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Clean and Tunable Phase Slip Qubit

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14. ABSTRACT
Quantum phase slips (QPS) is a fundamentally new physical phenomenon and can find a wide range of applications from metrology to building novel quantum computers. Previous work has demonstrated that the critical current of superconducting nanowires could be gated by external electric fields (aka "superconducting field effect"). the question of whether this effect can be used to produce QPS was a central question of our project. Although we have observed evidence of QPS. our results could not confirm the existence of QPS in electrically gated nanowires. this was the first direct test of the applicability of electrical gating for phase slips which will have an impact on the field and future experiments. We have developed a theoretical framework to design QPS qubits and several generations of chips were designed, fabricated and measured. the precursor of a qubit behavior was only observed for granular Al chips. However, the evidence of electric gating for nanowires has not been observed. We learned that Ti is not a preferred material for the fabrication neither for the readout resonator nor for QPS qubit possibly due to its prone to oxidation which likely increases losses at microwave frequencies. GrAl has been proven to be a promising material for the fabrication of QPS qubits. However, more efforts are needed to develop a reliable fabrication recipe.

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Fedorov-AOARD-20IOA087-Clean and Tunable Phase Slip Qubit

BAA Name: FA9550-19-S-0003
Most relevant BAA Section: PKG00249988
Principle Investigator: Associate Professor Arkady Fedorov (University of Queensland)
Key Researcher(s) involved in the Proposed Project: Dr. Eugen Sachkou (University of Queesnland), Dr. Rohit Navarathna (University of Queensland), Andrea Iorio (Scuola Normale Superiore), Dr. Angelo Greco (Scuola Normale Superiore), Dr. Francesco Giazotto (Scuola Normale Superiore).
Proposed Period-of-Performance: 12 months
Proposed Total Cost (for each year): US $150,000$

1 ACCOMPLISHMENTS

1.1 The major goals and objectives of this project

1. *Design and fabricate a QPS qubit with an electrically gated nanowire incorporated in a superconducting loop. The loop will be inductively coupled to a microwave resonator for a dispersive readout*

   To accomplish this goal three generations of samples were designed and fabricated for the project. The first batch was designed at the University of Queensland (UQ) but fabricated in Italy by the group of Dr. Francesco Giazotto. Two more generations were both designed and fabricated at UQ.

2. *Perform microwave transmission measurement through the resonator at different magnetic and electric fields. Observe the effect of changing control fields on the linewidth and frequency of the resonator. Extract kinetic inductance and dissipation of the nanowire as a function of the electric field.*

   All the samples were mounted inside a dilution refrigerator to perform microwave transmission measurements at different magnetic fields applied through the external magnetic coil and electric fields applied through a local gate line partnered near the nanowire in a loop. The magnetic field sweeps showed flux periodicity for a sample where the quantum phase slips (QPS) loop was made out of granular Aluminium (GrAl) which is an indirect evidence of quantum phase slips. The electric field sweep did not produce any conclusive effect.

3. *Perform two-tone spectroscopy in search for a transition between two different numbers of flux quanta in the loop which will form the basis for a QPS qubit. Observation of the level splitting when the external magnetic flux bias is near half of the flux quantum ($\Phi_{\mathrm{ext}} = \Phi_0/2$) will be the direct manifestation of quantum phase slips in the system.*

   Two-tone spectroscopy was performed for the sample where flux modulation of the resonator frequency was observed. However, QPS qubit transitions were not observed.

1.2 Accomplishments under these goals

1.2.1 Design

A typical design for our devices is shown in Fig. 1. The design contains a superconducting loop made out of a superconductor. The loop contains a constriction with a width of a few hundred of nanometers which can be easily defined with electron beam lithography. Without an external electric field, the constriction is not small enough to observe any measurable phase slips.

As it was experimentally observed that the critical current of the constriction could be reduced by external electric field [1, 2]. It was conjectured that with the external electric field applied through the nearby charge control line, the effective cross-section of the nanowire would be reduced allowing for a phase slip rate sufficient to form a qubit with GHz frequency range. The latter can be observed spectroscopically using a readout resonator following the theoretical proposal [3].

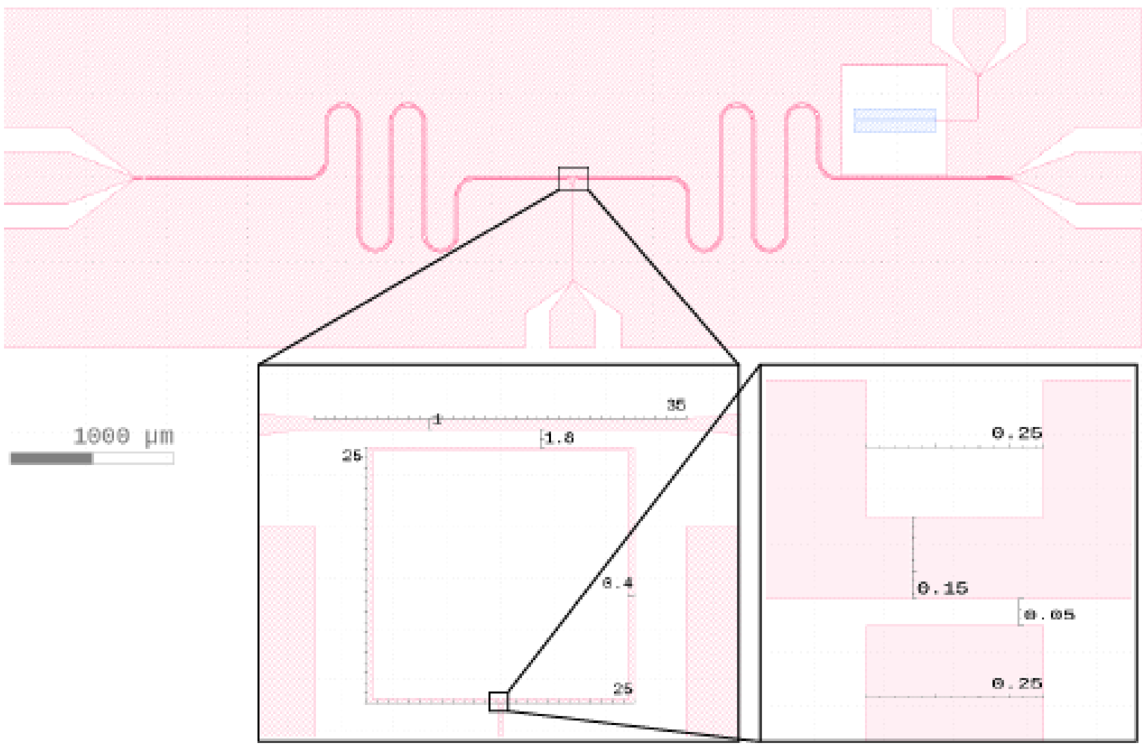

Figure 1: An actual GDS image of the chip design. The design consists of a QPS qubit coupled to a CPW readout resonator. Inset shows the qubit loop which is inductively coupled to the center conductor of the CPW resonator. At the boom of the loop there is a nanowire (second inset) which can be gated with electric field by applying a voltage to the external line. The dimensions in the insets are shown in μm.

The design of a QPS consists of several steps and the following main considerations were taken into account:

- The estimated phase slip rate should be within our standard measurement bandwidth of 4-8 GHz. This ensures ground state initialization of the qubit and the ability to measure it within our standard measurement band.
- The expected persistent current in the qubit loop should be smaller than the critical current of the nanowire.
- The persistent current of the loop and the mutual inductance to the CPW readout resonator should be large enough to be able to detect it using the dispersive readout scheme.

  When designing the samples, we assumed that the electrical gating of a nanowire leads to the effective reduction of its cross-section from the designed value to zero. The details of the calculations are presented in technical report [4].

1.2.2 Samples with Ti floating loop coupled to Nb resonator

The first batch of samples was designed at UQ and fabricated on sapphire substrate in Italy (see Fig. 2a,b). The original choice of sapphire was dictated by its relatively high value of Schottky barrier that could prevent an undesired leakage current and isolate the field-effect control of the supercurrent.

A CPW resonator was designed to have with a frequency in the range of $\sim$5 GHz and was made of 100 nm Nb film using optical lithography. The resonator is coupled inductively to a superconducting loop. The loop was fabricated using electron beam lithography with subsequent deposition of 15 nm of Ti.

We selected Ti as the loop material as its parameters such as low-temperature resistivity, diffusion constant and density of states at Fermi level and superconducting gap were well characterised by Dr. Giazotto group [2]. The size of the loop 25 μm by 25 μm was chosen to provide enough inductive coupling to the superconducting resonator to guarantee observable dispersive shift for detection of the quantum phase slip (QPS) qubit. The nanowire width was 150 nm while the charge control line was patterned 50 nm away. These dimensions were chosen to be as small as possible but large enough to reliably patterned them with electron beam lithography without substantial geometry disorder.

After mounting samples in a dilution refrigerator, we performed transmission measurements through the readout resonator while sweeping the magnetic field threading the sample from the external magnetic coil mounted below the chip. An example of such measurement is shown in Fig. 3. The resonator quality factor was according to our designed values and exhibited frequency shift with the external magnetic field. The shift is associated with the inductive coupling of the Ti qubit loop and

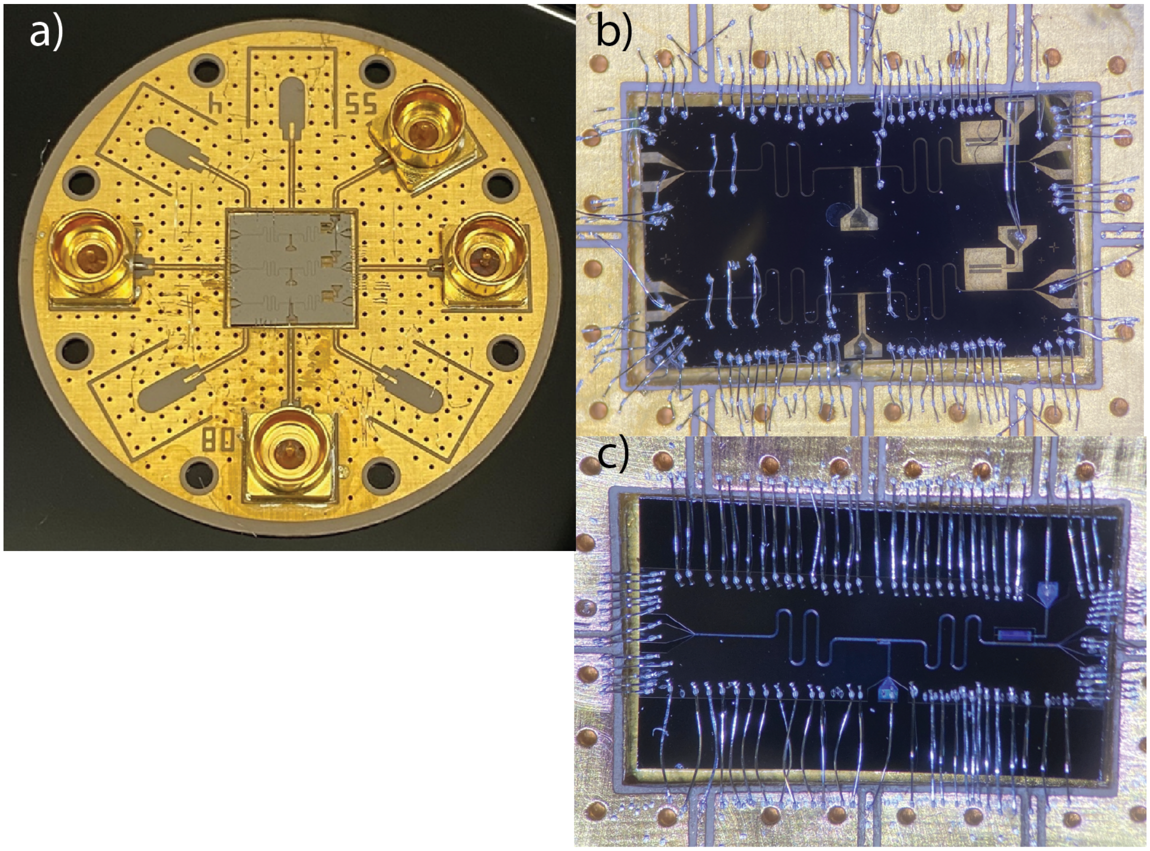

Figure 2: a) First generation of samples fabricated on a sapphire mounted and bonded onto a PCB b) Close-up image of a sample fabricated on sapphire c) Close-up image of a sample fabricated on Si.

the resonator as expected by our design. The exact mechanism is associated with an increase of the kinetic inductance of the loop for larger persistent currents generated by the external magnetic loop.

The application of the external voltage to the gate did not demonstrate any effect on the resonator. It was concluded that the absence of the effect could be explained by the fact that the loop is electrically floating. Thus, the electric field near the nanowire was lower than one in DC measurements done earlier by Giazotto [2] and was not enough to suppress the critical current of the nanowire.

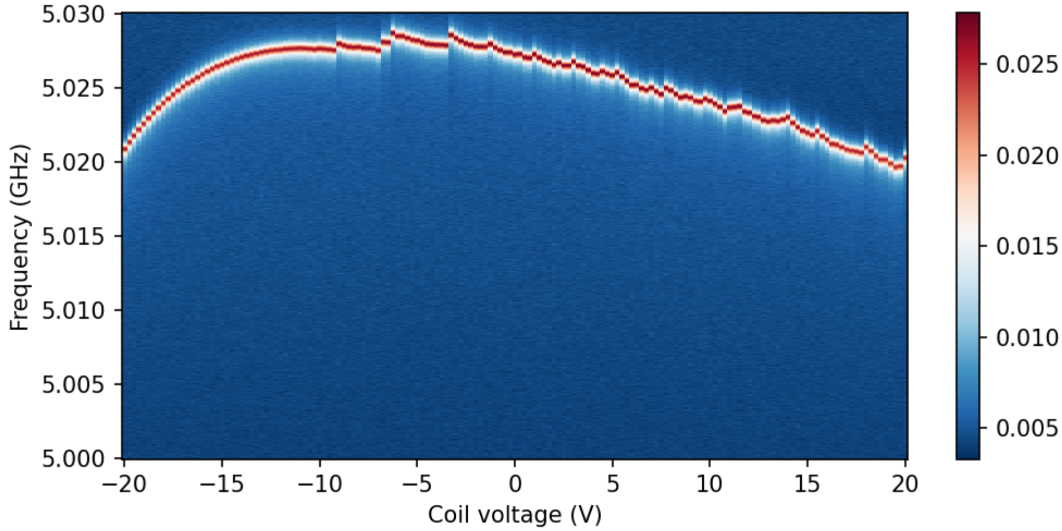

Figure 3: The absolute value of the transmission through a readout resonator measured at different magnetic flux through a QPS loop controlled by the external voltage applied to a magnetic coil. High transmission values indicate the resonant frequency of the resonator. The change in the resonant frequency indicates the existence of inductive coupling of the superconducting loop to the resonator. Discontinuities in the right side of the spectrum are likely explained by flux jumps and fluxon pinning.

1.2.3 Samples with Ti grounded loop coupled to Ti resonator

In the next attempt to fabricate our devices, we shorted the qubit loop to the ground (see Fig. 4a). That should dramatically increase the electric field applied to the nanowire making it comparable to the DC experiments [2].

Due to the lack of Nb fabrication at UQ at that time, we could not split the fabrication of the resonator and the loop into two different lithography steps. Also, the fabrication on the sapphire was problematic because of charging effects and the failure of the lithography machine to focus (due to the transparency of the sapphire). Because of these limitations, the chip was fabricated on a Si substrate using electron beam lithography and evaporation of Ti (see more details in Ref. [4]).

We fabricated two batches of samples. The first sample was fabricated with 15 nm of Ti for both the loop and the resonator. However, no resonance peaks were observed in transmission. We associated this with the oxidation of Ti film and degradation of the film superconductivity.

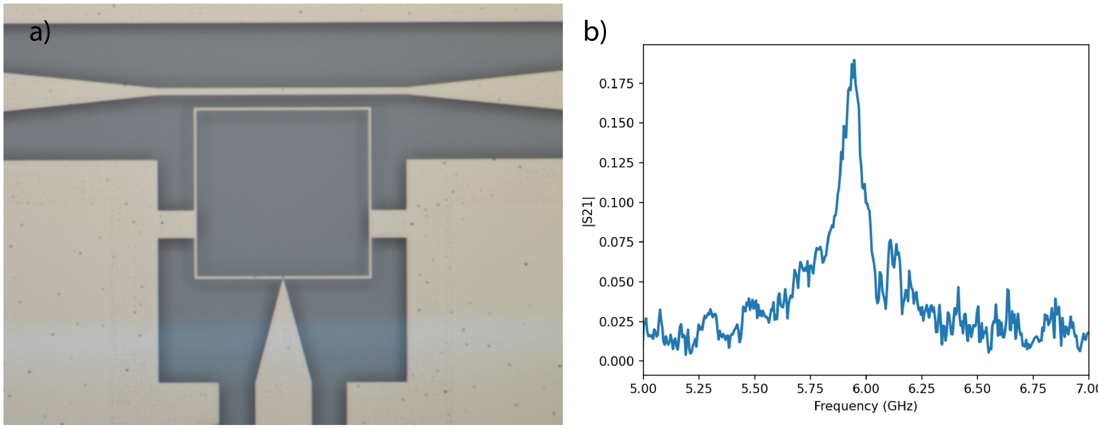

Figure 4: a) An optical microscope image of the QPS loop made of Ti. The loop is galvanically connected to the ground plane, allowing for a much stronger electric field applied to the nanowire. The nanowire is not visible at this scale. b) The resonance peak of a Ti resonator.

In the second bath, we modulated the thickness of Ti. While we kept the thickness of the loop to 15 nm, we evaporated the resonator with 40 nm of Ti. Transmission measurements revealed a resonance peak for the resonator of a slightly lower quality factor than expected (see Fig. 4b). However, no change in resonance frequency was observed when we swept both magnetic and electric fields. We concluded that 15 nm Ti is not suitable for the fabrication of QPS qubit.

1.2.4 Granular Al loop

Granular Aluminum is a disordered material formed by grains of Al of a few nm in size, coupled through an oxide barrier between them. it belongs to a family of materials typically called "granular electronic systems" [5]. Thus, GrAl is a highly disordered superconductor and has very high normal resistance (as well as high kinetic inductance). GrAl can be fabricated by evaporating Al in oxigen atmosphere and the resistivity of the film can be tuned by changing the evaporation rate of Al and the oxygen pressure in the chamber during evaporation.

Due to its high normal resistivity, GrAl is a promising material for observing phase slips [6]. At the same time GrAl has been successfully used for qubit fabrication [7]. A disadvantage of this material its relatively low reproducibility of parameters from one evaporation to another.

The chip was drastically redesigned for GrAl material. In particular, due to the higher inductance of the loop and subsequently lower persistent current, we had to increase mutual inductance between the QPS qubit loop and the resonator. The new dimensions of the loop were adjusted to 5 μm by 200 μm as shown in Fig. 5.

The transmission measurement showed period behavior with magnetic flux which is the first signature of the QPS qubit existence (see Fig. 6). The additional sweep of the voltage through the charge control line showed some effect on the signal but the change was not periodic with voltage and thus was not conclusive (see Fig. 7).

We also observed the current when applying a voltage to the gate line which we associated with the leakage through the capacitor which was part of the low pass filter incorporated into the DC wiring. We warmed up the refrigerator, removed the capacitor and attempted the second cool-down of the sample. We observed that the resonance lines shifted and the results of Fig. 6 could not be reproduced.

1.2.5 Conclusions

We have developed a theoretical framework to design QPS qubits and several generations of chips were designed, fabricated and measured. The precursor of a qubit behavior was only observed for granular Al chips. However, the evidence of electric gating for nanowires has not been observed.

We learned that Ti is not a preferred material for the fabrication neither for the readout resonator nor for QPS qubit possibly due to its prone to oxidation which likely increases losses at microwave frequencies. GrAl has been proven to be a promising material for the fabrication of QPS qubits. However, more efforts are needed to develop a reliable fabrication recipe. That will allow a thorough characterization of the properties of QPS qubits and an investigation of the effect of the electric field on the qubit.

1.3 Opportunities for training and professional development has the project provided.

The project was done in collaboration between two groups from Australia and Italy. The University of Queensland group has extensive knowledge in qubit design, fabrication, and microwave measurement. The Italy group are the experts in superconductivity and DC transport measurements. During the project, The University of Queensland hosted two visitors from Italy: a PhD student Andrea Iorio and a postdoctoral researcher Angelo Greco. The Italian researchers visited for one month each and participated in the design and measurement of the samples. We also had several Zoom calls between Australia and Italy with Dr. Giazotto and his other

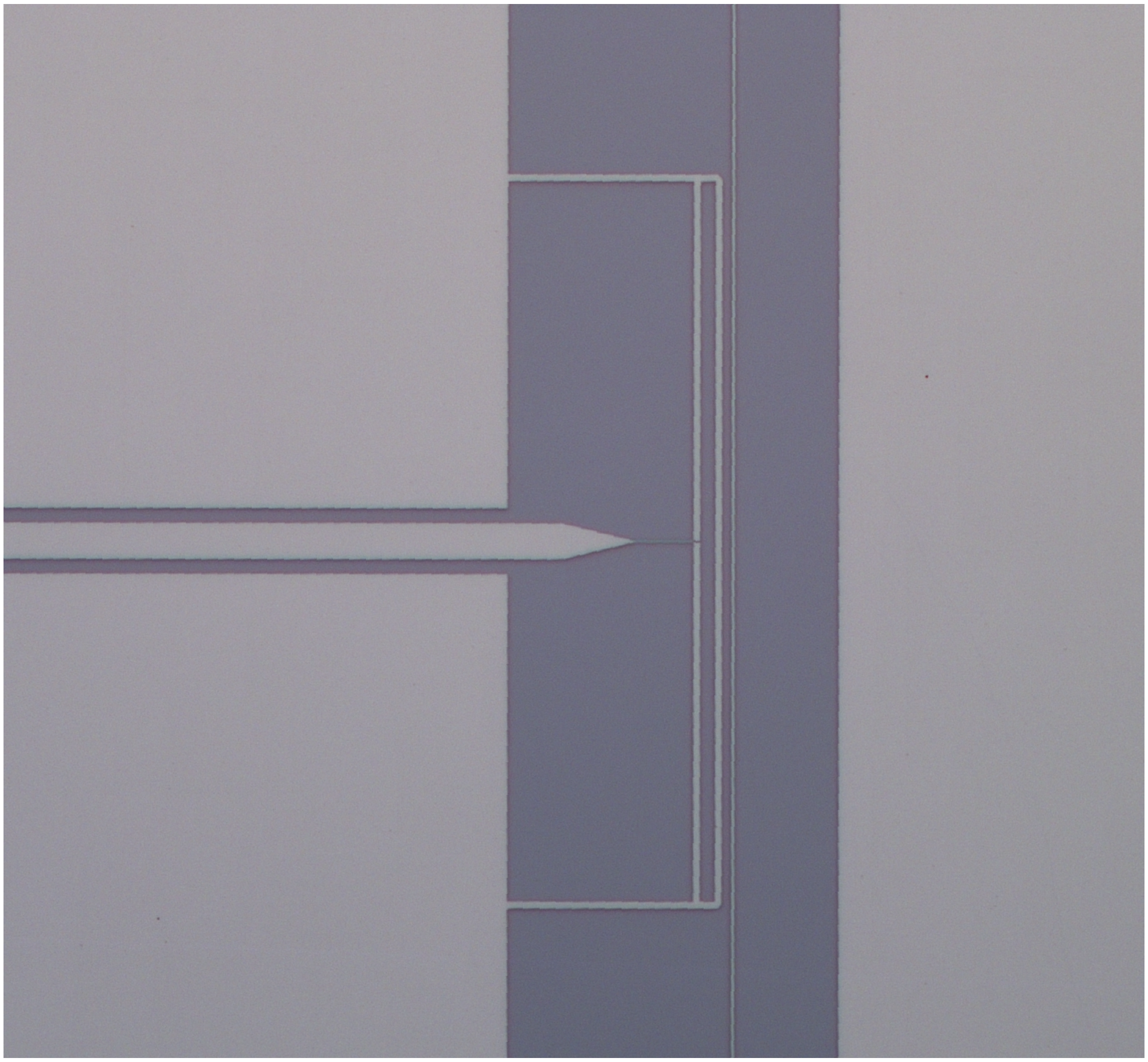

Figure 5: An optical microscope image of the QPS qubit loop fabricated with GrAl. A thin line on the left is the central conductor of the resonator. The gate charge line is approaching the loop horizontally from the left. Due to a very high kinetic inductance of the loop and low persistent currents for the QPS qubit states the mutual inductance between the QPS loop and the central line of the resonator was maximised by increasing the vertical side of the loop to 200 μm. The loop is galvanically connected to the ground plane by two additional wires.

group members.

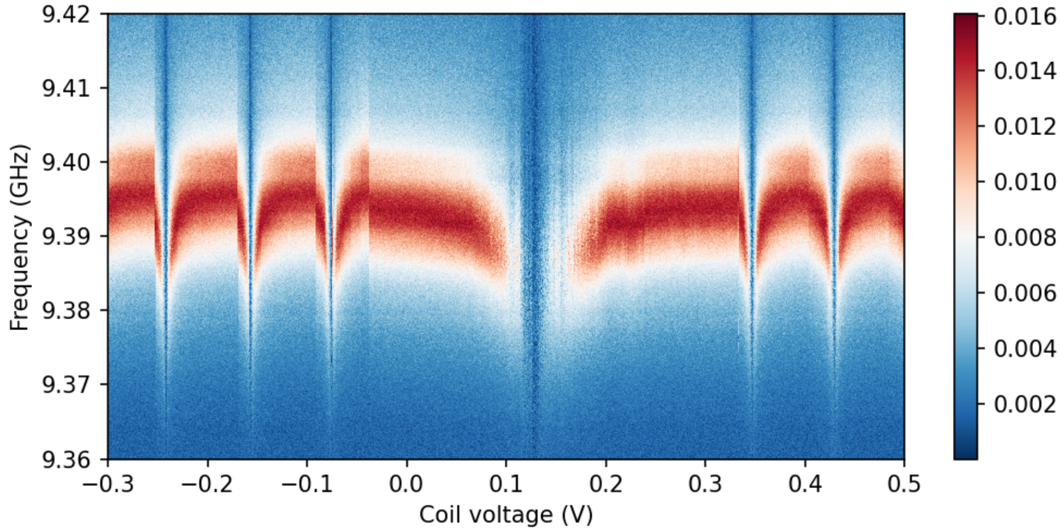

Figure 6: The absolute value of the transmission through a readout resonator measured at different magnetic flux through a QPS loop controlled by the external voltage applied to a magnetic coil. High transmission values indicate the resonant frequency of the resonator. Periodic modulation indicates 'quantum' behavior which could be associated with the existence of a QPS qubit. Strong discontinuous associated with flux jumps and fluxon pinning are also observed.

The project was a perfect ground to exchange complementary expertise. The Italian group learned qubit design and microwave measurement techniques while UQ group obtained expertise in superconducting materials and borrowed the techniques for the gate voltage biasing of the samples.

2 PRODUCTS

2.1 Technologies or techniques

We have developed design workflow for QPS qubits and fabrication recipes for the fabrication of resonators and loops using Ti and GrAl superconductors. The techniques were shared between the two groups.

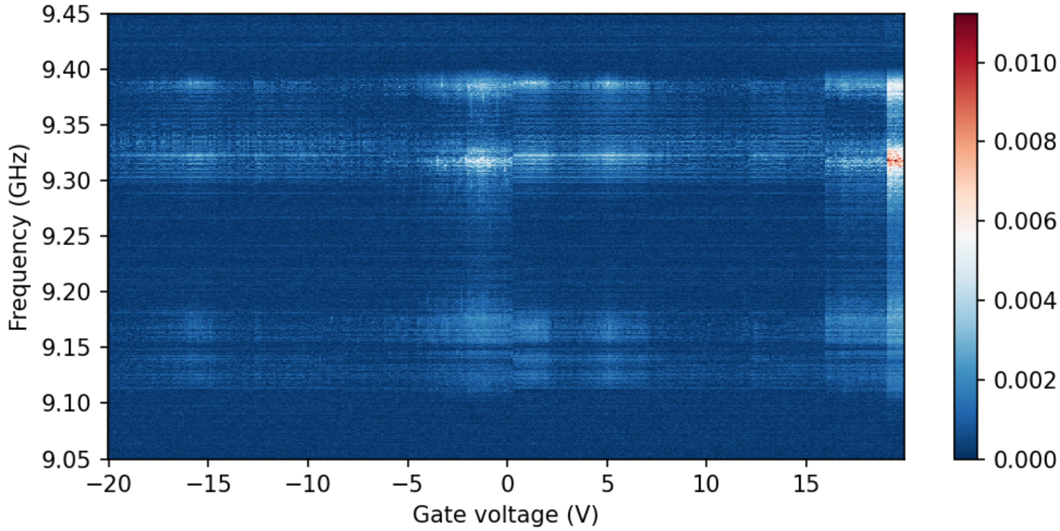

Figure 7: The absolute value of the transmission through a readout resonator measured at different gate voltages applied to the QPS loop though the local gate control line with the background signal subtracted. Some modulation of transmission signal is visible.

3 PARTICIPANTS AND OTHER COLLABORATING ORGANIZATIONS

3.1 Individuals who have worked on this project

Name: Total Number of Months: Project Role: Contribution to Project:	Arkady Fedorov 2.4 PI Leader of the project. Supervised the postdoctoral researcher, guided the design, fabrication, and measurement.
Name: Total Number of Months: Project Role: Contribution to Project:	Eugene Sachkou 10 Postdoctoral Designed samples with Ti loops. Fabricated and measured samples made of Ti. Helped Andrea Iorio to measure samples fabricated in Italy. Measured GrAl samples in the second cool-down.
Name: Total Number of Months: Project Role: Contribution to Project:	Rohit Navarathna 1.3 Postdoctoral Fabricated and measured samples made of GrAl. Measured GrAl samples in the first cool-down.
Name: Total Number of Months: Project Role: Contribution to Project:	Andrea Iorio 2 PhD student Fabricated and measured samples in Italy based on UQ designed. Measured the samples during his to UQ.
Name: Total Number of Months: Project Role: Contribution to Project:	Angelo Greco 1 Postdoctoral Helped to design samples made of GrAl during his visit to UQ.

3.2 other organizations have been involved as partners

The project was done in collaboration with the group of Dr Francesco Giazotto from Scuola Normale Superiore, Pisa, Italy. A PhD student of Dr. Giazotto, Andrea Iorio fabricated the first batch of the samples based on the UQ design using cleanroom facilities of Scuola Normale Superiore. He then visited UQ for one month (May 2022) to help to perform measurements of these samples in the lab of Dr. Fedorov. Another postoc of Dr. Giazotto, Angleo Greco, visited UQ in July 2022 and helped to design samples fabricated with GrAl. During the project life we had several zoom calls to discuss the project and future directions.

3.3 Other collaborators or contacts been involved

The project involved extensive nanofabrication activities which were performed in the Centre for Microscopy and Microanalysis at UQ. A CMM engineer, Dr. Elliot Cheng, provided substantial help to our team with our nanofabrication efforts.

4 IMPACT

4.1 The impact on the development of the physics of the project

Quantum phase slips (QPS) is a fundamentally new physical phenomenon and can find a wide range of applications from metrology to building novel quantum computers. The experiments by Giazotto et. al. demonstrated that the critical current of superconducting nanowires could be gated by external electric fields (aka "superconducting field effect"). The question of whether this effect can be used to produce QPS was a central question of our project. Although we have observed evidence of QPS, our results could not confirm the existence of QPS in electrically gated nanowires. This was the first direct test of the applicability of electrical gating for phase slips which will have an impact on that field and future experiments.

4.2 The impact on other disciplines.

Nothing to report.

4.3 The impact on the development of human resources.

The project was an indisciplinary project linking quantum devices field and material science, providing a platform for exchanging expertise as well as technical skills in design, fabrication and cryogenic measurement.

4.4 The impact on teaching and educational experiences.

Nothing to report.

4.5 The impact on physical, institutional, and information resources that form infrastructure.

Nothing to report.

4.6 The impact on technology transfer

Nothing to report.

4.7 The impact on society beyond science and technology.

Nothing to report.

4.8 Percentage of the award's budget was spent in foreign country(ies).

The budget was 100% spent in Australia.

5 CHANGES/PROBLEMS

5.1 Actual or anticipated problems or delays and actions or plans to resolve them

There was a substantial delay in work due to COVID19 in 2021 due to the closure of nanofabrication facilities and the university lab. Additional problems happened due to the physical relocation of the lab to a different building on campus in 2022. Due to multiple delays during the relocation, the experiments were disrupted, and it took substantial time to rebuild the measurement setup in the new lab which affected the last stage of the project. To minimize the effect of these delays we requested a no-cost extension for the project.

One of the electron-beam lithography machines broke down and could not be fixed until the end of the project. The lithography machine was necessary for the fabrication of samples on sapphire and significantly delayed our project. To resolve this problem, we switched to Si substrates and used another machine that was suitable for this substrate material.

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