Hybrid Solid State Quantum Circuits, Sensors, and Metrology

722. WE-Heraeus-Seminar

13 Dec - 16 Dec 2021

ONLINE

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HERAEUS-STIFTUNG

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

Aims and scope of the 722. WE-Heraeus-Seminar:

Macroscopic solid-state quantum effects like the Josephson and quantum Hall effect have been routinely applied in electrical metrology institutes worldwide for more than two decades and are now introduced in companies for industrial calibrations. Additionally, metrological electrical quantum circuits have heavily contributed to the upcoming redefinition of the SI systems of units based on elementary constants which will enter into force on May 20th, 2019. Josephson junction-based SQUID circuits are applied as high-resolution field sensors for e.g. medical applications and scaling towards nano-SQUID systems is advancing. Single electron circuits are used for the generation of quantized electrical currents for electrical metrology and as highly sensitive electrometers allowing to detect the presence and absence of individual charge quanta. In parallel the development of quantum detection schemes based on superconducting cavities and below shot noise superconducting parametric amplifiers may open a way to further enhance the sensitivity of the above detectors. Other fields of solid-state quantum devices have delivered quantum bits, single electron sources with non-classical noise properties, as well as diamond NV center magnetometers with nano scale resolution. More recently, the development of novel topological materials has opened bright new opportunities both for electrical quantum metrology and for topologically protected quantum computation. This seminar aims at bringing together scientists from these different fields of solid-state quantum systems, quantum circuits, and quantum metrology, namely: (i) Single Electron Circuits; (ii) Josephson Circuits; (iii) Spin-Based Quantum Systems; and (iv) Topologically Protected Materials and Devices. The workshop will prepare the ground to discuss the opportunities and challenges of the individual subfields as well as potential synergy between them to foster the development of truly hybrid quantum circuits for future applications in quantum information technology, quantum sensing, quantum metrology and beyond.

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Program

Program

Monday, 13 December 2021

08:30 – 08:45	Hans Werner Schumacher & Patrik Recher	**Welcome and Organization**
08:45 – 09:00	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
09:00 – 09:50	Masaya Kataoka	**Tomography and two-particle interactions of hot electrons in quantum Hall regime**
09:50 – 10:40	Heung-Sun Sim	**Anyon braiding in quantum Hall anyon collider**
10:40 – 11:10	*COFFEE BREAK*	
11:10 – 12:00	Christopher Bäuerle	**Surface acoustic waves as testbed for electron flying qubits**
12:00 – 12:50	Vyacheslavs Kashcheyevs	**Metrology of on-demand electrons by energy-selective time-dependent scattering**
12:50	*LUNCH*	
14:00 – 15:40	**Poster Session A**	
15:40 – 16:00	*COFFEE BREAK*	
16:00 – 16:50	Guoji Zheng	**Embedding silicon spins in superconducting circuits**
16:50 – 17:40	Fedor Jelezko	**Quantum sensing with diamond spin qubits**
17:40 – 18:05	Hugo Bartolomei (C1)	**Single electron interferences in Fabry-Perot cavities**

Program

Tuesday, 14 December 2021

09:00 – 09:50	Oliver Kieler	**The pulse-driven AC Josephson voltage standard of Josephson voltage standard of PTB**
09:50 – 10:40	Dieter Koelle	**NanoSQUIDs for sensing magnetic fields on the nanoscale**
10:40 – 11:10	*COFFEE BREAK*	
11:10 – 12:00	Ioan Pop	**Quantum Circuits Resilient to Magnetic Fields**
12:00 – 12:50	Fabrizio Nichele	**Suppression of superconductivity via out-of-equilibrium electrons and phonons**
12:50	*LUNCH*	
14:00 – 15:40	**Poster Session B**	
15:40 – 16:00	*COFFEE BREAK*	
16:00 – 16:50	Alfredo Levy-Yeyati	**Detection and manipulation of Andreev states in hybrid nanowire Josephson junctions using cQED techniques**
16:50 – 17:40	Hans Hübl	**Boosting coupling rates in nano-electromechanics**
17:40 – 18:05	Pasquale Scarlino (C2)	**Hybrid Circuit Quantum Electrodynamics with Semiconductor QDs and Superconducting Resonators**

Program

Wednesday, 15 December 2021

09:00 – 09:50	Audrey Cottet	**Engineered interactions between photons in Mesoscopic Quantum Electrodynamics**
09:50 – 10:40	Martin Weides	**Quantum sensing with superconducting circuits**
10:40 – 11:10	*COFFEE BREAK*	
11:10 – 12:00	Ewelina Hankiewicz	**Fingerprint of Majorana bound states in heat transport and thermodynamics**
12:00 – 12:50	Srijit Goswami	**Semiconductor-superconductor hybrids for Majorana-based topological quantum computing**
12:50	*LUNCH*	
14:00 – 14:50	Jelena Klinovaja	**Majorana bound states in topological insulators without a vortex**
14:50 – 15:15	Fernando Dominguez Tijero (C3)	**Fraunhofer pattern in the presence of Majorana modes**
15:15 – 15:40	Ciprian Padurariu (C4)	**Quantum Locking and Synchronization in Josephson Photonics Devices**
15:40 – 16:00	*COFFEE BREAK*	
16:00 – 16:50	Christian Schönenberger	**AC Josephson effect in junctions fabricated with topological and non-topological materials**
16:50 – 17:40	Charles Gould	**Towards the Universal Quantum Electrical Standard**
17:40 – 18:15	Rubén Seoane Souto (C5)	**Charge-transfer based operations on Majorana systems**

Program

Thursday, 16 December 2021

09:00 – 09:50	Joachim Ullrich	**The revised SI for innovation, science and the second quantum revolution**
09:50 – 10:40	Shuichi Murakami	**Kinetic magnetoelectric effect in topological insulators**
10:40 – 11:10	*COFFEE BREAK*	
11:10 – 12:00	Claudia Felser	**Magnetic Materials and Topology**
12:00 – 12:50	Karin Everschor-Sitte	**Reservoir Computing with Magnetic Skyrmions**
12:50 – 14:00	Hans Werner Schumacher & Patrik Recher	**Closing remarks and poster awards**

Posters

Posters A

1	Austris Akmentins	**Charging of a shallow quantum dot**
2	Ģirts Barinovs	**4D wave-packet simulation of two-electron quantum optics experiments**
3	Lena Bittermann	**Probing Majorana bound states via a pn-junction containing a quantum dot**
4	Clémont Geffroy	**Picosecond electronic pulse generation for flying qubits**
5	Simon Geisert	**Modular architecture for circuit quantum electrodynamics**
6	Daniel Haxell	**Phase escape dynamics in InAs/Al Josephson junctions**
7	Yuchi He	**The topological phase of one-dimensional mass-imbalanced repulsive Hubbard model**
8	Felicitas Hellbach	**Quantum-correlated photons generated by nonlocal electron transport**
9	Richard Hess	**Local and non-local quantum transport due to Andreev bound states in finite Rashba nanowires with superconducting and normal sections**
10	Max Karrer	**Josephson junctions and SQUIDs created by focused Helium ion beam irradiation of YBa2Cu3O7**
11	Patryk Krzysteczko	**Anodization spectroscopy for superconducting devices**
12	June-Young M. Lee	**Fractional Mutual Statistics on Integer Quantum Hall Edges**

Posters A

13	Peter Lemmens	**Case studies of spectroscopic OAM transfer in chiral phases of matter**
14	Luca Magazzù	**Transmission spectra of the driven, dissipative Rabi model in the USC regime**
15	Marco Marín Suárez	**Precise power production by a hybrid electron turnstile**
16	Stephanie Matern	**Transient dynamics and metastability in interacting parallel quantum dots**

Posters B

17	Francisco Jesús Matute	**Signatures of interactions in the Andreev spectrum of nanowire Josephson junctions**
18	Ameya Nambisan	**Quantum electrodynamics of cold deposited granular aluminum**
19	Fabian Oppliger	**High Impedance Microwave Technology for QD-cQED devices**
20	Wanki Park	**A quantum dot pump coupled with a single quantum Hall edge channel**
21	Ganesh C. Paul	**Fate of metal insulator transition in an interacting kagome lattice under periodic drive**
22	Elina Pavlovska	**Classical solution of two electron scattering at a saddle point potential in strong magnetic field limit**
23	Markus Ritter	**Semiconductor Epitaxy in Superconducting Templates**
24	Deividas Sabonis	**Parity switching in a semiconductor-based transmon qubit**
25	Baha Sakar	**Quantum calibrated magnetic force microscopy**
26	Peter Silvestrov	**Theory of two-electrons optics experiments with smooth potentials**
27	Hubert Souquet-Basiège	**Probing quantum electromagnetic magnetic fields with subnanosecond time resolution: the single electron radar**
28	Junliang Wang	**Electron Collision Enabled by Sound Waves**

Posters B

29	Patrick Wittig	**Coulomb blockade effects in minimally twisted bilayer graphene**
30	Katja Wurster	**Heteroepitaxial growth of single crystalline $YBa_2Cu_3O_7$ and $Sr_3Al_2O_6$ thin films on $SrTiO_3$ substrates**
31	Xuexin Xu	**Mitigating parasitic interactions in superconducting circuits**
32	Yefei Yin	**Epitaxial graphene by F4-TCNQ molecular doping for quantum Hall resistance standards**

Abstracts of Lectures

(in alphabetical order)

Single electron interferences in Fabry-Perot cavities

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We study propagation of a train of single electron wavepackets generated by a Lorentzian pulses [1,2] along the edge channels of the integer quantum Hall effect. Using quantum point as electronic beam-splitters we define a Fabry-Perot (FP) cavity [3,4,5] and study the single electron interference pattern of the transmitted current as a function of a plunger gate voltage. In addition to a DC voltage, we add an AC square voltage to the plunger gate potential, adding a time dependent component to the Aharonov bohm phase accumulated by particles moving around the cavity. By changing the time delay between the single electron pulses and the plunger gate voltage, we are able to sample the temporal shape of the AC potential.

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Surface acoustic waves as testbed for electron flying qubits

H. Edlbauer,[1] J. Wang,[1] S. Ota,[2,3] A. Richard,[1] B. Jadot,[1] P.-A. Mortemousque,[1,4] Arne Ludwig,[5] Andreas D. Wieck,[5] M. Urdampilleta,[1] T. Meunier,[1] T. Kodera,[2] N.-H. Kaneko,[3] S. Takada[3], and C. Bäuerle,[1]

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A surface acoustic wave (SAW) is surprisingly efficient to transport a single electron between distant quantum dots [1,2] while preserving in flight its quantum coherent properties [3,4]. The acousto-electric shuttling technique provides thus a perfect testbed to investigate the feasibility of electron-flying-qubit implementations [5]. Here we present our latest results on SAW-driven single-electron transport in a circuit of coupled quantum rails. Mastering picosecond triggering of the transfer process [6] verified via time-of-flight measurements [7], we are capable of synchronising transport along parallel quantum rails. Sending two electrons simultaneously through the coupling region, we observe distinct Coulomb-dominated repulsion – the central ingredient to realise a controlled phase gate for electron flying qubits. Discussing partitioning data of a single electron in the coupling region [5], we further point out the importance of SAW confinement for coherent in-flight manipulation. To address this critical aspect, we finally demonstrate SAW engineering via chirp synthesis enabling single-electron transport with a solitary electro-acoustic pulse. Our results lay the ground for quantum logic circuits with electron flying qubits surfing on sound.

References

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Engineered interactions between photons in Mesoscopic Quantum Electrodynamics

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Cavity QED techniques have turned out to be instrumental to probe or manipulate coherently two level systems. The success of this field relies on the implementation of a strong coupling between two level systems and cavity photons. A decade ago, these experiments have been generalized to hybrid mesoscopic circuits embedded in coplanar microwave cavities[1, 2]. This Mesoscopic QED architecture is appealing since new degrees of can be used in the context of cavity QED. One specificity of Mesoscopic QED, namely the presence of fermionic reservoirs in the mesoscopic circuits and dissipative quasiparticle transport, has been overlooked so far [3]. This ingredient could offer new ways to manipulate cavity photons, in the spirit of reservoir engineering [4], but a theoretical framework is lacking to investigate this possibility. In this talk, I will present a theoretical description of Mesoscopic QED based on a powerful quantum path integral approach, in which the mesoscopic electronic degrees of freedom are integrated out and the light/matter interaction is treated at fourth order [5]. We have established conditions in which a Lindbladian description of the cavity dynamics is relevant. This equation reveals that, if the light/matter coupling is strong enough, the mesoscopic circuit induces an effective Kerr interaction and two-photon dissipative processes. We apply these results to a cavity coupled to a double quantum dot with normal metal reservoirs. If the cavity is driven at twice its frequency, the double dot circuit generates photonic squeezing and non-classicalities visible in the cavity Wigner function. In particular, we find a counterintuitive situation where mesoscopic dissipation enables the production of photonic Schrödinger cats. Such an effect could have applications for a bosonic encoding of quantum information with autonomous quantum error correction [6].

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Fraunhofer pattern in the presence of Majorana modes

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We investigate signatures of the presence of Majorana bound states that can arise in the Fraunhofer pattern of Josephson junctions made of Top. Sc/Qu. Spin Hall /Top. Sc. In this setup, the presence of Majorana bound states at the NS interfaces introduces electron-hole reflections with parallel spin [1], which due to spin-momentum locking, are forced to take place between opposite edges. In contrast to local electron-hole reflections (with opposite spin), the presence of such non-local processes do not accumulate a geometrical phase [2] and therefore, they can drastically or partially change the periodicity of the Fraunhofer pattern. In order to observe such a change in the Fraunhofer pattern, the quantum spin-Hall edges have to be coupled either directly or through the bulk. Here, we propose two different scenarios where this can occur and provide numerical results from a scattering and tight-binding models.

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Reservoir Computing with Magnetic Skyrmions

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Novel computational paradigms in combination with proper hardware solutions are required to overcome the limitations of our state-of-the-art computer technology [1-3]. In this talk, I will focus on the potential of topologically stabilized magnetic whirls – so-called skyrmions for reservoir computing. Reservoir computing is a computational scheme that allows to drastically simplify spatial-temporal recognition tasks. We have shown that random skyrmion fabrics provide a suitable physical implementation of the reservoir [4,5] and allow to classify patterns via their complex resistance responses either by tracing the signal over time or by a single spatially resolved measurement [6]. Efficient task agnostic metrics benchmarking the reservoir's key features – non-linearity, complexity and fading memory – drastically speed up the parameter search to design efficient and high-performance reservoirs [7].

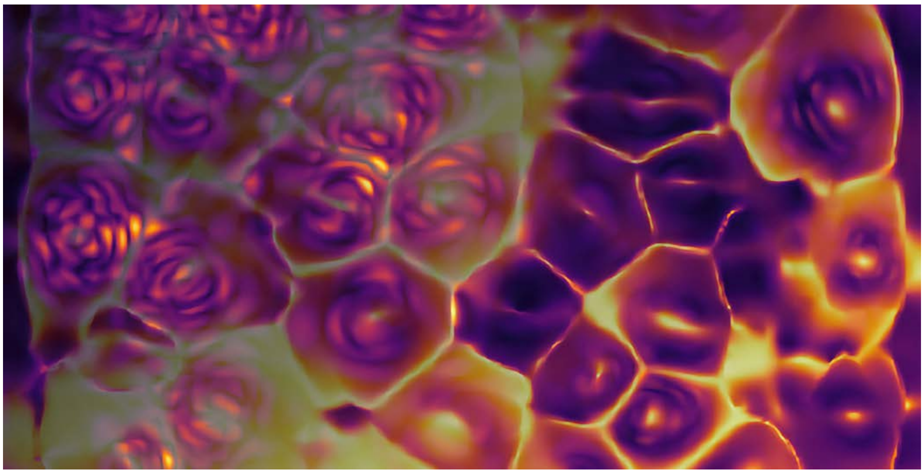

Fig. 1: Artistic view superimposing the spatially resolved non-linearity and memory measure of a skyrmion fabrics.

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Magnetic Materials and Topology

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Topology, a mathematical concept, recently became a hot and truly transdisciplinary topic in condensed matter physics, solid state chemistry and materials science. All 200 000 inorganic materials were recently classified into trivial and topological materials: topological insulators, Dirac, Weyl and nodal-line semimetals, and topological metals [1]. Around 20% of all materials host topological bands. Currently, we have focussed also on magnetic materials, a fertile field for new since all crossings in the band structure of ferromagnets are Weyl nodes or nodal lines [2], as for example Co_2MnGa and $Co_3Sn_2S_2$. Beyond a single particle picture and identified antiferromagnetic topological materials [3].

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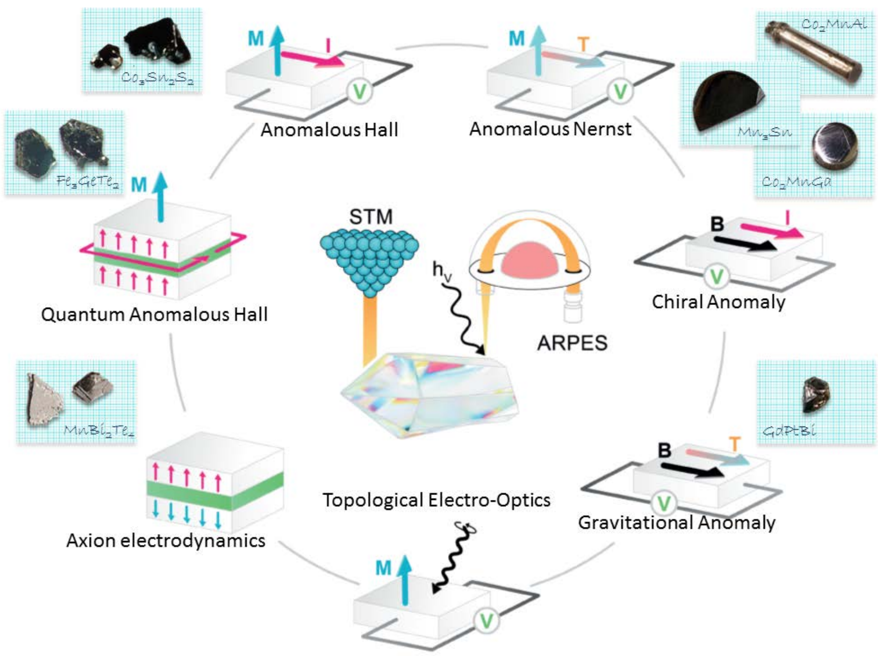

Towards the Universal Quantum Electrical Standard

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Quantum standards are the backbone of the international system of units (SI) with all electrical units based on magnetic flux quantization in units of $h/2e$ from the superconducting Josephson effect, and conductance quantization in units of Klitzing given by e^2/h from the quantum Hall effect. With the recent revision of the SI system the last holdouts, the units of mass (kilogram) and temperature (Kelvin) are now defined to quantum standards, realizing the vision of James Maxwell and Max Planck of a truly universal system of units. In particular, the Kilogram is now tied to the Planck constant, which can be determined from simultaneous knowledge of the Josephson and Klitzing constants. Both electrical quantum standards require cryogenic temperatures of about T=4.2 K or lower to access. The current metrological standards for the quantum Hall effect, however, require a large external magnetic field, which is incompatible with the superconductivity required for accessing the Josephson effect. It is thus impractical to combine both in a single system (for example a Kibble balance).

In this talk, I will introduce a new material concept which promises to bridge this issue: Ferromagnetic topological insulators (TI). In our case, we work with the ferromagnetic TI V-doped $(Bi, Sb)_2Te_3$. The recently discovered quantum anomalous Hall effect in this material class [1,2] exhibits conductance quantization without any external magnetic field, providing a realistic path for uniting quantum standards with all units based on h and e into a single measurement setup.

In this talk, I will introduce the material class, and describe how its properties lead to the establishment of a robustly quantized quantum Hall state in the absence of a magnetic field. I will then present metrologically comprehensive measurements of the zero field conductance quantization in a samples patterned from an MBE grown 9 nm thick layer of V-doped $(Bi, Sb)_2Te_3$ previously shown to exhibit quantum anomalous Hall related phenomena [3,4,5]. Excellent agreement with the von-Klitzing constant $R_k = h/e^2$ was found. Any potential deviation of the quantized anomalous Hall resistance from R_k, was determined to be 0.17 ± 0.25 ppm [6], the most precise value reported to date. We currently understand this value to be limited only by the experimental environment and contact issues, both of which we expect can be improved on in the near future.

The metrological measurements were carried out at millikelvin temperatures, which at present is an experimental requirement for the observation of a fully quantized anomalous Hall effect. While the requirement of such low temperatures is not a fundamental obstacle to implementing devices such as a Kibble balance, for practical reasons of portability, being able to work in a simple liquid He dewar at 4 K would be much better. I will end this talk with very recent results that show that the experimental observation currently being limited to deep sub-Kelvin temperatures is not resulting from any fundamental properties of the quantum anomalous Hall edge channels, which we can clearly show survive up to the Curie temperature (circa 20 K) of the material. Rather, the deviation from quantization in the experiments as the temperature increases purely results from parasitic conductance which activates in the insulating bulk of the material. These results show that by improving the quality of the insulating bulk (either through an improvement in growth properties, or by choosing another material of the same class, but with a larger bulk band-gap), there is every reason to expect that this new paradigm could eventually unite the Klitzing and the Josephson in a 4 K, zero magnetic field device.

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Fingerprint of Majorana bound states in heat transport and thermodynamics

Ewelina Hankiewicz

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We demonstrate that phase-dependent heat currents through superconductor-topological insulator Josephson junctions provide a useful tool to probe the existence of Majorana bound states, even for multichannel surface states [1,2,3]. We predict that in the tunneling regime Majorana bound states lead to a minimum of the thermal conductance for a phase difference $\phi=\pi$, in clear contrast to a maximum of the thermal conductance at $\phi=\pi$ that occurs for trivial Andreev bound states in superconductor–normal-metal tunnel junctions[1,2,3]. This opens up the possibility for phase-dependent heat transport and heat capacity to distinguish between topologically trivial and nontrivial 4π modes [1,2,3]. Furthermore, using topological Josephson junctions, we introduce the concept of topological thermodynamics [3] and a topological Josephson heat engine [4]. The thermodynamic cycle of such engines reflects the hallmark 4π-periodicity of topological Josephson junctions, which represents complementary approach to test topological superconductivity [4].

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Boosting coupling rates in nano-electromechanics

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The field of nano-electromechanics challenges force sensitivity limits and has the potential to study quantum mechanical phenomena in the literal sense. Demonstrated achievements range from $zN/\sqrt{Hz}$ force sensitivities, the preparation of mechanical elements in is ground state, squeezing of mechanical states, to microwave storage applications. However, all of these accomplishments are based on the linearization of the nano-electromechanical interaction in the limit of large photon numbers, and hence do not utilize the full wealth of the interaction Hamiltonian.

Most experimental implementations of nano-electromechanical devices combine superconducting microwave resonators with mechanically compliant elements employing a capacitive coupling scheme. However, it was realized early on that inductive coupling schemes based on SQUIDs represent an alternative route and promise a tunable interaction strength with the potential to reach the strong vacuum coupling regime.

In this presentation, we explore inductively coupled nano-electromechanics based on a partly suspended SQUID shunting a coplanar microwave resonator to ground. We discuss the scaling of the flux tuning and demonstrate interaction rates exceeding 50kHz. Moreover, the tunability of the coupling also allows to control the mechanical resonance frequency. We discuss the experimental demonstration of this tuning mechanism and its quantitative understanding also in context with sensing the mechanical properties of the superconducting aluminum.

We acknowledge funding via the cluster of excellence MCQST and EU project MaqSens.

Quantum sensing with diamond spin qubits

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Single nitrogen vacancy (NV) color centers in diamond currently have sufficient sensitivity for detecting single external nuclear spins and resolve their position within a few angstroms. The ability to bring the sensor close to biomolecules by implantation of single NV centers and attachment of proteins to the surface of diamond enabled the first proof of principle demonstration of proteins labeled by paramagnetic markers and label-free detection of the signal from a single protein. Single-molecule nuclear magnetic resonance (NMR) experiments open the way towards unraveling dynamics and structure of single biomolecules. However, for that purpose, NV magnetometers must reach spectral resolutions comparable to that of conventional solution state NMR. New techniques were proposed for this purpose and realized recently including technique that employs quantum entanglement. The ability to sense nuclear spins by NV centers also enables the transfer of polarization from optically polarized spins of NV centers to external nuclear spins. Such diamond based techniques for dynamic nuclear spin polarization are very promising for the enhancement of sensitivity of conventional MRI imaging. Most of mentioned above results obtained so far with diamond centers are based on optical detection of single NV color centers. We will show that photoelectrical detection of NV centers based on spin selective photoionization can provide robust and efficient access to spin state of individual color centers and improve quantum sensing at nanoscale.

Metrology of on-demand electrons by energy-selective time-dependent scattering

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Energy selectivity of tuneable tunnel barriers underpins metrological precision of modern quantized current sources [1] and provides versatile beam-splitters for electron quantum optics experiments with hot electrons in quantum Hall edge states [2]. The principle of time-energy filtering of on-demand electrons can be used either as a tomography technique [3,4] to probe the time-energy distribution of ballistic electrons by referencing to a known (e.g., linear [3]) waveform or alternatively as a sampling oscilloscope [5] sensing a fast voltage signal with calibrated single-electron wave-packets.

We consider scattering of non-interacting electrons on a time-dependent energy-sensitive potential barrier. The transmission probability can be cast as a linear functional of the energy-time Wigner quasiprobability distribution of the incoming electrons. In the case of spatially uniform modulation this functional is determined by the transmission function of the static barrier and the time-dependence of the modulating potential [4]. We identify quantum observables that are measured by the scattering outcome for a given (arbitrary) modulation using the recently developed framework for processing of quantum signals carried by electrical currents [6]. This allows generalization of the time-energy-filtering-based quantum tomography [3] to modulation by arbitrary waveforms. We use this to discuss how to interpret the results of on-demand electron scattering experiments in the quantum limit and consider the intrinsic limits on resolution of tomography and signal sampling setups.

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Tomography and two-particle interactions of hot electrons in quantum Hall regime

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On-demand generation of electron excitations in quantum Hall edge states can be used in electron quantum optics experiments [1] with potential applications in electrical metrology and quantum sensing. A tunable-barrier single-electron pump can be used to emit hot electrons [2]. While an ideal excitation is a Gaussian state with minimum uncertainty in energy and time distributions [3], the tunnelling process and a finite experimental bandwidth in pump drive may eject an electron into a less well-defined state. Furthermore, Coulomb interactions can affect the coherence of electron transport [4]. These non-ideal scenarios can impede the development of electron quantum optics applications. Here, we report our study of tomographic mapping [5] of hot-electron states in the energy-time phase space and Coulomb interactions between generated excitations in a Hong-Ou-Mandel geometry [6]. We show that the hot electrons emitted from a tunable barrier has a chirp imprinted by the emission process [7]. The purity of excitations is low, suggesting that they are emitted into a mixed state. When two electrons collide at a beam splitter, we see a signature of antibunching effect due to Coulomb repulsions, masking a potentially underlying Pauli effect. These observations reveal challenges in performing coherent electron quantum optics experiment with hot electrons.

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The pulse-driven AC Josephson voltage standard of PTB

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The pulse-driven AC Josephson voltage standard or “Josephson Arbitrary Waveform Synthesizer” (JAWS), enable quantized output waveforms with extremely high spectral purity (SNR > 120 dB), which can deliver arbitrary waveforms in frequency or time domain. Because of the quantum nature of the JAWS, the output waveforms show extremely low noise and no drift too. The high precision of the JAWS was demonstrated by direct comparison with other quantum voltage standards [1]

The JAWS is based on SNS (S…superconductor, N…normal metal) Josephson junctions with NbxSi1-x as barrier material. Large arrays of up to 5-stacked SNS junctions have been implemented at PTB, with up to 15 000 Josephson junctions for a single array. Up to 8 arrays (integrated on 4 chips) are operated in series and output voltages of more than 2 V RMS [2, 3] have already been demonstrated. To further increase the output voltage of the JAWS system and/or to reduce the complexity/costs of the JAWS setup, it is necessary to achieve large output voltages with less electrical pulse-channels at room temperature.

Recently, we developed an optical pulse-drive using fast photodiodes operated at 4 K, close to the JAWS chip. Lensed photodiodes are mounted by flip-chip technique to a custom-made silicon-carrier chip [4]. Unipolar sinusoidal waveforms were synthesized with an JAWS array of 3000 junctions and an output voltage of more than 18 mV Peak-Peak at a clock-frequency of 15 GHz [5].

Another approach to reduce the number of electrical pulse-channels at room temperature was realized by implementing on-chip power dividers. At PTB we realized CPW-CPS and Wilkinson divider (CPW: coplanar waveguide, CPS: coplanar stripline) to split one pulse channel into 4 parallel JAWS arrays. First promising results will be presented [6].

The JAWS is already used for many applications in voltage metrology. A brief overview about these activities at PTB will be shown.

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Majorana bound states in topological insulators without a vortex

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In my talk, I will discuss topological phases in a three-dimensional topological insulator (TI) wire with a non-uniform chemical potential induced by gating across the cross-section [1]. This inhomogeneity in chemical potential lifts the degeneracy between two one-dimensional surface state subbands. A magnetic field applied along the wire, due to orbital effects, breaks time-reversal symmetry and lifts the Kramers degeneracy at zero-momentum. If placed in proximity to an s-wave superconductor, the system can be brought into a topological phase at relatively weak magnetic fields. Majorana bound states (MBSs), localized at the ends of the TI wire, emerge and are present for an exceptionally large region of parameter space in realistic systems. Unlike in previous proposals, these MBSs occur without the requirement of a vortex in the superconducting pairing potential, which represents a significant simplification for experiments. Our results open a pathway to the realisation of MBSs in present day TI wire devices. In the second part of my talk, I will switch from non-interacting systems, in which one neglects effects of strong electron-electron interactions, to interacting systems and, thus, to exotic fractional phases. In particular, I will focus on second-order TIs [2-7] and discuss two-dimensional fractional second-order topological superconductors, hosting zero-energy parafermion corner states.

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NanoSQUIDs for sensing magnetic fields on the nanoscale

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Magnetic properties of micro- and nanoscale objects, are currently a topic of intensive research. Their investigation requires the development of appropriate tools, e.g. for detection of the magnetization reversal of individual magnetic nanoparticles (MNPs) or for imaging magnetic field profiles on the nanoscale. Promising candidates for this task are strongly miniaturized superconducting quantum interference devices (SQUIDs) – so-called nanoSQUIDs. A SQUID consists of a superconducting loop, intersected by one or two weak links (Josephson junctions). SQUIDs are the most sensitive detectors for magnetic flux, and their sensitivity improves with shrinking size (inductance of the SQUID loop). As they enable direct detection of magnetization changes in small spin systems, that are placed close to the SQUID loop, nanoSQUIDs are very promising sensors for nanoscale applications. Moreover, if miniaturized SQUIDs can be brought in close vicinity to sample surfaces, they enable magnetic scanning probe microscopy on the nanoscale [1,2].

In this talk, I will review recent progress in the development and application of nanoSQUIDs, and I will present our approaches for developing sensitive Nb and $YBa_2Cu_3O_7$ (YBCO) nanoSQUIDs, which can be used for continuous measurements of magnetization loops of single MNPs in intermediate and strong magnetic fields up to the tesla range. Moreover, I will discuss recent developments in using nanoSQUIDs for scanning SQUID microscopy.

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Detection and manipulation of Andreev states in hybrid nanowire Josephson junctions using cQED techniques

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Although the existence Andreev bound states in SNS Josephson junctions was predicted by Kulik already in the 70's, it was not until rather recently that direct evidence of these phase sensitive states was obtained experimentally using different techniques. On the other hand, the combination of high quality hybrid nanostructures and circuit QED techniques are allowing to explore the physics of Andreev states in novel conditions with unprecedented accuracy.
In this presentation I'll give an overview on the theory that we have developed [1-5] to describe Andreev states in semiconducting nanowire Josephson junctions and their detection using circuit-QED techniques. Using a simple multichannel model we are able to identify the main effects on the Andreev states due to spin-orbit interactions [1,2]. Our theory allows to understand the line intensities in their microwave absorption spectrum and the absence of selection rules as observed in recent experiments [3,4]. Furthermore, I'll discuss the signatures of electron-electron interactions that can be identified in the Andreev spectrum [5].
Finally, I'll briefly discuss the prospects of using these states as a platform for different type of qubits.

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Kinetic magnetoelectric effect in topological insulators

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The kinetic magnetoelectric effect is an orbital analog of the Edelstein effect and offers an additional degree of freedom to control magnetization via the charge current. It occurs in chiral systems [1-3], and it is analogous to a solenoid in electromagnetism [1,2]. A related experiment has been reported in tellurium [4], and *ab initio* calculation has been performed on current-induced orbital and spin magnetization [5]. Here we theoretically propose a gigantic kinetic magnetoelectric effect in topological insulators and interpret the results in terms of topological surface currents (Fig. 1(a)) [6]. We construct a theory of the kinetic magnetoelectric effect for a surface Hamiltonian of a topological insulator, and show that it well describes the results by direct numerical calculation. This kinetic magnetoelectric effect depends on the details of the surface, meaning that it cannot be defined as a bulk quantity. We propose that Chern insulators and Z2 topological insulators can be a platform with a large kinetic magnetoelectric effect, compared to metals, because the current flows only along the surface. We demonstrate the presence of said effect in a topological insulator, identifying $Cu_2ZnSnSe_4$ as a potential candidate (Fig. 1(b)(c)) [6].

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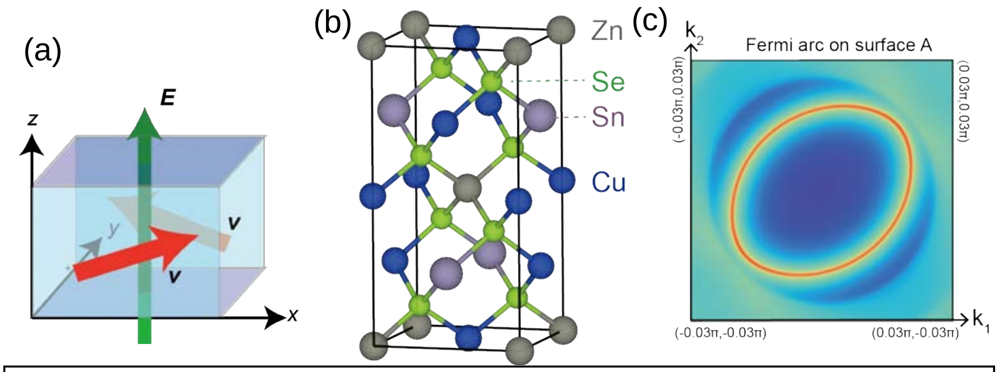

Fig.1: (a) Schematic figure of the kinetic magnetoelectric effect. (b) Crystal structure of $Cu_2ZnSnSe_4$. (c) Its surface Fermi surface.

Suppression of superconductivity via out-of-equilibrium electrons and phonons

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Recent experiments with metallic nanowires devices suggest that superconductivity can be controlled by the application of moderate electric fields [1,2]. In such experiments, critical currents are tuned and eventually suppressed by relatively small voltages applied to nearby gate electrodes, at odds with current understanding of electrostatic screening in metals. We demonstrate that this effect is linked to gate currents below 100 fA at the onset of critical current suppression in our devices [3]. Employing novel device geometries, we disentangle the roles of electric field and electron-current flow. Our results show that suppression of superconductivity does not depend on the presence or absence of an electric field at the surface of the nanowire but requires a current of high-energy electrons [4]. The suppression is most efficient when electrons are injected into the nanowire, but similar results are obtained also when electrons are passed between two remote electrodes at a distance d to the nanowire (with d in excess of 1 µm). In the latter case, high-energy electrons decay into phonons which propagate through the substrate and affect superconductivity in the nanowire by generating quasiparticles. We show that this process involves a non-thermal phonon distribution, with marked differences from the loss of superconductivity due to Joule heating near the nanowire or an increase in the bath temperature.

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Quantum Locking and Synchronization in Josephson Photonics Devices

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Phase stability is an important characteristic of radiation sources. For quantum sources exploitation and characterization of many quantum properties, such as entanglement and squeezing, may be hampered by phase instability.
Josephson photonics devices, where microwave radiation is created by inelastic Cooper pair tunneling across a *dc-biased* Josephson junction connected in-series with a microwave resonator are particularly vulnerable lacking the reference phase provided by an ac-drive. To counter this issue, sophisticated measurement schemes have been used in [1] to prove entanglement, while in [2] a weak ac-signal was put in to lock the phase and frequency of the emission.

Here, we extend a recent classical theory [3] to describe locking and the synchronization of several Josephson-photonics devices to the quantum regime. We describe phase diffusion due to voltage noises generated by current shot-noise and a residual in-series resistor. We show how this purely quantum source of noise is related to the Full Counting Statistics of emitted radiation. From the full numerical description, we demonstrate locking by a weak injection, as well as synchronization between two different devices. We find the rate of phase slips in this quantum regime and reveal implications on the statistics of emitted light in the phase locked region.

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Quantum Circuits Resilient to Magnetic Fields

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Superconducting quantum information processing machines are reliant on mesoscopic Josephson junctions to provide a source of nonlinearity. This can severely limit their coherence when operating in magnetic fields above tens of mT in hybrid platforms. A promising alternative are circuits which exploit the intrinsic nonlinearity of disordered superconductors, such as granular Aluminum (grAl). I will argue that grAl forms a compact effective junction array with high kinetic inductance and amenable nonlinearity [1,2], which can be in-situ integrated with standard aluminum circuit processing in state of the art fluxonium qubits [3,4], and which can be operated without loss of coherence in magnetic fields exceeding 1 Tesla [5]. An ongoing challenge is to suppress and mitigate quasiparticle poisoning in grAl [6,7].

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Hybrid Circuit Quantum Electrodynamics with Semiconductor QDs and Superconducting Resonators

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Semiconductor qubits rely on the control of charge and spin degrees of freedom of electrons or holes confined in quantum dots (QDs). Typically, semiconductor qubit-qubit coupling is short range, effectively limiting qubit distance to the spatial extent of the wavefunction of the confined particle (a few hundred nanometers). This is a significant constraint towards scaling of the QD-based architectures to reach dense 1D or 2D arrays of QDs. Inspired by techniques originally developed for circuit QED, we demonstrated the strong coupling limit of individual electron charges [1,2] confined in GaAs quantum dots, by using the enhancement of the electric component of the vacuum fluctuations of a resonator with impedance beyond the typical 50 Ohm of standard coplanar waveguide technology.

By making use of this hybrid technology, we have realized a proof-of-concept experiment, where the coupling between a transmon and a double QD (DQD) is mediated by virtual microwave photon excitations in a high impedance SQUID array resonator, which acts as a quantum bus enabling long-range coupling between dissimilar qubits [3]. Similarly, we achieved coherent coupling between two DQD charge qubits separated by approximately ~50 um [4].

We have further investigated how to *in-situ* tuning the strength of the electric dipole interaction between the DQD qubit and the resonator [5]. We find that the qubit-resonator coupling strength, qubit decoherence, and detuning noise can be tuned systematically over more than one order of magnitude. By employing a Josephson junction array resonator with an impedance of $\sim$4 kΩ and a resonance frequency of $\omega_r/2\pi\sim$5.6 GHz, we observe a coupling strength of $g/2\pi\sim$630 MHz, demonstrating the possibility to achieve the ultrastrong coupling regime for electrons hosted in a semiconductor DQD.

The methods and techniques developed in this work are transferable to QD devices based on other material systems and can be beneficial for spin based hybrid systems [6].

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AC Josephson effect in junctions fabricated with topological and non-topological materials

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In the search for topological superconductivity, we are studying the AC Josephson effect in Josephson junctions of various materials in a “low-ohmic” environment allowing for DC bias. The materials are two-dimensional graphene, carbon nanotubes, the Dirac semimetal cadmium arsenide, the Weyl semimetal tungsten telluride WTe_2, InAs nanowires and carbon nanotubes, as well as conventional Al-based reference Josephson junctions.

In the form of a monolayer WTe_2 has been shown to be a topological insulator, while for thicker crystals. a higher-order topological insulator with helical hinge states has been predicted. Evidence of such 1D states along certain crystallographic directions in thin WTe_2 has been obtained in a few experiments employing Josephson junctions.

Not too surprisingly, in all our devices the strongest radiation peak occurs at the Josephson frequency $f_J = 2eV/h$ given by the applied voltage of V. However, we do find higher order terms, frequencies that are integer multiples of the fundamental f_J. We think that this observation suggests a non-sinusoidal current-phase relation, which is due to the presence of superconducting modes with high transparency. We also observe spurious resonances in the environment with frequency f_S which are mixed with f_J leading to sidebands $f = f_J \pm f_S$. We have also fabricated Josephson junctions that are part of a designed on-chip resonator. Here, we find strong correlations between features in the differential conductance in DC transport and dispersive resonance shift measurements in circuit QED-type experiments.

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Charge-transfer based operations on Majorana systems

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By now, there has been a lot of evidence of the existence of Majorana bound states (MBSs) at the ends of 1-D topological superconductors (TSs) [1]. However, a definitive proof of their topological origin will rely on the demonstration of their non-abelian statistics, which emerge after the exchange of MBSs. First proposals to demonstrate non-abelian statistics used gate electrodes to tune segments of the 1-D superconductor between the trivial and the topological phases [2]. Alternatively, non-abelian statistics can be demonstrated using charge-transfer based operations, where the charge of a quantum dot (QD) is transferred to two TSs, reducing the required number of gate electrodes [3].

In this presentation I will analyze the efficiency of charge-transfer based operations between a QD and to two TSs, showing how they can reveal MBS non-abelian statistics [4,5]. Using a full counting statistics analysis, we set bounds to the manipulation time scales. We use adiabatic perturbation theory to optimize the way charge-transfer operations are performed. Using realistic parameters, we find that operations can be performed with a fidelity close to unity in the ms to μs timescales, demonstrating the absence of dephasing and accumulated dynamical phases.

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Anyon braiding in quantum Hall anyon collider

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A mesoscopic collider, formed by a quantum point contact connecting quantum Hall edge channels, is useful for studying partition noise of electrons or fermionic statistics effects such as electronic Hong-Ou-Mandel interference. Recently, Bartolomei et al. [1] experimentally studied a collider in the fractional quantum Hall regime of filling factor 1/3, and their observation of current cross correlations cannot be explained by the electronic Hong-Ou-Mandel interference. We theoretically investigate the fractional quantum Hall collider, and find that a new process involving anyon braiding and fractional statistics appears in the collider [2]. In the typical parameter regime of the collider, the braiding process dominantly determines the current cross correlation. The braiding process has no connection with the fermionic antibunching and bosonic bunching that is the origin of the Hong-Ou-Mandel interference of noninteracting fermions or bosons. Fractional statistics effects in the integer quantum Hall regime will be also discussed [3,4].

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The revised SI for innovation, science and the second quantum revolution

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In November 2018, the General Conference for Weights and Measures, CGPM, established by the Metre Convention in 1875, decided in its 26th meeting on the revision of the International System of Units (SI). The signatory states of the Metre Convention represent about 98% of the world's economic power and, thus, the SI forms the very foundation of global, international trade and the reliability of measurements worldwide.

As envisioned by Max Planck in his famous paper of 1900 postulating the "Planck constant", the revised SI shall be based on fixing the numerical values of "defining constants": the speed of light, the elementary charge, the Boltzmann, Avogadro, and the Planck constants, the caesium hyperfine clock transition and the luminous efficacy. The revision represents our current theoretical understanding of the microscopic world and aims to ensure that the units are valid and realisable "for all times, for all people", the vision formulated during the French revolution, extended by Max Planck "for all times and civilizations, throughout the Universe".

In the talk, an overview will be provided on the revised SI and its advantages as compared to the previous definitions. In particular, the talk focuses on future perspectives with an improved realisation of the units exploiting innovative technologies. The innovative potential unlocked by the revision of the SI is extremely versatile and covers a wide spectrum of scientific and industrial sectors, ranging from nanometrology and novel electronic devices to digitalisation and QT-based space applications.

Quantum sensing with superconducting circuits

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Today, realising the second quantum revolution appears feasible, with superconducting quantum circuits having matured over the last years to the leading platform for quantum coherent information processing devices. Here, we demonstrate their application potential as local sensors. The on-chip amplitude and frequency of a microwave signal can be inferred from the ac Stark shifts of higher transmon levels.

Analysing weak microwave signals in the GHz regime is a challenging task if the signal level is very low and the photon energy widely undefined. A superconducting qubit can detect signals in the low photon regime, but due to its discrete level structure, it is only sensitive to photons of certain energies. With a multilevel quantum system (qudit) in contrast, the unknown signal frequency and amplitude can be deduced from the higher level ac Stark shift. The measurement accuracy is given by the signal amplitude, its detuning from the discrete qudit energy level structure, and the anharmonicity. Using spectroscopic measurements, we demonstrate an energy sensitivity in the order of 10^{-3} with a measurement range of more than 1 GHz by observing shifts in the transition frequencies involving up to three levels. These shifts are in good agreement with an analytic circuit model and master equation simulations. For large detunings, we find the shifts to scale linearly with the power of the applied microwave drive. In our time-resolved measurements we employ Ramsey fringes, allowing us to detect the amplitude of the systems transfer function over a range of several hundreds of MHz with an energy sensitivity on the order of 10^{-4}.

Combined with similar measurements for the phase of the transfer function, our sensing method can facilitate pulse correction for high fidelity quantum gates in superconducting circuits. Exploiting this effect, we demonstrated a power meter which makes it possible to characterize the microwave transmission from source to sample. Additionally, the potential to characterize arbitrary microwave fields promotes applications in related areas of research, such as quantum optics or hybrid microwave systems including photonic, mechanical or magnonic subsystems.

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Embedding silicon spins in superconducting circuits

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Long coherence times and small dimensions of single electron spins in silicon quantum dots make these systems attractive as qubits for quantum computation. However, the realization of a large network of spin qubits requires advancements in coherent long-range interconnects between qubits and efficient qubit readout that is compatible with 2D architectures [1]. A promising approach that addresses these two challenges is by embedding spin qubits in superconducting cavities [2].

In this talk, we will give an overview of our efforts in hybrid circuit quantum electrodynamics with charges and spins in silicon. With regard to long-range interconnects, we first report the strong coupling between a single spin in a double quantum dot (DQD) and a microwave photon in an on-chip superconducting cavity [3]. Next, we scale the system up to two spins, one at either end of the cavity, and demonstrate coherent spin-spin interaction mediated by real photons and then, more challenging, virtual photons [4]. Key to achieving these results was the development of high-impedance resonators [5] to enhance the coupling to the electron charge as the spin-photon coupling realized here is an indirect coupling that relies on the charge degree of freedom. These results could enable long-range two-qubit gates between spin qubits.

Regarding efficient qubit readout, we use the on-chip cavity to perform single-shot readout of singlet-triplet spin states by rapidly detecting the different DQD charge susceptibilities associated with the spin states [6]. This is an important step in gate-based sensing where gates already in place for confining electrons can also be used for qubit readout, thereby eliminating the need for additional structures nearby the qubits to make detectors for readout.

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Abstracts of Posters

(in alphabetical order)

Charging of a shallow quantum dot

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We consider the problem of single-electron capture by a tuneable-barrier semiconductor quantum dot. This is known to be the crucial non-equilibrium process that determines the ultimate precision of on-demand electron sources employed in metrology [1] and hot-electron quantum optics [2].

We augment the widely used decay-cascade model for backtunneling [3] by microscopic modeling of tunneling rates beyond the WKB approximation. We argue for universality of 1D cubic confinement in the shallow direction of an emerging quantum dot and derive a scaling relation for capture probabilities as a function of gate voltage and entrance tunnel barrier closing speed. The relation generalizes the double-exponential formula for modelling the quantized current of tuneable-dot-based metrological charge pumps and enables estimation of the microscopic confinement potential parameters of a shallow quantum dot that are inaccessible with conventional bias spectroscopy. Preliminary comparison with experimental data obtained at the German National metrology institute PTB shows good agreement of the cubic potential model with tunneling rates measured by counting over multiple orders of magnitude in driving rates. The universal model presented here has implications for the speed and precision limits of metrological charge pumps and fast selective initialization of quantum states in few-electron dots [4].

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4D wave-packet simulation of two-electron quantum optics experiments

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Few-electron quantum optics devices provide novel opportunities for development of quantum technologies since electrons in contrast to photons are fermions and easily interact with each other. Realistic simultaneous numerical modelling of electron-electron interaction and quantum effects in two-dimensional quantum devices is complicated due to high numerical cost of doing quantum mechanical calculations [1]. The quantum mechanical description of interacting electrons can be significantly simplified on a saddle point potential, which acts as realistic model of an electron beam splitter for electron quantum optics experiments. Time-dependent evolution of electron wave-packets can be analytically derived [2] for a case of non-interacting electrons on the saddle point potential with and without inclusion of electron exchange symmetry effect. Restriction of the electrons to the lowest Landau level in magnetic field allows us to reduce the dimensionality of the problem, greatly simplifying numerical wave-packet propagation and allowing numerical characterization of different contributions to the outcome of electron interferometry experiments arising from the wave packet evolution, electron exchange and electron-electron interaction.

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Probing Majorana bound states via a pn-junction containing a quantum dot

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We propose an alternative route to transport experiments for detecting Majorana bound states (MBSs) by combining topological superconductivity with quantum optics in a superconducting pn-junction containing a quantum dot (QD). We consider two spatially separated MBSs (n-side) coherently tunnel-coupled to electrons on a QD which is placed closer to one of the MBSs, while holes on the QD get refilled from a normal conducting reservoir (p-side). Via electron-hole recombination photons are emitted, which have direct information on the MBSs, their non-locality, and spinor-polarization. We analyze the intensity and noise of the emitted photons by using a master equation approach. In the weak coupling regime, we find an analytical expression for the emission intensity which allows to clearly distinguish the cases of well separated MBSs at zero energy from overlapping MBSs. For separated MBSs, the relative width of the emission peaks is proportional to the spinor-polarization of the nearer MBS. For overlapping MBSs, a coupling to the more distant MBS causes a shift of the emission peaks. Additionally, we show that quasiparticle poisoning influences the photon emission drastically and changes its shot noise from super-Poissonian to sub-Poissonian.

Picosecond electronic pulse generation for flying qubits

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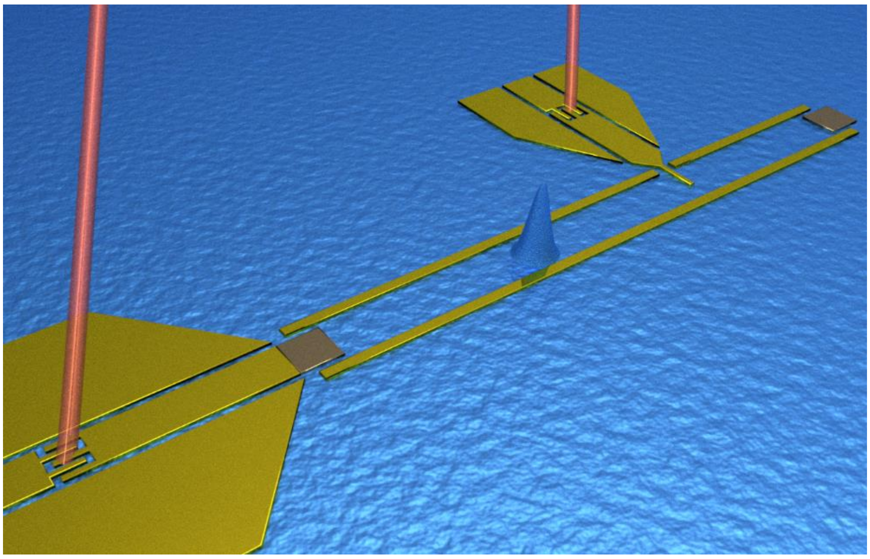

In electron-quantum-optics, the short coherence time of the electrons presently limits the possibility to fully exploit them for quantum computing purposes. To profit from this scheme for quantum information processing, the electron wave packet has to be short as compared to the propagation distance and gate operations have to be much shorter than the phase coherence time. Considering present state-of-the-art 30 picoseconds short voltage pulses and a typical phase coherence length of a few tens of micrometres, only a limited number of quantum operations are possible. To overcome this bottleneck, voltage pulses of the order of a picosecond have to be engineered. One possibility is to convert optical femtosecond pulses into picosecond electrical pulses by means of an ultrafast photodetector integrated onto the electronic chip.

Here we present the development of a cryo-optoelectronic setup to generate picosecond voltage pulses for quantum applications. The system consists of 4 optical fibres which are integrated into a cryogenic setup. A femtosecond laser pulse is converted on-chip (and at low temperature) into an electrical voltage pulse via a photo-switch deposited onto a low temperature grown GaAs layer with picosecond photo response time. We demonstrate picosecond pulse generation via time-resolved pump-probe measurements. This ultra-short electronic pulse can be conveyed using a coplanar waveguide and injected into a high mobility two-dimensional electron gas. This on-chip integration of picosecond voltage pulses into quantum nanoelectronic devices paves the way for ultrafast control of electronic flying qubits.

Modular architecture for circuit quantum electrodynamics

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Superconducting quantum circuits play a pioneering role in finding a scalable architecture for the realization of coherent quantum processors. In this context, keeping the integrity, individual addressability and controllability of each circuit component while increasing the complexity of the whole system is paramount to building a functional device. Fulfilling these key requirements becomes more difficult when increasing the connectivity in the circuit since parasitic cross-talk and the number of decay channels inevitably increase at the same time. For these reasons, the coupling, readout and control mechanisms of every architecture need to be understood in great detail. Here, we investigate a flip-chip architecture in which we implement the readout and flux control of generalized flux qubits[1] fabricated with superconducting granular aluminum[2]. With our approach, circuits serving different tasks within the system can be prepared individually and exchanged in case they don't fulfil the requirements. In our first realization, two flux qubits and control structures for readout and flux control are fabricated and tested regarding their microwave properties. The dispersive readout is achieved by inductively coupling the flux qubits to harmonic modes located on the same chip. Furthermore, the developed circuit architecture enables a suitable easy-access framework for future experiments on qubit-qubit coupling in a well-controlled microwave environment.

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Phase escape dynamics in InAs/Al Josephson junctions

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We present the phase escape mechanisms of highly transparent Josephson junctions (JJs) defined in a planar InAs/Al heterostructure [1]. Such devices have several quantum computing applications: from gate-controlled transmons [2] and flux qubits [3], to harnessing topological states of matter [4]. We show that quantum fluctuations are the dominant mechanism of phase escape, with phase diffusion becoming significant for higher temperatures or lower critical currents. Furthermore, the transition temperature T* between the two phase-escape regimes can be controlled using a gate electrode or an in-plane magnetic field. In addition, we measure the phase dynamics in an asymmetric SQUID geometry, whereby two JJs with different critical currents are embedded in a superconducting loop. In this device, we observe a flux dependent T*, as well as protection of the JJ with smaller critical current from phase escape, resulting in a threefold increase of its switching current relative to a measurement of the JJ when independent from the loop. This effect is interpreted to be due to phase locking between the two JJs. An understanding of the phase dynamics of JJs in hybrid materials is crucial for harnessing the potential of the platform in quantum computing applications.

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The topological phase of one-dimensional mass-imbalanced repulsive Hubbard model

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We investigate the phase diagram of the one-dimensional repulsive Hubbard model with mass imbalance. Using DMRG, we show that this model has a “triplet" paired phase (dubbed πSG) at generic fillings, consistent with previous theoretical analysis. We study the topological aspect of πSG phase, determining long-range string orders and the filling anomaly which refers to the relation among the single particle gap, inversion symmetry, and filling imbalance for open chains. We also find, using DMRG, that at 1/3 filling, commensurate effects lead to two additional phases: a crystal phase and a trion phase; we construct a description of these phases using Tomonaga-Luttinger liquid theory.

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Quantum-correlated photons generated by nonlocal electron transport

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Since the realization of high-quality microwave cavities coupled to quantum dots, one can envisage the possibility to investigate the coherent interaction of light and matter in semiconductor quantum devices. Here we study a parallel double quantum dot device operating as single-electron splitter interferometer, with each dot coupled to a local photon cavity. We explore how quantum correlation and entanglement between the two separated cavities are generated by the coherent transport of a single electron passing simultaneously through the two different dots. We calculate the covariance of the cavity occupations by use of a diagrammatic perturbative expansion based on Keldysh Green's functions to the fourth order in the dot-cavity interaction strength, taking into account vertex diagrams. In this way, we demonstrate the creation of entanglement by showing that the classical Cauchy-Schwarz inequality is violated if the energy levels of the two dots are almost degenerate. For large level detunings or a single dot coupled to two cavities, we show that the inequality is not violated.

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Local and non-local quantum transport due to Andreev bound states in finite Rashba nanowires with superconducting and normal sections

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We analyze Andreev bound states (ABSs) that form in normal sections of a Rashba nanowire that is only partially covered by a superconducting layer. These ABSs are localized close to the ends of the superconducting section and can be pinned to zero energy over a wide range of magnetic field strengths even if the nanowire is in the nontopological regime. For finite-size nanowires (typically $\lesssim 1\mu m$ in current experiments [1]), the ABS localization length is comparable to the length of the nanowire. The probability density of an ABS is therefore nonzero throughout the nanowire and differential-conductance calculations reveal a correlated zero-bias peak (ZBP) at both ends of the nanowire. When a second normal section hosts an additional ABS at the opposite end of the superconducting section, the combination of the two ABSs can mimic the closing and reopening of the bulk gap in local and nonlocal conductances accompanied by the appearance of the ZBP. These signatures are reminiscent of those expected for Majorana bound states (MBSs) but occur here in the nontopological regime. Our results demonstrate that conductance measurements of correlated ZBPs at the ends of a typical superconducting nanowire or an apparent closing and reopening of the bulk gap in the local and nonlocal conductance are not conclusive indicators for the presence of MBSs [2].

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Josephson junctions and SQUIDs created by focused Helium ion beam irradiation of YBa2Cu3O7

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Fabrication of Josephson junctions (JJs) and Superconducting Quantum Interference devices (SQUIDs) based on conventional metallic superconductors, like niobium, is highly developed. There are several techniques existing, e.g. shadow evaporation or advanced trilayer thin film technology, enabling the realisation of different kind of high-quality JJs and SQUIDs and their applications. In contrast, the JJ technology for high-transition temperature cuprate superconductors, like YBa2Cu3O7 (YBCO), is much less mature. YBCO has a complex crystal structure and a small coherence length, which leads to a high sensitivity to defects on the atomic scale. As a consequence, the realization of YBCO JJs requires epitaxially grown single crystalline films, and the fabrication of high-quality JJ barriers and interfaces is demanding.

The recently developed helium focused ion beam (He-FIB) technique, offers the chance to modify YBCO on the nanoscale, i.e., to directly write JJ barriers into the material by driving locally the material into the insulating state [1]. In addition, He-FIB irradiation can also be used to pattern YBCO films on the nanoscale, without removing material [2]; this provides an alternative way to define insulating areas, e.g. for nanoSQUID fabrication.

Here, we present our recent progress in the fabrication of He-FIB-induced YBCO JJs and SQUIDs as well as the analysis of their electric transport and noise properties, in particular with respect to the possible control of the critical current density of the JJs by variation of the He-FIB dose [3]. This approach may be also applied to the realization of YBCO-based quantum devices.

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Anodization spectroscopy for superconducting devices

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This work is concerned with a critical aspect of the fabrication of superconductive devices. Those devices are based on superconductive Josephson junctions (JJ) - the building blocks not only of qubits but also of many applications like single-photon detectors [1] and magnetometers [2]. An insulating layer needed between the top and bottom electrode of the JJ is usually grown by anodic oxidization [3]. The advantages of this method, compared with e.g. sputter deposition, are a very good coverage of side walls and the absence of rip-off edges. There is, however, an additional advantage: During anodization, not only a thin layer of oxide is grown on top of the metallic layers, but also the thickness and the interface quality of those layers can be analyzed. The latter is called anodization spectroscopy [4] and shall be the topic of this work.

The experimental setup for anodization spectroscopy contains a galvanic cell with one electrode being the structured wafer and a silver or platinum grid as counter electrode. The cell is filled with an electrolyte consisting of ammonium pentaborate, ethylene glycol and water. A source measure unit (SMU) is used to drive electric currents through the galvanic cell and to monitor the voltage during growth of the oxide layer. The voltage signal (or "spectrum") delivers information on the sample via

$$dV/dt=\lambda\, jE\, M/nZ\rho F$$

with λ the efficiency of oxidation, j the current density, M the molecular mass of the oxide, ρ the oxide density, nZ the valency of oxidation reaction, F the Faraday constant, E the differential electric field strength, and j the current density. The anodization spectrum dV/dt reflects the modifications of the magnitudes included in the above expression and reflects depth-variations of the anodized object in terms of composition and density. The analysis of these modifications makes it possible to get information about surface, bulk, and interfaces of the films.

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Fractional Mutual Statistics on Integer Quantum Hall Edges

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Fractional charge and statistics are hallmarks of low-dimensional interacting systems such as fractional quantum Hall (QH) systems, but the detection of the fractional statistics is a challenging task due to their strongly interacting nature. Integer QH systems are regarded non-interacting, yet they can have fractional charge excitations when they couple to another interacting system [1] or time-dependent voltages [2]. The integer QH systems provide good experimental controllability.

Here, we notice the Abelian fractional mutual statistics between such a fractional excitation and an electron, and propose a setup for the detection of the statistics [3]. We first show that a fractional excitation can appear in a metallic island connected to the multiple integer QH edges [4]. Then, we suggest to inject the fractional excitation to a Mach-Zehnder interferometer (MZI) with asymmetric arm lengths. In a parameter regime, the dominant interference process involves braiding, via double exchange, between an electron excited at an MZI beam splitter and the fractional excitation. The braiding results in the interference phase shift by the phase angle of the mutual statistics. This proposal for directly observing the fractional mutual statistics is within experimental reach.

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Case studies of spectroscopic OAM transfer in chiral phases of matter

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A complete characterization of quantum systems implies the detection of both amplitude and phase. This relates to the use of interferometric techniques. On the other side, there exist a large number of recent quantum phases in solids that involve nonlocal invariants, phases, and chiral degrees of freedom. So the question arises, whether methods that are supplemented by phase factors could lead to relevant information [1, 2]. We have recently started to extend our repertoire of experimental techniques by considered structured light for inelastic light scattering. Such photon states carry orbital angular momentum (OAM) in addition to spin angular momentum (SAM, chirality). Presently, applications of OAM exist in super resolution microscopy and the manipulation of trapped ions and BECs, using intensity singularities and transfer of quantized angular momenta [3].

In the limit of paraxial beams, so called twisted (or vortex) light has a helical phase front that can be described, e.g. by Laguerre-Gaussian functions. They can be prepared from circularly polarized light (SAM) using spiral plates that introduce a topological charge into the wave front. Despite its simple generation, the coupling of optical OAM to matter is far from trivial. In lowest order (dipole approximation) there exist no coupling and early studies of so called chirooptical effects, i.e. circular dichroism or the rotation of OAM beams in chiral media did not achieve a clear result [4]. More recently, it has been claimed that strong focusing (optical spin-orbit entanglement), higher order couplings, and electronic resonances could lead to large effects [5].

We have performed exploratory experiments on chiral / topological model systems to search for OAM features. Here chiral liquid crystals and semimetals have been investigated. We will demonstrate low energy, diffusive fluctuations in chiral phases possibly related to OAM transfer and a Hanle – like effect (resonant scattering, polarization anomaly). Such observations could lead to an avenue of novel optical phenomena using OAM.

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Transmission spectra of the driven, dissipative Rabi model in the USC regime

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We present theoretical transmission spectra of a strongly driven, damped flux qubit coupled to a dissipative resonator in the ultrastrong-coupling regime. Such a qubit-oscillator system, described within a dissipative Rabi model, constitutes the building block of superconducting circuit QED platforms. The addition of a strong drive allows one to characterize the system properties and study novel phenomena, leading to a better understanding and control of the qubit-oscillator system. In this work, the calculated transmission of a weak probe field quantifies the response of the qubit, in frequency domain, under the influence of the quantized resonator and of the strong microwave drive. We find distinctive features of the entangled driven qubit-resonator spectrum, namely resonant features and avoided crossings, modified by the presence of the dissipative environment. The magnitude, positions, and broadening of these features are determined by the interplay among qubit-oscillator detuning, the strength of their coupling, the driving amplitude, and the interaction with the heat bath. This work establishes the theoretical basis for future experiments in the driven ultrastrong-coupling regime.

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Precise power production by a hybrid electron turnstile

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Nanometric normal-metal islands coupled to two superconducting leads through insulating tunnel junctions are suitable as single-electron turnstiles when the excess charge is periodically driven by a capacitively coupled gate electrode. The superconducting leads extend the stability zone along the whole gate-voltage parameter space making it possible to create single-electron currents by only allowing one tunneling event per cycle per junction [1]. In this device, electric charge is carried by superconducting excitations injected into the leads in each tunneling event. We demonstrate [2] that these excitations are created close to the superconducting gap edge. Consequently, the average energy current, i.e., power injected to the leads, is given by a simple frequency to power conversion relation, namely the superconducting energy gap times the operation frequency per tunneling event. Furthermore, we test the accuracy of this relation, showing that it enables this device as a candidate for a power standard, in the same way as the frequency to current conversion relation of the single-electron turnstile. The power production is shown to be possible even in the absence of particle current since the bias voltage only plays a role in how the injection is distributed among the junctions. Further improvements in the accuracy of the device are proposed.

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Transient dynamics and metastability in parallel quantum dots

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We investigate the impact of quantum coherences on the stationary state properties as well as the transient dynamics of two interacting parallel quantum dots weakly coupled to metallic leads. This quantum system is extremely sensitive to perturbations much smaller than any other energy scale in the system, specifically compared to the system-lead coupling and the temperature [1]. In the stationary state, this leads to a current suppression while beyond the small parameters introduce new timescales in the dynamical behaviour. In particular, we find a metastable regime where the dynamics are effectively described by long-time dynamics [3,4]. We analyse the full system's dynamics analytically and numerically within a Lindblad description. Finally, we investigate if the double dot system can be used as charge sensor by explicitly making use of the quantum coherence effects.

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Signatures of interactions in the Andreev spectrum of nanowire Josephson junctions

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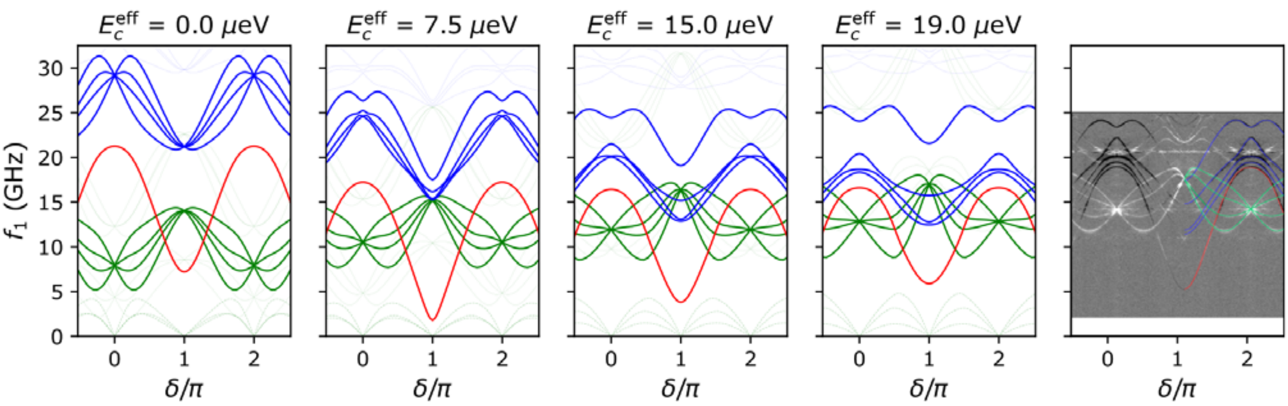
Hybrid semiconducting/superconducting nanostructures combined with circuit-QED techniques are allowing to explore superconducting proximity effects with an unprecedented degree of detail. For instance, these techniques have permitted to reveal the fine structure, due to spin-orbit interactions, of Andreev states in semiconducting nanowire Josephson junctions [1]. While some of the observed features of the microwave spectrum could be explained in terms of non-interacting models [1-3], other expected transitions lines from these models could not be clearly identified and some other experimental features remained unexplained.

In this work we show that the inclusion of electron-electron interactions is necessary to account for these unexplained features.



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Quantum electrodynamics of cold deposited granular aluminum

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In recent times, superconducting granular aluminum (grAl) has found increasing interest in the superconducting quantum circuits community because of its promising characteristics such as its tunable kinetic inductance [1], low microwave losses [2], high in-plane critical magnetic field [2,3], and a higher critical temperature compared to pure Al [3].

In general, the critical temperature of a grAl film depends on its resistivity until it reaches a superconducting-to-insulator transition [4,5]. For samples evaporated at room temperature, a maximum of around 2.2K is reached for resistivity of about 1000 μΩ. The critical temperature rises even above 3K when grAl is deposited on a substrate held at a lower temperature of 100K [5,6].

This project aims to answer the question of increased Tc, which is yet to be understood microscopically, and other consequences of cold deposition, such as how a generally smaller -- while more homogeneous -- grain size positively affects the electrodynamics of the film. The test-bed used to characterize the electrodynamics are stripline resonators fabricated entirely from cold-deposited grAl, and measured in a cylindrical copper waveguide sample holder at cryogenic temperatures.

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High Impedance Microwave Technology for QD-cQED devices

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Typically, semiconductor qubit-qubit coupling is short-range, which limits the scaling capabilities of QD-based architectures. Circuit QED can be a promising platform to solve this issue since it allows to couple the qubit state to microwave photons stored in superconducting resonators. A way to improve the coupling between QD-qubit and microwave photons is to increase the impedance of the resonator.

We present high-impedance resonators fabricated in a high kinetic inductance superconductor disordered thin film, exhibiting quality factors of Q_{int}~10^5 in the single-photon regime. To properly control the electrochemical potential of the QD, to which the resonator is capacitively coupled, it is necessary to have the possibility to apply a DC voltage to the resonator gate while keeping a high Q_{int}. This can be achieved by incorporating compact distributed Bragg reflectors, which act as a stopband filter confining the microwave signals to the resonator. The high kinetic inductance allows defining a compact Bragg filter in the same fabrication step.

In addition, by making use of arrays of coupled compact NbN high-impedance LC resonators, we defined non-trivial photonic density of states, which could represent an important new resource for a future spin-photon hybrid architecture.

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A quantum dot pump coupled with a single quantum Hall edge channel

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Development of single-electron sources is a crucial step towards a fermion version of quantum optics and a solid-state quantum processing [1,2]. Further development of single-electron sources is desired, since existing sources do not cover the emission energy range of 1 – 60 meV. We theoretically and experimentally propose a new type of a single-electron source, which is composed of an interacting quantum dot and a single lead. As the quantum dot is coupled to the single lead (a chiral quantum Hall edge), electron-hole pairs are pumped by AC modulation of the quantum dot. The energy of pumped electrons can be 10 - 60 meV with help of the charging energy in the quantum dot while the hole energy is near the Fermi energy. Utilizing the energy separation, the electron and the hole of a pumped pair are spatially split by applying a tunable-potential barrier located on the path of the pumped pair. We theoretically describe the pumping mechanism using a master equation. We find that the single-electron generation resulting from the pumping and splitting of the electron-hole pairs is identified by characteristic triangular shape regions in the pump map. Our single-electron source is experimentally realized, and the obtained pump map is in good agreement with the theoretical result.

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Title: Fate of metal insulator transition in an interacting kagome lattice under periodic drive

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Abstract:

We theoretically study the interplay between electron-electron interaction and external periodic drive on a kagome lattice with drive frequency being much larger than t and U. For U=0, using Brillouin-Wigner perturbation theory for obtaining effective hamiltonian in the high frequency limit, we see that the external drive modulates the bare hopping and generates emergent nearest neighbour and next-nearest neighbour spin orbit coupling terms which in turn induces topological phase transition that are characterized by change in band Chern numbers. Drive strength gives a control over the position of the flat bands in the system. Within a slave rotor mean field theory, it is shown that in the presence of the drive, and small U, the system exhibits repeated metal-insulator transitions as a function of the drive amplitude A. The charge gap between the low energy bands oscillates periodically with A and leads to a semi-metallic phase at specific values of A where the band gap becomes zero.

Presenter: Ganesh C. Paul, TU Braunschweig, Germany.

Classical solution of two electron scattering at a saddle point potential in strong magnetic field limit

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Few-electron semiconductor quantum optics devices have numerous applications in quantum metrology, sensing and quantum computing. In recent years, several hot electron collision experiments in HOM (Hong-Ou-Mandel) configuration have been developed. Dependance of the transmission of the barrier on energy [1] and nonlinearity due to interactions [2] distinguishes them from near-Fermi-energy electron quantum optics. Coulomb interaction can play an important role in two-electron collisions. If chiral electrons move in a strong magnetic field, it is important to understand the behavior of the system when electron scattering correlation is dominated by Coulomb interaction.
We solve the scattering problem of two interacting electrons in the saddle point potential in strong magnetic field limit where quantum effects (time-energy broadening and exchange statistics) can be ignored. Separation of variables into center-of-mass and relative coordinates for two electrons in quadratic potential is introduced. The results can be represented as a classical phase diagram that determines the scattering outcome of two electron scattering as function of incoming electron energies and relative time-of-arrival at the scattering barrier. We identify a particularly simple limiting form of the phase diagram where the scattering outcomes are deterministic and the boundaries between different deterministic outcomes can be calculated efficiently using very few parameters which are directly related to the microscopic parameters of the Hamiltonian. Interaction-dominated correlation features and ways to quantify them in experimental signals are discussed.
This research is funded by the Latvian Council of Science, project *Electron-electron interaction models for solid-state electron quantum optics devices*, project No. lzp-2020/2-0281.

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Semiconductor Epitaxy in Superconducting Templates

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Integration of high-quality semiconductor-superconductor devices into scalable and CMOS compatible architectures remains an outstanding challenge which currently hinders their practical implementation. Here, we demonstrate epitaxy of InAs nanowires monolithically integrated on Si inside lateral cavities containing superconducting TiN elements [1]. A hybrid semiconductor-superconductor interface is formed during InAs nanowire growth. Devices based on our new approach are characterized by sharp semiconductor-superconductor interfaces and are aligned along arbitrary crystallographic directions. Electrical characterization at low temperature reveals proximity induced superconductivity in InAs via a transparent interface.

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Parity switching in a semiconductor-based transmon qubit

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Unpaired quasiparticles can adversely affect the performance of superconducting devices, including qubits based on Majorana zero modes. We study charge parity switching in a superconductor-semiconductor nanowire-based transmon device that shows Little-Parks oscillations of its frequency as a function of magnetic field. In the recovery regime, where a single flux quantum threads the cross-section of the wire transport measurements recently revealed signatures compatible with Majorana zero modes.

We read out the charge parity by dispersive monitoring of a readout resonator to which the transmon qubit is coupled. At zero magnetic field, we measure parity switching times in the range of milliseconds. As the magnetic field is increased toward the first closing of the superconducting gap, the switching time is decreased and is consistent with the superconducting gap reduction. In the recovery regime where the gap is re-opened, the switching time is reduced below the sensitivity of our measurement, putting a bound on the minimum observable Majorana hybridization energy in a full-shell nanowire system.

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Quantum calibrated magnetic force microscopy

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Quantitative characterizations of magnetic micro- and nanostructures are required for industry and research. One of the most common and versatile tool for such characterizations is quantitative magnetic force microscopy (MFM) which depends on the calibration of the magnetic tip. However, the classical MFM calibration approach is limited by the knowledge on the calibration sample and the tip.

Here in this study, we report the quantum calibration of an MFM by measuring the two-dimensional magnetic stray field distribution of the MFM tip using a single nitrogen vacancy (NV) center in diamond. From the measured stray field distribution and the mechanical properties of the cantilever a calibration function is derived allowing to convert MFM images to quantum calibrated stray field maps. This novel approach overcomes limitations of prior MFM calibration schemes and allows quantum calibrated nanoscale stray field measurements in a field range inaccessible to scanning NV magnetometry. Quantum calibrated measurements of a stray field reference sample allow its use as a transfer standard, opening the road towards fast and easily accessible quantum traceable calibrations of virtually any MFM.

Theory of two-electrons optics experiments with smooth potentials

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Large experimental progress in tomography of quantum Hall edge electrons have been achieved in recent years, leading to production of sufficiently coherent single- and two-electron distributions with the sizes of several 10-ths of nanometers and the possibility to measure details of these distributions. Here, we consider the effect of interaction between two electrons on the real time evolution of such distributions in the experimentally relevant case of smooth confining and quantum point contact (QPC) potentials. Both Hanbury Brown & Twiss and Hong-Ou-Mandel setups are investigated. The theoretical consideration is strongly simplified due to the possibility of the separation of coordinates leading to the independent motion of the center of mass and the motion of the relative coordinate of two electrons. The most prominent effect of this separation is the prediction of molecular states, where two electrons propagate together along the center of mass trajectory while simultaneously rotating around each other.

The existence of a large number of such (semiclassical) molecular states should naturally strongly affect the outgoing electrons'

distribution in the Hanbury Brown & Twiss kind of experiments. But also in the Hong-Ou-Mandel setup we predict new effects due to the quantum tunnelling of two electrons colliding at the QPC into the joint molecular states. As a specific measure of the interaction we investigate the probability for both injected electrons to stay an anomalously long time at the QPC.

Probing quantum electromagnetic magnetic fields with subnanosecond time resolution: the single electron radar

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In this poster we discuss how an electronic interferometer can be used to measure a time dependent electric field on a sub-nanosecond time scale based on alteration of the wave function of a single electronic excitation propagating across a Mach-Zehnder interferometer when the fast-varying potential is applied to one of the two branches, thereby realizing the electronic analogue of a radar.

Our key result is the electron radar equation that connects the experimental signal — the Aharonov-Bohm dependent part of the finite frequency average outgoing current — to the electronic wave function used as a probe and to the electromagnetic field to be probed. It is valid in the presence of Coulomb interactions within the interferometer and quantum electromagnetic field and incorporates the back-action effects of the quantum electromagnetic field to be probed onto the electron fluid. The detection of a squeezed vacuum which exhibits time dependent quantum fluctuations will be used as an illustration of this general framework.

Electron Collision Enabled by Sound Waves

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A surface acoustic wave (SAW) can transfer a single electron via a surface-gate-defined channel between distant quantum dots [1,2]. The acousto-electric transport technique offers an original platform for quantum-optics-like experiments with single flying electrons employing their spin [3] or charge degree of freedom [4], with transfer efficiency beyond 99% [5]. Here we present a SAW-driven single-electron circuit with two tunnel-coupled transport channels and investigate the anti-bunching effect in a Hou-Ou-Mandel interferometer by synchronizing two single-electrons with picosecond voltage pulses. We observe an increase of 30% of the coincidental probability (P11) only when both electrons are trapped in the same moving potential. Thanks to a 40-µm-long coupling region, we can dynamically control the tunnel-coupling and further investigate the quantum state of the electrons during transport. The presented in-flight investigation sheds light on the interactions of flying electrons and thus paves the way for electron-quantum-optics implementations driven by sound.

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Coulomb blockade effects in minimally twisted bilayer graphene

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In the presence of a finite interlayer electric field, minimally twisted bilayer graphene displays a triangular network of chiral valley Hall states that propagate along the AB/BA interfaces and scatter at the metallic AA regions. Previous studies model the chiral network using a phenomenological scattering matrix approach based entirely on the symmetries of the system. So far, the physics of the metallic AA scattering regions has been disregarded, and indeed, the finite size of the AA regions (order of nm) can give rise to similar physics as quantum dots: a discrete energy spectrum and also interacting effects such as Coulomb blockade physics. In our contribution, we include these effects and study the resulting network of chiral modes and quantum dots through the energy spectrum and magneto-conductance calculations.

Heteroepitaxial growth of single crystalline YBa2Cu3O7 and Sr3Al2O6 thin films on SrTiO3 substrates

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Scanning SQUID microscopy (SSM) is a powerful technique for imaging magnetic fields or dissipation processes. The development of the SQUID-on-tip (SOT) led to a breakthrough in spatial resolution and flux sensitivity for SSM. However, so far SOTs are based on metallic superconductors, e.g., Pb or Al, which limits their operation range to temperatures below about 10 K and magnetic fields below about 1 T.
The use of the high-Tc cuprate superconductor $YBa_2Cu_3O_7$ (YBCO) could enable SSM in the Tesla range and at temperatures up to about 80 K. However, YBCO has a complex crystal structure and a small coherence length, which leads to a high sensitivity to defects on the atomic scale. High quality YBCO films can only be obtained by epitaxial growth on lattice-matched substrates. Therefore, the SOT approach is not a viable option for the realization of YBCO-based SSM.
An alternative approach to realize YBCO nanoSQUIDs for SSM with high spatial resolution is based on the fabrication of nanoSQUIDs on custom made AFM cantilevers that are fabricated from Si wafers [1]. Here, the challenge is the integration of YBCO thin films on Si wafers. In this work, we present our approach to address that challenge. We intend to use Sr3Al2O6 (SAO), which is lattice-matched to perovskite materials, such as SrTiO3 (STO). SAO can be dissolved in water, i.e. it can be used as a sacrificial layer for the realisation of free-standing single-crystalline perovskite thin films [2], including YBCO [3].
We present the development of an epitaxial SAO thin film growth process, based on pulsed laser deposition (PLD) and discuss the properties of the grown SAO films. Furthermore, we describe our process for the heteroepitaxial growth of YBCO/STO/SAO trilayers on STO (001) single crystal substrates and discuss the optimization of growth conditions and properties of the trilayers. And finally, we present our preliminary attempts to transfer YBCO films onto Si surfaces.

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Mitigating parasitic interactions in superconducting circuits

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Implementation of high-performance two-qubit gates is a key factor for scalable quantum computation. However, the state-of-the-art superconducting two-qubit gates are yet far from being perfect due to the parasitic ZZ coupling. In this poster, we introduce a general theory to evaluate the “static” ZZ interaction between seemingly idle qubits [1] as well as the “dynamical” ZZ interaction between driving entangled qubits, and find the characteristics of both static and dynamical ZZ freedoms [2]. Moreover, we demonstrate the two freedoms can be realized in one circuit with a tunable coupler so as to eliminate ZZ interaction throughout gate operations [3]. Our theory shows that using these methods the fidelity of a CR gate is able to achieve the coherence limit.

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Epitaxial graphene by F4-TCNQ molecular doping for quantum Hall resistance standards

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Epitaxial graphene grown on SiC substrates has proven itself to be the best candidate for quantum Hall resistance (QHR) standards due to the advanced performance at higher temperatures (~ 4 K) and lower magnetic fields (< 6 T) in comparison with conventional GaAs-based QHR devices. Since as-grown epi-graphene exhibits a high intrinsic n-type carrier density of up 10^{13} cm^{-2}, a main challenge for the development of graphene-based electronics is the reliable control of the charge carrier density. An attractive method is the charge transfer doping by adsorption of acceptor molecules on the epitaxial graphene surface. By using the molecular dopant F4-TCNQ the electron density in epitaxial graphene can be reduced via a charge transfer mechanism. [1,2] However, precise tuning of the carrier density over a wide range from n-type regime to p-type regime in air-stable conditions for applications as graphene-based QHR devices is challenging and widely unexplored.

Here we investigate molecular doping of epitaxial graphene with F4-TCNQ doping stacks. [3] The stacks that include 2 layers of F4-TCNQ dopant blend separated by 3 layers of PMMA, were deposited on Hall bar devices from epi-graphene fabricated by the polymer-assisted sublimation growth (PASG) method. [4] The doping concentration was systematically varied by adjusting the F4-TCNQ/PMMA ratio in the doped layers. The magneto-resistance measurements reveal that the carrier density can be tuned in a wide range from *n*- to *p*-type (7.0×10^{11} cm-2 for electrons to -2.0×10^{10} cm^{-2} for holes) across the charge neutrality point without external gating voltage. For low carrier densities an onset of the Hall plateau at magnetic fields as low as $B \sim 0.2$ T is observed. Electron mobilities up to 57500 cm^2/Vs indicate the high quality of the produced devices. The calculated density of charge impurities related to donor-like states at the SiC/graphene interface shows a reduction with increasing F4-TCNQ dopant concentration which is a result of the compensation doping by the adsorbed molecules. High precision Hall resistance measurements by means of a cryogenic current comparator (CCC) based bridge reproduces the nominal quantized resistance value (R_K / 2) with an uncertainty $(R_H - R_K / 2) / (R_K / 2) \leq (0.7 \pm 7.1)\times10^{-9}$ in the magnetic field range from 4 to 12 T, which coincides with R_{xx} values lower than (20.1 ± 23.0) μΩ. Our results show that graphene-based QHR standards can replace their GaAs counterparts by operating in as-convenient cryogenic condition and over an extended magnetic field range.

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