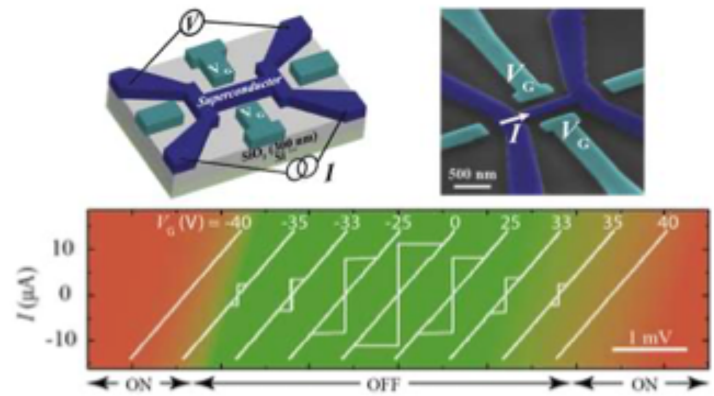
SUPER GATE 2024

Gate-Controlled Superconductivity

Status, Current Understanding and Perspectives about Gate-Controlled Superconductivity

October 6th - October 9th 2024
Paestum (SA), Italy



	Sunday 6 October	
14:00-17:00	**Excursion to Paestum Archeological Area**	
17:30-19:00	**Registration**	
19:30	**Welcome drink**	

	Monday 7 October	
8:45-9:00	**Opening** E. Scheer, SUPERGATE Coordinator, University of Konstanz, Germany	
	Chairs: M. Cuoco, *CNR SPIN and* F. Giazotto *CNR NANO*	
9:00-9:40	J. Basset, University Paris Saclay, France	*Gate-assisted phase fluctuations in all-metallic Josephson junctions*
9:40-10:20	Y. Pashkin, Lancaster University, UK	*Field effect in superconductors: reality or delusion?*
10:20-10:50	G. De Simoni, CNR NEST, Italy	*Gate-tunable superconducting devices for digital electronics*
Coffee Break		
	Chairs: M. Cuoco, *CNR SPIN and* F. Giazotto, *CNR NANO*	
11:20- 12:00	A. Amoretti, University of Genova, Italy	*Superconductors in strong electric fields: Quantum Electrodynamics meets superconductivity*
12:00-12:30	Y. Fukaya, Okayama University, Japan	*Suppression of Josephson current by gating: role of spin-orbit coupling and low crystalline symmetry*
12:30-12:45	S. Annabi, Ecole Polytechnique, France	*Quantum phase-transitions and non-locality in ultraclean carbon nanotube-based Josephson junctions*
12:45-13:00	C. Guarcello, University of Salerno, Italy	*Anomalous Josephson effects in nanowire-based junctions*
Lunch Break		
	Chairs: A. Di Bernardo, *University of Salerno and* W. Belzig, *University of Konstanz*	
14:30-15:10	K. Delfanazari, University of Glasgow, UK	*Gate-voltage addressable superconducting-semiconducting hybrid circuits*
15:10-15:50	J. Cha, KRISS, South Korea	*Coupling of Photons and Phonons in Superconducting Microwave Circuits*
Coffee Break		
	Chairs: A. Di Bernardo, *University of Salerno and* W. Belzig, *University of Konstanz*	
16:15-16:30	J. Koch, University of Konstanz, Germany	*Gate-controlled switching in non-centrosymmetric superconducting devices*
16:30-16:45	L. Kupas, Budapest University of Technology and Economics, Hungary	*Switching dynamics of Al superconducting nanocircuits*
16:45-17:00	G. Trupiano, Scuola Normale Superiore, Italy	*A superconducting microwave relaxation oscillator with quasiparticle injection*
17:00-17:30	D. Nikolic, University of Greifswald, Germany	*Microscopic theory of gate-controlled surface depairing and anomalous in mesoscopic superconductors*
17:30-18:00	M. Berke, Budapest University of Technology and Economics, Hungary	*Switching dynamics in Al/InAs nanowire-based gate-controlled superconducting transistor*
18:00	**SUPERGATE Project Meeting**	
19:00	**Free time/discussion**	

	Tuesday 8 October	
	Chairs: A. Caviglia, *University of Geneve and* A. Vecchione, *CNR SPIN*	
9:00-9:40	J. Berger, University of Regensburg, Germany	*Gate tunable supercurrent diode and anomalous Josephson effect*
9:40-10:20	C. Degen, ETH Zurich, Switzerland	*Scanning nitrogen vacancy magnetometry and imaging of Meissner screening*
10:20-10:35	K. Knapp, ETH Zurich, Switzerland	*Imaging of gate-controlled suppression of superconductivity by scanning nitrogen vacancy magnetometry*
10:35-10:50	H. Riechert, Ecole Polytechnique, France	*Coherent control of a carbon nanotube-based gatemon qubit*
Coffee Break		

	Chairs: A. Caviglia, *University of Geneva and* A. Vecchione, *CNR SPIN*	
11:20- 12:00	J. Meyer, University Grenoble Alpes, France	*Josephson tunneling at odd parity*
12:00-12:30	L. Ruf, University of Konstanz, Germany	*Gate controlled superconducting currents in Nb devices*
12:30-12:45	L. Marian, Université de Sherbrooke, Canada	*Observation of microwave Higgs modes in superconducting titanium nanostructures*
12:45-13:00	L. Andersson, Chalmers University, Sweden	*Real-time detection of quasiparticle tunneling events using a transmon qubit directly coupled to a waveguide*
Lunch Break		
	Chairs: K. K. Berggren, *MIT and* M. Arzeo, *SeeQc-EU*	
14:30-15:10	D. Daghero, University of Torino, Italy	*Reversible tuning of superconductivity in ion-gated NbN thin films*
15:10-15:50	B. Trauzettel, University of Wuerzburg	*Dynamics of biased Josephson junctions*
Coffee Break		
16:15-18:00	**Industry/EU Session**	
	Chairs: K. K. Berggren, *MIT and* M. Arzeo, *SeeQc-EU*	
16:15-16:30	M. Ritter, European Commission DG CNECT	*The European Vision for Quantum Technologies*
16:30-16:50	C. Puglia, DSQM, Italy	*Exploitation of laboratory results through DSQM: A superconducting electronics spin-off*
16:50-17:05	M. Eichinger, Quantum Machines, Denmark	*Beyond qubits: what does it take to run Shor's algorithm on a fault tolerant computer?*
17:05-17:20	D. Salvoni, Photon Technology Italy	*Superconducting Single Photon Detectors for Quantum Information*
17:20-17:35	R. Acharya, IMEC, Belgium	*Superconducting Qubit Control with Ultra-Low-Power Cryo-CMOS Multiplexer at Millikelvin Temperatures*
17:35-17:50	M. Arzeo, SEE-QC EU, Italy	*SFQ electronics for chip-based quantum computing*
17:50-18:00	Closing remarks	
19:30	**Conference dinner Hotel Cerere Paestum**	

	Wednesday 9 October	
	Chairs: E. Scheer, *University of Konstanz and* P. Makk, *Budapest University of Technology and Economics*	
9:00-9:40	T. Jalabert, University of Grenoble, France	*Probing the dynamics of quasiparticles in a superconducting nanowire by scanning critical current microscopy*
9:40-10:20	K. K. Berggren, MIT, USA	*Superconducting Microstrip-Based Electronics: Revisiting the Cryotron*
10:20-10:35	L. Lakic, University of Copenhagen, Denmark	*Proximitized gate-controlled quantum dots in germanium*
10:35-10:50	D.C. Ohnmacht, University of Konstanz, Germany	*Full counting statistics of Yu-Shiba-Rusinov states*
Coffee Break		
	Chairs: E. Scheer, *University of Konstanz, and* P. Makk, *University of Budapest*	
11:20- 11:50	J. van den Brink, IFW Leibniz Dresden, Germany	*Topological surface superconductivity in* $PtBi_2$
11:50-12:20	V. Buccheri, Chalmers University, Sweden	*Microwave characterization of gate controlled superconducting nanowires*
12:20-12:35	I. Aupias, University of Geneve, Switzerland	*Local and ultrafast dynamics of NbTiN superconducting nanowires*
12:35-12:50	A. Guarino, CNR SPIN, Italy	*Gate Induced Nanoscale Currents Distribution in Nb Dayem Bridges*
12:50-13:05	C. Autieri, MagTop Warsaw, Poland	*Dirac surface states and superconductivity in Nb- and Ta-based A15 compounds*
13:05-13:15	**Closing**	
Lunch		
Afternoon	**Departure**	

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Gate-assisted phase fluctuations in all-metallic Josephson junctions

J. Basset, O. Stanisavljević, M. Kuzmanović, J. Gabelli, C. H. L. Quay, J. Estève, and M. Aprili
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We study the reduction of the supercurrent by a gate electrode in a purely metallic superconductor–normal metal–superconductor Josephson junction by performing, on the same device, a detailed investigation of the gate-dependent switching probability together with the local tunneling spectroscopy of the normal metal. We demonstrate that high energy electrons leaking from the gate trigger the reduction of the critical current which is accompanied by an important broadening of the switching histograms. The switching rates are well described by an activation formula including an additional term accounting for the injection of rare high energy electrons from the gate. The rate of electrons obtained from the fit remarkably coincides with the independently measured leakage current.
Concomitantly, a negligible elevation of the local temperature in the junction is found by tunneling spectroscopy which excludes stationary heating induced by the leakage current as a possible explanation of the reduction of the critical current. This incompatibility is resolved by the fact that phase dynamics and thermalization effects occur at different timescales.

Field effect in superconductors: reality or delusion?

I. Golokolenov[1,2], A. Guthrie[1], S. Kafanov[1], Yu. A. Pashkin[1], and V. Tsepelin[1]
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In my talk, after a brief introduction, I will present our results on studying the properties of superconducting coplanar quarter-wavelength waveguide resonators [1]. The resonators were formed in a vanadium film and grounded through a gated nanoscale constriction about 50 nm wide and 50 nm long. We have found that at high enough gate voltage, $|V_g| > 25$ V, the resonance frequency starts to fall, which is accompanied by the decrease of the quality factor and increase of the low-frequency noise. At the same time, the leakage current between the gate and constriction grows rapidly and perfectly follows the Fowler-Nordheim model of electron field emission from a metal electrode [2]. The observed effects do not depend on the polarity of applied gate voltage, which makes the gate dependences of the frequency shift, quality factor and noise exponent perfectly symmetric. Our observations can be explained by the injection of high-energy quasiparticles into the constriction region resulting in weaker superconductivity and suppression of the critical current. As the kinetic inductance is inversely proportional to the critical current, this leads to the decrease of the resonance frequency. Larger dissipation at higher gate voltages gives a lower quality factor and higher noise magnitude. This interpretation was proposed to explain the observed suppression of critical current in references [3,4] and can also be applied to references [5-8].

[1] I. Golokolenov et al. Nature Communications 12, 2747 (2021).
[2] R.H. Fowler and L. Nordheim. Proc. R. Soc. Lond. A 119, 173 (1928).
[3] M.F. Ritter et al. Nature Communications 12, 1266 (2021).
[4] L.D. Alegria et al. Nature Nanotechnology 10.1038/s41565-020-00834-8 (2021).
[5] G. De Simoni et al. Nature Nanotechnology 13, 802 (2018).
[6] F. Paolucci et al. Nano Lett. 18, 4195 (2018).
[7] G. De Simoni et al. ACS Nano 13, 7871 (2019).
[8] F. Paolucci et al. Phys. Rev. Appl. 11, 024061 (2019).

Gate-Tunable Superconducting Devices for Digital Electronics

G. De Simoni, G. Trupiano, A. Paghi, S. Battisti, C. Puglia, D. Margineda, F. Soofivand, A. Greco, A. Crippa, E. Strambini, and F. Giazotto
NEST, Istituto Nanoscienze and Scuola Normale Superiore, I-56127, Pisa

Starting with a brief recap of the primary tasks carried out within the framework of the Supergate project by the Superconducting Quantum Electronic Group at CNR-Nano in Pisa, we discuss the most significant results achieved through these activities. Specifically, we focus on fully metallic devices based on Nb, Nb compounds, and MoGe, which we deem particularly interesting regarding operating gate voltage. Next, we present some new architectures for superconducting transistors that align with the objectives of Supergate. In particular, we introduce a family of devices based on proximity-effect Josephson junctions constructed from InAs epilayers and discuss their advantages and disadvantages compared to the fully metallic approach. Finally, we outline a superconductive transistor implemented using a tunnel junction as the gate electrode.

Superconductors in strong electric fields: Quantum Electrodynamics meets Superconductivity

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Traditionally, a static electric field has been considered to have minimal influence on the physics of ideal conductors due to the screening effects of mobile carriers, which prevent the field from penetrating deeply into the bulk of a metal. However, recent experimental evidence suggests that static electric fields can manipulate the superconductive properties of metallic BCS superconducting thin films, particularly by weakening the critical current. In this paper, I will explore possible explanations for this phenomenon, drawing on the analogy between superconductivity and quantum electrodynamics observed by Nambu and Jona-Lasinio in the 1960s. Utilizing this parallelism, I will predict a new phenomenon: the superconducting Schwinger effect. Additionally, I will explain how this microscopic effect can be integrated into a modified Ginzburg-Landau theory, which incorporates additional couplings between the electric field and the superconductive condensate. Finally, I will connect these theoretical predictions to experimental observations, proposing them as a potential explanation for the weakening of superconductivity due to an external electric field. If time permits, I will also discuss ongoing work aimed at linking the microscopic Schwinger picture to the effective Ginzburg-Landau description.

[1] A. Amoretti et al. “Destroying superconductivity in thin films with an electric field.” Phys.Rev.Res. 4 (2022) 3, 033211.
[2] P. Solinas et al. “Sauter-Schwinger effect in a Bardeen-Cooper-Schrieffer superconductor.” Phys.Rev.Lett. 126, 117001 (2021).

Suppression of Josephson current in gate-controlled junctions through spin-orbit coupling and low crystalline symmetry

Y. Fukaya[1], M. T. Mercaldo[2], C. Guarcello[2,3], F. Giazotto[4], L. Chirolli[4], M. Cuoco[1]
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[2]*Dipartimento di Fisica "E. R. Caianiello", University of Salerno, Italy*
[3]*INFN, Sezione di Napoli Gruppo Collegato di Salerno, Complesso Universitario di Monte. S. Angelo, Italy*
[4]*NEST, Istituto Nanoscienze-CNR and Scuola Normale Superiore, Italy*

Josephson current flows across a superconducting junction due to the phase difference between the superconducting order parameters in the leads. In the presence of spin-orbit coupling, Josephson effect has been considered in weak links with the aim to evaluate the behavior of the supercurrents through two-dimensional electron systems. For time-reversal symmetric superconductors, a novel path to design the Josephson effect is based on the potential to exploit resources that employ strain and gate fields which reduce the crystalline symmetry.

In our work, we study the Josephson effect of a superconducting junctions whose leads are marked by conventional spin-singlet/s-wave pairing with electronic states having distinct mirror parity, which are coupled through spin-orbit interaction and crystalline potential. We show that Josephson current is generally expressed as the sum of two terms that can have opposite sign depending on the strength and character of the mirror symmetry breaking interactions and the spin-orbit coupling. We demonstrate that the amplitude of the supercurrent can be suppressed by varying the sign and amplitude of the crystalline symmetry breaking interactions in the leads and at the interface. We discuss how an external applied gate field can tune the strength of the crystalline symmetry breaking interactions. Our findings indicate a distinct physical regime for which the Josephson current can be controlled by suitably designing the electronic configuration of the superconductor.

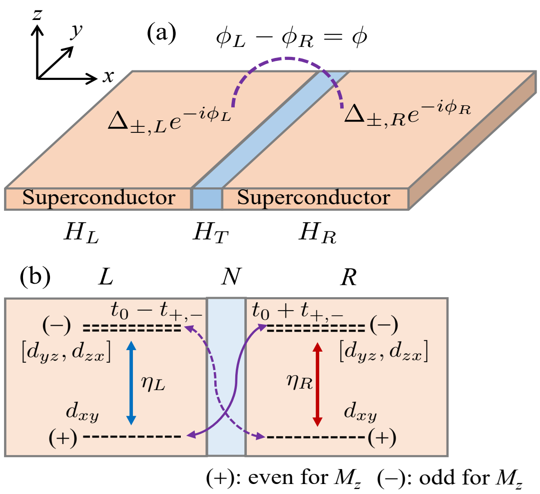

Fig: (a) Illustration of Josephson junction and (b) the relevant processes for the Josephson current flow within a multi-orbital model.

Quantum phase transitions and non-locality in ultraclean carbon nanotube-based Josephson junctions

S. Annabi[1], H. Riechert[1], A. Peugeot[1], E. Arrighi[1], J. Griesmar[1], K. Watanabe[2], T. Taniguchi[2], L. Bretheau[1], J.-D. Pillet[1]

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[2] *National Institute for Materials Science, Namiki 1-1, Ibaraki 305-0044, Japan.*

Gate-tunable superconductivity in low-dimensional systems has emerged as a significant research topic due to its implications for quantum technologies. Carbon nanotubes (CNTs), with their quasi-one-dimensional nature and unique electronic properties, offer a promising platform for investigating such phenomena. In this work, we report low temperature transport measurements of CNT-based Josephson junctions, fabricated using a novel technique designed to minimize disorder and contamination [1].

The exceptional cleanliness of our CNT devices reveals a clear fourfold periodicity in the supercurrent as a function of gate voltage, attributed to the spin and orbital degrees of freedom. The experimental observations demonstrate quantum phase transitions involving a change of parity in the ground state. These measurements are well reproduced by theoretical simulations, which suggest a non-trivial combination of both the Andreev bound states (ABS) and the continuum contributions.

In a second experiment, we probe the electronic properties of a device made of two junctions close to each other. We observe non-local Josephson effect which reveals the hybridization of ABS leading to the formation of an Andreev molecule [2]. The individual control of each junction made with an elementary quantum conductor allows us to investigate this effect at the microscopic level.

Our work demonstrates the potential of gate control not only in tuning local superconducting properties but also in manipulating non-local superconducting states.

[1] S. Annabi et al. "Ultraclean carbon nanotube-based Josephson junctions." arXiv:2405.19192 (2024).

[2] J.-D. Pillet et al. "Nonlocal Josephson effect in Andreev molecules." Nano Lett., vol. 19, no. 10, pp. 7138–7143, 2019, doi: 10.1021/acs.nanolett.9b02686.

Anomalous Josephson effects in nanowire-based junctions

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[4] *INFN, Gruppo collegato di Cosenza, Italy*
[5] *CNR-SPIN c/o Università degli Studi di Salerno, Fisciano (SA), Italy*

Recent advancements in the study of Josephson junctions engineered from 2D electron gases at oxide interfaces have unveiled novel quantum effects related to Rashba spin-orbit interactions and specific geometric configurations. In our analysis, we delve into three aspects of this context. Firstly, we explore the anomalous critical current behavior changing the applied magnetic field, relating this phenomenon with the emergence of Majorana bound states at the edges of superconducting leads, which significantly impact the current-phase relation of the junction [1]. This study provides insights into topological superconductivity in noncentrosymmetric materials under small magnetic fields. Then, we discuss the emergence of fractional Shapiro steps induced by an AC current in this kind of systems, revealing another pathway to detect Majorana bound states and offering new perspectives on the manipulation of quantum states via external drives. Finally, we introduce a novel geometric-field controlled diode effect in short Josephson junctions shaped into kinked nanostrips [2]. This analysis not only advances our understanding of phase-dependent transport phenomena, but also outlines the coexistence of Majorana and Andreev bound states under different external conditions. These investigations pave the way for designing next-generation nanoscale devices with tailored electronic properties, enhancing our understanding of quantum systems with strong spin-orbit coupling and nontrivial topology.

[1] A. Maiellaro et al. “Hallmarks of orbital-flavored Majorana states in Josephson junctions based on oxide nanochannels.” Phys. Rev. B **107**, L201405 (2023).
[2] A. Maiellaro et al., "Engineered Josephson diode effect in kinked Rashba nanochannels." arXiv:2405.17269.

Gate-voltage addressable superconducting-semiconducting hybrid circuits

K. Delfanazari
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Stable, reproducible, scalable, addressable, and controllable hybrid superconductor–semiconductor (S–Sm) junctions and switches are key circuit elements and building blocks of emerging quantum processors. The electrostatic field effect produced by the split gate voltages facilitate the realization of nano-switches that can control the conductance or current in the hybrid S–Sm circuits based on $In_{0.75}Ga_{0.25}As$ quantum wells integrated with Nb superconducting electronic circuits. In this talk, in the first section, the experimental realization of large-scale scalable, and gate voltage controllable hybrid field effect quantum chips will be discussed and demonstrated. In the second section, we present an innovative realization of nanoscale hybrid superconducting quantum point contact (SQPC) arrays with split gate technology in semiconducting 2D electron systems. Finally, in the last section, the application of our proposed hybrid quantum integrated circuit architecture for emerging cryogenic quantum technologies will be discussed.

[1] K. Delfanazari, et al. Advanced Electronic Materials 10 (2), 2470006 (2023).
[2] K. Delfanazari, et al. Advanced Materials 29 (37), 1701836 (2017).
[3] K. Delfanazari, et al. Phys. Rev. Applied 21, 014051 (2024).

Coupling of Photons and Phonons in Superconducting Microwave Circuits

J. Cha
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Hybrid quantum devices employ superconducting microwave circuits as basic building blocks, realizing interactions between microwave photons and various quantum states such as qubits, electrons, spins, phonons, and magnons. My talk will discuss various interesting phenomena arising from the coherent interactions of microwave fields and nanomechanical phonons in niobium-based superconducting nanoelectromechanical devices. We utilize niobium as a base superconducting material due to its superior superconducting properties, which make it suitable for quantum transduction. Our device demonstrates fundamental optomechanical back-action effects including motional cooling and amplification, and optomechanically induced transparency at 4.2 K and in strong magnetic fields up to 0.8 T [1]. We further explore nonlinear optomechanical effects by applying a strong microwave drive. Our device realizes the generation of microwave frequency combs via nonlinear wave-mixing processes [2]. I will also describe a new approach for frequency-tunable superconducting microwave resonators by employing the gate-controlled supercurrent (GCS) effect [3]. The resonators implement titanium-nitride nanowires which act as a variable inductor with the GCS effect which leads to 150-MHz tuning of microwave resonances. The results from our study will provide new opportunities in quantum sensing and transduction.

[1] J. Cha et al. "Superconducting nanoelectromechanical transducer resilient to magnetic fields." Nano Letters 21.4 (2021): 1800-1806.
[2] J. Shin et al. "On-chip microwave frequency combs in a superconducting nanoelectromechanical device." Nano Letters22.13 (2022): 5459-5465.
[3] Y. Ryu et al. "Utilizing Gate-Controlled Supercurrent for All-Metallic Tunable Superconducting Microwave Resonators." Nano Letters 24.4 (2024): 1223-1230.

Gate-controlled switching in non-centrosymmetric superconducting devices

J. Koch[1], L. Ruf[1], E. Scheer[1], A. Di Bernardo[1,2]
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[2]*Dipartimento di Fisica "E. R. Caianiello", Università degli Studi di Salerno, via Giovanni Paolo II 132, 84084 Fisciano (SA), Italy.*

Gate-controlled superconducting devices have become of great interest for the development of energy-efficient hybrid superconductor/semiconductor computing architectures. The idea behind this technology stems from the recent discovery that superconducting devices can be controlled electrically with the application of a gate voltage [1-3]. We investigate gate-controlled switching devices made of the non-centrosymmetric superconductor $Nb_{0.18}Re_{0.82}$ and compare how the fabrication process influences the physical properties. We examine the differences between devices fabricated with the top-down (dry-etching) and bottom-up (lift-off) approaches, as well as how the usage of different gases in the dry-etching step affects the GCS.

[1] G. De Simoni et al. "Metallic supercurrent field-effect transistor." Nature Nanotechnology 13, 802-805 (2018).
[2] F. Paolucci et al. "Ultra-Efficient Superconducting Dayem Bridge Field-Effect Transistor." Nano Letters 18, 4195-4199 (2018).
[3] F. Paolucci et al. "Magnetotransport Experiments on Fully Metallic Superconducting Dayem-Bridge Field-Effect Transistors." Phys. Rev. Applied 11, 024061 (2019).

Switching dynamics of Al superconducting nanocircuits

Z. Scherübl, M. Kocsis, L. Kupás, T. Elalaily, M. Berke,
G. Fülöp, P. Makk and S. Csonka
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Integrated circuits with superconducting building blocks would have several benefits, such as high speed and low power consumption. In recent years, surprisingly, control of the supercurrent with voltage applied on a nearby electrode in all-metallic materials has been observed. This phenomenon can be used to fabricate gate-controlled transistors from superconducting materials, analogous to the field effect transistors. The suppression of the supercurrent was investigated in several materials, however there is no scientific consensus on the microscopical explanation [1-3].
We studied gate tuneable supercurrents in Al superconducting shells epitaxially grown on the top of InAs nanowires [4-5]. The investigated device can be switched from superconducting state to normal state by applying fast voltage pulses on the gate, which is important for standard electronical applications. We examined the switching dynamics of the investigated nanowire and analysed the possible switching speed of ours. We have separated two different switching mechanism and reached switching speeds on the ns-timescale. Our studies are promising towards realizing fast superconducting gate tuneable switches.

[1] G. De Simoni et al. Nature Nanotechnology 13.9 (2018): 802-805.
[2] M. F. Ritter et al. Nature Communications 12.1 (2021): 1-6.
[3] L. D. Alegria et al. Nature Nanotechnology 16.4 (2021): 404-408.
[4] T. Elalaily et al. Nano Letters 2021, 21, (22), 9684-9690.
[5] T. Elalaily et al. arXiv:2312.15453.

A superconducting microwave relaxation oscillator with quasiparticle injection

G. Trupiano, G. De Simoni, and F. Giazotto
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We present a microwave relaxation oscillator based on a superconducting $S_2IS_1IS_2$ double tunnel junction with an additional tunnel injector for control. The device utilizes a frequency modulation mechanism achieved by applying a DC voltage to a Normal Metal-Insulator-Superconductor (NIS_1) tunnel junction. This induces quasiparticle injection and localized heating in the S_1 island, effectively controlling the switching supercurrent. Oscillations are initiated when the switching current falls below a DC bias current.

The use of tunnel junction technology allows for a compact size, while the DC voltage control mechanism simplifies its operation. The oscillator is designed for straightforward integration with superconducting circuits and exhibits low power dissipation inherent to superconducting devices. These attributes make it particularly suitable for a range of applications in low-power and low-temperature electronics. For instance, in quantum information processing, the oscillator can serve as a tunable microwave source for qubit control or readout. Its potential extends also to microwave technology, where it can be employed in high-frequency communication systems or as a local oscillator in superconducting mixers.

Microscopic theory of gate-controlled surface depairing and anomalous Josephson effect in mesoscopic superconductors

D. Nikolić[1,2], S. Chakraborty[2], J. Carlos Cuevas[3], F. Giazotto[4], A. Di Bernardo[2,5], E. Scheer[2], M. Cuoco[6], W. Belzig[2], and M. Eschrig[1]

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[2] *Fachbereich Physik, Universität Konstanz, D-78464 Konstanz, Germany*
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Recently, gate-mediated supercurrent suppression in superconducting nanobridges has been reported in many experiments [1]. Those experiments suggest that this could be either a direct or an indirect gate effect and the underlying physical mechanism has not been completely understood until now. Using the quasiclassical Green’s function method, we show that a small concentration of magnetic impurities at the surface of the bridges can significantly suppress superconductivity and hence the supercurrent inside the systems while a gate field is applied. Our model suggests that the gate field can enhance the spin-flip depairing at the surface through the modification of the exchange interaction between magnetic impurities and the superconductor. We also obtain a symmetric suppression of the supercurrent concerning the gate field, which is a signature of a direct gate effect. We discuss the parameter range of applicability of our model and its capability to qualitatively capture the main aspects of the experimental observations [2].
In the second part of the talk, we will talk about equal-spin Cooper pairs formed at the interface between a superconductor (S) and a helical ferromagnet (F) [3]. The theory is done in the framework of the quasiclassical Green’s function formalism. However, assuming the large splitting between the spin bands in F, the standard quasiclassical approach cannot be applied directly and requires a somewhat modified description [4]. Applying this approach, we account for the long-ranged (equal-spin) Josephson current-phase relation (CPR) in an SFS weak link considering (a) homogeneous and (b) helimagnetic state in F. Remarkably, the CPR takes a nontrivial form leading to both the anomalous and Josephson diode effects. These effects have clear physical interpretations based on the coupling between the superconducting phase and an effective U(1) gauge field induced either by inhomogeneous magnetization of F or relative orientations between magnetizations of the spin-active SF interfaces and F inhomogeneous state.

[1] L. Ruf et al. arXiv:2302.13734.
[2] S. Chakraborty et al. Phys. Rev. B 108, 184508 (2023).
[3] A. Spuri et al. Phys. Rev. Res. 6, L012046 (2024)
[4] M. Eschrig, Phys. Rev. B 80, 134511 (2009); R. Grein et al. Phys. Rev. Lett. 102, 227005 (2009); R. Grein et al. Phys. Rev B 81, 094508 (2010).

Switching dynamics in Al/InAs nanowire-based gate-controlled superconducting transistor

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The observation of the gate-controlled supercurrent in superconducting nanostructure revived the hope in the pursuit of realising a superconducting equivalent of the semiconducting field-effect transistor. Integrating superconducting elements into circuits holds promise for high-speed operations and low power consumption. Despite the extensive investigations into the superconducting gating effect across different materials and systems, such as nanowires, Josephson junctions, Dayem bridges, there is still no scientific consensus on the microscopic origin of the phenomenon [1-6].
In this study we report on a gate-induced two-level voltage fluctuation between the superconducting and the normal state in Al/InAs nanowires [7]. Noise correlation measurements reveal a strong coherence between voltage fluctuations of the nanowire device and the fluctuations of the leakage current. We show that in a specific regime the fluctuations follow Poisson statistics. The detailed analysis of the measurements is consistent with the so-called stress-induced leakage current (SILC) mechanism, in which inelastic tunnelling accompanied with phonon generation is the dominating transport mechanism.
We believe that with the help of our findings we can get closer to understand the gating mechanism, which is essential for future practical use.

[1] G. De Simoni et al. Nature nanotechnology 13.9, 802-805 (2018).
[2] M. F. Ritter et al. Nature communications 12.1, 1-6. (2021).
[3] L. D. Alegria et al, Nature Nanotechnology 16.4, 404-408 (2021).
[4] T. Elalaily et al. Nano letters 21.22, 9684-9690 (2021).
[5] T. Ealaiaily et al. ACS Nano 17.6, 5528-5535 (2023).
[6] L. Ruf et al. APL Materials 11.9, (2023).
[7] T. Elalaily et al. arXiv preprint, (2023) arxiv:2312.15453.

Gate tunable supercurrent diode and anomalous Josephson effect

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The discovery of the supercurrent diode effect by Ando et al. [1] and its observation in a rich variety of systems caused an increasing interest in the physics of non-reciprocal superconductivity.
Simultaneous breaking of inversion- and time-reversal symmetry in Josephson junctions can lead to an anomalous phase shift φ_0 in the supercurrent phase relation.
Here, we present a study on Josephson junctions in hybrid Al/InGaAs/InAs structures, which harbor strong Rashba spin-orbit interaction. In combination with a Zeeman field, this gives rise to a non-reciprocal Josephson inductance and supercurrent diode effect [2,3,4]. Using a superconducting quantum interferometer we simultaneously measure the φ_0-shift and supercurrent diode effect on a single junction [5]. By electrostatic gating of the junction, we reveal the link between the φ_0-shift and supercurrent diode effect.

[1] F. Ando et al. Nature 584, 373–376 (2020).
[2] C. Baumgartner et al. Nature Nanotechnology 17, 39 (2022).
[3] A. Costa et al. Nature Nanotechnology 18, 1266–1272 (2023).
[4] C. Baumgartner et al. Journal of Physics Condensed Matter 34, 154005 (2022).
[5] S. Reinhardt et al. Nature Communications 15, 4413 (2024).

Imaging of Gate-Controlled Suppression of Superconductivity by Scanning Nitrogen-Vacancy Magnetometry – Part 1: Introduction

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Scanning nitrogen-vacancy microscopy (SNVM) has emerged as a unique tool for investigating nanoscale magnetism with high sensitivity and sub-50-nm spatial resolution. While mostly applied at room temperature, the SNVM can be extended to the cryogenic regime down to millikelvin temperatures, allowing for the study of superconducting systems.

In this talk, we will give an introduction into the SNVM and its application to imaging Meissner screening in superconducting nanostructures [1].

[1] P. J. Scheidegger et al. Applied Physics Letters 120, 224001 (2022).

Imaging of Gate-Controlled Suppression of Superconductivity by Scanning Nitrogen-Vacancy Magnetometry – Part 2: Results

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Scanning nitrogen-vacancy microscopy (SNVM) has emerged as a unique tool for investigating nanoscale magnetism with high sensitivity and sub-50-nm spatial resolution. While mostly applied at room temperature, the SNVM can be extended to the cryogenic regime down to millikelvin temperatures, allowing for the study of superconducting systems. In this talk, we will discuss an experiment aimed at elucidating the mechanism behind the gate-controlled suppression of superconductivity [1] in gated Nb islands by spatially imaging the Meissner screening.

[1] G. De Simoni et al. Nature Nanotechnology 13, 802 (2018).

Coherent control of a carbon nanotube-based gatemon qubit

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The standard transmon qubit may be modified by using a Josephson junction with few well-transmitted channels. The qubit resonance frequency and coherence properties depend on the supercurrent through the junction. Via a gate the junction’s transmission and thus qubit properties become tunable. Previous works have shown coherent measurements in such gatemon qubits with nanowire- or graphene-based junctions.
We present a qubit design using ultraclean single carbon nanotubes as junction material. Measurements of the resonance frequency show signatures of charge parity change in the quantum dot formed by the carbon nanotube. We measured Rabi oscillations demonstrating coherent control. Currently we work on a microwave design to reduce energy relaxation.

Josephson tunneling at odd parity

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The superconducting phase difference across a Josephson junction controls the dissipationless supercurrent via the phase dependence of the so-called Josephson energy. It becomes a quantum-fluctuating variable if the junction is embedded in an electromagnetic circuit. The resulting quantum mechanics of the Josephson effect is the core ingredient for quantum technologies with superconducting circuits.
On a microscopic level, the Josephson energy is related to Andreev bound states (ABS) in the junction and does depend on their occupation. Notably, quasiparticle poisoning, where a single quasiparticle gets trapped in an ABS, quenches the contribution of that ABS to the supercurrent. Due to parity conservation, such a poisoned state in the odd parity sector may have a long lifetime.
Here we study the Josephson quantum mechanics of a poisoned tunnel junction embedded in an ohmic environment [1]. We find that the effect of the electromagnetic environment gives rise to a fundamentally different phenomenology than in the even parity sector. Our analysis covers several representative cases. In particular, we show that the supercurrent in the odd parity sector can become parametrically larger than the one in the even parity sector. Furthermore, a current-biased junction may undergo a new type of quantum dissipative (Schmid) phase transition.
Hybrid superconductor/semiconductor/superconductor junctions are a promising platform to study these effects.

[1] M. Houzet et al. "Josephson quantum mechanics at odd parity." Physical Review B 110.2, L020504 (2024).

Gate controlled superconducting currents in Nb devices

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Gate controlled superconductivity (GCS) has recently attracted great attention. It was reported [1] that the superconducting state can be suppressed in a gated nanoconstriction by the application of a gate voltage. The authors explained their findings by an electric field induced perturbation of the superconducting state, giving the next milestone for future superconducting and CMOS compatible transistors. However, the mechanism of the GCS is strongly under debate. Other works report about mechanism which are related to a leakage current: high-energy quasiparticle injection [2], low-energy-mediated phonon excitation [3] or the generation of a hot-spot [4]. Here we are studying Nb Dayem bridges fabricated by electron beam lithography and lift off. We show not only a high reproducibility of the GCS across our devices, but also discuss relevant performance parameters such as output voltage, wire-width, suppression voltage and choice of substrate. Further, we discuss our findings in the context of the proposed mechanism.

[1] G. De Simoni et al. Nature Nanotechnology 13, 802 (2018).
[2] L. D. Alegria et al. Nature Nanotechnology 16, 404 (2021).
[3] M. F. Ritter et al. Nature Electronics 5, 71-77 (2022).
[4] J. Basset et al. Phys. Rev. Research 3, 043169 (2021).

Observation of microwave Higgs modes in superconducting Titanium nanostructures

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The spontaneous breakdown of a continuous symmetry, as in superconductors, leads to the emergence of a fluctuation mode for the amplitude of the order parameter, the so-called Higgs-Anderson mode (HM). Its weak coupling to the electromagnetic field usually requires the use of nonlinear effects for its experimental detection [1].
However, a recent theory predicts that HM could be revealed on the linear complex conductivity as the appearance of an anomaly at frequencies of the order of twice the superconducting gap Δ in the presence of a DC supercurrent [2]. This has been experimentally confirmed in NbN macroscopic films exposed to THz radiations at temperature of 5K [3].
In order to gain a deeper understanding of the properties of HM, such as their propagation, stability, the relaxation mechanisms, etc., it is highly desirable to be able to generate, control and detect them in circuits, where the electromagnetic wave and dc currents could be controlled at small scale. We implemented a broadband, calibrated cryogenic microwave reflectance setup to measure the frequency-dependent complex impedance of superconducting Titanium wires up to 33GHz in a dilution refrigerator, at temperature adjustable from 10mK to 800mK. We measured samples of various dimensions corresponding to different limits of superconductivity and investigated the effect of the material that constitutes the contacts on the nanostructures (Ti, a normal metal or a superconductor with higher gap). In the absence of DC supercurrent, we compare our results with Mattis Bardeen theory [4] as a function of temperature. Adding a current result in the appearance of an anomaly in the real and imaginary parts of the impedance at a frequency $\sim 2\Delta/h$. This feature behaves as predicted in [2] with a much larger width than expected. The amplitude of the anomaly depends on the geometry and contacts of the nanostructures.
Our experiment opens the route towards the use of Higgs modes to control and modulate the high frequency properties of superconducting circuits.

[1] R. Shimano and N. Tsuji. Annu. Rev. Condens. Matter Phys. 2020. 11:103–24 (2019).
[2] A. Moor et al. Phys. Rev. Lett. 118, 047001 (2017).
[3] S. Nakamura et al. Phys. Rev.Lett. 122, 257001 (2019).
[4] D. C. Mattis and J. Bardeen. Phys Rev. 111,412 (1958).

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

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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 [3]. 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 [4]. 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 components, paving the way towards optimized performance in superconducting quantum devices.

[1] L. Glazmanand and G. Catelani. "Bogoliubov quasiparticles in superconducting qubits." SciPost Physics Lecture Notes (2021): 031.
[2] R. T. Gordon et al. "Environmental radiation impact on lifetimes and quasiparticle tunneling rates of fixed-frequency transmon qubits." Applied Physics Letters 120.7 (2022).
[3] K. R. Amin et al. "Direct detection of quasiparticle tunneling with a charge-sensitive superconducting sensor coupled to a waveguide." arXiv preprint arXiv:2404.01277(2024).
[4] M. Scigliuzzo et al. "Primary thermometry of propagating microwaves in the quantum regime." Physical Review X 10.4 (2020): 041054.

Reversible tuning of superconductivity in ion-gated NbN thin films

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The ionic-liquid-gating technique has been successfully used in many compounds with low carrier density but only rarely in metals and metallic superconductors, where it is generally thought to be hampered by the small screening length. However, our liquid-gating experiments in thin films of NbN, a metallic electron-phonon superconductor, provided evidence of reversible *enhancements* (for electron depletion) and *suppressions* (for electron doping) of the normal-state resistance and of the critical temperature. The magnitude of these effects increases as the film thickness decreases from 40 nm to 10 nm [1]. For instance, in 10-nm thick films, we observed a T_c suppression of 0.5% at an induced surface density of electrons $\Delta n_{2D} = 10^{15}$ cm^{-2}. This result implies that the SC pairing is suppressed in the whole film, although electronic screening confines the extra charges to the topmost layer. This puzzle can be solved within the strong-coupling BCS model for the proximity effect, supported by ab-initio calculations of the doping-dependent density of states [1,2].
The 10-nm NbN films displayed irreversible effects at the highest gate voltages, due to electrochemical interactions with the ionic liquid. To extend the study to thinner films (5 nm) we thus had to protect them by growing an ultrathin (2.6 nm) self-encapsulation layer of Nb_2O_5 by controlled in-situ oxidation [3]. We found that the encapsulation layer is not detrimental for ionic-liquid-gating operations since it withstands gate voltages beyond the electrochemical stability window of the electrolyte, allows a fully reversible tuning of both the normal-state resistivity and the T_c of the films, and has a capacitance comparable to that of non-encapsulated ionic transistors [3]. We indeed observed reversible T_c shifts over three times larger than in unprotected, thicker devices, and for $\sim$10 times smaller values of Δn_{2D}. By combining XPS and tunnel spectroscopy, we discovered that the only non-volatile effect of gating is an increase in the thickness (from about 0.3 nm to about 1 nm) of the interfacial layer of sub-stoichiometric Nb oxynitride between NbN and Nb_2O_5.
The effectiveness of self-encapsulation suggests that it may be extended to other materials and devices where more standard encapsulation techniques are not readily applicable.

[1] E. Piatti et al. Phys. Rev. B 95, 140501(R) (2017).
[2] E. Piatti et al. Appl. Surf. Sci. 461, 17-22 (2018).
[3] E. piatti et al. Phys. Rev. Appl. 18, 054023 (2022).

Dynamics of biased Josephson junctions

B. Trauzettel
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Current- or voltage-biased Josephson junctions (JJs) are characterized by particular dynamics of the phase difference across the junction. In these junctions, retardation effects matter, which are typically neglected in theoretical modelling. We discuss observable signatures in Josephson junctions that genuinely stem from retardation effects including spikes in the I-V characteristics of current-biased JJs and the non-equilibrium 4π Josephson effect in voltage-biased JJs.

The European Vision for Quantum Technologies

M. Ritter
European Commission, DG CNECT, Luxembourg

In this talk, I will outline the European Commission's vision for the development and deployment of quantum technologies in Europe. At the heart of this strategy sits the Quantum Technologies Flagship, the European Commission’s 1 billion € funding initiative to drive innovation in European quantum technologies. The scope of the Quantum Flagship spans across all four quantum technology pillars: computing, simulation, sensing, and communication.

I will highlight the activities and accomplishments of past and current Flagship projects focusing particularly on quantum computing and enabling technologies. This notably includes the recent launch of long-term Framework Partnership Agreements, an initiative which supports leading consortia to push the boundaries of all major quantum computing and simulation hardware platforms.

Moreover, the European Commission, together with the EuroHPC Joint Undertaking and the Member States, is integrating European quantum computers into high-performance computing infrastructure. Such hybrid platforms unlock new areas of research and enable applications beyond the capabilities of classical HPC systems.

The Member States’ commitment to quantum technologies is further signified by the recent signature of the ‘Quantum Declaration’, recognizing the strategic importance of quantum technologies for the scientific and industrial competitiveness of the EU.

At the end of my talk, I will present the current portfolio of quantum technology calls and actions launched by the European Commission and the European Innovation Council.

Exploitation of laboratory results through DSQM: A superconducting electronics spin-off

C. Puglia, F. Giazotto, E. Strambini, G. De Simoni, F. Paolucci, A. Di Bernardo
DSQM SRL, Via Nino Pisano 14, 56122, Pisa

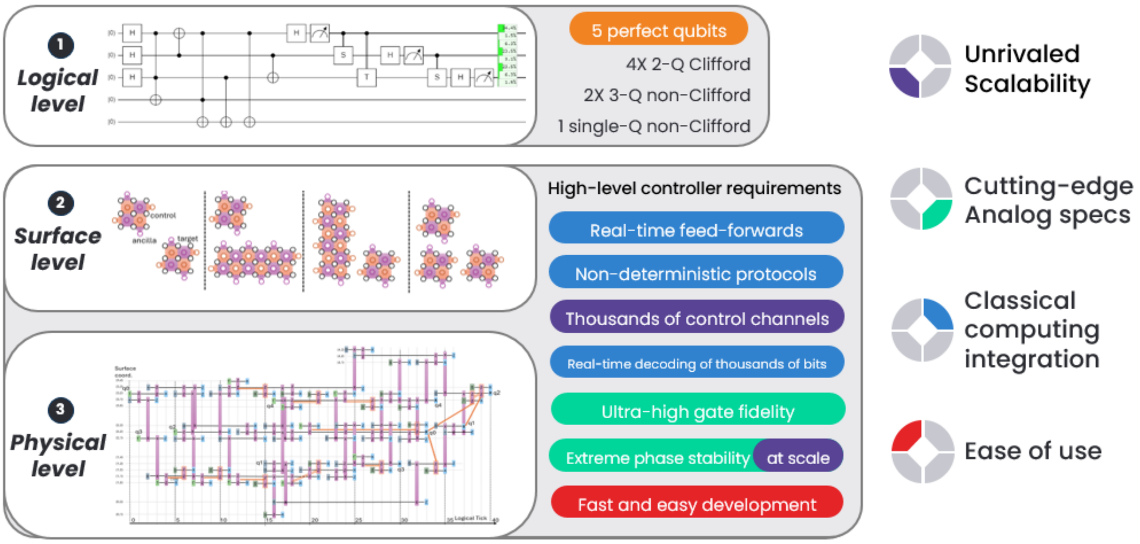
DSQM is working to successfully translate cutting-edge laboratory research into commercial applications via the creation of novel superconducting electronics. Originating from breakthrough scientific results developed within CNR, DSQM epitomizes the pathway from theoretical innovation to marketable technology.
The journey begins with our foundational research in superconductivity, highlighting key experimental outcomes and the technological challenges overcome. By leveraging advanced materials and novel design principles, our lab made significant strides in enhancing the efficiency and performance of superconducting components. These innovations laid the groundwork for DSQM's establishment, aimed at harnessing this technology for practical applications. DSQM has since evolved into a vibrant enterprise, focusing on the development and commercialization of superconducting electronic devices and offering fabrication and characterisation services to universities and companies. Our products and services cater to a diverse range of industries, including quantum computing, medical imaging, and telecommunications.
We will also discuss the strategic steps undertaken to bridge the gap between academia and industry, including securing intellectual property, navigating regulatory landscapes, and forging key partnerships. Furthermore, the role of funding and investment in scaling our operations will be examined, providing insights into the financial aspects of tech-based spin-offs.
In conclusion, DSQM's trajectory from a research concept to a market-leading enterprise serves as a case study in successful technology transfer. Attendees will gain an understanding of the critical factors that contribute to the commercialization of scientific research, underscoring the potential of superconducting electronics to revolutionize various sectors.

Beyond qubits: what does it take to run Shor's algorithm on a fault tolerant computer?

M. Eichinger, PhD – Quantum Machines

Fault-tolerant quantum computers that implement quantum error correction at scale is considered the most practical path towards realizing the full potential of quantum computing. In this talk, we take a concrete example and discuss what classical control system is needed to run Shor's algorithm fault tolerantly on a superconducting QPU and demonstrate how Quantum Machines' control suite meets these requirements. Moreover, we showcase how the various capabilities and unique features have been used by the community.

High-level controller requirements for Factoring 21



Superconducting Single Photon Detectors for quantum information

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Superconducting Nanowires Single Photon Detectors (SNSPDs) have been introduced in 2001 [1] and in twenty years the performances of these devices have achieved unparallel levels. Indeed, they exhibit almost unit system detection efficiency, extremely low dark counts, high speed and high temporal resolution, also at the wavelength of 1550nm, typically used for telecommunications [2]. With similar devices, it is also possible to resolve the number of input photons, and this is a very powerful tool for quantum information [3].
Recently, also Superconducting Microstrips (SMSPD) have been demonstrated to be able to detect single photons with excellent performances, offering the advantage of an easier fabrication process and larger areas [4].
With this variety of solutions, superconducting single photon detectors are becoming an enabling technology in many applications, but they're playing a crucial role specially in quantum information. Indeed, they're being largely used in quantum key distribution, quantum computing, quantum optics, quantum metrology and so on.
In this work we present our recent achievements using Superconducting detectors in quantum information experiments.

[1] G. N. Gol'Tsman et al. "Picosecond superconducting single-photon optical detector." Applied Physics Letters 79.6 (2001): 705-707.
[2] I. Esmaeil Zadeh et al. "Superconducting nanowire single-photon detectors: A perspective on evolution, state-of-the-art, future developments, and applications." Applied Physics Letters 118.19 (2021).
[3] T. Zhang et al. "Superconducting single-photon detector with a speed of 5 GHz and a photon number resolution of 61." Photonics Research 12.6 (2024): 1328-1333.
[4] G.-Z. Xu, et al. "Superconducting microstrip single-photon detector with system detection efficiency over 90% at 1550 nm." Photonics Research 9.6 (2021): 958-967.

Superconducting Qubit Control with Ultra-Low-Power Cryo-CMOS Multiplexer at Millikelvin Temperatures

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Quantum computing has the potential to revolutionize the way we process information, but scaling up the number of qubits presents a formidable challenge. Large-scale superconducting quantum computers require high-fidelity control and readout of large numbers of qubits at millikelvin temperatures, resulting in a massive input-output bottleneck. Moreover, the instrumentation and hardware required to control and manipulate qubits scale approximately linearly with the number of qubits, imposing significant economic, spatial, and thermal constraints. An intriguing solution to this problem is to place custom-designed control electronics at the same temperature stage as the qubits, thereby reducing the wiring problem. However, detrimental effects due to cross-coupling between the qubits and the electronic and thermal noise generated during cryo-electronics operation need to be avoided, as superconducting qubits are extremely sensitive to thermal noise at microwave frequencies [1]. In this talk, we will present our work on a cryo-CMOS multiplexer for superconducting qubits [2], [3], with a static power consumption of only 0.6 μW (Fig. 1). This low power consumption allows the multiplexer to interface with superconducting qubits at millikelvin temperatures without affecting single qubit gate fidelity, which remains as high as 99.93%. This approach has the potential to ease the wiring problem and open new possibilities for scalable quantum computing architectures.

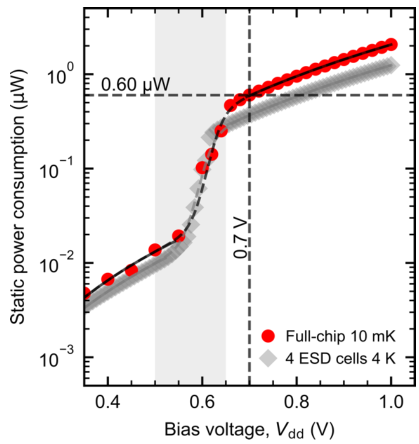

Fig. 1: Static power consumption of the bulk 28nm cryo-CMOS multiplexer at 10 mK. A significant portion of the static power consumption can be attributed to leakage in the standard ESD protection cells.

[1] A. Potočnik et al. Quantum Sci Technol, 7, 015004, (2021).
[2] R. Acharya et al. 2022 IEEE Symposium on VLSI Technology and Circuits.
[3] R. Acharya et al. Nat. Electron., 6, 900, (2023).

SFQ electronics for chip-based quantum computing

M. Arzeo on behalf of the SEEQC Team[1,2,3]
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Quantum computers promise to revolutionize science and industry leveraging a completely different computation paradigm. Despite the great progress made in the last years, the realization of a fault-tolerant quantum computer for real useful applications remains an enormous engineering challenge.
SEEQC is developing the first fully chip-based quantum computing platform for global businesses. SEEQC combines classical and quantum technologies to address the efficiency, stability, scalability and cost issues endemic to quantum computing systems. The company applies classical superconducting single-flux quantum (SFQ) electronics to perform digital readout and control of quantum bits in a unique chip-scale architecture. SEEQC’s quantum system provides the energy- and cost-efficiency, speed and digital control required to bring the first commercially scalable, problem-specific quantum computing application to market. In terms of scalability, this technology solution is eliminating many of the challenges of building fault-tolerant quantum computers. Moreover, SEEQC is one of the first companies to have built a superconductor multi-layer commercial chip foundry and through this experience has the infrastructure in place for design, testing and manufacturing of quantum-ready superconducting electronics.

By taking advantage of this chip-scale digital quantum computing architecture we can deliver a truly heterogenous platform that seamlessly integrates our Quantum Processor Units (QPUs) with GPUs and CPUs. In collaboration with NVIDIA, we are working toward the world’s first all-digital, ultra-low-latency chip-to-chip link between quantum computers and GPUs. This QPU to GPU interface is built to streamline QPU integration within existing HPC infrastructure, without the need for new software and hardware interfacing technology.

In this talk we will present our unique innovative solution and the path towards the first chip-based quantum computing platform, report on some relevant technological advances made and walk the audience through the company roadmap for the upcoming years.

Probing the dynamics of quasiparticles in a superconducting nanowire by scanning critical current microscopy

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Quasiparticles reduce the performance of superconducting circuits. Understanding the relaxation dynamics of quasiparticles is thus of primary importance. To address this issue, we have developed a new Scanning Critical Current Microscopy technique based on a very low temperature Scanning Tunneling Microscope (STM) working at 50 mK. The STM tip allows to inject quasiparticles while independently tuning their energy and their injection rate, through, respectively, the bias voltage and the tunneling current. We probe the effects of quasiparticle injection by measuring the critical current of a nanowire while injecting quasiparticles. For high energy quasiparticles (with an energy much larger than the superconducting gap), the reduction of the critical current is mainly controlled by the injected power and, marginally, by the injection rate. Our results prove a thermal mechanism for the reduction of the critical current and give insight into the rapid dynamics of the generated hot spot [1]. For quasiparticles at energies close to the superconducting gap, the critical current is decreased far beyond a simple heating effect. Our results suggest that this catastrophic quasiparticle poisoning is due to a long relaxation time of the order of hundreds of nanoseconds, two orders of magnitude larger than the diffusion thermalization time in our nanowire.

[1] T. Jalabert et al. "Thermalization and dynamics of high-energy quasiparticles in a superconducting nanowire." Nature Physics 19, 956–960 (2023).
[2] T. Jalabert et al. "Catastrophic quasiparticle poisoning at energies close to the superconducting gap." In preparation.

Superconducting Microstrip-Based Electronics: Revisiting the Cryotron

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Superconducting microstrips exhibit a range of nonlinear behaviors that could in principle be exploited for electronics. Indeed, starting in the 1950s, a two-port superconducting device called a cryotron was conceived of and pursued as a computing and storage element vigorously (until the mid 1970s). However, the advent of the integrated circuit reduced commercial interest in the device, and the discovery of the Josephson junction diverted interest from the physics community. Since 2014, however, members of my research group have developed a range of novel multi-terminal devices (ranging in dimensions from 10’s of nm to 10’s of µm’s) based on the cryotron which have been used to implement several small- and medium-scale circuits. Unlike the cryotron, these devices often use thermal or direct current injection to realize switching and have speed limitations associated with the thermal relaxation processes that necessarily accompany this approach.

In this talk, I will review our progress starting from the development of the first of these devices, the nanocryotron, and also discuss relevant work by others in the field. I will suggest some of the key principles that we used in developing circuits based on these devices and discuss what their performance limits are. I will also discuss some practical application areas for these and similar devices.

Proximitized gate-controlled quantum dots in germanium

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Planar germanium quantum wells have recently been shown to host a hard-gapped superconductor-semiconductor interface. Additionally, quantum dot spin qubits in germanium are well-suited for quantum information processing, with isotopic purification to a nuclear spin-free material expected to yield long coherence times. Therefore, as one of the few group IV materials with the potential to host superconductor-semiconductor hybrid devices, proximitized quantum dots in germanium are a crucial ingredient towards topological superconductivity and0 novel qubit modalities.
I will present our work on developing quantum-dot (QD) devices in a Ge/SiGe heterostructure proximitized by superconductor (SC) regions of platinum germanosilicide (PtGeSi), forming gate-tunable SC-QD-SC junctions. We show tunability of the QD-SC coupling strength, as well as gate control of the ratio of charging energy and the induced gap. We further exploit this tunability by exhibiting control of the ground state of the system between even and odd parity. Furthermore, we characterize the critical magnetic field strengths, finding a robust critical out-of-plane field of 0.91(5) T. Finally, we explore sub-gap spin splitting in the device, observing rich physics in the resulting spectra, that we model using a zero-bandwidth model in the Yu-Shiba-Rusinov limit. The demonstration of controllable proximitization at the nanoscale of a germanium quantum dot opens up the physics of novel spin and superconducting qubits, and Josephson junction arrays in a group IV material.

[1] L. Lakic et al. “A proximitized quantum dot in germanium.” arXiv:2405.02013 (2024).

Full counting statistics of Yu-Shiba-Rusinov states

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With the help of scanning tunneling microscopy (STM) it has become possible to address single magnetic impurities on superconducting surfaces and to investigate the peculiar properties of the in-gap states known as Yu-Shiba-Rusinov (YSR) states. These systems are an ideal playground to investigate multiple aspects of superconducting bound states, such as the occurrence of quantum phase transitions or the interplay between Andreev transport physics and the spin degree of freedom, with profound implications for disparate topics like Majorana modes or Andreev spin qubits. However, until very recently YSR states were only investigated with conventional tunneling spectroscopy, missing the crucial information contained in other transport properties such as shot noise. In this paper we adapt the concept of full counting statistics (FCS) to provide the deepest insight thus far into the spin-dependent transport in these hybrid atomic-scale systems. We illustrate the power of FCS by analyzing different situations in which YSR states show up including single-impurity junctions with a normal and a superconducting STM tip, as well as double-impurity systems where one can probe the tunneling between individual YSR states [1]. The FCS concept allows us to unambiguously identify every tunneling process that plays a role in these situations and to classify them according to the charge transferred in them. Moreover, FCS provides all the relevant transport properties, including current, shot noise, and all the cumulants of the current distribution. In particular, our approach is able to reproduce the experimental results recently reported on the shot noise of a single-impurity junction with a normal STM tip [2]. We also predict the signatures of resonant (and nonresonant) multiple Andreev reflections in the shot noise and Fano factor of single-impurity junctions with two superconducting electrodes and show that the FCS approach allows us to understand conductance features that have been incorrectly interpreted in the literature. In the case of double-impurity junctions we show that the direct tunneling between YSR states is characterized by a strong reduction of the Fano factor that reaches a minimum value of 7/32, a significant result in quantum transport. The FCS approach presented here can be naturally extended to investigate the spin-dependent superconducting transport in a variety of situations, such as atomic spin chains on surfaces or superconductorsemiconductor nanowire junctions, and it is also suitable to analyze multiterminal superconducting junctions, irradiated contacts, and many other basic situations.

[1] H. Huang et. al. “Tunneling dynamics between superconducting bound states at the atomic limit.” Nat. Phys. 16, 1227 (2020)
[2] U. Thupakula et. al. “Coherent and Incoherent Tunneling into Yu-Shiba-Rusinov States Revealed by Atomic Scale Shot-Noise Spectroscopy.” Phys. Rev. Lett. 128, 247001 (2022).

Topological surface superconductivity in $PtBi_2$

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Trigonal $PtBi_2$ is a layered semimetal without inversion symmetry, featuring 12 Weyl points in the vicinity of the Fermi energy. Its topological Fermi arcs were recently shown to superconduct at low temperatures where bulk superconductivity is absent. We present first-principles calculations to investigate in detail the bulk and surface electronic structure of $PtBi_2$ and obtain the spin texture as well as the momentum-dependent localization of the arcs. Motivated by the experimentally observed recovery of inversion symmetry under pressure or upon doping, we interpolate between the two structures and determine the energy and momentum dependence of the Weyl nodes. For deeper insights into the surface superconductivity of $PtBi_2$, we construct a symmetry-adapted effective four-band model that accurately reproduces the Weyl points of $PtBi_2$. We supplement this model with an analysis of the symmetry-allowed pairings between the Fermi arcs, which naturally mix spin-singlet and spin-triplet channels. Moreover, the presence of surface-only superconductivity facilitates an intrinsic superconductor-semimetal-superconductor Josephson junction, with the semimetallic phase sandwiched between the two superconducting surfaces. For a phase difference of π, zero-energy Andreev bound states develop between the two terminations.

[1] R. Vocaturo et al. “Electronic structure of the surface superconducting Weyl semimetal $PtBi_2$”, arXiv:2404.19606.
[2] A. Kuibarov et al. “Evidence of superconducting Fermi arcs”, Nature 626, 294 (2024).
[3] A. Veyrat et al. “Berezinskii–Kosterlitz–Thouless transition in the type-I Weyl semimetal $PtBi_2$”, Nano Lett. 23, 1229 (2023).

Microwave characterization of gate-controlled superconducting nanowires

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Gate-controlled superconductivity has recently gained attention due to its promising applications, particularly for superconducting logics and cryogenic switches, as well as the underlying microscopic mechanism, which remains debated [1, 2]. One way to approach this phenomenon is to study it in the microwave regime, by gating a portion of a superconducting resonator and observing how it affects the resonator frequency and quality factors [3, 4], or the time-domain response of the system [5].

In this talk, we present a microwave characterization of a gate-controlled superconducting nanowire embedded in a $\lambda/4$ coplanar waveguide resonator. The device is fabricated on silicon/silicon oxide substrate, with the circuitry made of aluminum, and the nanowire consists of a InAs core caped with a full shell of epitaxially grown aluminum. We show how resonator frequency and internal quality factor decrease as a function of the applied DC gate, consistent with the rising of the leakage current. Furthermore, we investigate the dynamics of the system under both continuous and pulsed excitation of the gate, measuring the sidebands amplitude in the first case and the characteristic response time in the second. Finally, we discuss how our results change with temperature.

[1] L. Ruf at al. “Effects of fabrication routes and material parameters on the control of superconducting currents by gate voltage.” APL Materials 11, 091113 (2023).
[2] M. F. Ritter et al. “A superconducting switch actuated by injection of high-energy electrons.” Nature Communications, 12, 1266 (2021).
[3] I. Golokolenov et al. “On the origin of the controversial electrostatic field effect in Superconductors.” Nature Communications 12, 2747 (2021).
[4] Y. Ryu et al. “Utilizing Gate-Controlled Supercurrent for All-Metallic Tunable Superconducting Microwave Resonators.” Nano Lett., 24, 1223-1230 (2024).
[5] F. Joint et al. “Dynamics of Gate-Controlled Superconducting Dayem Bridges.” arXiv:2405.07377.

Local and ultrafast dynamics of NbTiN superconducting nanowires

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In the context of Terahertz dynamics, superconductors have been already used to achieve ultra strong light-matter coupling [1] or for the ultrafast manipulation of THz waves through the collective modes of condensates [2]. In 2012, R. Matsunaga and R. Shimano demonstrated that superconductivity in NbN thin films can be suppressed, within a few picoseconds, using intense TeraHertz pulses that inject elementary excitations of the condensate. This study revealed that the resulting nonequilibrium state consists of normal state patches embedded within a superconducting matrix. The scale of these patches corresponds to the scale of the quasiparticle condensates (approximately 1 μm) [3].
Our research focuses on exploring the out-of-equilibrium dynamics at the local scale of the superconductor NbTiN through a metasurface state. First, we manufactured high-Q factor resonators using cut nanowires made of the superconductor NbTiN. Additionally, antennas were designed to concentrate intense terahertz light on specific micrometer-scale regions of the nanowires, corresponding to the characteristic scale of the quasiparticle condensates. Finally, employing 2D pump-probe terahertz spectroscopy, we track local changes in superconductivity within the nanowires at the picosecond scales.

[1] G. Scalari et al. "Superconducting complementary metasurfaces for THz ultrastrong light-matter coupling." New Journal of Physics. Volume 16, (2014).
[2] S. Duan et al. "Picosecond mode switching and Higgs amplitude mode in superconductor-metal hybrid Terahertz metasurface." Nanophotonics 11(18), (2022).
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Gate Induced Nanoscale Currents Distribution in Nb Dayem Bridges

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Gate-controlled supercurrent (GCS) effect is observed when, through an applied gate voltage (V_G), a superconducting device is switched between two states with different resistances, in analogy to what happens controlling the logic state of semiconductor transistors [1,2]. The explanation about the origin of this effect, that is detected on devices fabricated with many superconductors, several geometries and substrates, is still under debate having different possible scenarios been proposed by various research groups [2]. Among the main proposals, the measurement of a leakage current which flows from the gate electrode into the superconducting nano-constriction upon the V_G application is counted as possible explanation of the mechanism behind the GCS effect. Some works suggest this current could heat up the superconducting bridge and drive it to the normal state [3]; others demonstrate their results are consistent with a nonequilibrium superconducting state resulting from the absorption of phonons generated by the leakage current [4,5].

In this work, Nb Dayem bridge devices on Si/SiO_2 substrates have been fabricated with the aim to directly evaluate the leakage current measuring the resistance in the region of the gate. Room temperature local transport measurements have been performed by using a field emission scanning electron microscope equipped with four micromanipulators and nanometric tungsten tips to acquire spatial resistances maps in the region between the superconducting bridge and the lead of the V_G.

This study allows us to get insight into the electrical isolation of the Nb Dayem bridge, the gate thresholds to induce leakage currents, and the role of surface inhomogeneities in setting out the paths of leakage currents flow.

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[3] T. Elalaily et al. Nano Lett. 21, 9684 (2021).
[4] T. Elalaily et al. ACS Nano 17, 5528 (2023).
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Dirac surface states and superconductivity in Nb- and Ta-based A15 compounds

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Using first-principle calculations, we investigate the electronic, topological, and superconducting properties of Nb_3X (X=Ge, Sn, Sb) and Ta_3Y (Y=As, Sb, Bi) A15 compounds. We demonstrate that these compounds host Dirac surface states, which are related to a nontrivial $\mathbb{Z}_2$ topological value. The spin-orbit coupling (SOC) splits the highly degenerate R point close to the Fermi level enhancing the amplitude of the spin Hall conductance. Indeed, despite the moderate spin orbit of the Nb-compounds, a large spin Hall effect is also obtained in Nb_3Ge and Nb_3Sn compounds. We show that the Coulomb interaction opens the gap at the R point thus making the occurrence of Dirac surface states more obvious. We then investigate the superconducting properties by determining the strength of the electron-phonon BCS coupling. The evolution of the critical temperature is tracked down to the 2D limit indicating a reduction of the transition temperature, which mainly arises from the suppression of the density of states at the Fermi level. Finally, we propose a minimal tight-binding model based on three coupled Su-Schrieffer-Heeger chains with t_{2g} Ta and Nb orbitals reproducing the spin-orbit splittings at the R point among the π-bond bands in this class of compounds. We separate the kinetic parameters in π and δ bonds, in intradimer and interdimer hoppings, and discuss their relevance for the topological electronic structure. We point out that Nb_3Ge might represent a $\mathbb{Z}_2$ topological metal with the highest superconducting temperature ever recorded [1].

[1] R. M. Sattigeri et al. Phys. Rev. B **109**, 075119 (2024).

List of speakers