TT 28: Superconducting Electronics: SQUIDs and other Josephson Circuits and Components

Time: Tuesday 9:30–12:45 Location: CHE/0089

TT 28.1 Tue 9:30 CHE/0089

Gate-controlled switching in non-centrosymmetric superconducting devices - Large output voltage — •Jennifer Koch[1], Leon Ruf[1], Angelo Di Bernardo[1,2], and Elke Scheer[1] — [1]Universität Konstanz, Konstanz, Germany — [2]Università degli Studi di Salerno, Fisciano (SA), Italy

Gate-controlled supercurrent (GCS) devices have become of great interest as a superconducting equivalent to complementary metal-oxide-semiconductor (CMOS) logic. The underlying concept is based on the observation that supercurrent can be controlled electrically through the application of a gate voltage [1,2].
We investigate GCS devices made of the non-centrosymmetric superconductor $Nb_{0.18}Re_{0.82}$. By combining geometric adjustments with the material's high normal-state resistivity, we achieve a significant increase of the output voltage. The resulting voltage is high enough to drive CMOS transistors, demonstrating the potential of GCS devices to interface directly with conventional semiconductor electronics. This finding represents an important step towards hybrid computing architectures.

[1] De Simoni et al., Nature Nanotech 13, 802 (2018)
[2] Paolucci et al., Nano Letters 18, 4195 (2018)

TT 28.2 Tue 9:45 CHE/0089

Chemical-mechanical polishing process for the fabrication of cross-type Nb/Al-AlO$_x$/Nb Josephson tunnel junctions — •Alexander Stoll, Lukas Münch, Daniel Hengstler, Andreas Reifenberger, Andreas Fleischmann, and Christian Enss — Kirchhoff-Institute for Physics, Heidelberg University, Germany

The core elements at the frontier of superconducting electronic devices, such as qubits or superconducting quantum interference devices (SQUIDs), are the Josephson tunnel junctions (JJs). To enable scaling in production of these devices, good parameter control is required, including a uniform quality and reproducibility. We use a cross-type geometry for our JJs so that our junction area is not limited by alignment inaccuracies and, at the same time, parasitic capacitances and thus parasitic LC resonances can be avoided. A sputtered SiO_2 layer used for the insulation of the structured Nb/Al-AlO$_x$/Nb trilayer including its sidewalls usually requires a time-consuming lift-off and leaves behind undesired wings that can compromise the quality of subsequent layers. To mitigate these challenges, we introduced a chemical-mechanical polishing (CMP) step. We present our optimized fabrication process which achieves a well-embedded, smooth, and uniform post-CMP surface and substantially improves the reliability and yield of our JJs on 3 inch wafer-scale. A variety of tests to characterize the JJs based on their IV-characteristics and their Fraunhofer Patterns as well as the electrical properties of the superconducting Nb are discussed.

TT 28.3 Tue 10:00 CHE/0089

Towards the next generation of dc SQUID sensors — •Mauro Esattore[1], Oliver Kieler[1], Michael Paulsen[2], Rainer Körber[2], Patryk Krzysteczko[2], Mark Bieler[1], and Jörn Beyer[2] — [1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany — [2]Physikalisch-Technische Bundesanstalt, Abbestraße 2-10, 10587 Berlin, Germany

This is an update on our path towards next-generation SQUID devices, featuring "fine-pitch" input coils and window-type Nb/Al-AlOx/Nb Josephson junctions (JJs), both realized with sub-micrometer dimensions. The circuit elements are fabricated using electron beam lithography and are integrated into existing sensor designs which are currently fabricated using UV lithography, which limits the minimal dimensions. For current sensor SQUIDs, it is crucial to maximize the inductive coupling k between the signal input coil and the SQUID loop to minimize the coupled energy sensitivity $\varepsilon_c = \varepsilon/k^2$ - with ε being the intrinsic energy sensitivity. The SQUID energy sensitivity $\varepsilon \approx \sqrt(C_{JJ})$ can also be lowered by reducing the JJ capacitance C_{JJ}. Our aim is to achieve high sensor compactness as well as reduced coupling losses, without further modifying the sensors design. To that end, we fabricated fine-pitch coils with lateral width down to 0.3 μm - almost an order of magnitude smaller than coils fabricated with UV lithography - with inductance values ranging from 400 nH to 14 μH, depending on the number of coil windings. Details concerning design aspects of both circuit elements, their fabrication and characterization results are provided.

TT 28.4 Tue 10:15 CHE/0089

Tapping-mode SQUID-on-tip Microscopy with Proximity Josephson Junctions — •Matthijs Rog[1], Tycho J. Blom[1], Daan B. Boltje[1,2], Milan P. Allan[1,2,3], and Kaveh Lahabi[1,2] — [1]Institute of Physics, Leiden University, Leiden, The Netherlands — [2]QuantaMap B.V., Leiden, The Netherlands — [3]Faculty of Physics, Ludwig-Maximilians-University Munich, Munich, Germany

Understanding nanoscale dynamics in strongly correlated systems and quantum materials requires investigating the interplay between dissipation, magnetism and electronic transport. The local mapping of transport properties, such as current flow, and their relation to geometry and magnetism still remains a major challenge. Here, we introduce tapping-mode SQUID-on-tip, which combines atomic force microscopy (AFM) with nanoSQUID sensing. This microscope is able to simultaneously image magnetic flux, electrical currents, local heating and sample topography. Our probes minimize nanoSQUID-sample distance, provide in-plane magnetic sensitivity, and operate even on highly corrugated nanostructures and devices. Our fully electronic readout removes the need for optical elements and external radiation. By using proximity-junction nanoSQUIDs with large voltage output, we resolve nanoscale currents down to 100 nA using a simple four-probe electronic readout. In addition to demonstrating the technique, we will show the first applications to strongly correlated electron systems, where our microscope offers immediate new insights into the underlying physics.

[1] M. Rog et al., arXiv:2508.21575

TT 28.5 Tue 10:30 CHE/0089

Nanoscale SQUID on a wireframe tip cantilever by corner lithography — •Thijs Roskamp[1], Tim Horstink[2], Melissa Goodwin[1], Erwin Berenschot[1], Roeland Huijink[2], Edin Sarajlic[2], Niels Tas[1], and Hans Hilgenkamp[1] — [1]MESA+ Institute, University of Twente, Enschede, The Netherlands — [2]Bruker Nederland B.V., Bruker Corporation, Leiderdorp, The Netherlands

Superconducting quantum interference devices (SQUIDs) are the most sensitive magnetic flux sensors and are used in scanning SQUID microscopy (SSM) to spatially resolve and map magnetism. Conventional SSM probes make use of planar silicon substrates which limit their spatial resolution to several micrometers due to an increased sample-pickup area spacing.

Employing ideas from other scanning probe techniques like atomic force microscopy, moving the SQUID to the apex of tip on a scanning probe can significantly increase the spatial resolution.

We have used the principles of corner lithography and molding in silicon wafers to create freestanding superconducting wireframe tips on cantilevers on the wafer scale. With a focused ion beam we pattern superconducting weak links at the apex of the fabricated wireframe tips to create SQUIDs with sizes from sub-100 nm to several micrometers. By integrating the wireframe probe on a silicon nitride cantilever with pre-defined contact pads, leads, and resistive strain gauges, we create a SQUID on cantilever probe which will enable simultaneous magnetic and topographic imaging.

TT 28.6 Tue 10:45 CHE/0089

Low noise amplification using Nb trilayer Dimer Josephson Junction Array Amplifiers — •Bhoomika R Bhat, Asen L Georgiev, Fabian Kaap, Victor Gaydamachenko, Christoph Kissling, Judith Felgner, Mark Bieler, and Lukas Grünhaupt — Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

Minimizing added noise in amplification is crucial for quantum-based devices requiring microwave readout signals in the femtowatt range. For example, in superconducting qubits, it significantly improves readout fidelity. Extensive efforts over the last decade have been made in the development of parametric amplifiers to address this challenge. We develop a Dimer Josephson Junction Array Amplifier (DJJAA) [1], in which parametric amplification in the degenerate four-wave-mixing regime is facilitated by pairs of resonant modes, referred to as dimers. We design it to feature multiple flux-tunable dimers within the 2 to

8 GHz range, each of which could be utilized for parametric amplification. Our DJJAAs have 900 to 3000 dc-SQUIDs, and we fabricate them using Nb/Al-AlOx/Nb trilayer technology. We present the fabrication flow of our devices and provide an overview of the corresponding experimental results. Our devices show gain on the order of 20 dB with bandwidths in the range of 5 to 10 MHz and the typical input saturation powers are on the order of -110 dBm.

[1] P. Winkel et al., Phys. Rev. Applied 13, 024015 (2020).

15 min. break

TT 28.7 Tue 11:15 CHE/0089

Controlling three- and four-wave mixing processes in JTWPAs — •Daniil Bazulin[1,2], Johannes Schirk[1,2], Niklas Bruckmoser[1,2], Leon Koch[3], Yongjie Yuan[4], Michael Haider[4,5], Stefan Filipp[1,2,6], and Kirill G. Fedorov[1,2,6] — [1]Walther-Meißner-Institut, Bayerische Akademie der Wissenschaften, 85748 Garching, Germany — [2]Technical University of Munich, TUM School of Natural Sciences, Physics Department, 85748 Garching, Germany — [3]Peak Quantum GmbH, 85748 Garching, Germany — [4]TUM School of Computation Information and Technology, Technical University of Munich, 85748 Garching, Germany — [5]Universität der Bundeswehr München, 85579 Neubiberg, Germany — [6]Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany

Josephson travelling-wave parametric amplifiers (JTWPAs) are essential for scalable quantum computing with superconducting circuits. Their typical bandwidths of several gigahertz, in combination with quantum-limited noise performance, enable high-fidelity multiplexed readout of qubits. In JTWPAs, amplification occurs due to the interaction between the pump and signal modes in a nonlinear medium provided by superconducting nonlinear asymmetric inductive elements (SNAILs). Here, we experimentally investigate a robust JTWPA design based on SNAILs that is capable of operating in both three- and four-wave-mixing regimes. Our results show that we can fully suppress the three-wave mixing process while observing over 10 dB gain from the four-wave pumping over the bandwidth of 4 GHz.

TT 28.8 Tue 11:30 CHE/0089

Demonstration of natively phase-matched parametric amplification in a left-handed transmission line — •Christoph Kissling[1], Victor Gaydamachenko[1], Fabian Kaap[1], Melanie Ziegler[2], Hannes Toepfer[2], and Lukas Grünhaupt[1] — [1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig — [2]Technische Universität Ilmenau, Ehrenbergstraße 29, 98693 Ilmenau

Wideband amplification of weak microwave signals is a key ingredient for cutting-edge experiments ranging from quantum information processing to the search for dark matter. A class of devices that achieves this is the traveling-wave parametric amplifier (TWPA). So far, all TWPA implementations are based on right-handed transmission lines, which exhibit a positive refractive index. Recently, an alternative approach has been proposed that utilizes left-handed transmission lines, which have a negative refractive index [1]. This property allows for self-phase-matched parametric amplification in the four-wave-mixing regime, eliminating the need for any engineering of nonlinearity or dispersion for phase matching. Here, we present our implementation of this concept, which employs a left-handed transmission line with nonlinear inductors made from a granular aluminum thin film. First results show a signal power gain exceeding 10 dB, dynamically tunable across multiple GHz. With only one lithography step, and an order-of-magnitude reduction in circuit length, the concept is promising to significantly reduce the complexity of designing and fabricating a TWPA.

[1] C. Kow et al., Phys. Rev. Applied 24, 024026 (2025)

TT 28.9 Tue 11:45 CHE/0089

Towards 1 V Josephson Arbitrary Waveform Synthesizer — •Omar M. Aladdin[1], Oliver Kieler[1], Abdulrahman Widaa[1], Hannes Preissler[1], Erasmus Wolf[2], Marco Schubert[2], Judith Felgner[1], Rolf-Werner Gerdau[1], Johannes Kohlmann[1], and Mark Bieler[1] — [1]Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany — [2]Supracon AG, An der Lehmgrube 11, 07751 Jena, Germany

The Josephson Arbitrary Waveform Synthesizer (JAWS) provides quantum-accurate AC voltage waveforms with high spectral purity, low noise, and inherent long-term stability. Based on pulse-driven Josephson junction (JJ) arrays, JAWS is established as the primary AC voltage standard. Recent JAWS developments at PTB include increasing the output voltage per chip, targeting 1 V RMS to advance its use in high-accuracy metrological applications [1]. Current efforts focus on enhancing the JAWS fabrication process to enable larger array sizes using 5-stacked JJ arrays. The stacked junction technology is combined with improved on-chip Wilkinson power dividers, allowing the incorporation of more than two JJ arrays on one chip [2]. The power dividers have been successfully demonstrated with 3-stacked JJ arrays achieving 600 mV RMS per JAWS chip with a total of 36,000 junctions. In this contribution, we present the recent results of 5-stacked JJ arrays and Wilkinson power dividers with up to 60,000 JJs per JAWS chip.

[1] DOI: 10.1016/B978-0-323-90800-9.00001-9
[2] DOI: 10.1109/TASC.2021.3055161

TT 28.10 Tue 12:00 CHE/0089

Study on the feedthrough error in quantum-based superconducting RF waveform generators — •Michael Haas, Abdulrahman Widaa, Oliver Kieler, Marco Kraus, Ralf Behr, Johannes Kohlmann, and Mark Bieler — Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany

Quantum-based signal generators are of great interest for a variety of applications such as electrical metrology or quantum computing. The Josephson Arbitrary Waveform Synthesizer (JAWS) consisting of an array of Josephson junctions is one of such devices. It allows the generation of arbitrary, low-noise waveforms with high spectral purity by utilizing the Josephson effect. This approach is well established for signal frequencies in the kHz to low MHz range. However, modern applications typically demand increasing signal frequencies, reaching the microwave range. To satisfy the need for higher JAWS output frequencies, modified circuit designs and bias schemes are necessary. This is mainly because of the so-called feedthrough error, which denotes an input signal being fed through to the output. We will present recent developments of GHz-JAWS at PTB, comprising detailed investigations on the feedthrough error and methods for its reduction.

TT 28.11 Tue 12:15 CHE/0089

Nonequilibrium plasmon fluid in a Josephson junction chain — Anton V. Bubis[1], •Lucia Vigliotti[1], Maksym Serbyn[1], and Andrew P. Higginbotham[2] — [1]Institute of Science and Technology Austria, Am Campus 1, Klosterneuburg, 3400, Austria — [2]James Franck Institute and Department of Physics, University of Chicago, 929 E 57th St, Chicago, Illinois 60637, USA

With the recent push towards the development of quantum technologies, multimode quantum systems, such as superconducting resonators, have drawn considerable attention. These systems can be generally described as weakly nonlinear bosonic modes coupled to a thermal bath and subject to coherent driving. As the number of modes grows and extrinsic decoherence is reduced, understanding the mode-to-mode interaction becomes increasingly relevant, especially far from equilibrium. We consider the interacting plasmonic modes emerging in a long chain of Josephson junctions (JJs), probed via multitone microwave spectroscopy. We investigate the nonequilibrium kinetics of the resulting one-dimensional quantum fluid both theoretically and experimentally, focusing on four-wave-mixing processes. Under two coherent drives, we observe cascaded coupling between plasmonic modes, reproduced using input-output theory applied to nonlinear mode multiplets. Under incoherent broadband drive, we explore the kinetics of weakly populated modes and numerically implement a kinetic equation that predicts the non-equilibrium steady state and captures the excess linewidth of non-driven modes. Our work establishes the key role of four-wave-mixing nonlinearities in the non-equilibrium response of JJ chains.

TT 28.12 Tue 12:30 CHE/0089

Superconducting non-volatile memory device based on charge trapping in Al_2O_3. — •Leon Ruf[1], Jennifer Koch[1], Angelo Di Bernardo[1,2], and Elke Scheer[1] — [1]Department of Physics, University of Konstanz, 78464 Konstanz, Germany — [2]Department of Physics, University of Salerno, 84084 Salerno, Italy

Gate-controlled supercurrent (GCS) is a debated research topic. Experiments on three-terminal devices have shown that applying a gate voltage can modulate the supercurrent [1]. The authors interpret their findings as a direct electric-field effect, suggesting potential for CMOS-compatible superconducting transistors.

In contrast, other studies suggest that the observed modulation stems from a small leakage current flowing within the substrate [2,3], which can be as small as a few fA causing nonequilibrium phonons and/or electrons suppressing the supercurrent. A leakage current flowing through the substrate is typically undesirable for applications.

Here, instead, we show that the charge-trapping properties of the Al_2O_3 substrate can be harnessed to realize a non-volatile superconducting memory device based on the GCS effect [4]. We outline the device concept and operating principle and provide an outlook on future avenues for device optimization.

[1] De Simoni et al., Nat. Nanotechnol. 13, 802 (2018).
[2] Ritter et al., Nat. Electron. 5, 71 (2022).
[3] Basset et al., Phys. Rev. Research 3, 043169 (2021).
[4] Ruf et al., arXiv:2503.17241 (2025).