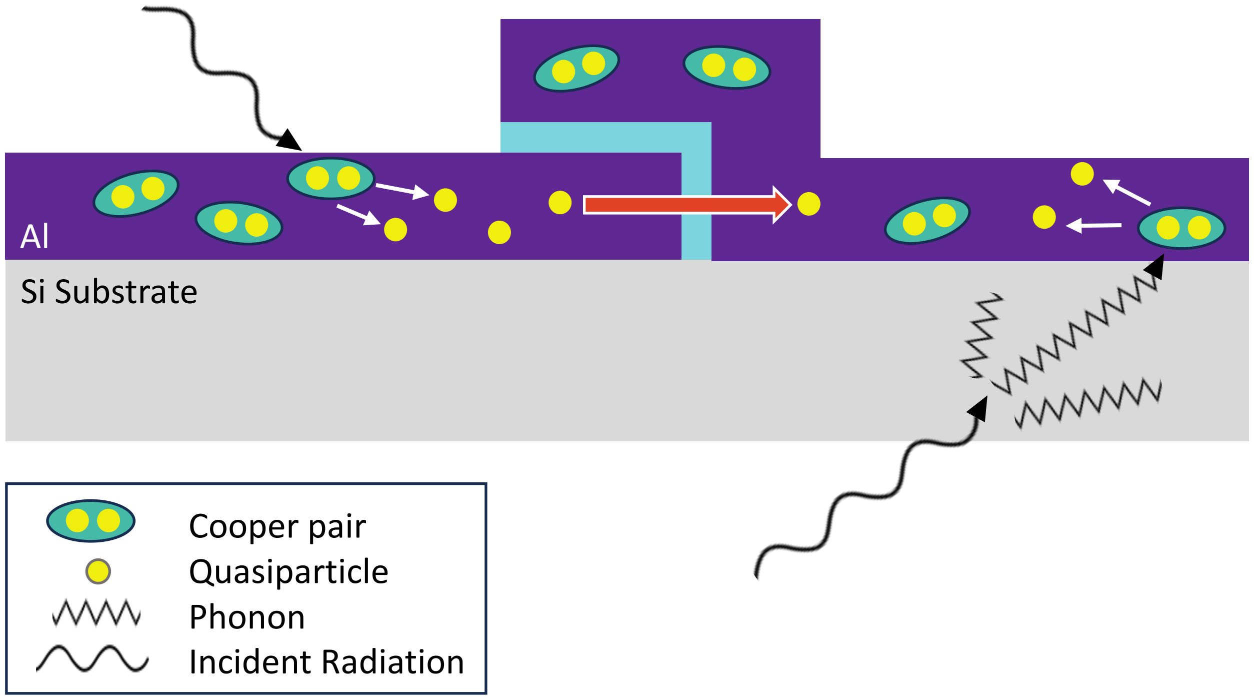
Superconducting Quasiparticle-Amplifying Transmons (SQUATs) for THz Photons and meV Phonons

Noah Kurinsky, *Hannah Magoon*, Jadyn Anczarski, Noshin Tabassum, Chiara Salemi, Caleb Fink, David Schuster

RISQ Workshop - 30 May 2024

Phonon Detection



Incident radiation can break Cooper pairs either directly in the superconductor, or indirectly through phonon pathways

Many groups have shown that these radiation events lead to correlated qubit errors:

- ❖ *McEwen et al., Nature (2021)*
- ❖ *Ristè et al., Nature (2013)*
- ❖ *Serniak et al., Phys. Rev. Letters (2018)*
- ❖ *Wilen et al, Nature 594, 369 (2021)*
- ❖ *Vepsäläinen et al., Nature (2020)*

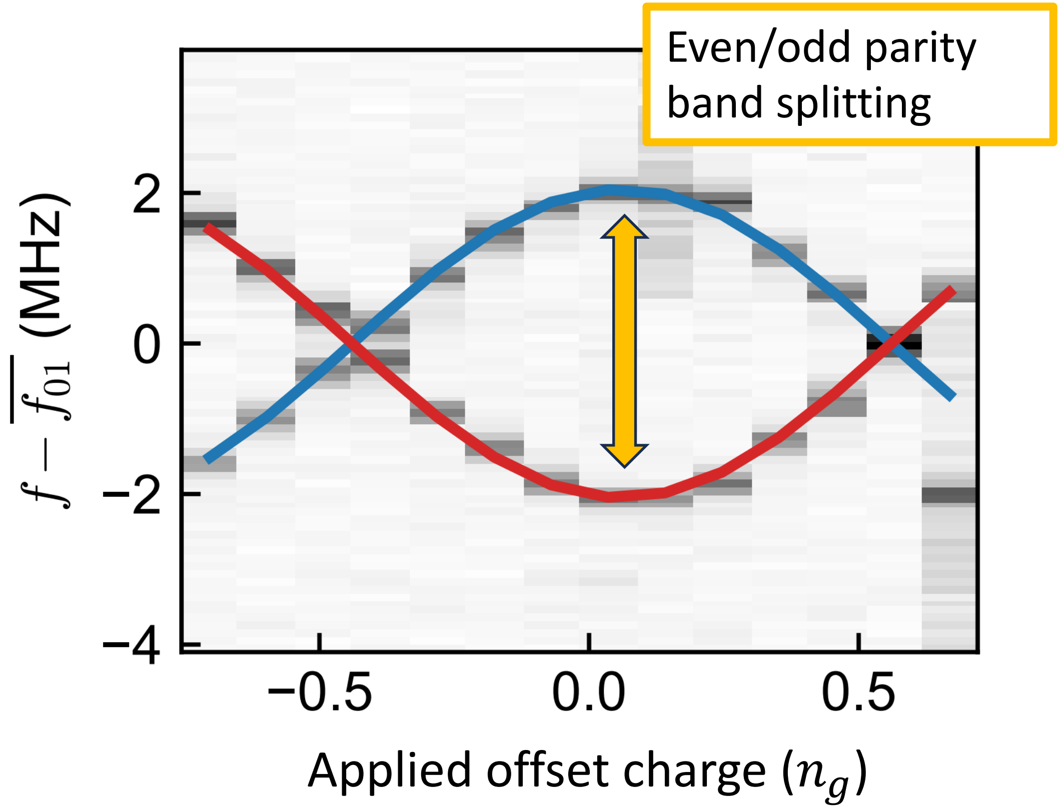
Transmons as Detectors

The effective transmon Hamiltonian parametrized by qubit charging energy E_c and tunneling energy E_J is given by:

$$\hat{H} = 4E_c(\hat{n} - n_g)^2 - E_J cos\phi$$

Giving us a transition energy of:

$$E_{01} \approx \hbar\omega_0 + \hbar\chi_0 \cos(\pi n_q)$$

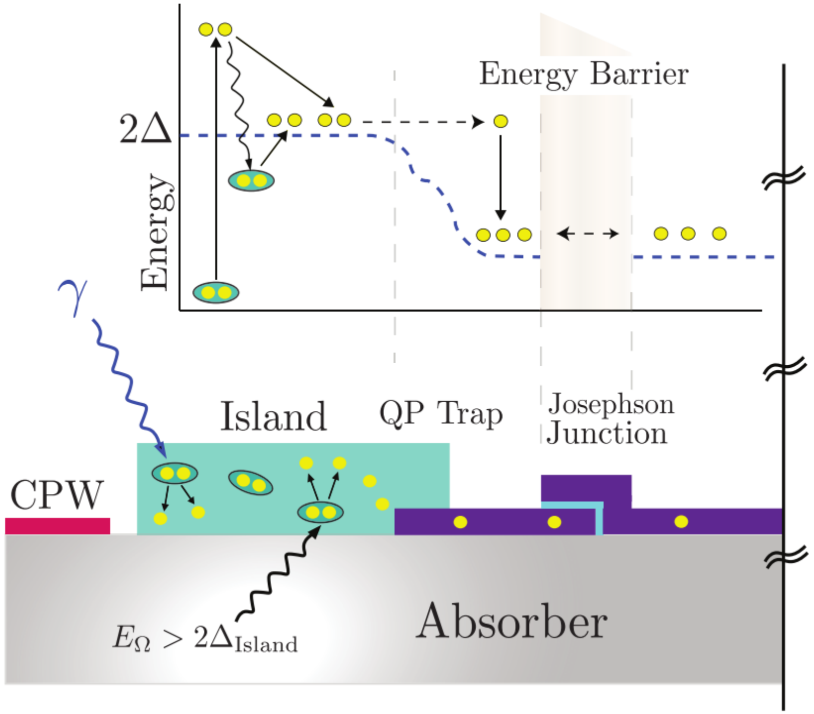


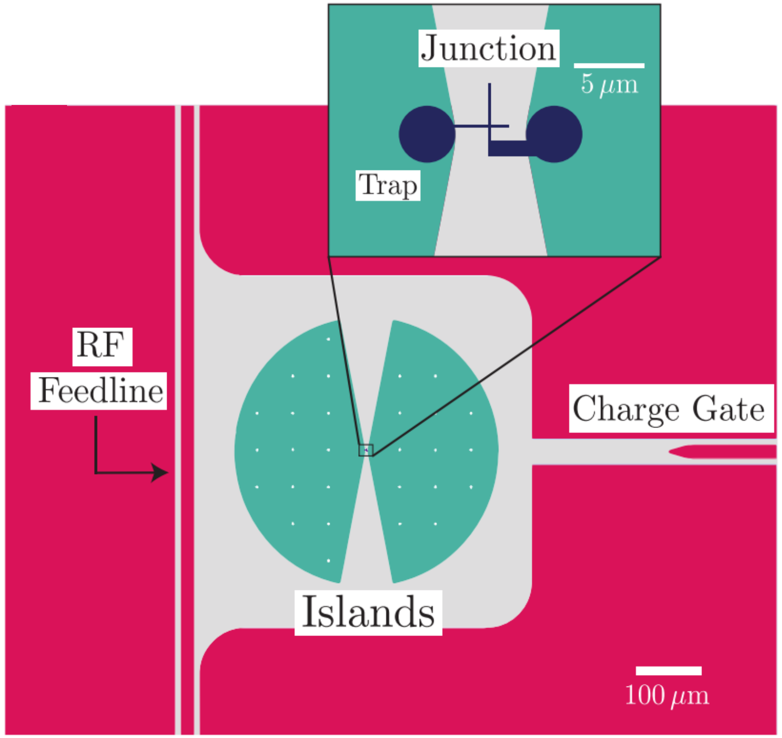
Wilen et al, Nature 594, 369 (2021) [arXiv:2012.06029]

Superconducting **Qu**asiparticle-**A**mplifying **T**ransmon (SQUAT)

- Detection
- Readout
- Efficiency
- Sensitivity
- First tests

"The Superconducting Quasiparticle-Amplifying Transmon: A Qubit-Based Sensor for meV Scale Phonons and Single THz Photons",
C.W. Fink, C.P. Salemi et al., [arXiv:2310.01345v2]



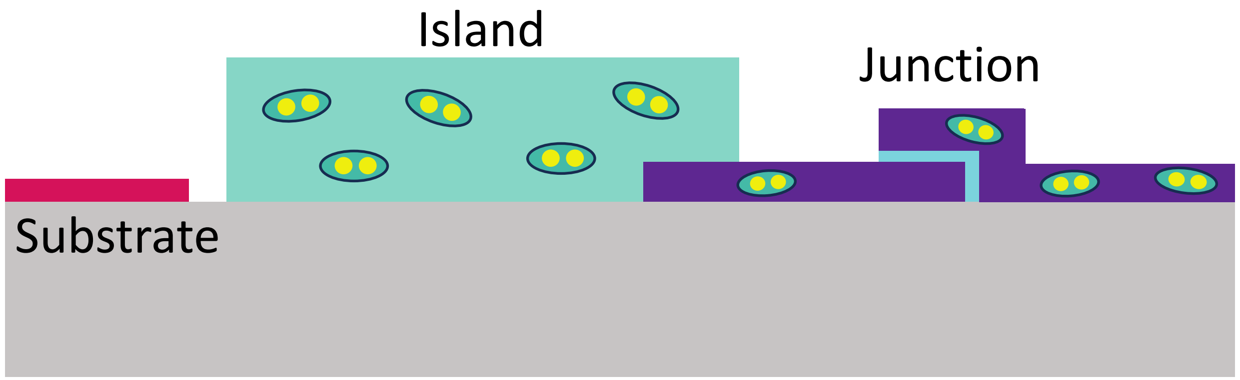


SQUAT Detection Scheme

- Detection
- Readout
- Efficiency
- Sensitivity
- First tests

Materials are chosen such that:

$$\Delta_{island} \gg \Delta_{junction}$$



SQUAT Detection Scheme

- **Detection**
- Readout
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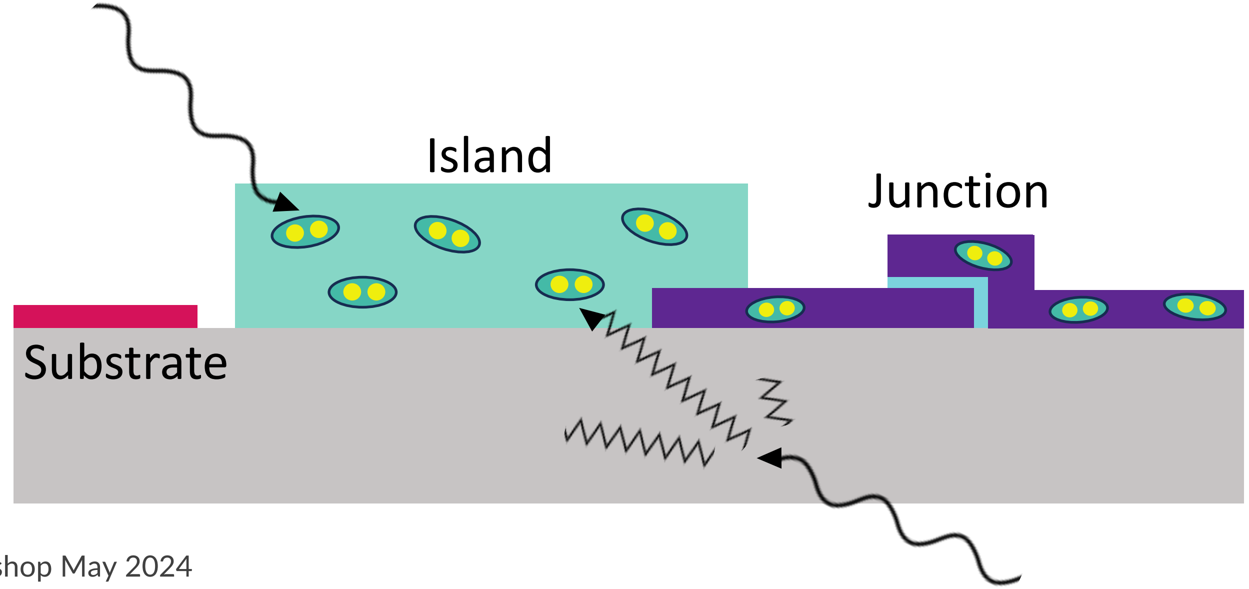
1.) A phonon or photon with energy $>2\Delta_{island}$ breaks a cooper pair into high energy quasiparticles



SQUAT Detection Scheme

Detection

Readout

Efficiency

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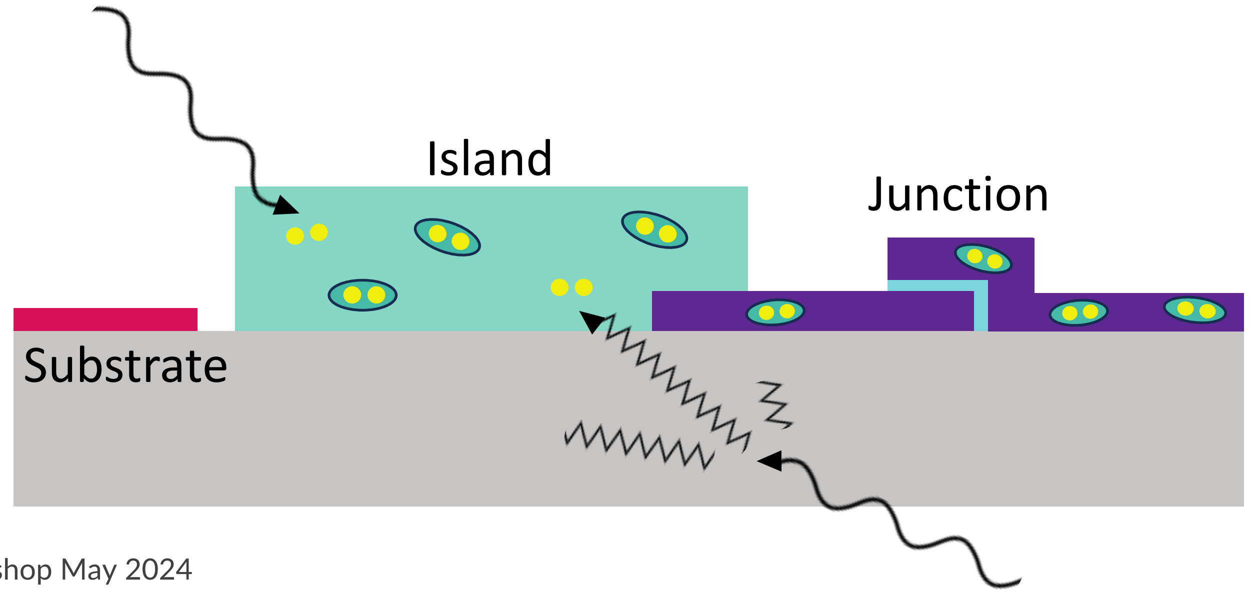

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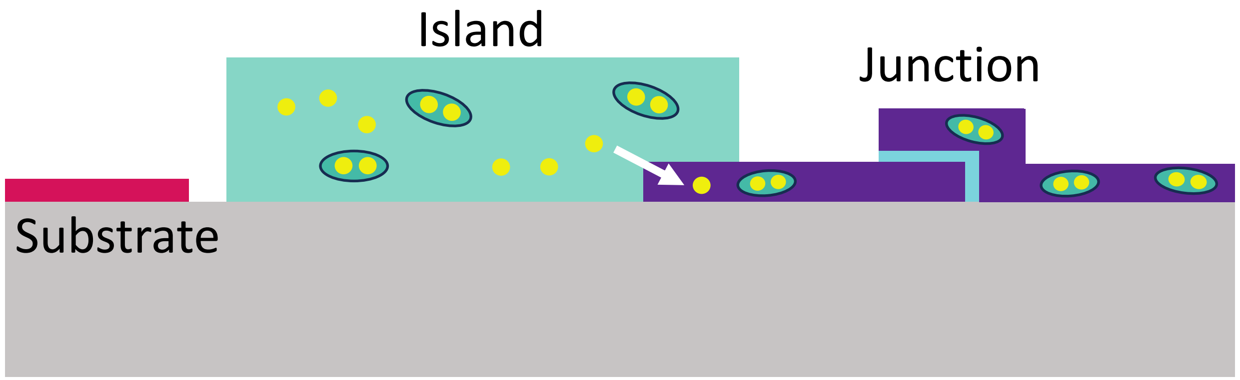

SQUAT Detection Scheme

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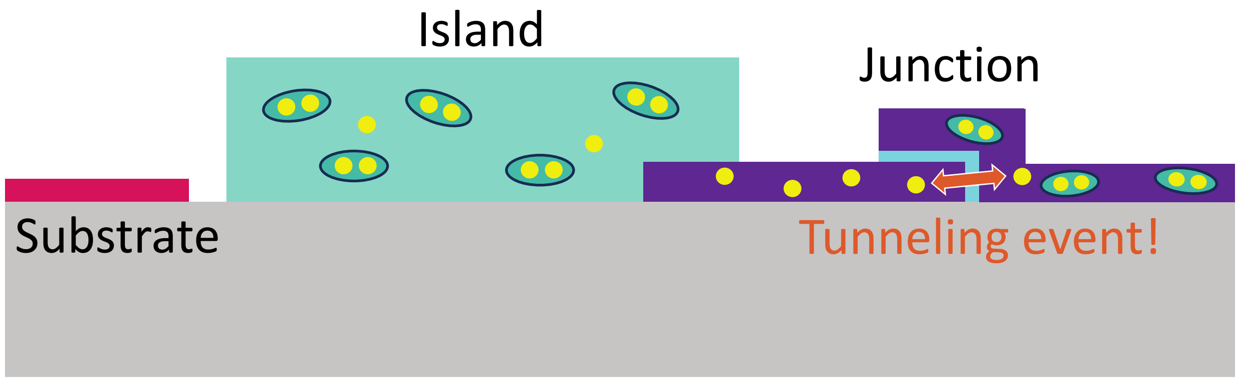
3.) Trapped quasiparticles may tunnel back and forth across the junction until recombination. Each tunneling event can be read out as a signal



SQUAT Readout of QP Tunneling Events

Detection

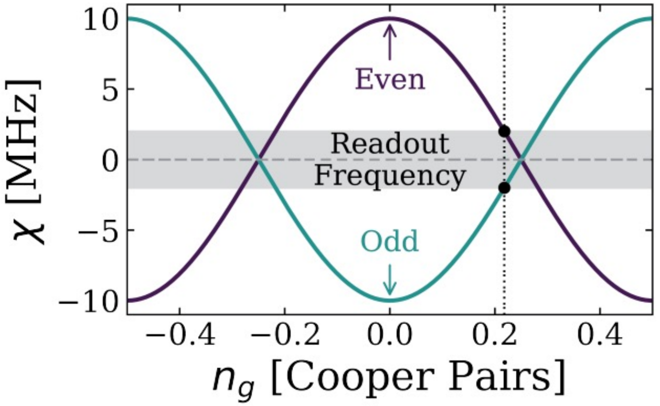
Readout

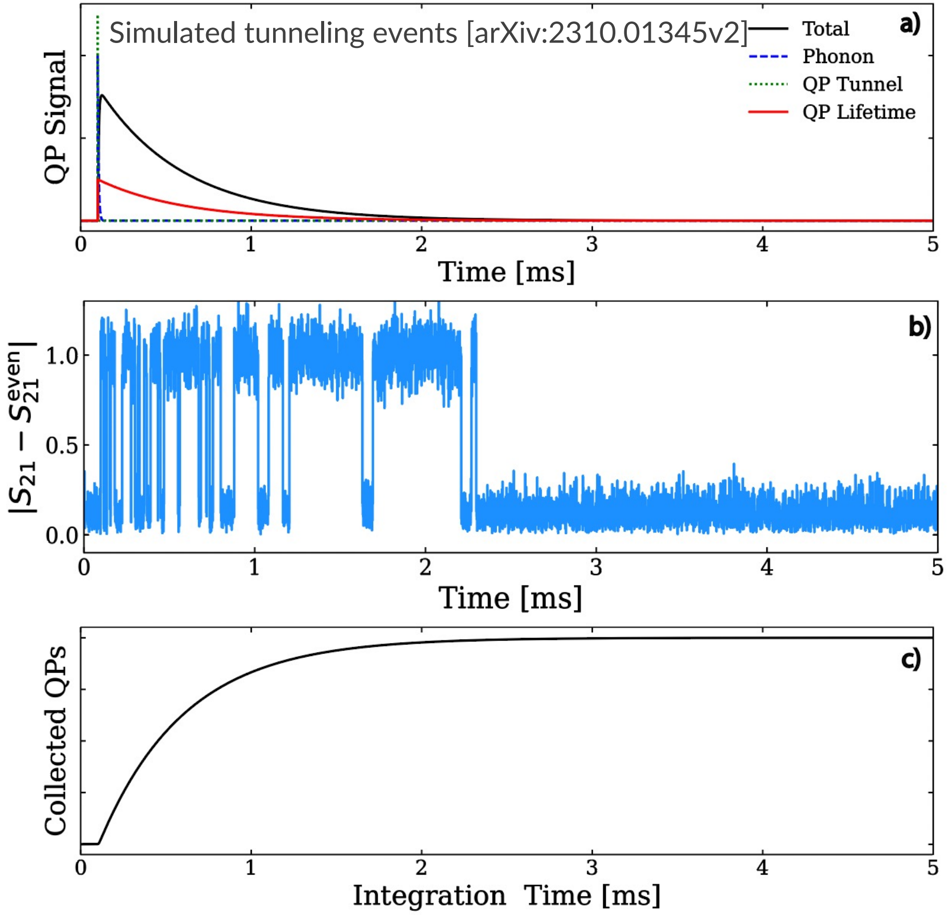
Efficiency

Sensitivity

First tests

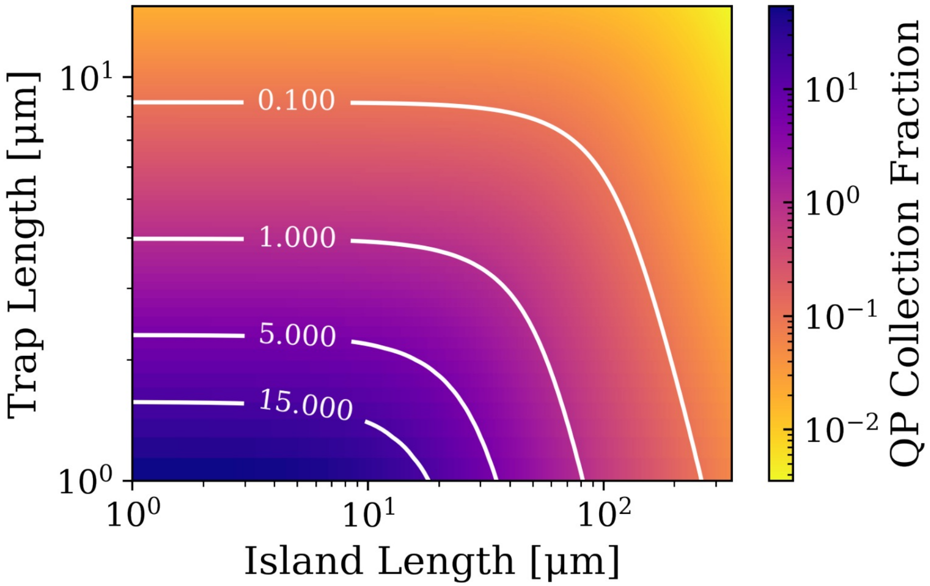
- Tunneling events flip the parity state of the qubit, thus changing its transition frequency
- By monitoring the qubit transition frequency, we can count single tunneling events
- SQUAT detector is designed without a readout resonator to reduce pixel size, limit coupling to TLSs, and increase detector efficiency
  - This increases bandwidth relative to Ramsey readout for quantum-limited amplification

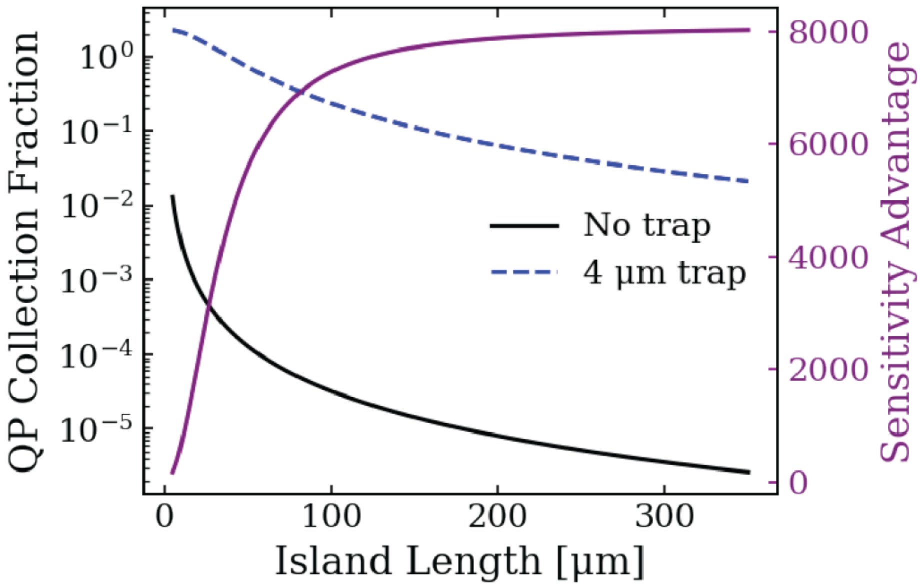




SQUAT Projected Efficiency

- Collection efficiencies above unity can be expected for small devices due to:
  - Quasiparticle multiplication in lower gap trapping material
  - Trapped quasiparticles can undergo multiple tunneling events





Simulated collection efficiencies [arXiv:2310.01345v2]

SQUAT Projected Efficiency

- Detection
- Readout
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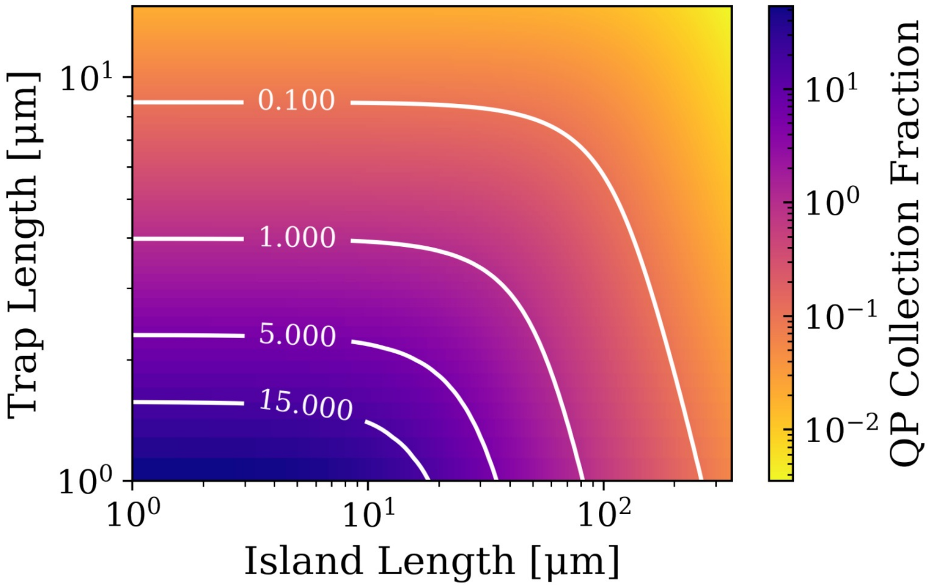
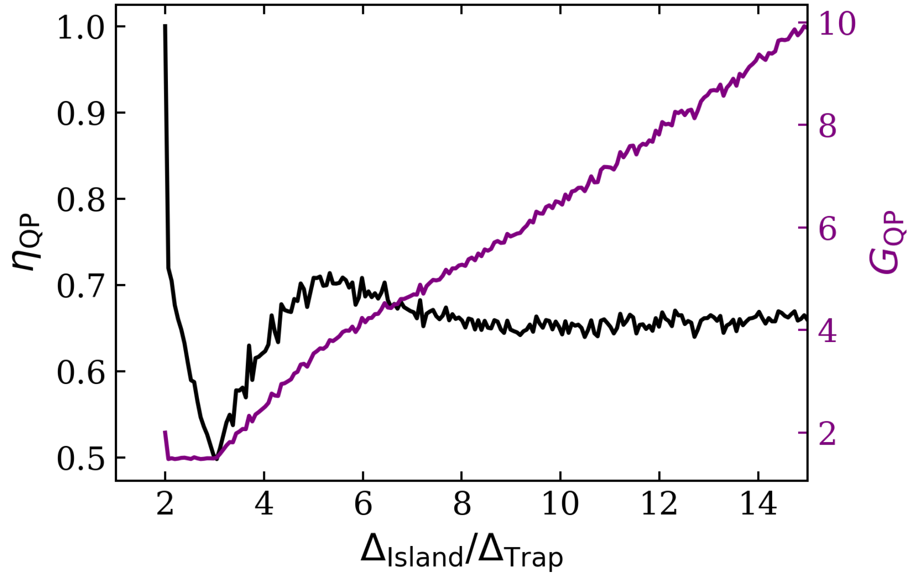




Simulated collection efficiencies [arXiv:2310.01345v2]

SQUAT Projected Sensitivity

Detection

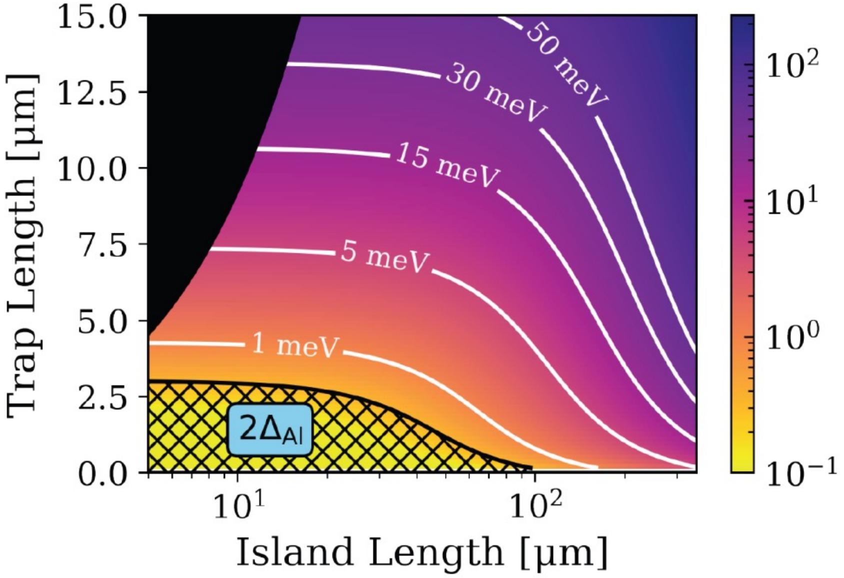
Readout

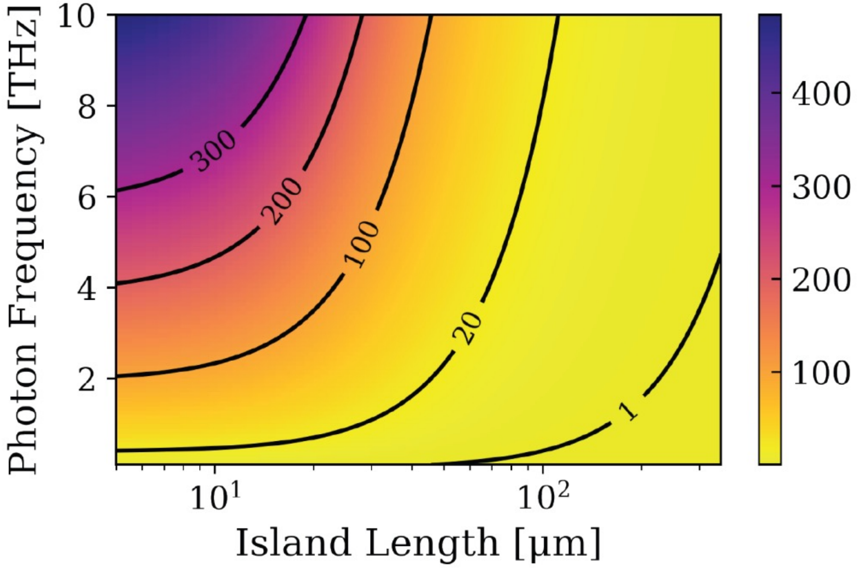
Efficiency

Sensitivity

First tests

- Measurements of initial devices will help benchmark trapping and tunneling efficiencies
- In devices with small geometric trapping regions, we expect sensitivities in the range of single meV phonons and THz photons





Simulated detector sensitivities [arXiv:2310.01345v2]

Detection

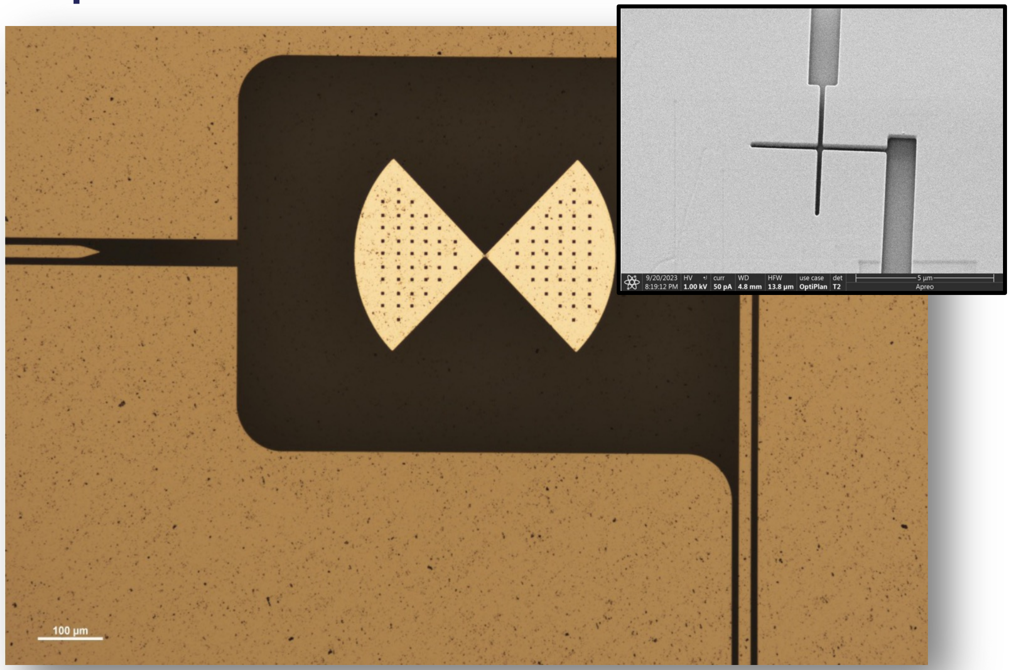
Readout

Efficiency

Sensitivity

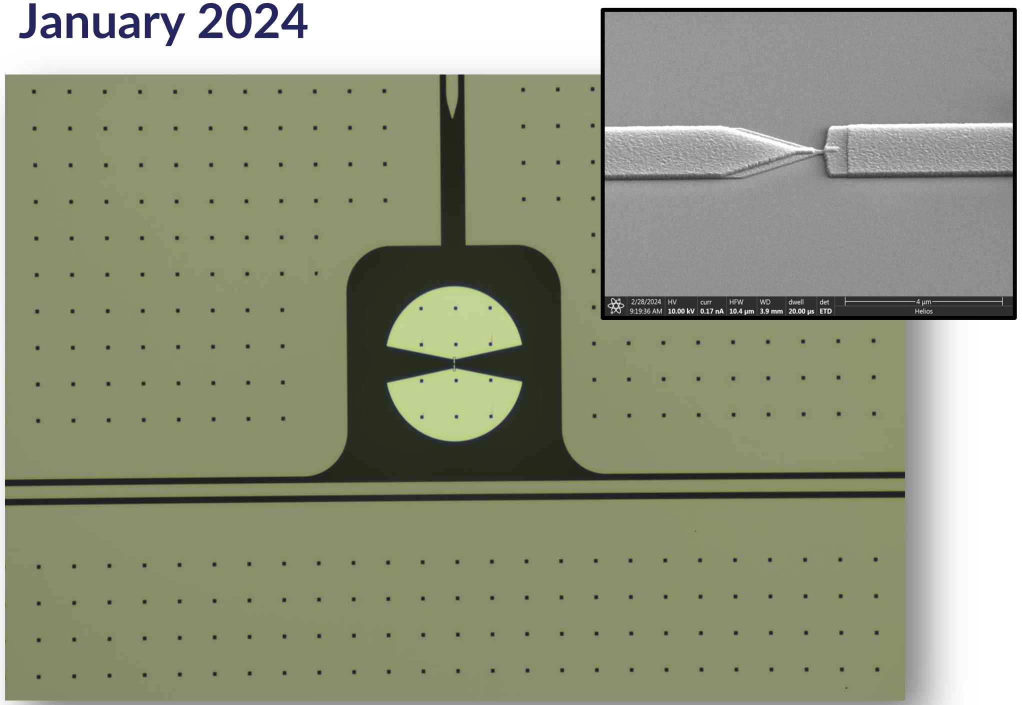
First tests

September 2023



- Aluminum islands
- Aluminum junctions (Manhattan)
- Sapphire substrate
- Fabricated by Jadyn Anczarski and Noshin Tabassum

January 2024



- Aluminum islands
- Aluminum junctions (Dolan)
- Sapphire substrate
- Fabricated by Hannah Magoon with recipe from Ziqian Li

Measurement Setup

Detection

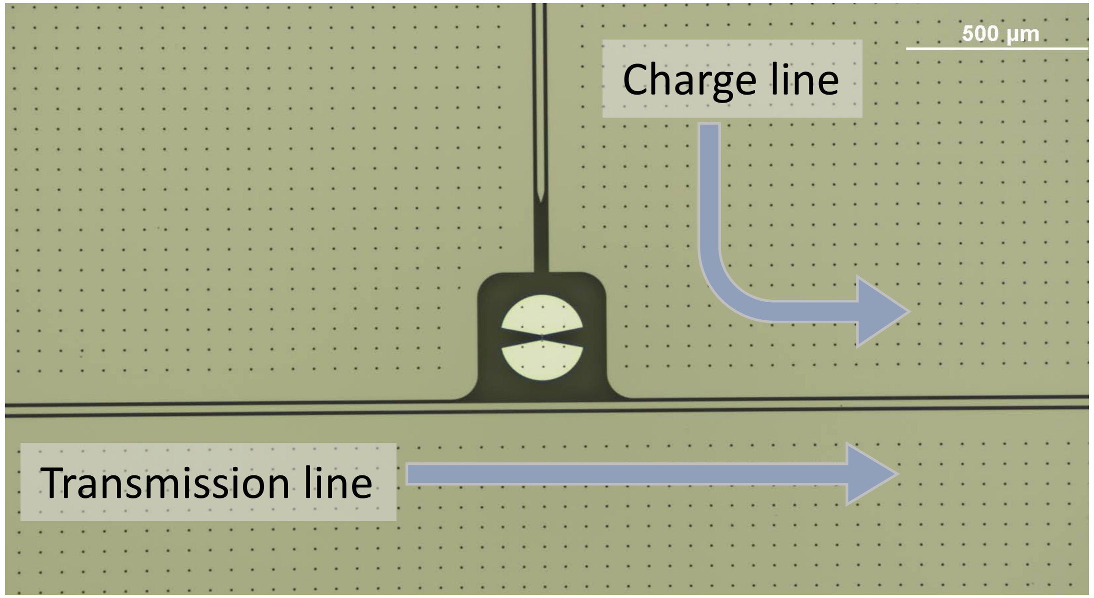
Readout

Efficiency

Sensitivity

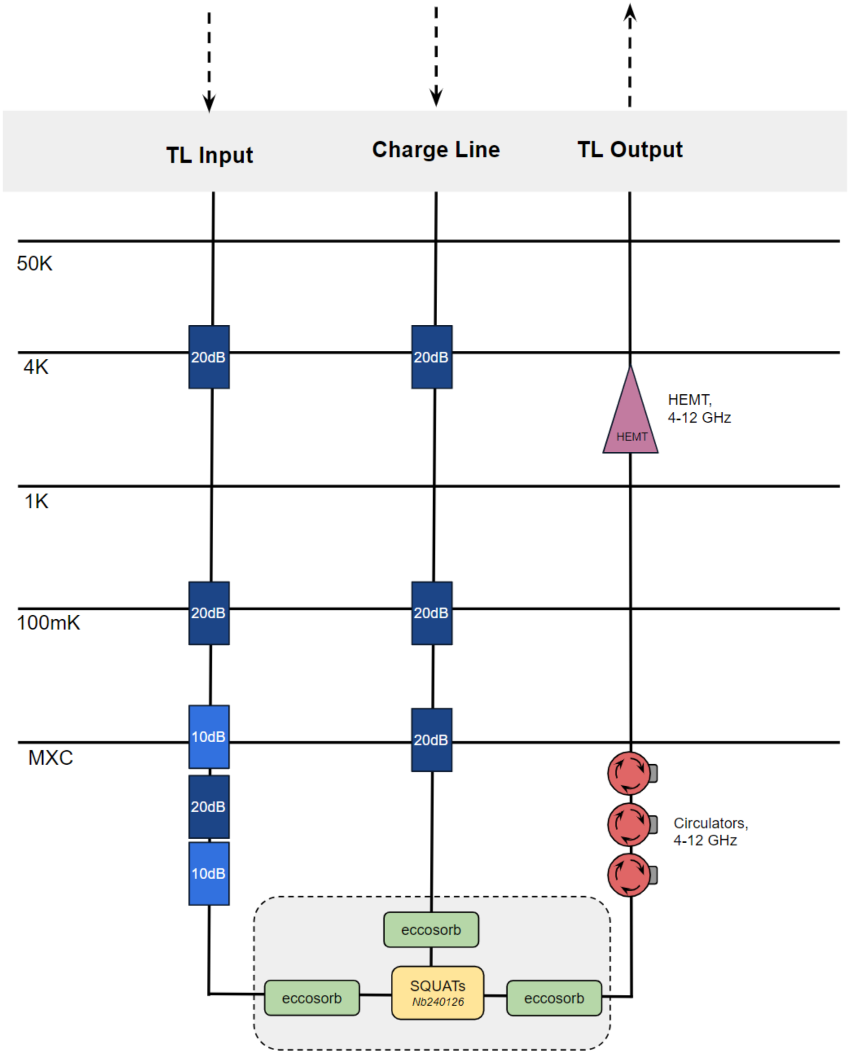
First tests

Tested two measurement paths



Transmission Line:
- Stronger coupling to SQUAT (so most of emitted photons pop up here)
- Emitted SQUAT photons are added to transmission line signal photons during readout

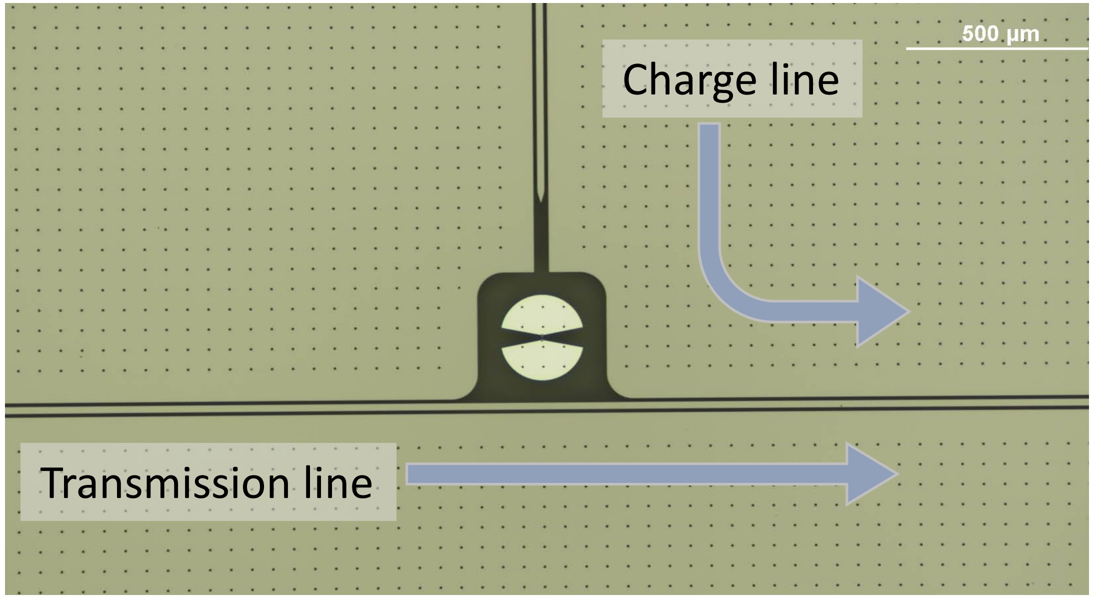
Charge Bias Line
- Weaker coupling to SQUAT (need to drive at higher gains)
- Emitted SQUAT photons are the only thing that are passed to the transmission line for readout



Measurement Setup

- Detection
- Readout
- Efficiency
- Sensitivity
- **First tests**

Tested two measurement paths



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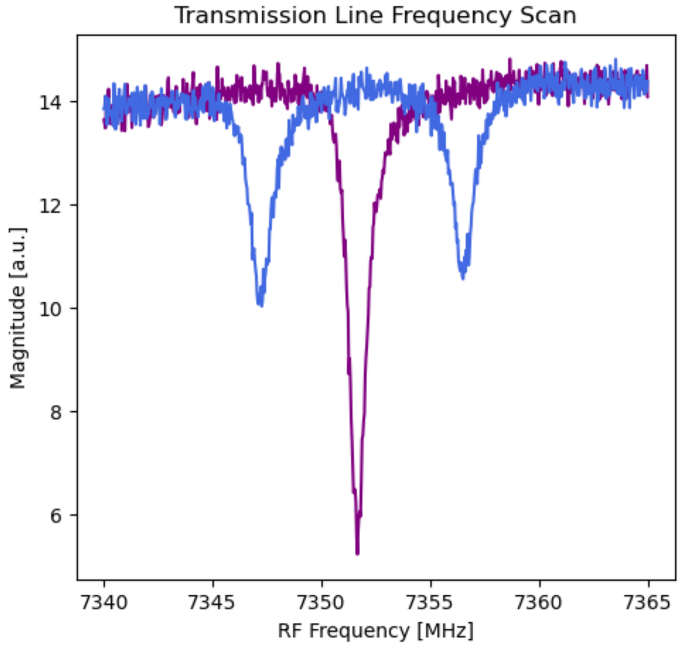
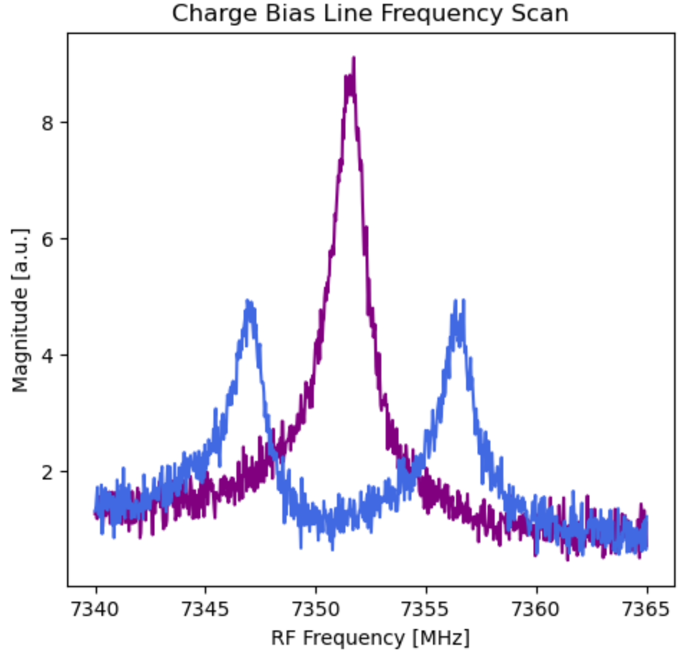




CW Measurements

Detection

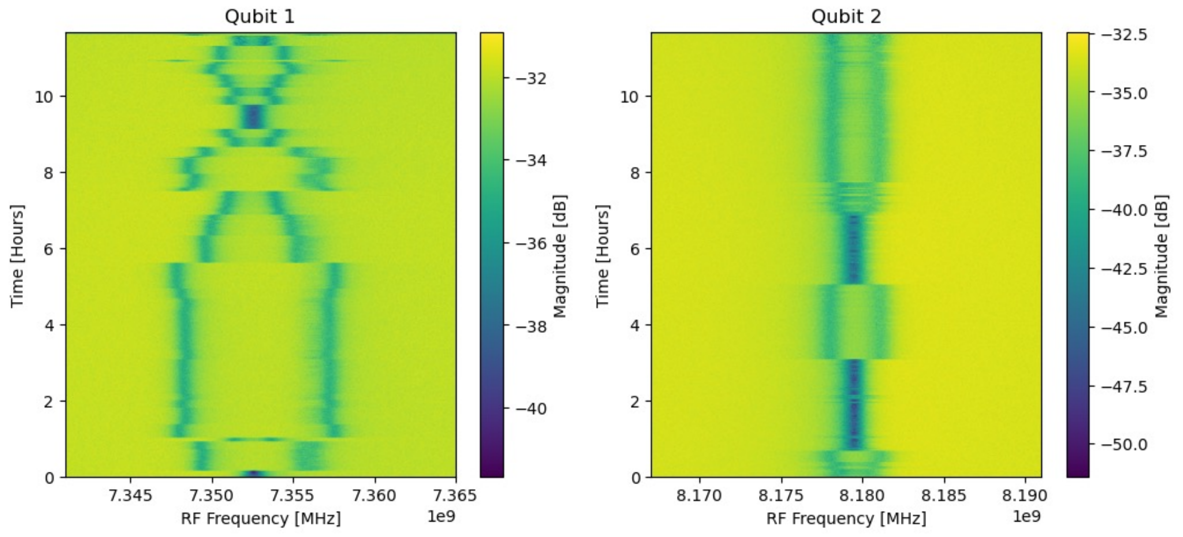
Readout

Efficiency

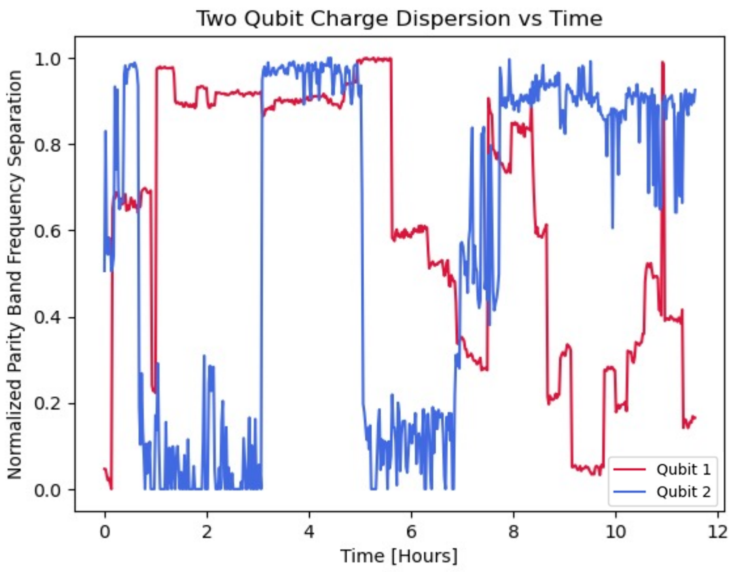
Sensitivity

First tests

To track charge offset on the SQUAT island, we can run repeated VNA frequency scans. By fitting the charge dispersion, we can identify correlated events on chip:



Repeated frequency scans display charge jumps over time for two SQUATs on the same chip



Charge dispersion fit values plotted for each qubit

Device Parameters

Detection

Readout

Efficiency

Sensitivity

First tests

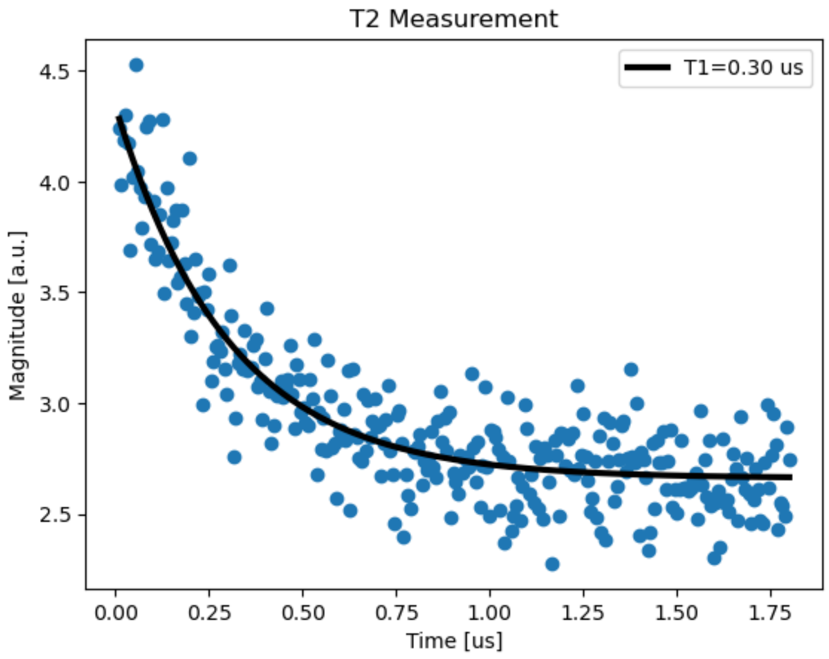
Measurement of two SQUAT devices:

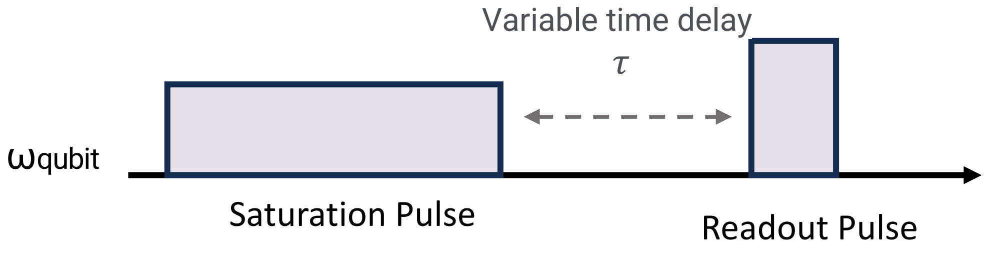
Center Frequency: 7.35 GHz and 8.18 GHz

Quality Factor: 5000-10000

Parity Band Dispersion: 10MHz and 3 MHz

Saturation Pulse Coherence Time: ~300ns





SLAC

Qubit Coupled to Waveguide

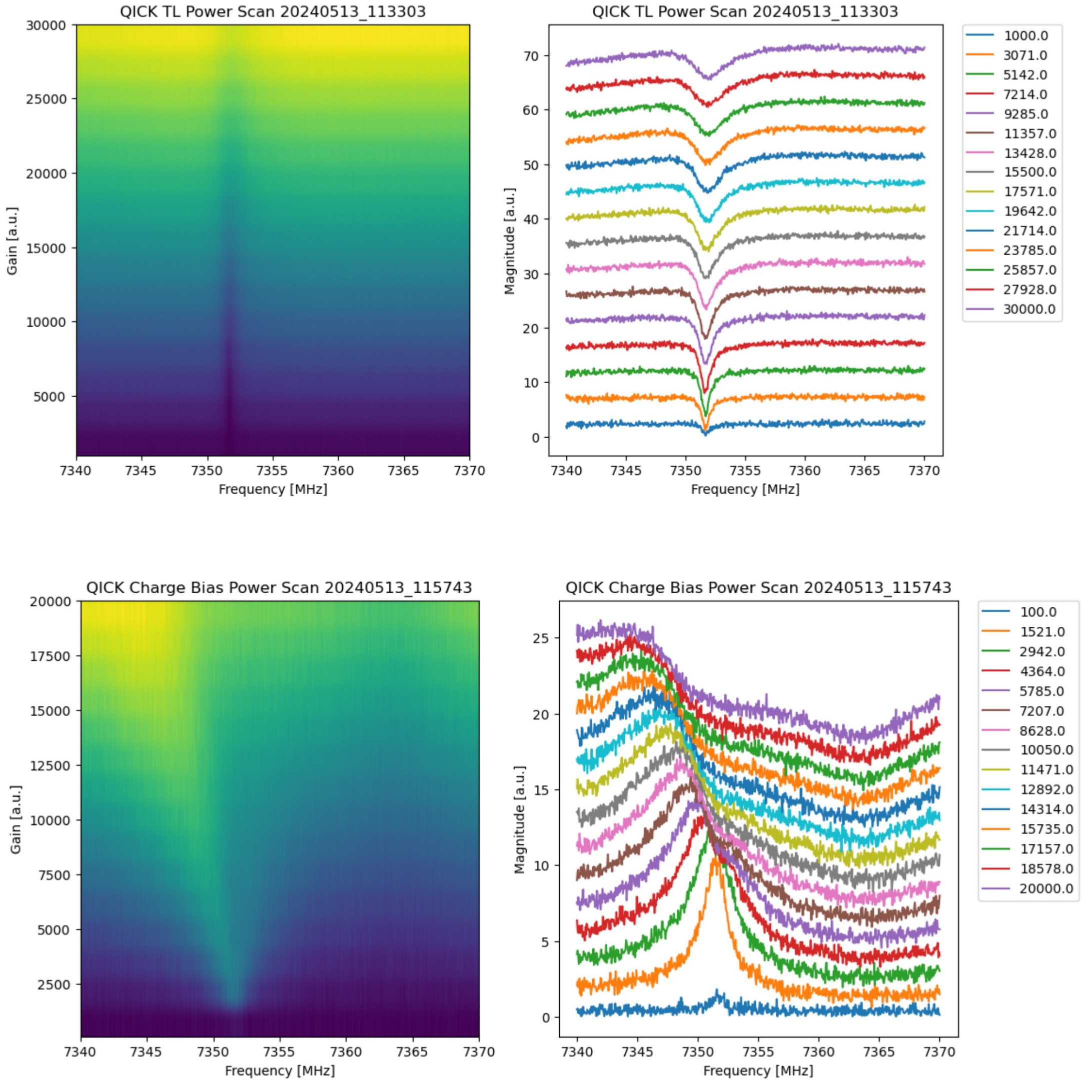
- Detection
- Readout
- Efficiency
- Sensitivity
- **First tests**

Interesting dynamics emerge as a result of directly reading out the SQUAT's emitted photons

Measurements appear different through the two readout lines as a result of interference with ambient signal photons

We can model this with the Hamiltonian for a two level qubit interacting with a coherent drive field:

$$H = \frac{\omega_q}{2}\sigma_z + \frac{\Omega}{2}\left(e^{+i\omega_d t}\sigma_+ + e^{-i\omega_d t}\sigma_-\right)$$



Next Steps

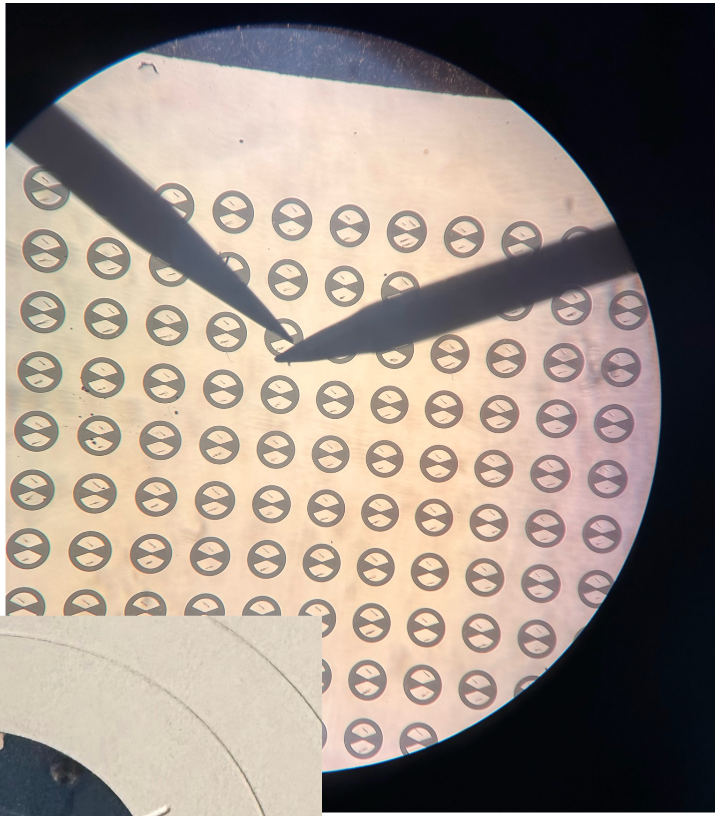
- Detection
- Readout
- Efficiency
- Sensitivity
- **First tests**

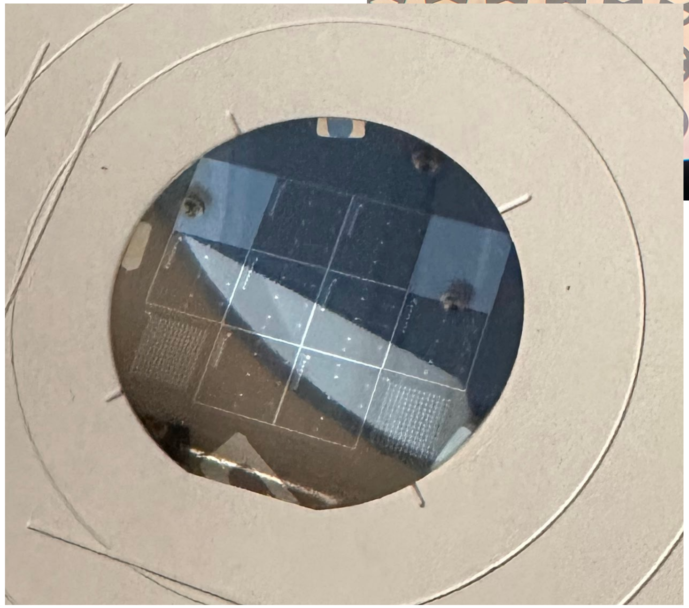
Development of low-Tc junctions is of interest for the broader quantum sensing community – whether this is beneficial for quasiparticle cooling is a major question

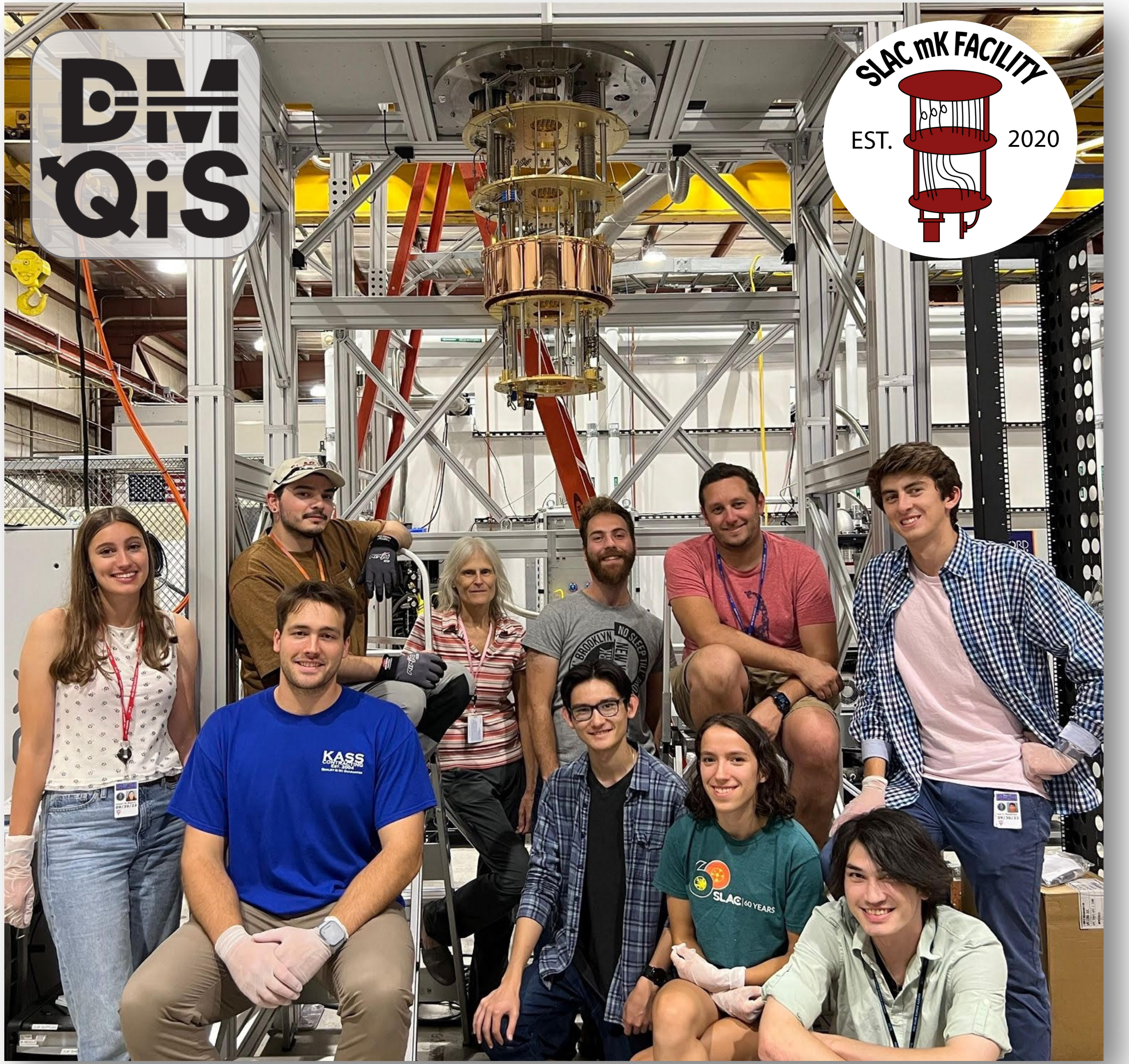
- Ti junctions made, testing underway
- Hf, AlMn junctions planned
- We will also explore tri-layer processes, but with low-gap materials

Developing readout protocols – likely next devices will have dual feelines to transmit through SQUAT arrays

Question: How low can we get background parity switching rates while maintaining high detection efficiency?







DMQIS Postdocs/Faculty

Noah Kurinsky (SLAC PI)
Kelly Stifter (SLAC Panofsky Fellow)
Betty Young (Santa Clara Professor)
Caleb Fink (Director's Fellow, LANL)
Chiara Salemi (Stanford Porat Fellow)
James Ryan (SLAC Postdoc)
Nico Linton (SLAC Staff)

DMQIS Students

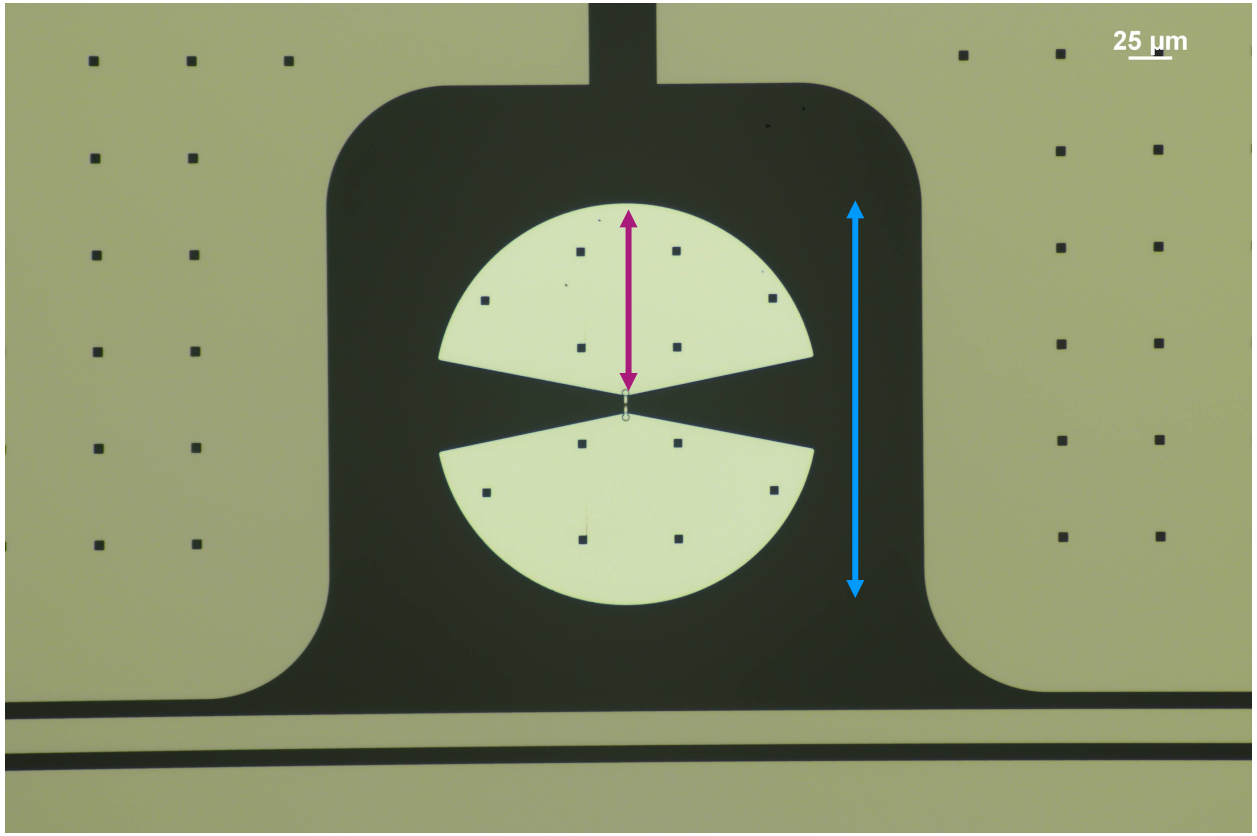
Jadyn Arczarski (Stanford grad)
Zoë Smith (Stanford grad)
Aviv Simchony (Stanford grad)
Taj Dyson (Stanford grad)
Hannah Magoon (Stanford grad)
Noshin Tabassum (SLAC post-bac)
Ivar Rydstrom (Santa Clara undergrad)
Riley Carpenter (Santa Clara undergrad)

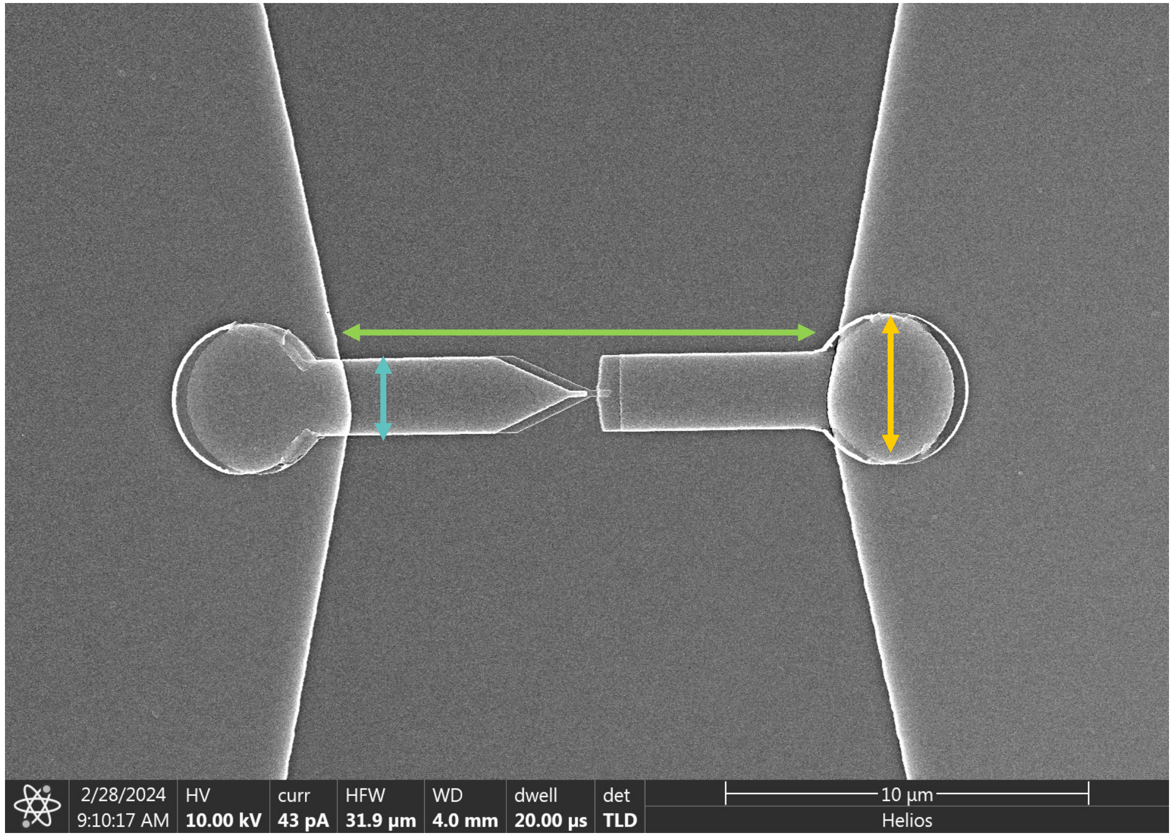
Schuster Lab Collaborators

David Schuster (Stanford Professor)
Shannon Harvey (SLab/QNEXT Postdoc)
Sebastien Leger (SLab postdoc)
Ziqian Li (Stanford grad)
Wendy Wan (Stanford grad)

Backup Slides

SQUAT Dimensions



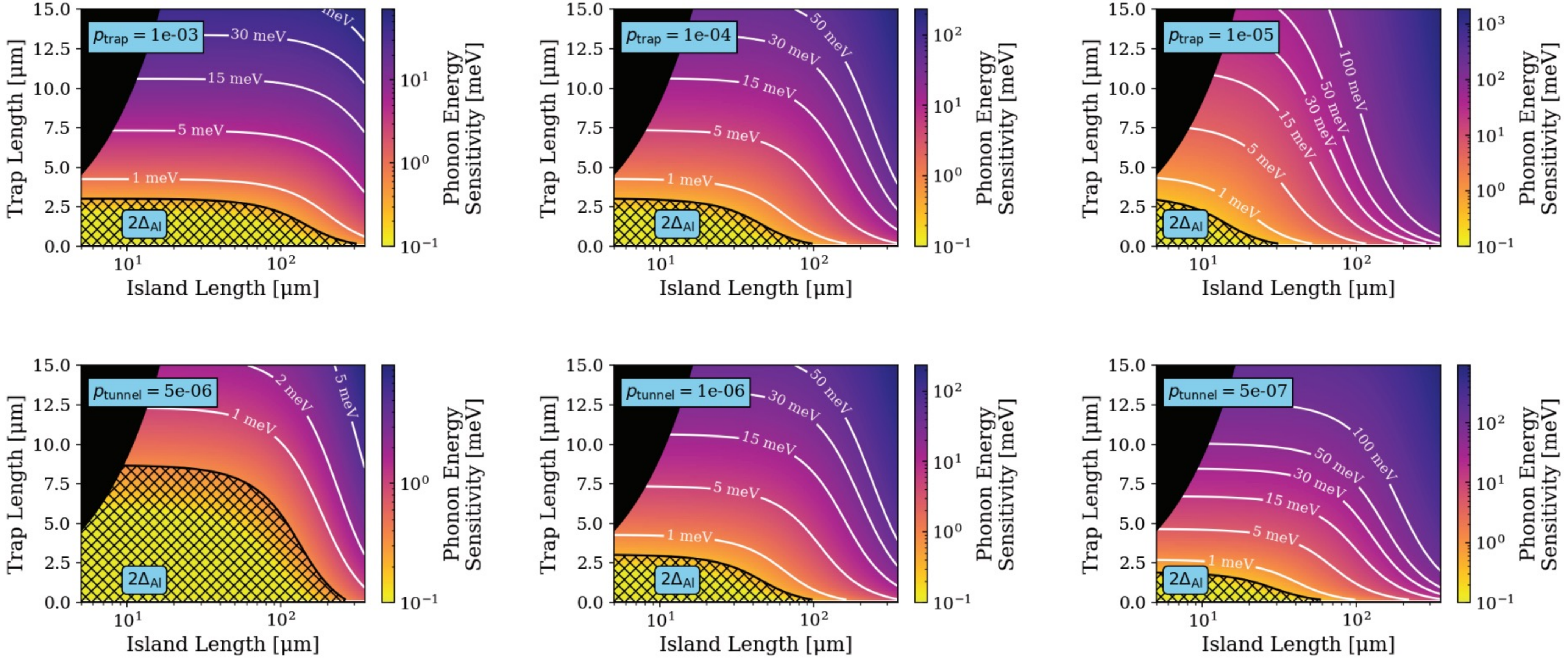


Nb Gnd Plane Thickness: 100 nm
Al Trap Thickness: 200 nm

Trap Radius: 112 µm
Pixel Diameter: 240 µm

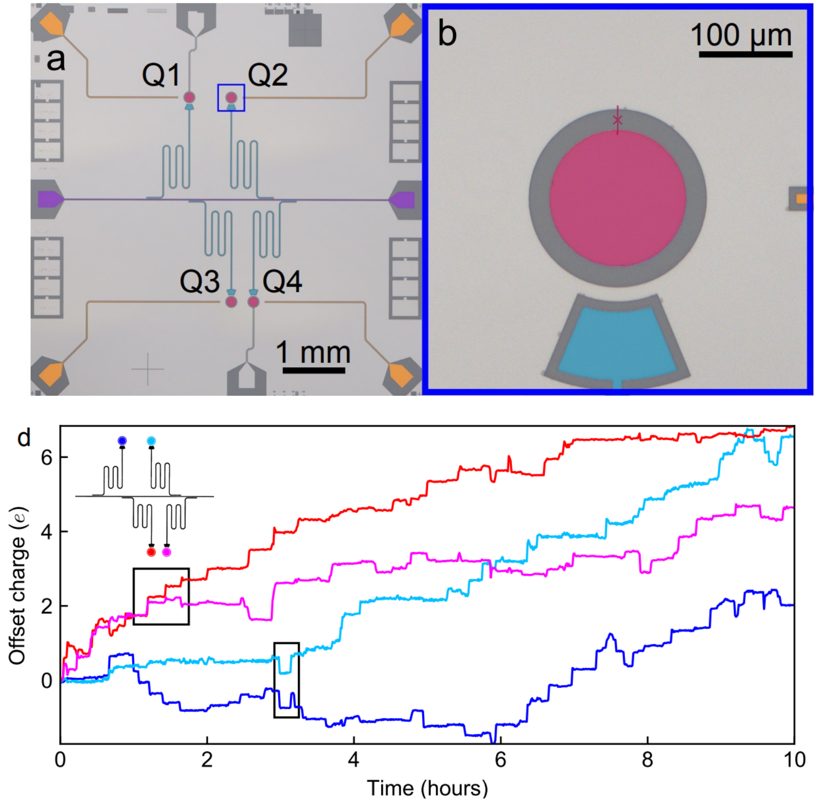
Connection Pad Diameter: 4 µm
Junction Length: 16 µm
Junction Width: 2 µm
(Minimum Junction Width: 0.12 µm)

SQUAT Sensitivity (varying trapping/tunneling efficiency)



Transmons as Detectors

- McDermott group at UW Madison fabricated an array of 4 weakly charge-sensitive qubits
- By running repeated Ramsey measurements, they were able to track drifts in qubit frequency due to changes in n_g, the island offset charge
- The qubits were found the exhibit spatially correlated jumps in charge due to ambient ionizing radiation
- Furthermore, all qubits on the chip were found to experience degradation in coherence time following radiation events



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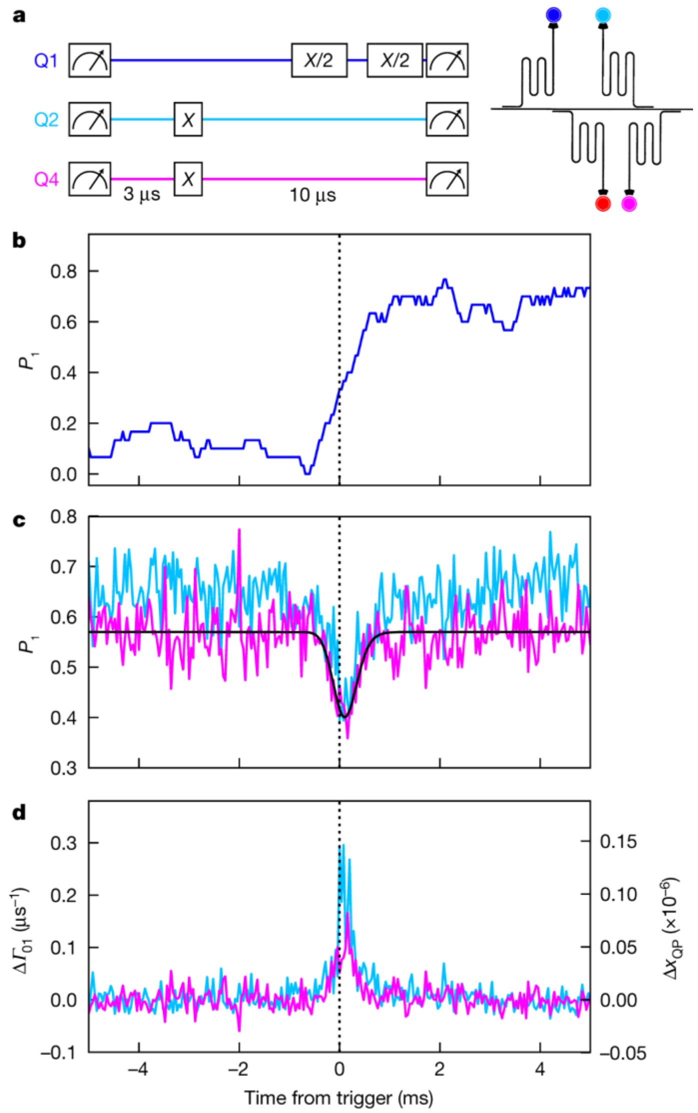
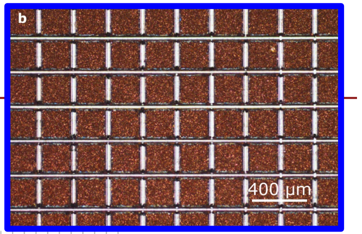


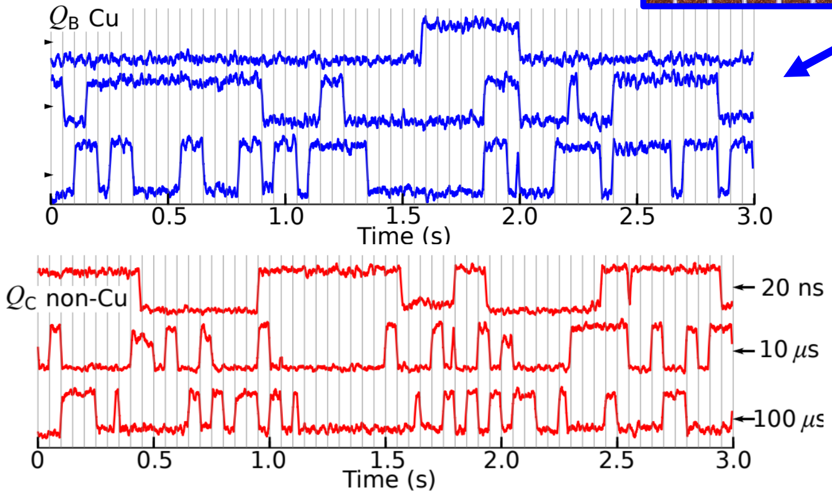
Wilen et al, Nature 594, 369 (2021) [arXiv:2012.06029]

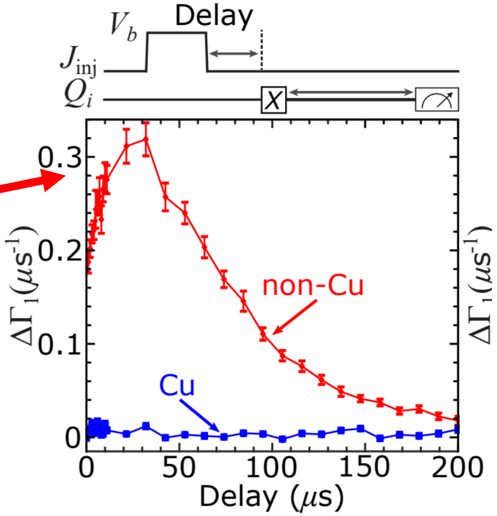
Transmons as Detectors

- Plourde group at Syracuse deposited thick electroplated Cu reservoirs on the back of a transmon chip to act as sinks for athermal phonons
- The chips with Cu reservoirs showed reduced ambient tunneling rates compared to identical chips without Cu reservoirs
- The chips with Cu reservoirs showed negligible response to phonon injection events compared to their non-Cu counterparts



Back-side Cu metallization





Evidence of phonon-mediated decoherence

Iaia, Ku, Ballard et al, Nature Communications (2022) [arXiv:2203.06586v2]

SQUAT Fabrication Process

Detection

Readout

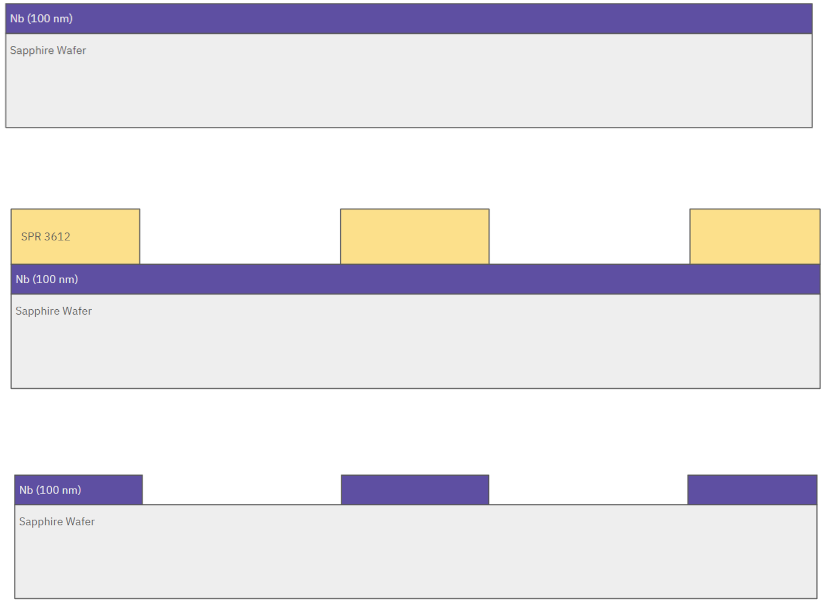
Efficiency

Sensitivity

Fabrication

First Optical Layer

Niobium ground plane and CPW transmission line, made using an optical layer and dry etch



SQUAT Fabrication Process

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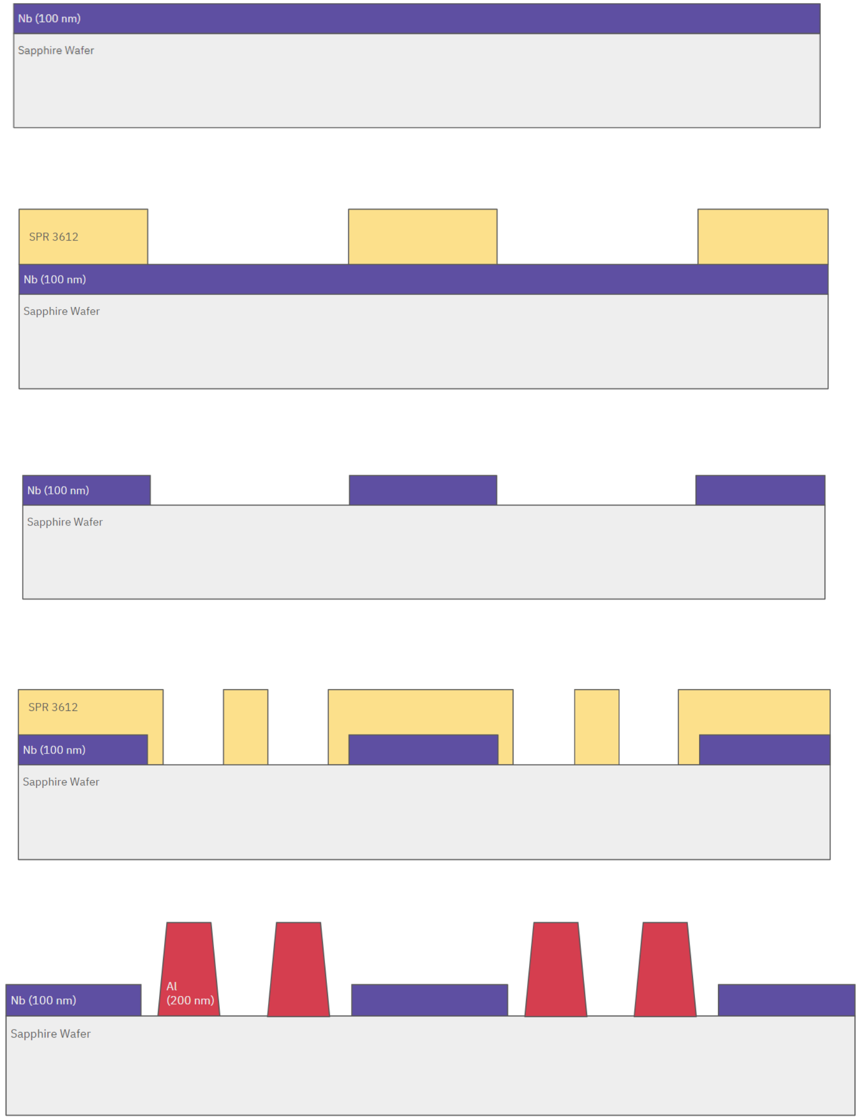
First Optical Layer

Niobium ground plane and CPW transmission line, made using an optical layer and dry etch

Second Optical Layer

Aluminum trap features, made with an optical layer and liftoff



SQUAT Fabrication Process

First Optical Layer

Niobium ground plane and CPW transmission line, made using an optical layer and dry etch

Second Optical Layer

Aluminum trap features, made with an optical layer and liftoff

Ebeam Junction Layer

Aluminum josephson junctions, made with e-beam exposure and liftoff