TT 55: Superconductivity: Tunneling and Josephson Junctions

Time: Thursday 9:30–13:00 Location: H23

TT 55.1 Thu 9:30 H23

Design of an on-Chip Sideband Separating (2SB) SIS Balanced Mixer for 400 to 500 GHz on a Silicon Membrane — •Sina Widdig, Karl Jacobs, Michael Schultz, Matthias Justen, Nadine Wehres, Netty Honingh, and Jürgen Stutzki — I. Physikalisches Institut, Universität zu Köln, Cologne, Germany

Superconductor-Insulator-Superconductor (SIS) tunnel junctions are currently used as heterodyne mixers with quantum limited sensitivity for receivers in astronomy. Well-engineered technology offers the opportunity to replace the single-ended double-sideband (DSB) mixers by balanced or sideband separating (2SB) mixers. 2SB mixers are used to prevent the increase of system noise due atmospheric noise in the image sideband. They are usually made in waveguide technology, using an assembly of separate pre-tested units. The large size of these mixers makes it difficult to build multi-pixel-array receivers where the footprint of each pixel must be reduced (10mm x 10mm e.g. for CHAI receiver).

We are developing the RF part of an on-chip 2SB balanced SIS mixer between 400 and 500 GHz, in the same technology as the existing balanced mixer. The total size of the complete RF part is 2.3mm x 1.7mm, including 3 hybrids, 4 SIS junctions, a LO-power divider and a RF load. The mixer reduces the LO AM noise due to the balanced mixers. For testing the RF performance of the chip we designed a prototype block with 4 separate SIS mixer IF-outputs. In addition THz spectrometer measurements are planned show the sideband suppression with detection of rotational lines of CH_3CN.

TT 55.2 Thu 9:45 H23

Fabrication and characterization of cross-type Nb/Al-AlO_x/Nb Josephson junctions — •Fabienne Bauer, Christian Enss, and Sebastian Kempf — Kirchhoff-Institute for Physics, Heidelberg University, Im Neuenheimer Feld 227, 69120 Heidelberg, Germany.

Josephson tunnel junctions are the basic element of numerous superconducting electronic devices such as SQUIDs or qubits. The performance and sensitivity of many of those devices depend on and particularly improve with decreasing junction capacitance. The latter depends on the material and the thickness of the tunnel barrier, the junction area as well as the overlap of different wiring layers adding parasitic capacitance. Therefore, the junction capacitance can be reduced by avoiding parasitic overlaps as well as by optimizing the oxidation parameters and the junction area.

Within this context, we present an anodization-free fabrication process for cross-type Nb/Al-AlO_x/Nb Josephson junctions. They are built by the overlap of two perpendicular superconducting stripes with the tunnel barrier in between eliminating any parasitic capacitance and making a reduced junction area easily possible. As a further advantage, restrictions in alignment accuracy do not limit the junction size. We will show that our cross-type tunnel junctions have a smaller capacitance compared to our window-type junctions and that they exhibit a reproducible high quality. In addition, we discuss the performance of dc-SQUIDs based on cross-type junctions to demonstrate the profit resulting from this new fabrication process.

TT 55.3 Thu 10:00 H23

Hysteresis in current-voltage characteristics of sub-micron Nb-HfTi-Nb SNS-type Josephson junctions — •Julian Linek[1], Benedikt Müller[1], Viacheslav Morosh[2], Thomas Weinmann[2], Oliver Kieler[2], Reinhold Kleiner[1], and Dieter Koelle[1] — [1]Physikalisches Institut and Center for Quantum Science (CQ) in LISA$^+$, Universität Tübingen, Germany — [2]Fachbereich Quantenelektronik, PTB Braunschweig, Germany

SNS-type Josephson junctions (JJs) based on superconducting (S) Nb thin films with a normal metal (N) HfTi barrier offer high critical current densities up to 1 MA/cm^2 with usually non-hysteretic current-voltage characteristics (IVCs) at temperature $T = 4.2$ K. By patterning a Nb-HfTi-Nb trilayer with e-beam lithography, highly sensitive dc SQUIDs with sub-μm lateral dimensions can be fabricated. Such nanoSQUIDs are suited for the investigation of magnetism at the nano scale. Unfavorably, hysteresis in the IVCs appears upon increasing the critical current; this prevents SQUID operation at the optimum working point and thus leads to a degradation in sensitivity. Main features of IVCs measured at variable T resemble those of constriction type JJs with thermaly induced hysteresis. We performed numerical simulations of IVCs and compared those to measurements on our SNS-JJs from 0.3 to 9 K. RSJ-based simulations include the balance of Joule heating and 1-dim. thermal heat flow to describe the increase of T in the barrier layer. Despite the simplicity of our model, major properties of the experimentally determined IVCs, such as the saturation of the return current $I_r(T)$ at low T, can be reproduced by our simulations.

TT 55.4 Thu 10:15 H23

$YBa_2Cu_3O_7$ Josephson junctions and SQUIDs defined by focused He ion beam irradiation — •Max Karrer, Benedikt Müller, Fabienne Limberger, Jianxin Lin, Christian Vöhringer, Malena Höhn, Edward Goldobin, Reinhold Kleiner, and Dieter Koelle — Physikalisches Institut and Center for Quantum Science (CQ) in LISA$^+$, Universität Tübingen, Germany

The invention of the He ion microscope (HIM) with sub-nm spatial resolution offers exciting perspectives, not only for high-resolution imaging of surfaces, but also for their nanoscale modification. For epitaxially grown thin films of the high-T_c cuprate superconductor $YBa_2Cu_3O_7$ (YBCO), He focused ion beam (He-FIB) irradiation can be used to directly write Josephson junction (JJ) barriers into the material by driving locally the material into the insulating state [1]. In addition to the fabrication of such beam-induced barrier junctions (bJJs), He-FIB irradiation can also be used to pattern YBCO films on the nanoscale, without removing material [2]. This may provide an alternative way to define insulating areas for nanoSQUID fabrication. Here, we will present our recent progress in the fabrication of He-FIB-induced bJJs 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 bJJs by variation of the He-FIB dose.

[1] S. Cybart *et al.*, Nature Nanotechnol. **10**, 598–602 (2015)
[2] E. Y. Cho *et al.*, Appl. Phys. Lett. **113**, 022604 (2018)

TT 55.5 Thu 10:30 H23

Scanning tunneling spectroscopy of superconducting Granular Aluminium — •Tim Storbeck, Fang Yang, Ioan Pop, and Wulf Wulfhekel — Karlsruhe Institut of Technology

Granular Al films are of high interest for quantum superconducting circuit design due to their large kinetic inductance and low intrinsic dissipation. Interestingly, it has been known for several decades that T_c can be increased by a factor more than 2 in granular Al compared to bulk Al. The enhancement of T_c has been attributed to microscopic mechanisms involving electron quantization and Kubo spins, however, the exact mechanisms are still debated. We report the measurement of scanning tunneling spectroscopy of granular Al films on Nb-doped $SrTiO_3$ in ultra-high vacuum at 30mK. We observed both superconducting and insulating grains in the same samples. The local single electron tunneling between the tip and the Al grains show rich features at energy scales from 1 eV down to 0.1 meV. The size of the gap in superconducting grains, in the range of 0.28-0.32 meV, agrees with previously reported values for similar films. We also observed signatures of in-gap states, hinting at unpaired electrons on the grains.

TT 55.6 Thu 10:45 H23

Electrical and mechanical behavior of Al/AlO_x nanobridges — •Patrick Haiber, Susanne Sprenger, Laura Sobral-Rey, and Elke Scheer — Universität Konstanz, Germany

Mesoscopic transport through single atom contacts is an intensively studied topic. Especially aluminum in a mechanically controllable break junction design (MCBJ) has received great attention for its superconducting properties [1,2]. Histograms show a pronounced peak at 0.8 G_0 signalling the single atom contact. These contacts have proven to be of high mechanical stability over several hours in cryogenic vacuum, enabling comprehensive investigation of the same atomic contact configuration. On the other hand Al/AlO_x/Al junctions are very popular realizations for studying mesoscopic transport in the superconducting state. Aluminium MCBJ in series with an Al/AlO_x junction have been used to build a tunable all superconducting SET [3]. In those experiments it has been shown that not only contacts with conductance close to 0.8 G_0 but also contacts of higher resistance can be

mechanically stabilized over several hours.

Here we study the role of the AlO_x layer on the contact formation. The oxide layer is formed on top of the Al MCBJ via plasma or thermal oxidation. We systematically compare oxidized Al MCBJ with non-oxidized MCBJ regarding their preferred conductance values and stretching behavior.

[1] Agraït et al., 2003 , PR 377 81-279
[2] Scheer et al., 1997, PRL 78 3535
[3] Lorenz et al., 2018, JLTP 191 301-315

TT 55.7 Thu 11:00 H23

Quantum properties of a strongly driven Josephson junction — Jennifer Gosner, •Björn Kubala, and Joachim Ankerhold — Institute for Complex Quantum Systems and IQST, University of Ulm, 89069 Ulm, Germany

A Josephson junction embedded in a dissipative circuit can be externally driven to induce nonlinear dynamics of its phase. Classically, under sufficiently strong driving and weak damping, dynamic multistability emerges associated with dynamical bifurcations so that the often used modeling as a Duffing oscillator, which can exhibit bi-stability at the most, is insufficient. Here, corresponding quantum properties in this regime are analyzed by mapping the problem onto a highly-nonlinear quasi-energy operator in a rotating frame. This allows us to identify in detail parameter regions where simplifications such as the Duffing one are valid, to explore classical-quantum correspondences and to study how quantum fluctuations impact the effective junction parameters as well as the dynamics around higher amplitude classical fixed points.

15 min. break.

TT 55.8 Thu 11:30 H23

Particle-conserving theory for transport through interacting Josephson junctions — •Jordi Picó-Cortés[1,2], Andrea Donarini[1], and Milena Grifoni[1] — [1]Institute for Theoretical Physics, University of Regensburg, 93040 Regensburg, Germany — [2]Instituto de Ciencia de Materiales de Madrid (CSIC), E-28049, Madrid, Spain

When two superconductors are coupled together through a weak link, tunneling of Cooper pairs gives rise to a supercurrent through the junction, as predicted by Josephson [1]. Usually, transport through mesoscopic Josephson junctions (JJ) is described using the mean field theory of superconductivity. This approach has the obvious limitation of treating an inherently many-body effect through an effective single-particle theory which violates particle's conservation. We investigate charge transport and the Josephson effect through an interacting quantum dot coupled to two superconductors within a particle-conserving theory of superconductivity. Within a reduced density matrix approach to transport [2], we can account for the many-body aspects of superconductivity and interactions in the dot on the same footing.

[1] B. D. Josephson, Phys. Lett. 1 , 251253 (1962)
[2] S. Koller, M. Leijnse, M. R. Wegewijs, and M. Grifoni Phys. Rev. B 82, 235307 (2010)

TT 55.9 Thu 11:45 H23

Local density of states in clean 2D SNS heterostructures — •Danilo Nikolic[1], Juan Carlos Cuevas[2], and Wolfgang Belzig[1] — [1]Fachbereich Physik, Universität Konstanz, D-78457 Konstanz, Germany — [2]Departamento de Física Teórica de la Materia Condensada, Universidad Autónoma de Madrid, Spain

The advent of 2D materials like graphene have reignited the interest in the study of the proximity effect in clean hybrid superconducting structures. Motivated by the recent experimental results [1] we present a systematic theoretical analysis of the local density of states in a clean 2D normal metal sandwiched between two standard s-wave superconductors. By solving the Eilenberger equation in the framework of quasiclassical Green's function theory we are able to describe the Andreev bound state spectrum in presence of, among others, a finite transparency of the junction or a weak magnetic field with different geometries of the junction. We analytically obtain a relation between the supercurrent and the global density of states.

[1] L. Bretheau, J.I.J. Wang, R. Pisoni, K. Watanabe, T. Taniguchi, P. Jarillo-Herrero, Nature Physics, doi:10.1038/nphys4110 (2017)

TT 55.10 Thu 12:00 H23

Phase-controlled triplet correlations and thermoelectric effects in a hybrid superconductor-ferromagnet device — •Ali Rezaei[1], Robert Hussein[1], Akashdeep Kamra[2], and Wolfgang Belzig[1] — [1]Department of Physics, University of Konstanz, Germany — [2]Center for Quantum Spintronics, Department of Physics, NTNU, Norway

We study charge and heat transport in superconductor-ferromagnet (S/FM) hybrid structures. Firstly, we analyse a bilayer tunnel junction consisting of a spin-split superconductor connected to a spin-polarized ferromagnet and find that spin-flip scattering strongly enhances the thermoelectric response of the system at low temperature and spin-splitting [1]. A large spin-splitting is also obtainable by employing an antiferromagnetic insulator (AFMI) adjacent to a superconductor in an S|AFMI device [2]. The advantage of using AFMs is the minimization of stray magnetic fields which normally accompany ferromagnets. Finally, we investigate the effects of spin-polarized quasiparticles and spin-mixing on the thermoelectric transport properties of a four-terminal hybrid device incorporating two superconductors which are connected to two ferromagnetic leads via a common central normal node. This geometry allows us to induce phase- and voltage-controlled triplet correlations, and to change the direction of the spin-currents.

[1] A. Rezaei, A. Kamra, P. Machon, and W. Belzig, New J. Phys. **20**, 073034 (2018)
[2] Akashdeep Kamra, Ali Rezaei, Wolfgang Belzig, arXiv:1806.10356 (2018); accepted in PRL

TT 55.11 Thu 12:15 H23

Tunneling Anomalous Hall (TAH) Effect in Ferromagnet/Superconductor Junctions — •Andreas Costa[1], Alex Matos-Abiague[2], and Jaroslav Fabian[1] — [1]University of Regensburg, Germany — [2]Wayne State University Detroit, USA

The competition of two antagonistic interactions, spin-singlet superconducting pairing and ferromagnetic exchange, in one heterojunction leads to extraordinary phenomena. Owing to the additionally broken inversion symmetry in such systems, not only the interplay of superconductivity and ferromagnetism, but also the induced strong spin-orbit fields (SOFs) offer interesting subjects for experimental and theoretical investigations; several studies unraveled an intriguing impact of interfacial SOFs on transport already in normal-conducting systems, e.g., TAMR [1] and TAH [2] effects. Our theoretical work focuses on ferromagnet/superconductor junctions, demonstrating the existence of a superconducting TAH effect. While the effect's fundamental characteristics are comparable to the normal-conducting analog [2], our numerical simulations predict a much larger tunability of the TAH conductance in the superconducting scenario. Together with the prediction of a simultaneously generated transverse supercurrent response in the superconductor, these findings might offer an interesting future perspective for experimentalists.

This work was supported by ENB IDK Topological Insulators and by DFG SFB No. 1277 (project B07).

[1] Phys. Rev. Lett. **99**, 056601 (2007)
[2] Phys. Rev. Lett. **115**, 056602 (2015)

TT 55.12 Thu 12:30 H23

Microwave spectroscopy reveals the quantum geometric tensor of topological Josephson matter — •Raffael L. Klees[1], Gianluca Rastelli[1], Juan Carlos Cuevas[2], and Wolfgang Belzig[1] — [1]Fachbereich Physik, Universität Konstanz, D-78457 Konstanz, Germany — [2]Departamento de Física Teórica de la Materia Condensada and Condensed Matter Physics Center (IFIMAC), Universidad Autónoma de Madrid, E-28049 Madrid, Spain

Concepts like Chern numbers and their relation to physical phenomena have become very familiar, but actually, key quantities like the quantum geometric tensor [1], which provides a much deeper information about quantum states, remain experimentally difficult to access. Recently it has been shown that multiterminal superconducting junctions constitute an ideal playground to mimic topological systems in a controlled manner [2]. We study the spectrum of Andreev bound states in topological Josephson matter and demonstrate that the quantum geometric tensor of the ground state manifold can be extracted with the help of microwave spectroscopy [3]. We develop the concept of artificially polarized microwaves, which can be used to obtain both the quantum metric tensor and the Berry curvature. The quantized integrated absorption provides a direct evidence of topological quantum properties of the Andreev states.

[1] M. Kolodrubetz *et al.*, Phys. Rep. **697**, 1 (2017)
[2] R.-P. Riwar *et al.*, Nat. Commun. **7**, 11167 (2016);
J. S. Meyer and M. Houzet, Phys. Rev. Lett. **119**, 136807 (2017);

H.-Y. Xie *et al.*, Phys. Rev. B **96**, 161406 (2017);
Phys. Rev. B **97**, 035443 (2018). [3] R. L. Klees *et al.*, arXiv:1810.11277

TT 55.13 Thu 12:45 H23

Manipulation of Cooper pair entanglement in hybrid topological Josephson junctions — Gianmichele Blasi, Fabio Taddei, Vittorio Giovannetti, and •Alessandro Braggio — NEST, Scuola Normale Superiore and Istituto Nanoscienze-CNR, I-56126 Pisa, Italy

We investigated the supercurrent in a hybrid topological Josephson junction consisting of two planes of topological insulator (TI), which allows both local (LAR) and crossed (CAR) Andreev processes at the interfaces with two conventional s-wave superconductors. We describe the effects of local Rashba-like and Zeeman-like fields applied to the edge states. In particular, we demonstrate that the Rashba-like field, as induced by local gating, allows the manipulation of the entaglement symmetry of non-local Cooper pairs associated to the CAR process. We establish a connection between the Josephson current-phase relationship of the system and the action of the two local fields, finding that they selectively modify the LAR or the CAR contributions. Remarkably, we find that the critical current of the junction takes a very simple form which reflects the change in the symmetry occurred to the entangled state and allows to determine the microscopic parameters of the junction.

[1] G. Blasi, F. Taddei, V. Giovannetti, A. Braggio, arxiv:1808.09709