many electrons residing in the dot. On the other hand, the top-gate configuration performed efficiently and allowed the realization of a few-electron region, in which the number of free electrons in the GeNW QD was tunable from zero [5].

Our recent efforts aim to fabricate quantum dots from InAs and InSb nanowires, which possess higher electron mobility and strong spin-orbital interactions.

References
Josephson current through an InSb nanowire with a strong spin-orbit interaction

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In quantum dot (QD) Josephson junctions, supercurrent transistor, pi-junction, correlation between superconductivity and Kondo effect, and Cooper pair splitter have been experimentally demonstrated and have been investigated [1,2]. Recently InSb nanowire devices, which have a large spin-orbit interaction (SOI), are used to explore the zero-bias conductance peak as a signature of Majorana fermion[3,4,5]. Here we focus on the Josephson current through InSb nanowires with a strong SOI. Though there are some theories discussing the influence of SOI and Zeeman effect on the supercurrent through a QD or 1-D conductor [6,7], no experimental works have been reported yet. Because it is experimentally reported that Rashba-type SOI in InSb nanowires shows a peculiar anisotropy [8], the effect of SOI on the supercurrent can be investigated by changing the magnetic field direction. Here we study the magnetic field angle dependence of the supercurrent in an InSb nanowire Josephson junction.

We fabricated InSb nanowire Josephson junctions and detected the zero-bias conductance peak at zero magnetic field, indicating supercurrent. Then, we measured the in-plane magnetic field angle dependence of the zero-bias conductance peaks using a vector magnet and evaluated the effect of SOI and Zeeman effect. When the magnetic field was parallel to the SOI effective field (e.g. perpendicular to the wire axis), the peak height took a maximum value whereas it became minimum when the magnetic field angle was perpendicular to the SOI field. This trend can be qualitatively explained in terms of the Zeeman splitting of an electronic state and the hybridization between the Zeeman split spin states due to SOI[6,7].

We also present the recent works on the InSb Cooper pair splitter.

Reference