Superconducting Kinetic Inductances

706. WE-Heraeus-Seminar

11 - 13 Nov 2019
at the Physikzentrum Bad Honnef/Germany

WILHELM UND ELSE
HERAEUS-STIFTUNG

Introduction

The Wilhelm und Else Heraeus-Stiftung is a private foundation that supports research and education in science with an emphasis on physics. It is recognized as Germany's most important private institution funding physics. Some of the activities of the foundation are carried out in close cooperation with the German Physical Society (Deutsche Physikalische Gesellschaft). For detailed information see https://www.we-heraeus-stiftung.de

Aims and scope of the 706. WE-Heraeus-Seminar:

Over the last two decades, the rapid advances in the mesoscopic physics of superconductors and superconducting devices have resulted in the branching out of the field into several research directions, such as radio-frequency detectors close to the quantum limit, quantum electronics, and fundamental electrodynamics of disordered or granular superconductors. Although the scientific goals and investigation methods can be quite different between communities, there are several overarching themes of interest which are relevant to researchers across these fields. One of the most important is the concept of kinetic inductance, which can play a central role in the electrodynamics of superconducting thin films, therefore being crucial for designing kinetic inductance detectors and high-performance quantum circuits for quantum information processing. The workshop on "Superconducting Kinetic Inductances" will bring together researchers from these three different fields, in order to profit from mutual experiences and foster synergies between communities.

The workshop will be particularly important for PhD students and young postdoctoral researchers: they will get exposed to key scientific results, relevant for their present research, but which they otherwise risk ignoring due to the current lack of communication bridges between the adjacent communities joining for the workshop. Last, but not least, the workshop is also an opportunity to network and branch–out of one's immediate scientific vicinity, providing precious exposure for young scientists, but also access to established researchers.

Scientific Organizers:

Dr. Laura Cardani	INFN, Rome, Italy E-mail: laura.cardani@roma1.infn.it
Dr. Ioan Pop	Karlsruhe Institute of Technology, Germany E-mail: ioan.pop@kit.edu
Dr. Marc Scheffler	University of Stuttgart, Germany E-mail: marc.scheffler@pi1.physik.uni-stuttgart.de

Program

Sunday, 10 November 2019

17:00 – 21:00	Registration	
from 18:30	*BUFFET SUPPER / Informal get together*	

Monday, 11 November 2019

07:45	*BREAKFAST*	
08:50 – 09:00	Scientific organizers	**Welcome and Introduction**
09:00 – 09:45	David Haviland	**Kinetic Inductance, Josephson Inductance and The Superconductor-Insulator Quantum Phase Transition**
09:45 – 10:30	Jochem Baselmans	**Microwave Kinetic Inductance Detectors: An introduction**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Christoph Strunk	**Superconductivity vs. insulation in strongly disordered metal films**
11:45 – 12:30	Guy Deutscher	**Fundamentals of granular superconductivity**
12:30 – 12:45	**Conference Photo** (in front of the Physikzentrum/Main entrance)	
12:45	*LUNCH*	

Program

Monday, 11 November 2019

14:15 – 15:00	Nimrod Bachar	**Electrodynamics of Superconductors : To BCS and Beyond…**
15:00 – 15:45	Nataliya Maleeva	**Granular Aluminum: from circuit quantum electrodynamics to applications**
15:45 – 16:15	*COFFEE BREAK*	
16:15 – 17:00	Marco Vignati	**KIDs for Particle Physics**
17:00 – 17:45	Angela Kou	**A gate-tunable, field-compatible fluxonium**
17:45 – 18:00	Stefan Jorda	**About the Wilhelm and Else Heraeus Foundation**
18:30	*HERAEUS DINNER at the Physikzentrum (cold & warm buffet, free beverages)*	
20:00	**Poster Session**	

Program

Tuesday, 12 November 2019

07:45	*BREAKFAST*	
09:00 – 09:45	Oleg Astafiev	**Highly disordered superconductors and quantum phase-slips**
09:45 – 10:30	Nicholas Roch	**High impedance superconducting quantum circuits**
10:30 – 11:00	*COFFEE BREAK*	
11:00 – 11:45	Gianluigi Catelani	**Quasiparticles in superconducting qubits and resonators**
11:45 – 12:30	Pieter de Visser	**Energy resolved detection of single visible/near-infrared photons with kinetic inductance detectors**
12:30	*LUNCH*	
14:15 – 15:00	Alessandro Monfardini	**KID for GHz to THz Astronomy and Particle Physics**
15:00 – 15:45	Raphaëlle Delagrange	**RF properties of superconducting silicon**
15:45 – 16:15	*COFFEE BREAK*	
16:15 – 17:00	Pasquale Scarlino	**Microwave Cavity Quantum Electrodynamics with superconductor-semiconductor hybrid technology**
17:00 – 17:45	Karl Berggren	**Nanowire-Based Detectors and Electronics Using Kinetic Inductance**
18:30	*DINNER*	
20:00	**Poster Session**	

Program

Wednesday, 13 November 2019

07:45	*BREAKFAST*	
09:00 – 09:45	Peter Day	**Superconducting Devices Based on Non-linear Kinetic Inductance**
09:45 – 10:30	**Poster Awards & Award Talks**	
10:30 - 11:00	*COFFEE BREAK*	
11:00 – 11:45	Hélène le Sueur	**Charged fluctuators as a limit to the coherence of superconductors**
11:45 – 12:30	Alexey Ustinov	**Superconducting Metamaterials**
12:30 – 12:40	Scientific organizers	**Closing remarks**
12:40	*LUNCH*	

End of the seminar and *FAREWELL COFFEE* / **Departure**

Posters

1	Lisa Arndt	**Dual Shapiro steps of a phase-slip junction in the presence of a parasitic capacitance**
2	Jason Austermann	**Far-Infrared Kinetic Inductance Detectors at NIST-Boulder: Materials and Performance**
3	Nimrod Bachar	**Kubo spins in granular aluminum**
4	Eoin Baldwin	**Developing a next generation Microwave Kinetic Inductance Detector readout system based on the Xilinx ZCU111 RFSoC**
5	Julien Basset	**High kinetic inductance microwave resonators made by He-Beam assisted deposition of tungsten nanowires**
6	Alexey Bezryadin	**Kinetic inductance in nanowires: superconducting memory loops, microwave response, and Duffing instability**
7	Karthik Srikanth Bharadwaj	**Al based microwave resonators in the clean and dirty limit**
8	Marina Calero de Ory	**Development of Superconducting Resonators for molecular spin quantum processors**
9	Nicola Casali	**Phonon and light read-out of a macro-calorimeter for rare event searches exploiting kinetic inductance detectors**
10	Andrew Dane	**Superconducting Nb Resonators with Gold Nanodot Decorations**
11	Alessandro D'Arnese	**Superconducting granular aluminum films grown at cryogenic condition**

Posters

12	Michiel de Dood	**The limits of single photon detection with highly disordered materials**
13	Mario De Lucia	**Development of an MKIDs camera for astronomical applications**
14	Fabien Defrance	**Lumped element titanium nitride kinetic inductance detector with low loss dielectric substrate**
15	Eduard Driessen	**Unconventional non-equilibrium effects observed in high kinetic inductance materials, notably TiN**
16	Nikolaj Ebensperger	**Probing disordered thin-films with microwave resonators**
17	Manuel Garcia Redondo & Juan Manuel Salum	**Design of a Read-Out System for Cosmic Microwave Background Radiation**
18	Aviv Glezer Moshe	**Optical conductivity of granular aluminum films near the Mott metal-to-insulator transition**
19	Daria Gusenkova	**High power dispersive qubit readout and state preparation without parametric amplifier**
20	Thomas Huber	**Kinetic Inductance Measurement using a lumped-element LC-circuit in the MHz regime**
21	Marian Janík	**Hole spin qubits in Ge hut wires coupled to a superconducting resonator**
22	Sebastian Kempf	**Design considerations and optimization of superconducting GHz resonators for microwave SQUID multiplexing**

Posters

23	Haruhisa Kitano	**FIB-based microfabrication of Bi2212 and Fe(Te,Se) single-crystal devices and its application to basic researches**
24	Jianxin Lin	**YBCO nanoSQUIDs based on grain boundary Josephson junctions on MgO bicrystal substrates**
25	Juho Luomahaara	**Kinetic inductance bolometer technology for THz imaging systems**
26	Patrick Paluch	**Development, fabrication and characterization of resonator arrays and a microwave SQUID multiplexer based on planar superconducting lumped-element microwave resonators**
27	Martin Rymarz	**Passive Error Correction with Grid States in a Non-Reciprocal Superconducting Circuit**
28	Yildiz Saglam	**Electric field control of the superfluid density at (111)LaAlO3/SrTiO3 interfaces by microwave resonators**
29	Clarke Smith	**High-impedance circuits for parity measurements of cat qubits**
30	Martin Spiecker	**Granular aluminium: A superconducting material for high-impedance quantum circuits**
31	Jeremy Stevens	**Reset of sub-GHz Fluxonium Qubits**
32	Gerhard Ulbricht	**MKIDs in Dublin: Multilayer films for single-photon counting Kinetic Inductance Detectors**

33	Francesco Valenti	**Phonon traps reduce the quasiparticle density in superconducting circuits**
34	Benedikt Wilde	**SQUIDs in the Vicinity of Microwave Transmission Lines**
35	Patrick Winkel	**Implementation of a transmon qubit using superconducting granular aluminum**
36	Simon Zihlmann	**High impedance superconducting resonators made from high kinetic inductance NbN films for spin-read-out in Si hole spin qubits**

Abstracts of Lectures

(in alphabetical order)

Highly disordered superconductors and quantum phase-slips

O. V. Astafiev[1]

[1]*Skolkovo Institute of Science and Technology, Moscow, Russia*
[2]*Royal Holloway University of London, Egham, UK*
[3]*National Physical Laboratory, Teddington, UK*

Thin films of highly disordered materials are physically interesting objects and a powerful tool for demonstration of new phenomena of superconductivity. Among the unusual properties these materials have high resistance in the normal state, which turns to a high kinetic inductance in the superconducting state; they also turn to insulating states, when superconductivity is suppressed. We use thin films of InO_x, TiN and NbN to study quantum phase-slips in nanowires and narrow constrictions. Compact meanders from the same materials allow us to form lossless high impedance environment for the nanowires to study DC-transport in superconducting nanowires and constrictions. With the structures we have demonstrated a series of phenomena such as Coherent Quantum Phase Slip (CQPS) Effect [1], in different materials; interference of two phase-slip amplitudes (Aharonov–Casher effect) [2]. In DC transport measurements of the nanowires we distinguish different regimes leading to blockade and argue that large blockades (~0.1 – 10 mV) are attributed to incoherent processes unrelated to CQPS [3].

References

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[2] S. E. de Graaf, S. T. Skacel, T. Hoenigl-Decrinis, R. Shaikhaidarov, H. Rotzinger, S. Linzen, M. Ziegler, U. Hübner, H.-G. Meyer, V. Antonov, E. Il'ichev, A. V. Ustinov, A. Ya. Tzalenchuk and O. V. Astafiev. Nature Physics **14**, 590–594 (2018).

[3] S. E. de Graaf, R. Shaikhaidarov, T. Lindström, A. Ya. Tzalenchuk, and O. V. Astafiev. Phys. Rev. B 99, 205115 (2019).

Electrodynamics of Superconductors: To BCS and Beyond..

Nimrod Bachar

Department of Quantum Matter Physics, University of Geneva, Geneva, Switzerland

Superconductivity is usually presented by its two inherent properties: perfect conducting and diamagnetic states. These properties are intimately coupled to the complex conductivity which can be measured by optical spectroscopy. However, in difference from other spectroscopy techniques, complex conductivity allows us to study not only the single particle excitations but also the collective excitations which cannot be probed by other means. The superconducting Cooper pairs are just a private example of such a collective mode at zero frequency.
In this talk I will cover the basic concepts of excitations both in the normal and the superconducting state, mainly from the experimental point of view. Starting from the metallic state, I will review several important properties of the complex conductivity which will come in handy in our trip to the SC realm. I will then review the temperature and frequency evolution of the complex conductivity in a conventional SC as was explained by the Mattis-Bardeen theory through the use of the BCS coherence factors. Important properties such as the SC energy gap and the superfluid density can be directly extracted from the dynamic conductivity data. I will draw the connections between the superfluid density and other observables such as the penetration depth, the superfluid stiffness and the kinetic inductance of a SC. In what will follow, I will review several advanced topics in the optical properties of conventional and unconventional SC such as sub-gap collective excitations, pseudo-gap, spectral weight transfer and more.

Microwave Kinetic Inductance Detectors: An introduction

Jochem Baselmans[1,2]

[1] *SRON Netherland institute for Space Research, Utrecht, the Netherlanfds*

[2] *Delft University of Technology, Delftm the Netherlands*

Microwave Kinetic Inductance Detectors (MKIDs) are the building block of the most sensitive detector arrays for THz astronomy, probing of the CMB and optical astronomy. MKIDs are microwave resonators capable opf aborbing radiation with a high efficiency are made from a superconducting thin film, which is either elemental (Aluminium, Hafnium), a compound (PtSi, TiN) or a bilayer (TiAl). Radiation with a photon energy exceeding the energy gap of the superconducting film modifies the complex surface impedance, thereby reducing the resonator Q factor and reducing its resonant frequency. Probing the resonator with a single frequency readout signal results in measurable changes in the readout signal that can be digitized and prost-processed. In my presentation I will explain the microscopic physics of MKIDs focusing on the above process of radiation absorption and detection. I will compare the standard theory with recent experimental results highlighting agreements and discrepancies.

Nanowire-Based Detectors and Electronics Using Kinetic Inductance

Karl Berggren

Massachusetts Institute of Technology,
Electrical Engineering and Computer Science, Cambridge, MA, USA

Superconducting-nanowire-based single-photon detectors have accommodated their anomalous kinetic inductance for more than 15 years to realize high-performance for applications ranging from LIDAR to integrated-circuit evaluation. Recently, the kinetic inductive properties of superconducting waveguides have been used to demonstrate high-pixel-number imagers. However, this technology can be equally useful in the realization of electronics, where non-Josephson-junction-based circuits can be demonstrated. The tunability of the resulting inductive devices furthermore suggests they may be of value for dynamic modulation of microwave signals, which could in turn be used to improve the performance of the single-photon detectors. As an engineering platform, this system thus presents fascinating opportunities for future work.

Quasiparticles in superconducting qubits and resonators

G. Catelani[1]

[1]JARA Institute for Quantum Information (PGI-11)
Forschungszentrum Jülich, Jülich, Germany

Superconducting qubits are one of the most promising hardware platform for quantum computation and simulation. Despite huge improvements over the past two decades, longer coherence times than those achieved so far would be helpful to reduce the overhead necessary for implementing quantum error correction algorithms. In this talk I will first review briefly the history of superconducting qubits and their coherence. Then I will focus on a particular decoherence mechanism, quasiparticles, that is known to affect the performance of other superconducting devices as well. I will summarize theoretical and experimental studies that together have advanced our understanding of quasiparticles: on one hand, the sensitivity of qubits to quasiparticles leads to decoherence; on the other hand, it makes it possible to measure the quasiparticle dynamics. Finally, I will discuss ongoing efforts aimed at reducing the detrimental effects of quasiparticles.

Superconducting Devices Based on Non-linear Kinetic Inductance

P.Day[1], B.H. Eom[1], N. Klimovich[2] and H. Leduc[1]

[1] *Jet Propulsion Lab, Pasadena CA, USA*
[2] *Caltech, Pasadena CA, USA*

The kinetic inductance of a superconducting film is current dependent, varying to first order as the square of the applied current. Under certain conditions, this current dependence is not associated with increased dissipation and represents an almost purely reactive nonlinearity. As a result, superconducting transmission lines made from thin films with high kinetic inductance can support nonlinear optical processes including three- and four-wave mixing. These processes can result in useful effects such as parametric amplification, harmonic generation or frequency conversion depending on which phase matching conditions are satisfied. Various devices and applications utilizing these effects will be discussed including a wide-band parametric amplifier that reaches quantum limited sensitivity.

Energy resolved detection of single visible/near-infrared photons with kinetic inductance detectors

Pieter de Visser[1], Vignesh Murugesan[1], David Thoen[2] and Jochem Baselmans[1,2]

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[2] Department of Microelectronics, Faculty of Electrical Engineering, Mathematics and Computer Science, Delft University of Technology, Mekelweg 4, 2628CD Delft, The Netherlands

A large camera, in which each pixel is a noiseless, photon counting detector, which can resolve the energy of each photon, is a deep wish for applications where every photon counts, e.g. in astronomy, biophysics and quantum optics. Novel space telescopes hunting for life on exoplanets require very low noise detectors (at wavelengths of 300 nm to 2 micron), ideally with an energy resolution E/dE>100. The energy resolution practically eliminates the dark counts that limit semiconductor detectors. We study superconducting energy-resolving Microwave Kinetic Inductance Detectors (MKIDs), where the photon energy breaks Cooper pairs, the number of which can be determined from the response of a superconducting microwave resonator. I will review the promises, status and challenges of MKIDs for visible/near-infrared light, after which I will focus on recent experiments that we performed to understand and improve the energy resolution.

A visible/near-IR photon (1-3 eV energy) which is absorbed in a superconductor, operated at 100 mK, creates a few thousand quasiparticles (at energy ~0.2 meV) through various stages of electron-phonon interaction. We have measured that hot, high-energy phonons lost in this downconversion process strongly comprise the energy resolution to E/dE<20 for aluminium MKIDs fabricated on a solid substrate at a wavelength of 400 nm. When fabricated on a 120 nm SiN membrane, we show that E/dE increases to ~50, clearly demonstrating that high-energy phonons are more effectively trapped. The resolving power at the longest measured wavelength increases from ~10 on substrate to ~20 on membrane. We plan to take the last step towards the fundamental limit by patterning the membrane into a phononic crystal to trap the phonons longer.

RF properties of superconducting silicon

P. Bonnet, R. Delagrange, D. Débarre and F. Chiodi

Centre de Nanosciences et de Nanotechnologies (C2N), CNRS, Univ. Paris Sud, Université Paris-Saclay, 91120 Palaiseau, France

D. Flanigan, H. le *Sueur*

Quantronics group, SPEC, CEA, CNRS, Université Paris-Saclay, CEA Saclay, 91191 Gif-sur-Yvette, France

Silicon can be made superconducting by ultra-doping with boron atoms. To reach the required out-of-equilibrium concentration, $10^{20} - 10^{21}$ cm^{-3}, we use a laser doping technique that provides Si:B layers with critical temperatures up to 0.7 K [1,2]. This material has been used to fabricate DC superconducting devices like SQUID, Josephson junctions and, now, high kinetic inductance resonators. It may thus be promising for applications, since its fabrication could be integrated in existing silicon industrial processes.

After reviewing the material itself by detailing the fabrication and the characterization of the doped layers, I will present its RF properties.

We made circuits in Si:B that resonate in the GHz range with a quality factor ~ 4000. Thanks to its low charge carrier density, its kinetic inductance is as high as a few hundreds of pH yielding a ratio L_k/L_{tot} close to one. We prove in addition that this kinetic inductance has an unexpectedly high Kerr non-linearity. At last, we probe the quasiparticles dynamics by monitoring the temporal response of the resonator to a pulse of light.

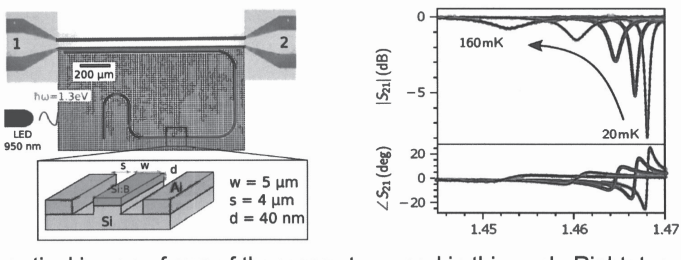

Figure: left: optical image of one of the resonators used in this work. Right: temperature dependence of the resonance.

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Fundamentals of granular superconductivity

Guy Deutscher
School of Physics and Astronomy, Tel Aviv University, Israel

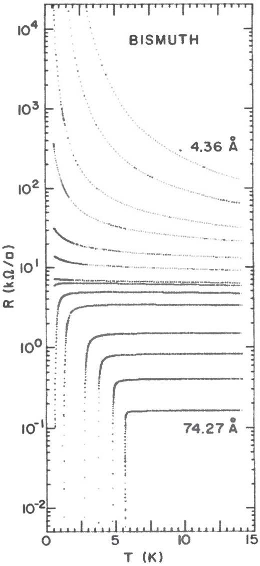
We define granular superconductors as composed of small well crystallised metallic grains of a material that is superconducting in bulk form, in which the small grain size induces a splitting of the energy levels that is larger than the energy gap of the bulk. When isolated, such grains cannot be superconducting because pairing cannot overcome the splitting of the energy levels. Besides, if they contain an odd number of electrons, they should bear the spin of the electron singly occupying the highest occupied energy level, another factor that is not favorable for superconductivity.
Yet experiments show that if such grains are weakly coupled through thin insulating barriers or Sharvin contacts, the resulting composite material can be superconducting with a critical temperature even higher than that of the bulk superconductor. This interesting phenomenon has been known for many years, but it is only recently that the respective roles of electron confinement and of the effective electrostatic charging energy of the grains have been disentangled. The vicinity of a Mott metal to insulator transition and of a BCS to Bose-Einstein Condensation cross-over appears to play a key role in the special properties of granular superconductors.
One of these remarkable properties is that up to very close to the Metal to Insulator (M/I) transition they can retain a large superconducting gap value, while at the same time having a very small superfluid density. On the contrary, for atomically disordered superconductors in which the M/I transition is of the Anderson type, the gap is strongly depressed. Fundamentally, it is granularity as found for instance in granular aluminum that allows its application for high inductance devices.

Kinetic Inductance, Josephson Inductance and The Superconductor-Insulator Quantum Phase Transition

D. B. Haviland[1]

[1]KTH Royal Institute of Technology, Stockholm, Sweden

Superconductors mediate a flow of energy with zero loss. The energy moves not only through the electromagnetic fields, but also as kinetic energy in the current of Cooper pairs which carries both charge and mass. From a phenomenological point of view, it is arbitrary what we attribute to charge or mass as both have the same



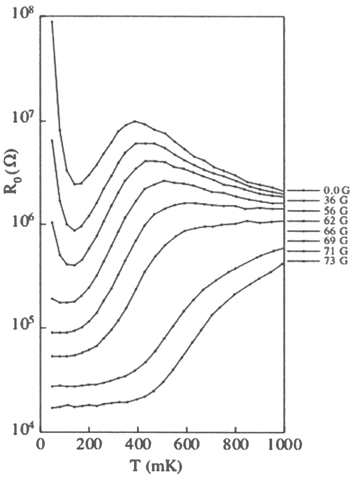


Figure 1: The superconductor-insulator transition induced by changing film thickness (left [1]), and by changing magnetic flux threading SQUIDs in a long series array (right

physical consequence. Both result in inductance of the superconducting circuit. Cooper pair scattering or tunneling reduces the number of pairs which carry a fixed current, resulting in larger kinetic inductance. When the total inductance becomes large enough, the superconductor becomes an insulator because the self-charge of a single Cooper pair gives rise to a Coulomb blockade that stops the flow. This talk will describe experiments with 2D superconducting films and series arrays of Josephson junctions demonstrating a superconductor-insulator transition. Possible applications of kinetic inductance in the burgeoning field of cavity optomechanics will also be mentioned.

References

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A gate-tunable, field-compatible fluxonium

M. Pita-Vidal[1], A. Bargerbos[1], C.-K. Yang[2], D. van Woerkom[2], W. Pfaff[2], P. Krogstrup[3], L. P. Kouwenhoven[1,2], G. de Lange[2] and <u>A. Kou</u>[2]

[1]QuTech and Kavli Institute of Nanoscience, Delft University of Technology, Delft, the Netherlands
[2] Microsoft Quantum Lab Delft, Delft, the Netherlands
[3] Microsoft Quantum Materials Lab and Center for Quantum Devices, Niels Bohr Institute, University of Copenhagen, Lyngby, Denmark

Superconducting circuits are one of the most flexible platforms for building detectors. They have been used to for magnetic field sensing [1], cosmic microwave background detection [2], and for measure quasiparticle lifetimes [3]. The fluxonium is a particularly useful circuit since its spectrum strongly depends on the properties of its phase-slip junction and has been shown to have narrow linewidths [4]. In this talk I will discuss our work building a fluxonium device based on a superconductor-proximitized semiconducting nanowire. We demonstrate in-situ tuning of the Josephson energy of the fluxonium using an electrostatic gate. Our fluxonium device can also be operated up to 1T. We use the fluxonium spectrum to map out the Josephson energy of the junction as a function of the magnetic field. At high magnetic fields, we observe the anomalous Josephson effect, which indicates the breaking of multiple symmetries in the junction. Our work demonstrates the utility of the fluxonium device for exploring mesoscopic physics and paves the way for detecting and manipulating Majorana zero modes with the fluxonium.

References

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Charged fluctuators as a limit to the coherence of superconductors.

H. le Sueur[1,2], A. Svilans[2], N. Bourlet[2], A. Murani[2], L. Bergé[1], L. Dumoulin[1], and P. Joyez[2]

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[2] *Quantronics group, SPEC, CEA, CNRS, Univ. Paris-Saclay, CEA Saclay 91191 Gif-sur-Yvette Cedex, France*

By analyzing experiments on thin-film resonators of NbSi and TiN, we elucidate a decoherence mechanism at work in disordered superconductors. This decoherence is caused by charged Two Level Systems (TLS) which couple to the conduction electrons in the BCS ground state, inducing fluctuations of the kinetic inductance.

Standard theories of mesoscopic disordered conductors are used to describe this effect, linking electronic (microscopic) decoherence and electromagnetic (macroscopic) decoherence in superconductors.

Given the omnipresence of charged TLS in solid-state systems, this decoherence mechanism affects all experiments involving disordered superconductors, and more strongly so devices with smaller cross-sections. In particular, we show it easily explains the poor coherence observed in quantum phase slip experiments and may contribute to lowering the quality factors in disordered superconductor resonators.

References

[1] H. le Sueur et al., arXiv:1810.12801, (2018)

Granular Aluminum: from circuit quantum electrodynamics to applications

N.Maleeva[1]

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Granular Aluminum [1, 2] (grAl), consisting of remarkably uniform grains connected by Josephson contacts [3] have attracted interest since the sixties thanks to their rich phase diagram [4, 5] and practical advantages, like increased critical temperature [2, 6], critical field [7, 8], and kinetic inductance [9]. Here we offer the measurement and modeling of circuit quantum electrodynamics [10] properties of grAl microwave resonators in a wide frequency range, up to the spectral superconducting gap. The self-Kerr coefficients we observed are ranged from 10^{-2} Hz to 10^{5} Hz, within an order of magnitude from analytic calculations based on grAl microstructure. According to the strength of the nonlinearity, we suggest to use thin film structures from grAl as superinductors [11–14] and microwave kinetic inductance detectors [15–17], the lowest possible Kerr nonlinearity; as parametric amplifiers and frequency converters, the self-Kerr nonlinearity is in kHz range; and as nonlinear element of transmon, the highest possible self-Kerr.

References

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KID for GHz to THz Astronomy and Particle Physics

A. Monfardini[1] for the Néel Astrophysics Instrumentation group, NIKA2, KISS and CONCERTO collaborations

[1] Institut Néel, CNRS, Grenoble, France

In this applicative talk, I will describe our developments, achieved and on-going, in the domain of Kinetic Inductance Detectors for Astronomy and particles detection. In particular, I will present recent astronomical results and status of NIKA2 imager/polarimeter. NIKA2 is currently the only instrument based on KID available to the astronomical community via open competitive calls. I will then describe briefly the KISS and CONCERTO large field-of-view spectrometers based on KID, our studies concerning the sub-gap KID and in the end the Wifi-KID, a contact-less detector allowing sensing a-thermal phonons in a massive crystal.

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High impedance superconducting quantum circuits

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Superconducting quantum circuits based on Josephson junctions have laid a very promising route to quantum information processing. As of today, most of these circuits are operated in the low impedance regime, since the impedance offered by conventional circuitry is close to 50 Ω. So far, very little is known about high impedance circuits, but the first incursion in this terra incognita gave birth to the most coherent superconducting qubit demonstrated so far: the Fluxonium. In this talk I will present our recent efforts to develop a new class of superinductors, based either on Josephson junction arrays or Indium Oxyde nanowire. Superinductors offer the promise of new charge-insensitive qubit prototypes, ultrasmall footprints amplifiers, and powerful analog simulators of many-body systems.

Microwave Cavity Quantum Electrodynamics with superconductor-semiconductor hybrid technology

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Semiconductor qubits rely on the control of charge and spin degrees of freedom of electrons or holes confined in quantum dots (QDs). Typically, semiconductor qubit-qubit coupling is short range, effectively limiting qubit distance to the spatial extent of the wavefunction of the confined particle (a few hundred nanometers). This is a significant constraint towards scaling of the QD-based architectures to reach dense 1D or 2D arrays of QDs.

Inspired by techniques originally developed for circuit QED, we recently demonstrated the strong coupling limit of individual electron charges [1,2] confined in GaAs quantum dots, by using the enhancement of the electric component of the vacuum fluctuations of a resonator with impedance beyond the typical 50 Ohm of standard coplanar waveguide technology.

By making use of this hybrid technology, we recently realized a proof of concept experiment, where the coupling between a transmon and a double QD (DQD) is mediated by virtual microwave photon excitations in a high impedance SQUID array resonator, which acts as a quantum bus enabling long-range coupling between dissimilar qubits [3]. Similarly, we achieved coherent coupling between two DQD charge qubits separated by approximately ~50 um [4]. In the dispersive regime, we spectroscopically observed qubit-qubit coupling as an avoided-crossing in the energy spectrum of the DQD charge qubits. The methods and techniques developed in this work are transferable to QD devices based on other material systems and can be beneficial for spin based hybrid systems [5].

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Superconductivity vs. insulation in strongly disordered metal films

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I will provide an overview over the peculiar superconducting properties of strongly disordered thin films, when the localization transition is approached. Upon an increase of disorder at first quantum corrections to the conductivity become sizable. In magnetic field the appearance of a quantum phase transition is signaled by a crossing point in the magnetoresistance isotherms. In materials like TiN and InO the quantum corrections become singular and a peculiar insulating state with strong spatial inhomogeneities is formed. There are strong indications for the presence of preformed Cooper pairs in the insulating regime. At the high-field side insulation, both quantum metallic behavior and more conventional hopping insulation is found. Other materials such as NbSi display apparent saturation of the resistance after an initially superconducting or insulating trend. Similar phenomenology appears in granular aluminium or artificial Josephson junction networks. This raises the question whether also homogeneously disordered films can be understood as self-organized random Josephson networks. As the information accessible by dc-charge transport measurements is limited, the potential of different complementary experimental probes in the vicinity of the transition is discussed.

Superconducting Metamaterials

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Metamaterials are artificial engineered media that enable tailored interactions with electromagnetic waves. The design flexibility of superconducting circuits allows for utilizing small structures down to the nanoscale while maintaining low loss properties, very strong and well-controlled nonlinearity, and frequency tunability in the microwave and mm-wave frequency ranges [1,2]. Compared to their normal counterparts, superconducting meta-atoms can be made extremely compact, down to a tiny fraction of the radiation wavelength, by employing high kinetic inductance effects. Superconductors also open door to designing quantum metamaterials comprised of arrays of superconducting qubits. This unlocks emerging new field for fundamental studies in quantum optics, opening a possibility to explore collective quantum dynamics under very strong coupling between electromagnetic field and artificial atoms [3,4].

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KIDs for Particle Physics

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Kinetic Inductance Detectors (KIDs) feature a straightforward scalability to hundreds or thousands detectors compared to other cryogenic sensors, such as superconducting transition edge sensors (TES) and Neutron Transmutation doped semiconductors (NTD). Invented for astrophysical applications, KIDs have been also proposed for particle physics research, were large and high-sensitivity detectors are required. In particular, they could play a leading role in searches for neutrinos and dark matter interactions, the most mysterious elementary particles.

Neutrinos are the lightest massive particles and they interact weakly with matter. They permeate our Universe and carry information on the matter-antimatter balance. On the other hand, neutrinos are part of the ordinary matter, that we know it is only a tiny fraction of the Universe's mass. The rest is contributed from an unknown form of matter, interacting very weakly with ordinary matter, possibly less than neutrinos, that we is dubbed "Dark Matter".

Sensing neutrinos or dark matter particles require large detector volumes (> kg), to enhance the interaction probability, and excellent sensitivity (< 100 eV) because the energy released in the interaction is small. In this application KIDs are coupled to a large solid absorber and the signal is carried by phonons: following the particle interaction, the generated athermal phonons travel through the absorber until they reach the KID, break the Cooper pairs and give rise to an electrical signal.

The challenge in phonon-mediated KIDs consists in realizing large absorbers and at the same time transmit phonons to KIDs with high efficiency. Phonons may be lost in the absorber supports, in the non-resonator parts of the lithography, and may decay below the superconductor gap if not quickly absorbed by the KID. All these effects reduce the signal to noise ratio, which is still a factor 5 smaller than in TES and NTD sensors.

In this talk we will review the efforts on phonon-mediated KIDs for Particle Physics, with particular emphasis on the R&Ds for experiments on Dark Matter, Neutrinoless Double Beta Decay, and Neutrino Coherent Scattering off Nuclei. KIDs coupled to absorbers with mass up to tens of grams have been realized, with very good opportunities to reach masses in the kg range, by implementing arrays of hundreds or thousands detectors. R&Ds on the superconducting material are also underway to improve the sensitivity and reduce the gap with other sensors.

Abstracts of Posters

(in alphabetical order)

Dual Shapiro steps of a phase-slip junction in the presence of a parasitic capacitance

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Bloch oscillations in a single Josephson junction in the phase-slip regime relate current to frequency. They can be measured by applying a periodic drive to a DC-biased, small Josephson junction. Phase-locking between the periodic drive and the Bloch oscillations then gives rise to steps at constant current in the I–V curve, also known as dual Shapiro steps. Unlike conventional Shapiro steps, a measurement of these dual Shapiro steps is impeded by the presence of a parasitic capacitance. This capacitance shunts the junction resulting in a suppression of the amplitude of the Bloch oscillations. The detrimental effect of the parasitic capacitance can be remedied by an on-chip superinductance. In addition, we introduce a large off-chip resistance to provide the necessary dissipation. We investigate the resulting system by a set of analytical and numerical methods. In particular, we obtain an explicit analytical expression for the height of dual Shapiro steps as a function of the ratio of the parasitic capacitance to the superinductance. Using this result, we provide a quantitative estimate of the dual Shapiro step height. Our calculations reveal that even in the presence of a parasitic capacitance, it should be possible to observe Bloch oscillations with realistic experimental parameters.

Far-Infrared Kinetic Inductance Detectors at NIST-Boulder: Materials and Performance

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Kinetic Inductance Detectors (KIDs) carry the promise of a truly scalable detector solution, capable of filling the ambitiously large and densely populated focal planes envisioned for future sub-millimeter and millimeter-wave instruments. As part of our effort to realize their full potential, we have developed and fabricated the first kilopixel-scale arrays of KIDs on 150 mm diameter silicon on insulator (SOI) substrates. In an effort to optimize device performance over a wide range of scientific experimental needs, we've explored the properties of multiple superconducting materials, namely Al and Ti/TiN multi-layers, that are relevant when incorporated into KID devices. Each material presents both advantages and disadvantages when used in a Far-Infrared KID. Here I describe various hybrid designs that incorporate multiple superconductor materials into each detector, leveraging some of the advantages of each material in optimizing overall detector performance.

Kubo spins in granular aluminum

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We report muon spin relaxation rate measurements on films composed of aluminum grains having a size of a few nm, with a large energy level splitting of the order of 100K. The films range from weakly metallic to insulating. In the insulating case the low temperature relaxation rate is consistent with the presence of single electron spins in grains having an odd number of electrons. The relaxation rate temperature dependence follows an activation law having an energy scale in agreement with the average level splitting. In weakly metallic films the relaxation rate is smaller and decreases faster with temperature. Overall our observations are in line with the presence of a Kubo spin in Al nano-size grains due to quantum size effects.

Developing a next generation Microwave Kinetic Inductance Detector readout system based on the Xilinx ZCU111 RFSoC

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At DIAS, in collaboration with Trinity College Dublin, we are developing visible and near-infrared Microwave Kinetic Inductance Detectors (MKIDs) for astronomical applications. These are superconducting photon detectors based on LC resonators capable of reading out single photons with intrinsic energy resolution. By designing an array of MKIDs with different resonant frequencies, an array of thousands of detectors can be readout with inherent frequency domain multiplexing (FDM).

As part of this project, we are developing a next generation MKID readout system, based on the recently released Xilinx ZCU111 Radio Frequency System-on-Chip (RFSoC) Evaluation Kit. This will be used to realise a more affordable, compact MKID readout which requires significantly less power than the current state of the art. Eight on-chip 14-bit digital-to-analogue converters (DACs), each with 6.5 Giga-Samples per Second (GSPS) and eight 12-bit analogue-to-digital converters (ADCs), each with 4 GSPS, provide ample bandwidth for up to 8,000 MKID resonators with 2 MHz spacing at a 1.0 MHz pixel sampling rate. Coupling this with an additional, external FPGA board, should provide ample FPGA to fully utilise this bandwidth, and readout upto 8,000 pixels at a cost of €3.50 per pixel.

We will present our future plans, and preliminary progress on developing this MKID readout system.

High kinetic inductance microwave resonators made by He-Beam assisted deposition of tungsten nanowires

J. Basset, D. Watfa, G. Aiello, M. Féchant, A. Morvan, J. Estève, J. Gabelli, M. Aprili, R. Weil, A. Kasumov, H. Bouchiat *and* R. Deblock

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We evaluate the performance of hybrid microwave resonators made by combining sputtered Nb thin films with Tungsten nanowires grown with a He-beam induced deposition technique. Depending on growth conditions, the nanowires have a typical width $w \in [35-75]$ nm and thickness $t \in [5-40]$ nm. We observe a high normal state resistance $R_\square \in [65-150]$ $\Omega/\square$ which together with a critical temperature $T_c \in [4-6]$ K ensures a high kinetic inductance making the resonator strongly nonlinear. Both lumped and coplanar waveguide resonators were fabricated and measured at low temperature exhibiting internal quality factors up to 3990 at 4.5 GHz in the few photon regime. Analyzing the wire length, temperature, and microwave power dependence, we extracted a kinetic inductance for the W nanowire of $L_K \approx 15$ pH/$\square$, which is 250 times higher than the geometrical inductance, and a Kerr non-linearity as high as $K_{W,He}/2\pi$ = 200±120 Hz/photon at 4.5 GHz. The nanowires made with the helium focused ion beam are thus versatile objects to engineer compact, high impedance, superconducting environments with a mask and resist free direct write process. [1]

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Kinetic inductance in nanowires: superconducting memory loops, microwave response, and Duffing instability

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We study superconducting loops made of ultra-thin superconducting nanowires,[1] templated with carbon nanotubes. The nanowires have a significant kinetic inductance, thus our devices exhibit multiple quasi-stable vorticity states.[2] We will present non-volatile kinetic-inductance memory elements having dimensions approaching ~200 nm.[3] We demonstrate that the vorticity states can be altered in a controlled fashion by applying calibrated current pulses.[4] A reliable read-out of the memory is also demonstrated.[3] A read-out of the vorticity has been also realized using microwave signals, and without dc biasing.[1,2] If included into a coplanar waveguide resonator, nanowires enable the Duffing instability, demonstrating that nanowires have a nonlinear kinetic inductance.[5] The Duffing instability can be used in low-noise parametric amplifier. Another significant result originating from the kinetic inductance of a nanowire is the observation of a crater-like structure on the resonance peak and the corresponding frequency comb spectrum.[6]

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Al based microwave resonators in the clean and dirty limit

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Resonators have become a very important part of superconducting Circuit QED. They are as well an excellent candidate to understand the dissipation sources in qubit systems. We present a simulated study of Aluminum superconductors of different film thicknesses. The behavior of the internal quality factor as a function of applied microwave power is discussed as well as the limiting dissipation mechanism of resonators for dirty limit superconductors.

Development of Superconducting Resonators for molecular spin quantum processors

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Spin qubits strongly coupled to superconducting resonators have been proposed as an implementation for large-scale quantum computation [1]. Controlling the superconducting resonators parameters such as the quality factor, resonance frequency or induced magnetic field is crucial to achieve the strong coupling regime. In this work, two different approaches are studied.

First, we propose to couple the molecular nanomagnets to Lump-Element Superconducting Resonators (LERs) [2]. In order to optimize the coupling between Niobium LERs and molecular magnets, different designs are studied based on simulations and low-temperature characterization.

The second approach is based on coplanar waveguide resonators. As variations in the geometry of this type of resonators is limited, the strategies to increase the coupling has been limited to reduce the width of the transmission line to constrictions where the molecules are deposited [3]. We propose to downscale further and reach the single-spin sensitivity limit by directly replacing the superconducting constriction with a carbon nanotube of around 1-2 nm width.

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Phonon and light read-out of a macro-calorimeter for rare event searches exploiting kinetic inductance detectors

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Next generation experiments searching for rare events are conceived to improve their sensitivity by increasing the source mass and reducing the background. A typical example is CUPID (CUORE Upgrade with Particle Identification) [1], which proposes a next generation neutrino-less double beta decay experiment upgrading the cryogenic calorimetric technique developed by the CUORE experiment [2], with the aim of decreasing the background from 10^{-2} to 10^{-4} counts/(keV kg yr). The main background of CUORE comes from α particles, as described in Ref. [3]. Therefore, the first step to achieve the goal of CUPID consists in rejecting such kind of interactions. This discrimination is achieved by coupling each calorimeter to a light detector in order to disentangle α from β/γ interactions, thanks to the different light yield and time development of scintillation light. Recently we demonstrate for the first time [4] that this technique can be implemented exploiting KIDs. In this contribution we will present this measurement discussing the possible future improvements.

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Superconducting Nb Resonators with Gold Nanodot Decorations

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While the operation of kinetic inductance detectors (KIDs) is well understood, reports of anomalous behaviors in KIDs fabricated from highly-disordered, thin-film superconductors indicate that a detailed understanding of the superconducting density of states and behavior of excited quasiparticles is necessary to reconcile experimental findings with theory. Anomalous behaviors include: (1) differences in the inductive and dissipative photo-response times, such that the shift in the frequency of the resonator outlasts the reduction in Q by a factor of four [1], (2) resonant frequency vs temperature that cannot be explained by Mattis-Bardeen theory without ad-hoc modifications [2]. It has been observed experimentally that in highly-disordered thin-film superconductors, spontaneous fluctuations of the superconducting gap can arise [3]. The interaction between excited quasiparticles and a spatially varying gap may explain the anomalous behaviors observed in KIDs, for instance if quasiparticle trap states exist that can temporarily localize excited quasiparticles.

In this work, we report on the fabrication and measurement of Nb CPW resonators, as well as progress towards a physical simulation of the case where the superconducting gap varies along the resonator body. The Nb used for fabrication was 50 nm thick, sputtered onto r-plane sapphire at 500 °C, and was not expected to have significant variation in the gap along the film. In order to produce a spatially varying gap, we lithographically defined arrays of gold nano-dots, on top of the CPW centerline, in an attempt to locally reduce the superconducting gap in the Nb due to the proximity effect. In undecorated resonators at high photon number, an internal Q of greater than one million was measured at 7 mK, while the internal Q of the decorated resonators was substantially less. The resonant behavior of these devices vs temperature and power, and their relevance to high-kinetic inductance materials will be discussed.

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Superconducting granular aluminum films grown at cryogenic condition

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The development of a new evaporation setup for superconducting thin granular aluminum films at cryogenic temperatures is presented. We implemented a bath cryostat able to reach liquid helium temperature during sample growth allowing us to grow samples with unique properties. This project focuses on growth, characterization and optimization of granular aluminum films. We also present DC- and microwave-data.

The limits of single photon detection with highly disordered materials

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Single photons at optical frequencies can be detected using nanowires made out of highly disordered superconductors. The efficiency of these detectors is limited by photon absorption and by the physics responsible for creating a resistive transition that leads to a photon detection event. We investigate these limitations in different materials by measuring I-V curves, ellipsometry and quantum detector tomography.

The optical absorption is governed by the optical properties of the material and we investigate if there exists a simple relation between the amount of disorder in the system, characterized by the sheet resistance, and the optical properties of superconducting films of amorphous MoGe. We use quantum detector tomography to separate the process of optical absorption from the internal detection efficiency and find that the detection mechanism of nanofabricated constrictions is best explained using a photon-assisted vortex entry model.

Our measurements on NbN nanodetectors succesfully predict the performance of commercial devices based on NbN and necessitate the introduction of a position dependent internal efficiency. New quantum detector tomography for NbTiN nanodetectors of different width show many similarities with nanodetectors made out of different materials (MoGe, MoSi, NbN). Surprisingly we also find important differences that are not yet fully understood. The NbTiN detectors show better saturation of the efficiency when compared to NbN and a much less pronounced Berezinski-Kosterlitz-Thouless (BKT) transition. We find that the nanodetectors add a width dependent resistance to the standard non-linear I-V curves used to explore the BKT transition. The I-V curves for the different nanowires show that the NbTiN nanowires are much more sensitivie to electronic latching which limits their performance. This raises important questions about the different material properties besides the amount of disorder that govern the physics of the detection process.

Development of an MKIDs camera for astronomical applications

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DIAS is working on the further development of Microwave Kinetic Inductance Detectors (MKIDs) for astronomical instrumentation in the visible and near-IR. MKIDs are superconducting LC resonators operated at 100 mK capacitively coupled to a transmission line to be readout. In collaboration with Trinity College Dublin we design, fabricate and analyse our detector prototypes and we intend to build and deploy an astronomical camera towards the project's end. We plan to use sub-stoichiometric TiNx multi-layered stacks of Ti and stoichiometric TiN, as well as Al and multi-layered stacks of Al and Ti. We intend to increase single-pixel energy resolution, quantum efficiency and pixel yield by further improvement of pixel design and the use post production optimisation techniques. We are also planning to increase MKID pixel numbers and push their sensitivity further towards longer wavelengths. We will present details about our experimental setup as well as first results of preparation studies performed on small test arrays.

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Lumped element titanium nitride kinetic inductance detector with low loss dielectric substrate

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Kinetic inductance detectors (KIDs) are highly multiplexable, and therefore are an attractive sensor option for large-format arrays. Microstripline-coupled architectures are particularly attractive because they provide flexibility in optical coupling (phased-array antennas, lens-coupled antennas, and feedhorns) and permit integration of on-chip bandpass filters. Our goal is to develop a microstrip-coupled KID architecture capable of background-limited performance for observations of the CMB and SZ effect from 30 GHz to 420 GHz.

To this end, we are developing microstrip-coupled titanium nitride (TiNx) KIDs in a coupling architecture amenable to this wide frequency range. TiNx's high normal-state resistivity ensures that two-level-system [1] and readout noise can be made subdominant to photon and recombination noise, and the variation of Tc with stoichiometry will enable operation down to 30 GHz. However, to avoid having an impedance mismatch between the low impedance microstrip exiting reception architectures and the high resistivity TiNx, we have designed a mm-wave coupler [2] that capacitively couples the microstrip with the TiNx inductor. Finally, parallel plate capacitors have been used for this novel KID design in order to mitigate direct absorption of the incoming light that was previously observed with interdigitated capacitors [3].

We have fabricated two versions of this TiNx lumped-element KID design, using two different low loss dielectrics: hydrogenated amorphous silicon (a-Si:H) [4], and the crystalline silicon (c-Si) layer of a SOI (Silicon on insulator) wafer [5]. We present here detailed cryogenic blackbody measurements for these two different prototypes.

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Unconventional non-equilibrium effects observed in high kinetic inductance materials, notably TiN

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Titanium nitride and related materials with a large normal-state resistivity have been proposed and used for kinetic inductance detectors at various wavelengths from near-IR to millimeter. The expected advantages of these materials are manifold, e.g. a tunable critical temperature, a large kinetic inductance fraction, and better matching to the incident radiation due to the large resistivity. However, whereas even large (2" diameter) telescope-ready detector arrays have come into sight, the detailed behavior of TiN detectors still shows many puzzling features, at odds with the perfectly understood behavior of "conventional" aluminum KIDs.

In this contribution I will give an overview of the different studies that have been performed on TiN resonators. In this overview, I will emphasize the unconventional behavior of the material, and the differences with aluminum. Among these differences are a smooth detection gap edge, an increasing sensitivity with optical power, and a quality factor that does not change with loading. I will argue that these differences are unavoidably linked to the large normal-state resistivity of the material and its accompanying intrinsic electronic inhomogeneity, and that they should be fully considered when considering this material for detectors.

Finally, I will discuss the status of TiN for use in (sub)-mm instruments and I will argue that some of the observed unconventional behavior might in fact prove an engineering opportunity for ground-based observation.

Probing disordered thin-films with microwave resonators

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Weakly superconducting materials pose a great opportunity in quantum information systems and superconducting devices as their kinetic inductance is often large, which opens opportunities for high-performance microwave devices. However, probing the fundamental properties of these often highly disordered or granular materials is challenging and experiments are not easily performed. In this study we present an experimental approach, which overcomes some experimental challenges, i.e. ultra-thin film-thickness, low order parameter energy, etc. and show first measurement results of the dielectric properties of highly disordered, insulating indium oxide films and on granular, insulating Sn-films close to the percolation transition. In this context we detail the experimental design of our microwave-resonator device as a discrete frequency probe in the GHz-range up to 20 GHz in an operable temperature range down to mK. Additionally we apply this method to a variety of different insulating/dielectric films with varying thickness and compare to simulations and theory.

Design of a Read-Out System for Cosmic Microwave Background Radiation

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QUBIC (Q&U Bolometric Interferometer for Cosmology) is an observational cosmology project. Its main goal is the study of the B-mode polarization of the Cosmic Microwave Background (CMB) radiation, a relic of the Big-Bang inflation epoch. Due to the intensity of the signal to be detected, a very sensitive instrument is required. Similar detection instruments for CMB measurements and particle detection, are currently based on Transition-Edge Sensors (TESs), but recently new detectors were developed and improved such as Metallic-Magnetic Calorimeters (MMCs). MMCs are known for their excellent energy resolution, high dynamic range and optimal linearity. Combined with superconducting quantum interference devices (SQUIDs) MMCs allows a frequency multiplexing enabling a high number of sensors in only one transmission line. The typical read-out electronics implementation consists of room temperature electronics (signal processing, high frequency electronics), low temperature electronics at around 4 K (low-noise amplifier (LNA)) and finally, between 20 mK and 300 mK the SQUIDs and cryogenic sensors (TESs, MMCs). One of our goals is to exploit the applicability of MMCs to CMB experiments. Among our planned activities are modifications to the MMC design, improvement of the signal-to-noise ratio through utilizing quantum-limited cryogenic amplifiers (travelling wave parametric amplifier (TWPA)) based on kinetic inductances, as well as optimizations of the room temperature readout electronics. As a result, we expect a large improvement of the CMB camera in terms of picture quality and resolution.

Optical conductivity of granular aluminum films near the Mott metal-to-insulator transition

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We report measurements of the energy gap of granular aluminum films by THz spectroscopy [1]. We find that as the grains progressively decouple, the coupling ratio $2\Delta(0)/k_BT_c$ increases above the BCS weak coupling ratio 3.53, and reaches a values consistent with a BCS-BEC crossover for the high resistivity samples. The Mattis-Bardeen (MB) formalism describes remarkably well the behavior of $\sigma_{1,s}/\sigma_{1,n}$ for all samples up to very high normal state resistivities. Further, a detailed comparison is made with NbN [2] which suggests that the nature of the metal to insulator is not the same. While it is of the Anderson type in NbN [3], we believe that it is of the Mott type in granular Al, as already proposed [4]. We argue that it is consistent with the large value of the coupling ratio. The existence of a well-defined SC gap along with low frequency dissipation up to high resistivities (~8000 μΩ cm) is crucial for quantum circuits. Kinetic inductance values that has been calculated from the penetration depth increase towards the Mott transition up to ~1 nH/sq.

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High power dispersive qubit readout and state preparation without parametric amplifier

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High-fidelity qubit readout is an essential requirement for implementation of fault-tolerant quantum algorithms. In circuit quantum electrodynamics architecture a quantum nondemolition measurement of the qubit can be realized by using dispersive interaction of qubit and resonator. A theory of dispersive readout predicts that state discrimination can be substantially improved if the resonator's photon population increases [1]. However, on practice the optimal photon number at which the best readout fidelity is obtained usually does not exceed 2.5 photons [2, 3], and parametric amplifiers with quantum-limited noise are needed to achieve substantial signal-to-noise ratio.

In order to investigate limitations on the readout fidelity in the high-power dispersive regime we used a fluxonium qubit with granular aluminum superinductance [4]. Such a high-impedance superinductance build with kinetic inductance of granular aluminum has an advantage of reduced nonlinearity in comparison to a previously used Josephson junction arrays. We demonstrate qubit measurements without parametric amplifier at readout power corresponding up to 200 photons in resonator. Finally, we discuss the main processes affecting the fidelity of readout: decrease of dispersive shift with photon number, spurious excitations and enhanced spontaneous emission of qubit.

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Kinetic Inductance Measurement using a lumped-element LC-circuit in the MHz regime

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We used a LC-circuit with a resonance frequency in the few MHz regime to determine the kinetic inductance of Al and TiN thin-films. For series resistances above a few Ohms the circuit is overdamped. Upon the superconducting transition the damping becomes very small and a resonance can be seen. Below the transition temperature the resonance frequency is shifted by the kinetic inductance of the superconducting film. From the quality factor and the resonance frequency we determine the full complex impedance of the films. We investigate the behavior of the superfluid stiffness down to mK temperatures and in parallel and perpendicular field. Of particular interest is the behavior of the kinetic inductance when the localization transition is approached.

Hole spin qubits in Ge hut wires coupled to a superconducting resonator

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The trend of increasing integration seems to approach its limit as the element's small size brings forward unfavorable quantum effects. However, this apparent dead end of classical electronics gives rise to a new generation of devices which takes advantage of these effects based on the quantum properties of charges and spins, e.g. spin states of coupled quantum dots can be used for quantum computing [1]. To achieve this goal initialization, low decoherence, manipulation and readout of the spin state are required [2]. Long spin coherence times were first achieved with electron spins in silicon quantum dots due to isotopic purification [3]. Using holes in silicon enabled all-electrical control of the spin qubit as a result of intrinsic spin-orbit coupling [4], which should be even stronger for holes in germanium [5]. We use hole spins qubits hosted in germanium quantum dots formed in hut wires randomly grown on silicon [6]. We are able to initialize the spin qubit in a given state due to Pauli spin blockade. We have fast and fully electrical control of the qubit leading to Rabi frequencies of 140 MHz and Ramsey experiments revealing dephasing times exceeding 130 ns [7]. We are able to perform single-shot readout of the state of the spin in a single quantum dot by integrating the charge sensor in a reflectometry setup [8]. The following step towards the next generation of devices is the establishment of long range coupling between qubits and scaling the system up [9]. Superconducting microwave cavities are good candidates for this purpose [10] and high kinetic inductance circuits could provide the required coupling strength between the hole spin qubit and the superconducting resonator [11].

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Design considerations and optimization of superconducting GHz resonators for microwave SQUID multiplexing

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Metallic magnetic calorimeters (MMCs) are energy-dispersive low-temperature single particle detectors that combine an excellent energy resolution, a fast signal rise time as well as an almost ideal linear detector response. At present, large-scale MMC based detector arrays are developed to enable, for example, future X-ray imaging or high-statistics experiments. For the readout of these arrays, the implementation of microwave SQUID multiplexing (µMUXing) is actively pushed forwards. Here, non-hysteretic rf-SQUID are coupled to high quality superconducting GHz resonators that are used for frequency encoding. The resonator bandwidth is about 1MHz to maintain the very fast signal rise time of MMCs and the frequency spacing between neighboring channels is about 10MHz to yield a resonator crosstalk level below 0.01%. Presently, both, quarterwave transmission line (TLR) and lumped-element resonators (LER) formed by a meander shaped inductor and an interdigital capacitor (IDC) are used. While the resonance frequency of TLRs is tuned by adjusting the physical length of the resonator, the resonance frequency of LERs is set by varying the number of IDC fingers. Although both resonator geometries can in general be applied, LERs somehow turn out to be better suited for µMUXing, e.g. due to the lower impact of surface atomic tunneling systems on the resonator phase noise as well as the possibility to perform a post-production fine-tuning of the resonance frequency to minimize electromagnetic crosstalk caused by fabrication inaccuracies. In this contribution, we will address different aspects related to the fabrication, characterization and optimization of superconducting GHz resonators to be used in a microwave SQUID multiplexer and discuss several aspects related to their readout that apply also to other fields of research such as MKID or qubit development where similar readout techniques are employed.

FIB-based microfabrication of Bi2212 and Fe(Te,Se) single-crystal devices and its application to basic researches

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Cuprate and iron based superconductors are intriguing candidates to realize novel superconducting devices, where the exotic properties such as the intrinsic Josephson junction (IJJ), Josephson π-junction, and Andreev (or Majorana) bound state are sophisticatedly utilized. The microfabrication technique using a focused-ion-beam (FIB) becomes more important to investigate such exotic nature and extract high performance in these devices.

Here, we show the detailed methods to fabricate the sub-micron sized bridges from single crystals of $Bi_2Sr_2CaCu_2O_y$ (Bi2212) and $FeTe_{1-x}Se_x$ by using the FIB etching technique (See also Fig.1). Two recent studies using such microbridges are presented. One is the microwave-induced resonant phase escapes in Bi2212-IJJs, suggesting the occurrence of nonlinear bifurcated phenomenon in IJJs [1]. It provides an important viewpoint to resolve the complicated issue on the anomalously-enhanced quantum phase escape in the 2nd and higher order phase switches. The other is the experimental determination of the *c* axis deparing current density of $FeTe_{1-x}Se_x$ (x=0.2, 0.4) single crystals [2]. The coupling between the superconducting layers in $FeTe_{1-x}Se_x$ is much stronger than IJJs. We found that the critical current density (~10^6 A/cm^2), obtained from the *c* axis microbridge with a width smaller than Pearl length, was almost an order of magnitude larger than the reported values obtained from the magnetization for ***B*** // *c* [3]. This suggests that the measured critical current is dominated by the depairing process rather than the depinning process.

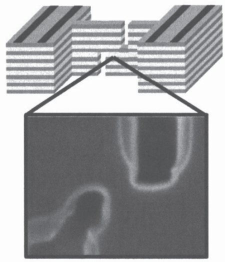

Fig. 1 *C* axis microbridge fabricated from Bi2212 or Fe(Te,Se).

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YBCO nanoSQUIDs based on grain boundary Josephson junctions on MgO bicrystal substrates

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We report on the fabrication and characterization of nanopatterned $YBa_2Cu_3O_{7-x}$ (YBCO) dc SQUIDs based on grain boundary Josephson junctions (GBJJs). The nanoSQUIDs are fabricated by epitaxial growth of YBCO films via pulsed laser deposition on MgO bicrystal substrates with 24□misorientation angle. Nanopatterning is performed by Ga focused ion beam (FIB) milling. Until now, most of YBCO Nano Superconducting Quantum Interference Devices are based on bicrystal $SiTrO_3$ (STO) with huge dielectric constant (10^4), which require an in situ evaporated Au layer serving as shunt resistance in order to provide nonhysteretic current-voltage characteristics (IVCs). However, the flux sensitivity is proportion to SQUID voltage (I_0R product) and the Au layer serving as shunt resistance decrease SQUID resistance, which limits the pursue of higher flux sensitivity. So, to some extent, the development of NanoSQUIDs reachs bottleneck period. Fortunately, the use of MgO substrates avoids a significant stray capacitance of the GBJJs and hence provides nonhysteretic current-voltage characteristics (IVCs) at low temperature (4.2 *K*), even without a resistively shunting Au layer on top of YBCO due to its much lower dielectric permittivity ε, as compared to $SrTiO_3$ (STO). Also, this leads to smaller voltage swings, but also lower white noise of high-T_c DC SQUIDs on MgO substrates compared to those on STO substrates. Hence, our approach of using MgO instead of STO offers the potential of achieving a much larger characteristic voltage (I_0R product) and therefore a significantly improved noise performance of unshunted YBCO nanoSQUIDs. On the other hand, the role of Au on top of YBCO as a protection layer during FIB milling has not been clarified yet. Here, we present the evolution of experimental results on electric transport and noise properties of our YBCO nanoSQUDs on MgO that have been fabricated with different Au shunt layer thicknesses or even without Au on top of YBCO. All of these findings demonstrate the huge potential to improve flux sensitivity to another plateau.

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Kinetic inductance bolometer technology for THz imaging systems

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The inherent multiplexing capability of kinetic inductance devices makes them well suited for cryogenic imaging systems equipped with large sensor/detector arrays. This is due to the fact that, in addition to simplifying the complex control and readout electronic schemes, the number of wires from cold to room temperature is minimized and, thus, the associated heat loss reduced. Moreover, it is the current and temperature dependence of kinetic inductance, as well as the high inductance value available with the reduction of the cross-section of the superconducting strip, which has drawn attention to these devices.

We present kinetic inductance bolometer (KIB) technology developed at VTT [1] for passive sub-millimeter and terahertz imaging systems. The basic operating principle of KIB is to absorb THz radiation on a nanomembrane with a resistive absorber, for example, and to detect corresponding temperature variations using the above mentioned temperature dependence of kinetic inductance in superconducting strip. Unlike their millikelvin counterparts, kinetic inductance detectors, KIBs can be operated at an elevated temperature range above 5 K. We review the operation and physics of KIB and show results, including imaging data, from a fully-staring THz camera equipped with a kilo-pixel 2D focal plane array [2],[3].

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Development, fabrication and characterization of resonator arrays and a microwave SQUID multiplexer based on planar superconducting lumped-element microwave resonators

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To read out large detector arrays based on metallic magnetic calorimeters, our research group has been working on the development and optimization of a microwave SQUID multiplexer which allows to transduce a detector signal into a resonance frequency shift of an associated microwave resonator. Obviously, capacitively coupling a large number of such resonators, each having a unique resonance frequency, to a common transmission line allows to read out hundreds or thousands individual detectors simultaneously.

In the past, quarterwave transmission line resonators have been exclusively used for frequency encoding. An alternative geometry are planar lumped-element resonators whose use within a microwave SQUID multiplexer has been studied for the very first time within this thesis. By characterizing a developed and fabricated resonator array with 400 resonators, it is shown that these resonators show very low intrinsic losses. In addition, they allow for a higher packing density as well as for trimming the resonance frequency of each resonator using a post-processing method in case that there are deviations from the actual design value. This significantly increases the yield of functional readout channels. Furthermore, a microwave SQUID multiplexer based on such resonators was developed, fabricated and characterized. Using this device, it was shown that there are no obvious disadvantages related to this resonator geometry such that they likely will be used in future for the development of microwave SQUID multiplexers.

Passive Error Correction with Grid States in a Non-Reciprocal Superconducting Circuit

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Non-reciprocal circuit elements play an essential role for the practical realization of a solid-state quantum computer, independent of the chosen implementation. For that matter, non-reciprocal circuit elements often constitute the interface between the classical and quantum description of an electrical network.

In electrical network theory, the gyrator proposed by Tellegen [1] in 1948 is considered to be the most fundamental non-reciprocal circuit element. The miniaturization of the actual device allows for the description of the gyrator within the lumped element model.

Besides the incorporation of the gyrator into the theory of circuit quantum electrodynamics [2], we propose a non-reciprocal superconducting circuit comprising a gyrator, whose effective dynamics is described by the Hofstadter Hamiltonian [3]. Thus, the eigenstates of the system constitute grid states, which can be used for passive error correction in terms of the continuous variable code proposed in 2001 by Gottesman, Kitaev and Preskill [4].

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Electric field control of the superfluid density at (111)LaAlO3/SrTiO3 interfaces by microwave resonators

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Atomically engineered interfaces between complex oxides (001)LaAlO3/SrTiO3 show remarkable properties such as two-dimensional superconductivity and strong spin-orbit coupling and has been a subject of great interest in condensed matter physics during the last decade. Recently (111) –oriented LaAlO3/SrTiO3 interfaces were synthesised and shown to possess a two-dimensional superconducting ground state [1] and an electronic structure with strong electronic correlations [2] derived from its six-fold crystalline symmetry. Here we explore the electrostatic field effect control of superconductivity and superfluid density by means of coplanar waveguide resonators fabricated on the interface itself [3]. We characterize the response of these devices as a function of field effect, temperature and power of RF field, disclosing a dome-shaped superconducting phase diagram.

[1] Two-dimensional superconductivity at the (111)LaAlO3/SrTiO3 interface
Physical Review B 96, 020504 (2017) arXiv:1703.04742

[2] Band inversion driven by electronic correlations at the (111) LaAlO3/SrTiO3 interface
Physical Review B 99, 201102(R) (2019) arXiv:1808.03063

[3] Bimodal Phase Diagram of the Superfluid Density in LaAlO3/SrTiO3 Revealed by an Interfacial Waveguide Resonator
Physical Review Letters 122, 036801 (2019) arXiv:1809.10993

High-impedance circuits for parity measurements of cat qubits

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Encoding a qubit in the two degenerate steady states of an oscillator—which only exchanges pairs of photons with its environment—can exponentially suppress the bit-flip rate for large phase-space separations. The unsuppressed phase flips of these so-called "cat qubits" correspond to a change in the photon number parity of the oscillator, and they could be corrected using redundant encoding. In such a scheme, errors are detected via measurements of the joint parity between cat qubits, which could be implemented at the Hamiltonian level using effective parity-type couplings. We show that a parity-type Hamiltonian emerges from the conventional Josephson potential in the limit of high oscillator impedance. Here, the high impedance guarantees large fluctuations of the superconducting phase, which translates into large displacements in oscillator phase space. We present the design of a superconducting circuit that effectively realizes the parity-type Hamiltonian, as well as the status of its experimental implementation.

Granular aluminum: A superconducting material for high impedance quantum circuits

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A promising alternative for the implementation of superinductors, compared to the predominantly used mesoscopic Josephson junction arrays, is granular aluminum (grAl), with a microstructure consisting of pure aluminum grains embedded in an AlOx matrix, effectively forming a self-assembled Josephson junction network [1]. This material offers a large kinetic inductance, while its non-linearity is orders of magnitude smaller than that of Josephson junction arrays [2]. We present a fluxonium qubit employing a granular aluminum superinductor with coherence times T_1 up to 23μs and T^*_2 up to 30μs at the flux bias sweet spot. The measured T_2 approaches the limit $2\times T_1$ [3]. These coherence times recommend granular aluminum for increasingly complex protected superconducting quantum circuits, while they also evidence the need to further investigate and mitigate loss mechanisms in high impedance qubits.

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Reset of sub-GHz Fluxonium Qubits

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Superconducting qubits are a subject of intense research as a platform for scalable quantum computing. While transmon qubits have received a lot of attention, currently all experiments with transmons suffer from surface loss, small anharmonicity and flux noise. The less ubiquitous Fluxonium qubit, consisting of a Josephson junction shunted by a super-inducting loop, has been shown to solve the second and third issues. By exploiting a much more anharmonic spectrum, we can lower the frequency of the Fluxonium qubit to the sub-GHz range at the flux sweet spot, whilst retaining the strong interactions necessary for qubit read-out and gates. Advantageously, lowering the frequency reduces the sensitivity of the qubit to many common decay channels, making Fluxoniums highly coherent: $T_1 = 300$ μs and $T_2 = 200$ μs at the current state-of-the-art [1] and relaxation times of several milliseconds [2]. Unfortunately, at such low frequencies, the thermal population of the qubit's first excited state can be very large even at cryogenic temperatures, which can make even the simplest computation impossible because of a lack of purity in the initial state. In our poster we present multiple strategies to reset the Fluxonium qubit to a desired state in times much shorter than the state-of-the-art, thus demonstrating that thermal excitations are not a barrier to using Fluxonium devices for quantum computation. A short introduction to the key properties of the fluxonium qubit as well as comments on correctly measuring qubit temperature with a non-ideal read-out will also feature.

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MKIDs in Dublin: Multilayer films for single-photon counting Kinetic Inductance Detectors

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Since about 2 years, the Dublin Institute for Advanced Studies hosts a small group working on Microwave Kinetic Inductance Detectors (MKIDs) for astronomic instrumentation in the visible and near-IR. We are in the process of establishing our own fabrication process in collaboration with Trinity College Dublin and as the first step intend to investigate the usability of Ti /TiN multilayers for single-photon counting optical MKIDs. Multilayer films have been demonstrated to be exceptionally well suited for lower energy kinetic inductance detectors but are challenging to be incorporated into the fabrication process of single photon energy resolving devices. I will elaborate on arguments for and against multilayer films for optical MKIDs, explain the challenges in their fabrication and present our first experiences with MKIDs fabricated in Dublin.

Phonon traps reduce the quasiparticle density in superconducting circuits

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Out of equilibrium quasiparticles (QPs) are one of the main sources of decoherence in superconducting quantum circuits, and are particularly detrimental in devices with high kinetic inductance, such as high impedance resonators, qubits, and detectors. Despite significant progress in the understanding of QP dynamics, pinpointing their origin and decreasing their density remain outstanding tasks. The cyclic process of recombination and generation of QPs implies the exchange of phonons between the superconducting thin film and the underlying substrate. Reducing the number of substrate phonons with frequencies exceeding the spectral gap of the superconductor should result in a reduction of QPs. Indeed, we demonstrate that surrounding high impedance resonators made of granular aluminum (grAl) with lower gapped thin film aluminum islands increases the internal quality factors of the resonators in the single photon regime, suppresses the noise, and reduces the rate of observed QP bursts. The aluminum islands are positioned far enough from the resonators to be electromagnetically decoupled, thus not changing the resonator frequency, nor the loading. We therefore attribute the improvements observed in grAl resonators to phonon trapping at frequencies close to the spectral gap of aluminum, well below the grAl gap.

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SQUIDs in the Vicinity of Microwave Transmission Lines

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In order to detect the magnetization change accompanying electron paramagnetic resonance (EPR), conventional methods require a bulk material sample in order to attain a sufficiently large signal. Superconducting quantum interference devices (SQUIDs) offer the possibility to detect small field changes with a very high resolution, which allows direct EPR measurements on very small particles. However, the presence of a microwave exciting the electrons spins may impair their operability. Different arrangements of SQUIDs close to and inside of coplanar waveguides were designed and SQUID characterizations performed with and without microwave signals passing through the waveguide. Among the effect of the microwave signal on the performance of the SQUIDs, ratchet effects were observed that lead to both positive and negative Shapiro steps at zero bias current. This allows a measurement of the currents induced in the SQUID wires.

Implementation of a transmon qubit using superconducting granular aluminum

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The high kinetic inductance offered by superconducting granular aluminum (grAl) [1] has recently been employed for linear inductors in fluxonium quantum bits [2] and kinetic inductance detectors. Due to its large critical current density compared to typical Josephson junctions [3], its resilience to external magnetic fields, and its low dissipation, grAl may also provide a robust source of non-linearity for strongly driven quantum circuits, topological superconductivity, and hybrid systems. Having said that, can the grAl non-linearity [4] be sufficient to build a qubit? Here we show that shunting a small grAl volume ($10\times200\times500\text{nm}^3$) with a thin film aluminum capacitor results in an anharmonicity α much larger than the spectral linewidth κ, with $\alpha \approx 100\times\kappa$, effectively forming a transmon qubit. With increasing drive power, we observe several multi-photon transitions starting from the ground state, from which we extract $\alpha = -2\pi\times4.48\text{MHz}$. Resonance fluorescence measurements of the $g \rightarrow e$ transition yield an intrinsic qubit linewidth $\gamma = 2\pi\times10\text{kHz}$, corresponding to a lifetime of 16μs. This linewidth remains below $2\pi\times150\text{kHz}$ for in-plane magnetic fields up to $\sim$ 100mT.

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High impedance superconducting resonators made from high kinetic inductance NbN films for spin-read-out in Si hole spin qubits

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Quantum computing is a major new frontier in technology promising computing power unattainable by conventional computers. Many different materials and approaches have been explored so far, with an increasing effort on scalable implementations based on solid-state platforms. Among these, silicon is emerging as a promising route to quantum computing with true potential in terms of scalability and manufacturability. With the recent development of spin-orbit qubit based on hole spins in silicon [1], it is nowadays conceivable to use a microwave photon as a « quantum bus » [2] for long distance spin-spin interaction.

Here we present our effort towards the co-integration of a superconducting microwave cavity with silicon CMOS qubits. The superconducting cavity consists of a coplanar transmission line resonator made of NbN. Thin films of 10nm have been chosen to boost the kinetic inductance of NbN to produce high impedance resonator. We obtain critical temperatures of around 10K for our films on SiO_2 and internal quality factors of several 10'000. The kinetic inductance, extracted from the dispersion relation, reaches values as high as 100 pH/sq.

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