Institute Q

Workshop in Hybrid Quantum Electronics

Location: Micronova (Lehtisali) Tietotie 3, Otaniemi Espoo
Date: Friday 19th January, 2024

08:45 Arrival

09:00 M. Möttönen (Aalto) - *Single-Shot Readout of a Superconducting Qubit Using a Thermal Detector*

09:30 L. Andersson (Chalmers) - *Real-time detection of quasiparticle tunneling events using a transmon qubit directly coupled to a waveguide*

10:00 F. Lefloch (CEA/Grenoble) - *Tunable charge-4e supercurrent in Ge-based Josephson field effect transistor*

10:30 Coffee break

10:45 S. Ilic (Jyväskylä) - *Supercurrent diode effect in diffusive systems with Rashba spin-orbit coupling: bulk superconductors and Josephson junctions*

11:15 N. Paradiso (Regensburg) - *Nonreciprocal effects in 2D -Josephson junction arrays*

11:45 Coffee break

12:00 A. Generalov (VTT) - *Wafer-scale CVD graphene-based Josephson field-effect transistors with local top-gate tunability*

12:30 T. Heikkilä (Jyväskylä) - *Nonreciprocal Josephson linear response*

13:00 Closing Remarks

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This work is co-funded by EU's HORIZON-RIA Programme under Grant No. 101135240 (JOGATE).

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Mikko Möttönen, Aalto/VTT

Title: Single-Shot Readout of a Superconducting Qubit Using a Thermal Detector

Abstract: Measuring the state of qubits is one of the fundamental operations of a quantum computer. Currently, state-of-the-art high-fidelity single-shot readout of superconducting qubits relies on parametric amplifiers at the millikelvin stage. However, parametric amplifiers are challenging to scale beyond hundreds of qubits owing to practical size and power limitations. Nanobolometers have a multitude of properties that are advantageous for scalability and have recently shown sensitivity and speed promising for qubit readout, but such thermal detectors have not been demonstrated for this purpose. In this work, we utilize an ultrasensitive bolometer in place of a parametric amplifier to experimentally demonstrate single-shot qubit readout. With a readout duration of 13.9 μs, we achieve a single-shot fidelity of 0.618 which is mainly limited by the energy relaxation time of the qubit, T_1=28 μs. Without the T_1 errors, we find the fidelity to be 0.927. In the future, high-fidelity single-shot readout may be achieved by straightforward improvements to the chip design and experimental setup, and perhaps most interestingly by the change of the bolometer absorber material to reduce the readout time to the hundred-nanosecond level and beyond.

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Linus Andersson, Chalmers University

Title: Real-time detection of quasiparticle tunneling events using a transmon qubit directly coupled to a waveguide

Abstract: Generation and tunneling of non-equilibrium quasiparticles (QPs) [1] due to the absorption of high energy radiation is known to have adverse effects on the performance of superconducting quantum devices [2]. In this study, we investigate the statistics of QP tunneling events in a charge sensitive transmon qubit, strongly coupled to a waveguide. A second charge-insensitive qubit, strongly coupled to the same waveguide, is used to measure the temperature of the radiation field at the resonant frequency of the qubit [3]. Using these two sensors, we study the thermalization timescale of the radiation field and the equilibration of QP tunneling rates after a sudden burst in temperature caused by toggling of a cryogenic mechanical switch. This multi-sensor detection technique offers a unique opportunity to investigate the effects of cryogenic filtering and thermalization strategies on thermal population and QP tunneling rates, paving the way for optimized performance in superconducting quantum devices.

1. Bogoliubov quasiparticles in superconducting qubits, SciPost Phys. Lect. Notes 31 (2021)

2. Environmental radiation impact on lifetimes and quasiparticle tunneling rates of fixed-frequency transmon qubits, Appl. Phys. Lett. 120, 074002 (2022)

3. Primary Thermometry of Propagating Microwaves in the Quantum Regime, Phys. Rev. X 10, 041054 (2020)

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Francois Lefloch, CEA/Grenoble

Title: Tunable charge-4e supercurrent in Ge-based Josephson field effect transistor

Abstract: Parity-protected superconducting qubits, in which the quantum information is encoded in wavefunctions with disjoint support, have recently emerged as promising candidates to enhance the lifetime of quantum states. This innovative approach leverages cos(2φ) Josephson elements dominated by charge-4e supercurrent – the coherent transfer of pairs of Cooper pairs. In this work, we investigate highly transparent superconductor-semiconductor-superconductor Josephson field effect transistor (JoFET) fabricated from SiGe/Ge/SiGe heterostructures. First, employing a SQUID featuring a wide and a narrow JoFET, we explore the current phase relation (CPR). It exhibits gate-tunable higher order harmonics, revealing both charge-2e and charge-4e dissipationless transport, a finding confirmed by Shapiro steps measurements. Second, by harnessing the superconducting diode effect within a SQUID made of two similar JoFETs, we identify the regime of perfect critical current symmetry. In this configuration, Shapiro steps measurements at half flux quantum bias exhibit a pronounced reduction in the first harmonic, thereby realizing a cos(2φ) Josephson element. These results pave the way for the realization of Ge-based parity-protected qubits using CMOS compatible processes.

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Stefan Ilic, University of Jyväskylä

Title: Supercurrent diode effect in diffusive systems with Rashba spin-orbit coupling: bulk superconductors and Josephson junctions

Abstract: Supercurrent diode effect (SDE) is a phenomenon of non-reciprocal current flow when both time-reversal and inversion symmetries are broken in a superconducting system: supercurrent can flow in one direction, whereas only a normal dissipative current can flow in the other. One of the best studied systems hosting SDE are two-dimensional superconductors with Rashba spin-orbit coupling (SOC) with an applied in-plane Zeeman field. Most theoretical studies of this system to date focused on the clean case [1-3], neglecting the effect of impurities. The behavior of SDE is significantly modified once disorder is introduced, as shown in our work [4]. In this talk, I will present our latest results on SDE in strongly disordered (diffusive) systems with Rashba SOC, based on the quasiclassical formalism [5], both in the bulk and in Josephson junctions. In the bulk, the SDE monotonically increases as the magnetic field is increased and temperature is reduced, in contrast to the non-monotonic behavior in the clean case. In Josephson junctions, we show that the SDE dramatically increases and changes its sign close to the 0-pi transition of the junction. Our result may contribute to understanding the SDE measured in numerous recent experiments, as disorder is unavoidable in most experimentally available structures.

[1] He, Tanaka and Nagaosa, New J. Phys. 24 (2022)

[2] Yuan and Fu, PNAS 119 (2022)

[3] Daido, Ikeda and Yanase, Phys. Rev. Lett. 128 (2022)

[4] Ilić and Bergeret, Phys. Rev. Lett. 128 (2022)

[5] Virtanen, Bergeret and Tokatly, Phys. Rev. B 105 (2022)

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Nicola Paradiso, University of Regensburg

Title: Nonreciprocal effects in 2D -Josephson junction arrays

Abstract: We experimentally investigate nonreciprocal effects in 2D square arrays of Josephson junctions, where a Zeeman field induces an anomalous phase shift in the current-phase relation. We show that nonreciprocity is due to –induced ratchet-like deformation of the egg-crate potential which pins Josephson vortices. As a result, the supercurrent diode effect for the array does not necessarily require the diode effect in single junctions. Instead, a simple analysis reveals that second neighbor coupling between the islands is necessary to break the symmetry. The nonreciprocal effect is demonstrated by measuring both the critical current and the array inductance-versus-current asymmetry. For dilute vortices, the experimental results match what is expected from simple models. For finite frustration, measurements show a similar nonreciprocity for all major commensurate fractions. Intriguingly there is an exception: for f=1/3, the nonreciprocity changes sign. Our results open a new research direction in the field of Josephson junction arrays, namely, the possibility to control the real-space shape and symmetry of vortices and of their potential by an external Zeeman field.

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Andrey Generalov, VTT

Title: Wafer-scale CVD graphene-based Josephson field-effect transistors with local top-gate tunability

Abstract: Critical current (Ic) tunability with an electrostatic gate in superconductor-graphene-superconductor (SGS) junctions is essential for superconducting electronics based on Josephson field-effect transistor (JoFET). Previously, CVD graphene JoFETs were demonstrated using the global Si-wafer back-gate. Here, we present tunable SGS junctions encapsulated with atomic layer deposition (ALD) grown Al_2O_3 dielectric and lithography-defined local top gates.

Starting with 6” CVD graphene on Si/SiO_2 wafers provided by Graphenea, our graphene devices are encapsulated with Al_2O_3, the top contacts are then evaporated using Ti/Al, the gate dielectric is grown using ALD, and finally the top gate is evaporated with Ti/Al. Using process optimization, we achieve contact resistances down to 300 Ω·µm.

The resulting device arrays fabricated on 6” wafers consist of SGS junctions with length from 150 nm to 350 nm and width from 10 µm to 50 µm. Cooling down JoFETs with different dimensions in a dilution refrigerator, we observed repeatable superconducting proximity effect in all tested devices. We show the Ic tunability with top gate and analyze the temperature dependence of Ic. Our results constitute an important milestone toward scalable superconducting electronics based on graphene JoFETs.

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Tero T. Heikkilä & Pauli Virtanen, University of Jyväskylä

Title: Nonreciprocal Josephson linear response

Abstract: We consider the finite-frequency response of multiterminal Josephson junctions and show how non-reciprocity in them can show up at linear response, in contrast to the static Josephson diodes featuring non-linear non-reciprocity. At finite frequencies, the response contains dynamic contributions to the Josephson admittance, featuring the effects of Andreev bound state transitions along with Berry phase effects, and reflecting the breaking of the same symmetries as in Josephson diodes. We show that outside exact Andreev resonances, the junctions feature non-reciprocal reactive response. As a result, the microwave transmission through those systems is non-dissipative, and the electromagnetic scattering can approach complete non-reciprocity. Besides providing information about the nature of the weak link energy levels, the non-reciprocity can be utilized to create non-dissipative and small-scale on-chip circulators whose operation requires only rather small magnetic fields.

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