Low Gap Hf-HfO_x-Hf Josephson Junction for meV-Scale Particle Detection

Yashwanth Balaji[1], Mythili Surendran[1], Xinran Li[1], Aidar Kemelbay[1], Arian Gashi[1], Chiara Salemi[2,3], Aritoki Suzuki[2], Aeron T Hammack[2], and Adam Schwartzberg[1]

[1]Molecular Foundry, Lawrence Berkeley National Laboratory
[2]Physics Division, Lawrence Berkeley National Laboratory
[3]Department of Physics, University of California Berkeley

SQUAT/QPD Measurement Workshop | Oct. 29th, 2025

Who are we?

The Molecular Foundry

- **Nanofabrication** ★
- **Imaging and Manipulation of Nanostructures**
- **Theory of Nanostructured Materials**
- **Inorganic Nanostructures**
- **Biological Nanostructures**
- **Organic and Macromolecular Synthesis**
- **Data Science and Digital Infrastructure**
- **National Center for Electron Microscopy**

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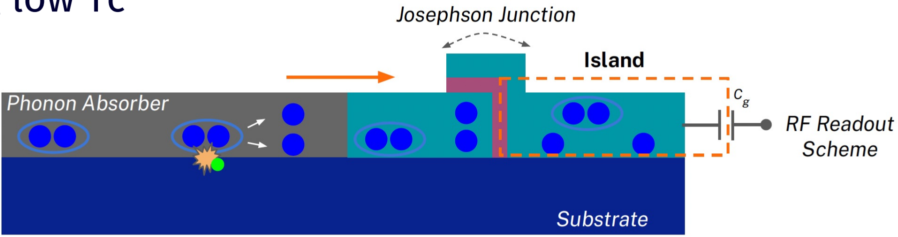
What’s the plan?

1. High Tc materials as absorber
2. Low Tc material for quasiparticle trapping
3. Josephson Junctions using low Tc materials



C. W. Fink, C. P. Salemi, et al. A qubit-based sensor for mev-scale phonons and single thz photons, Phys. Rev. Applied 22, 054009 (2024).

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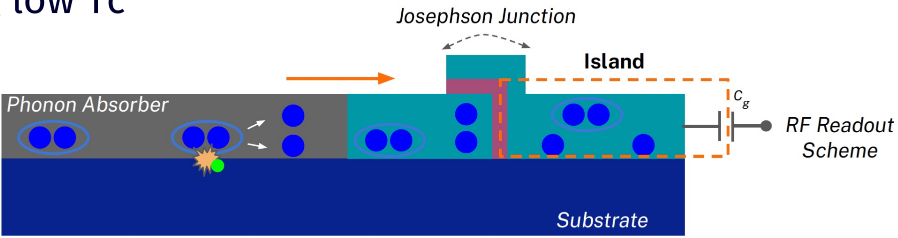

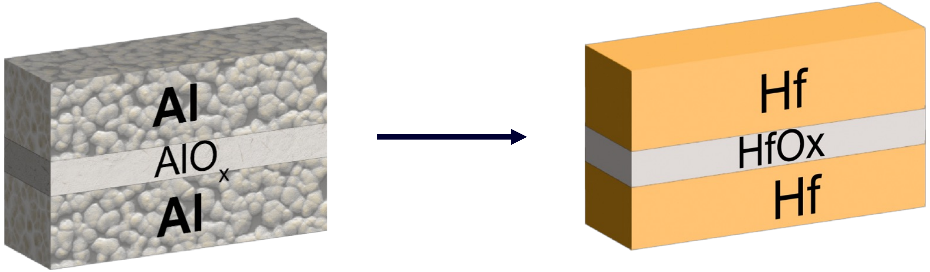

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Fabrication overview

Substrate preparation

e-beam lithography

Josephson junction

Deposition

Josephson junction

DC Measurements

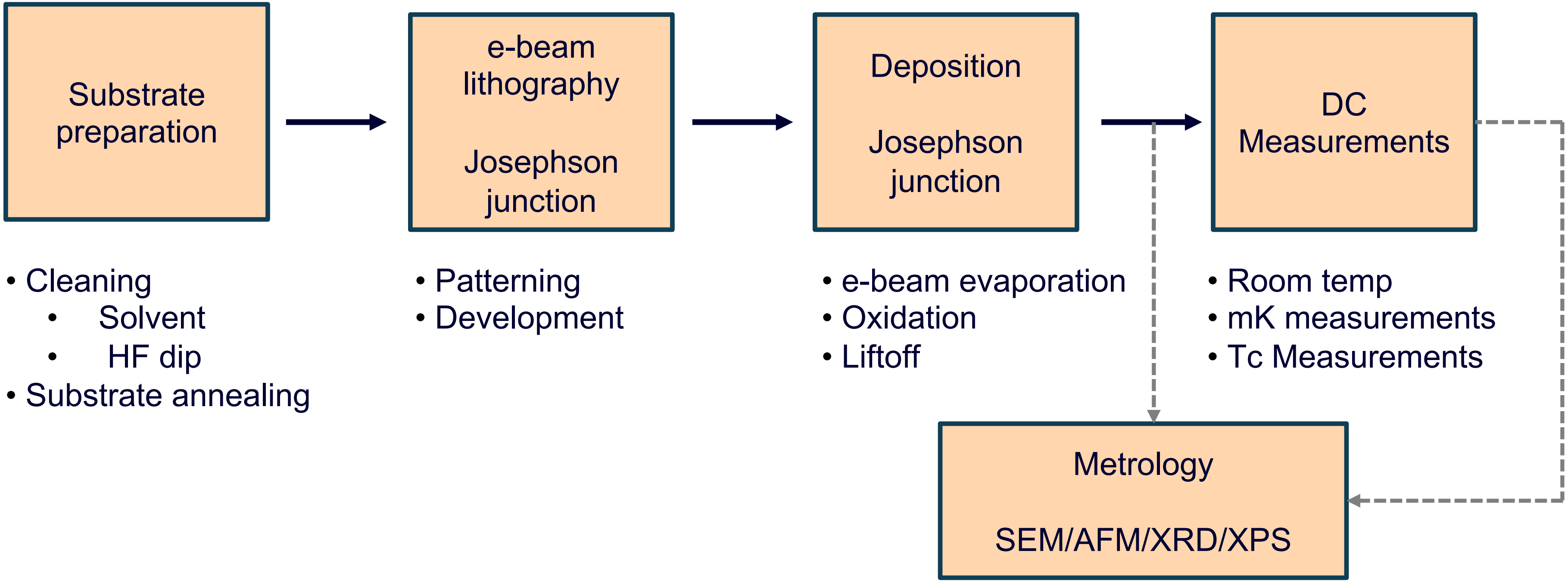
- Cleaning
    - Solvent
    - HF dip
- Substrate annealing

- Patterning
- Development

- e-beam evaporation
- Oxidation
- Liftoff

- Room temp
- mK measurements
- Tc Measurements

Fabrication overview



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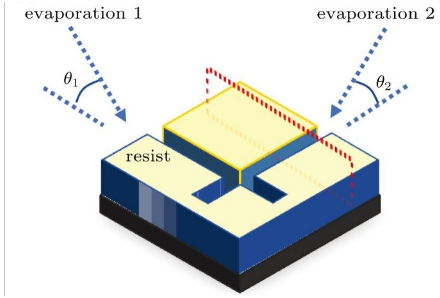
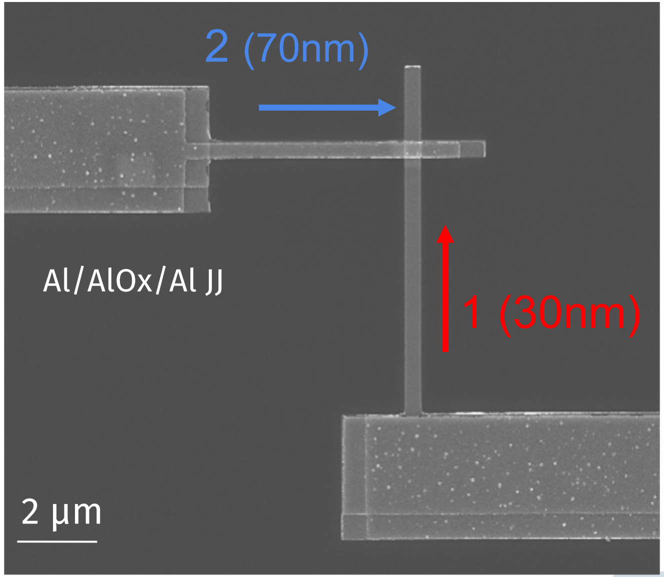
Metrology

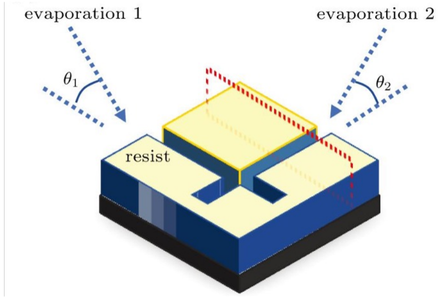
SEM/AFM/XRD/XPS

JJ angled evaporation technique



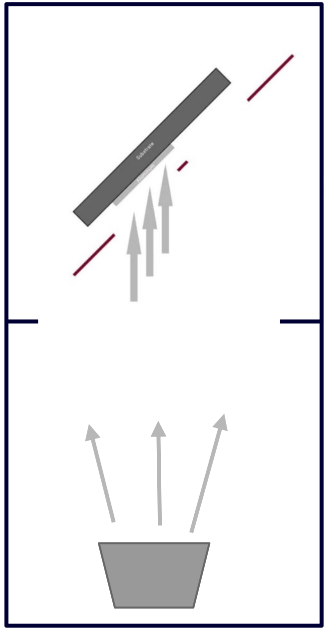


JJ angled evaporation technique



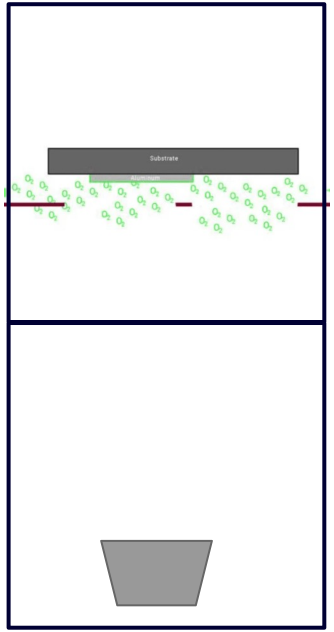
1st lead

30nm at 45° - 2A/sec



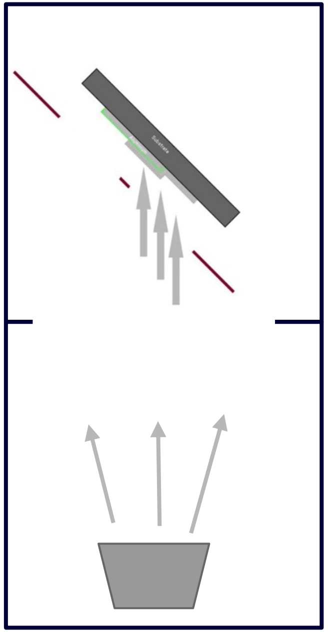
Oxidation

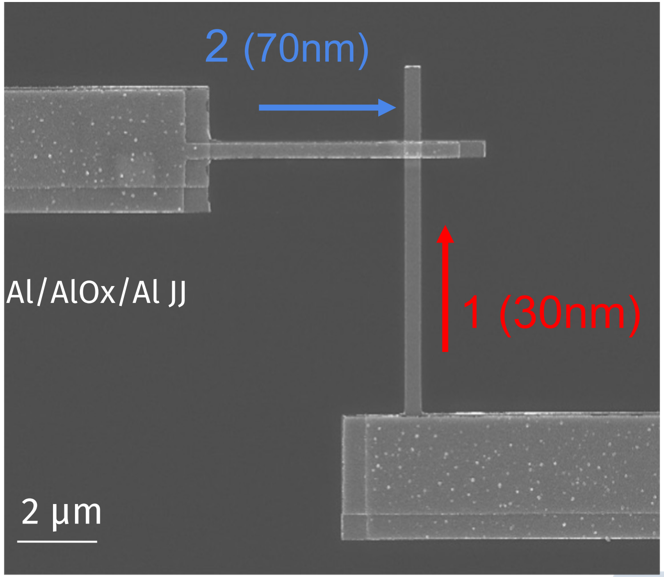
15mBar 15 mins



2nd lead

70nm at 45° - 2A/sec
90° rotation





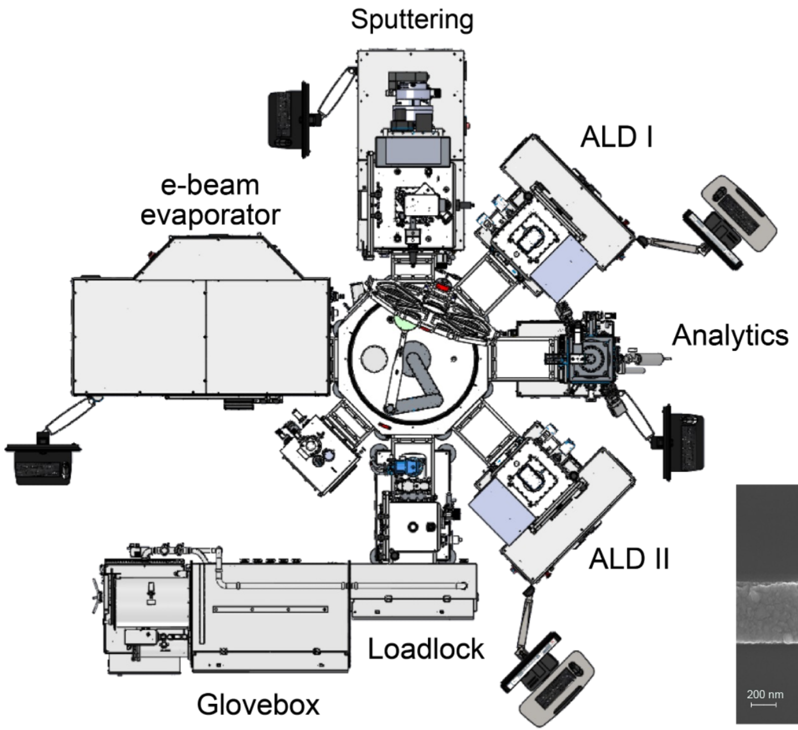
Quantum Cluster system

1. Multi-Tool Deposition System
2. Inert Sample Handling
3. In-Situ Characterization Suite

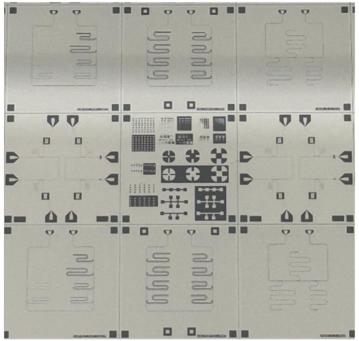
Materials

e-beam evaporation	Sputtering	ALD oxides	ALD nitrides
Al	Nb	AlOx	TiN
Nb	Ta	HfOx	AlN
Ti	NbN	ZrOx	
Hf	TiN		
	NbTiN		

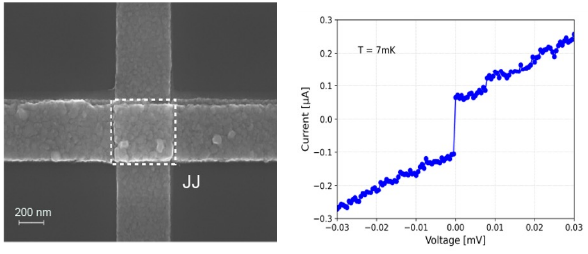
SC Transition Metal Nitrides



ANGSTROM ENGINEERING

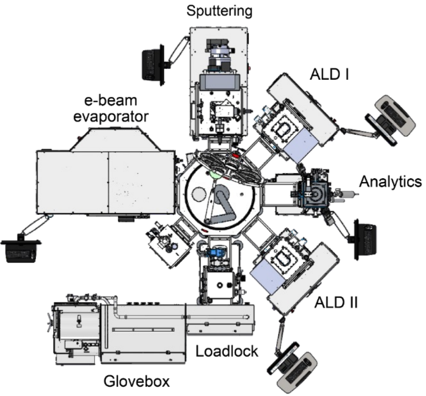


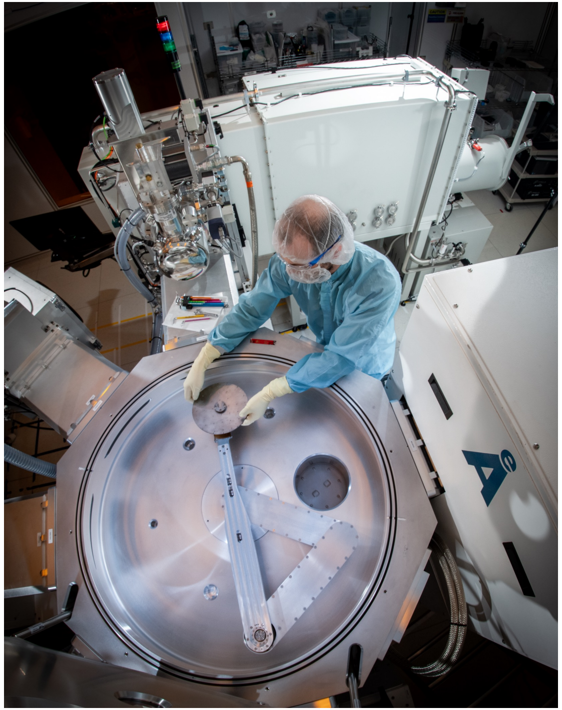
Resonator and qubit fabrication

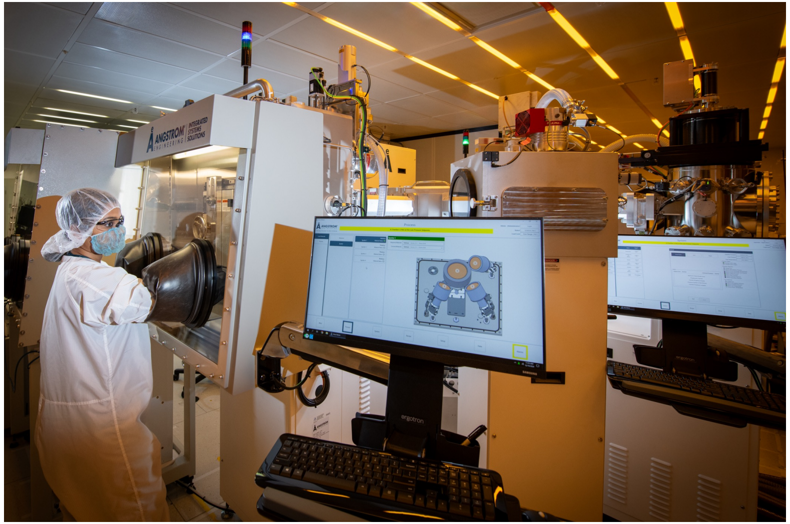


Josephson junction Fabrication

Quantum Cluster system

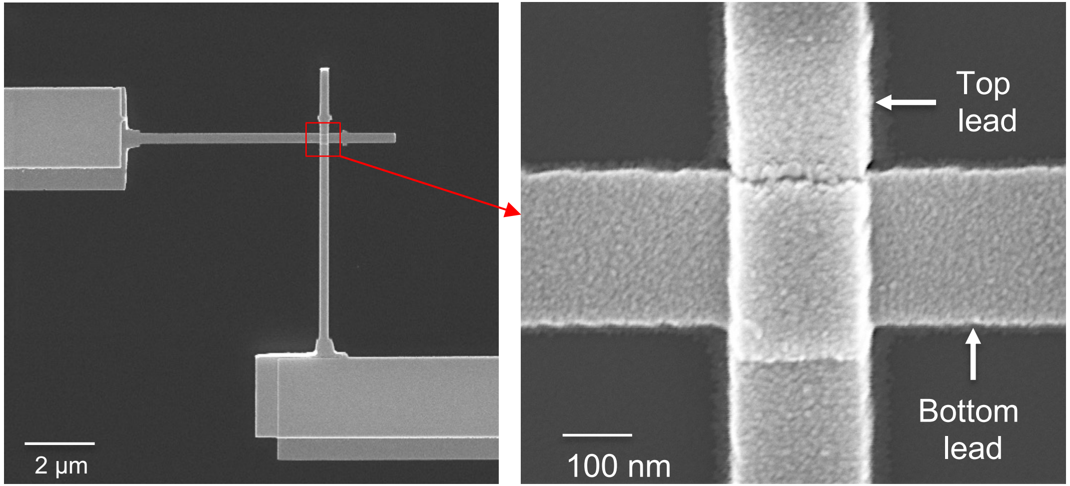






Device Characterization

SEM



1. Double angled shadow evaporation technique
2. Hf deposited using e-beam evaporation
3. In-situ oxidation of HfOx tunnel barrier

Device Characterization

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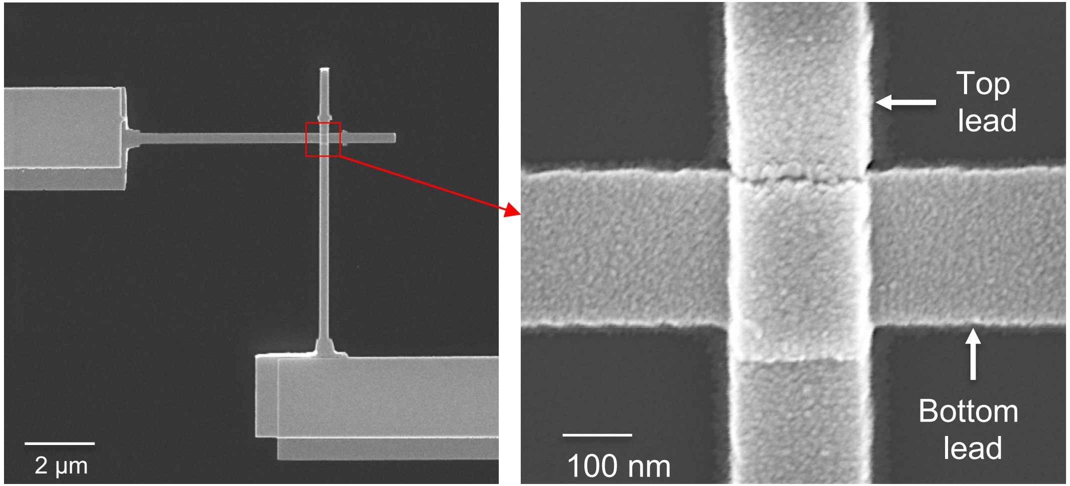
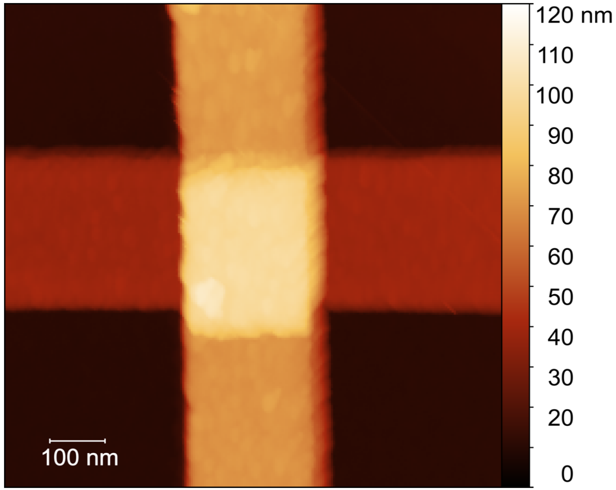


AFM



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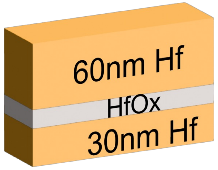
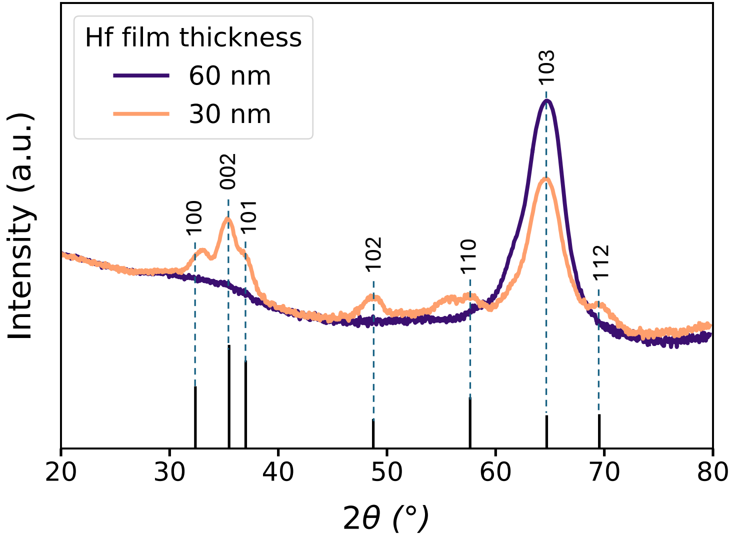
Lead thickness

Bottom lead = 30 nm
Top lead = 60 nm



Hf film Characterization

X-ray Diffraction (XRD)



- Polycrystalline with a hexagonal close-packed (hcp) structure.
- No HfO_2- related peaks observed

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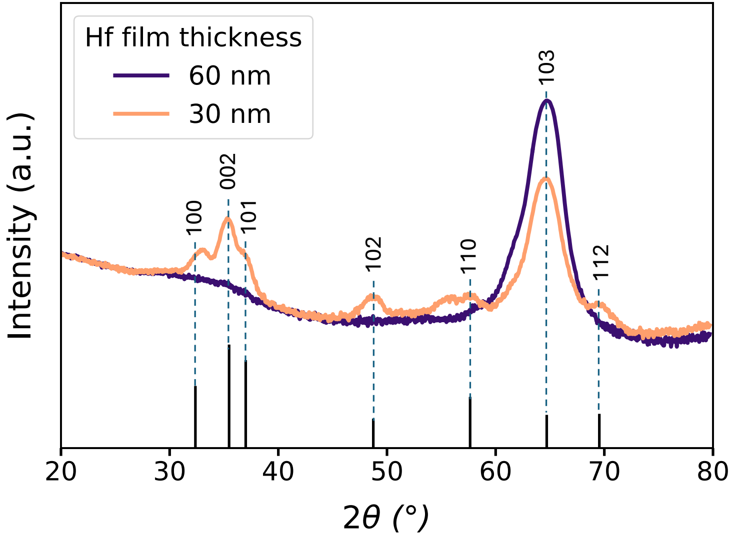

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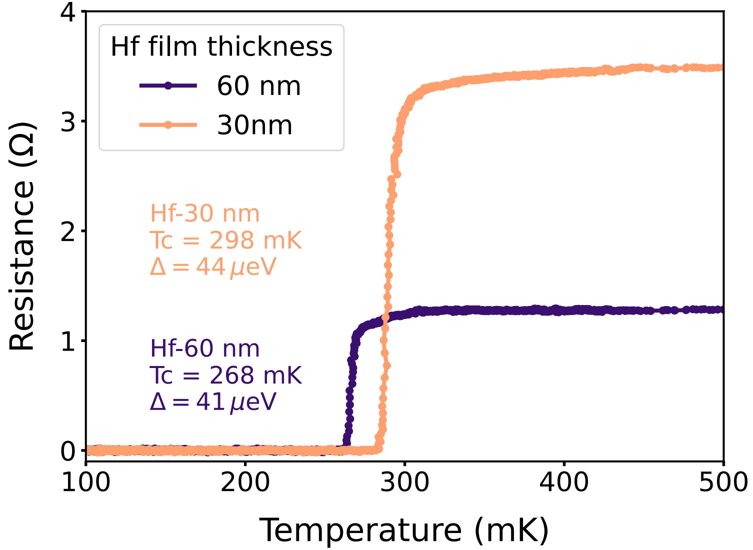
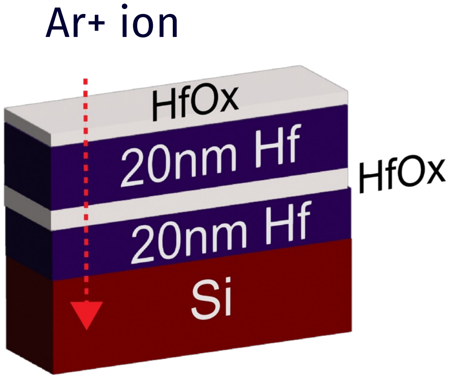
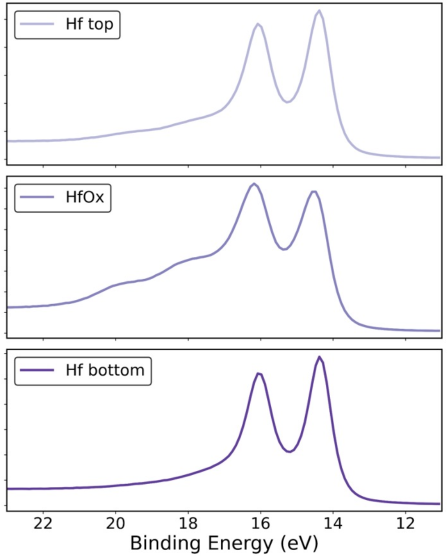
Critical temperature measurements



- 4-wire resistance measurements as a function of temperature.

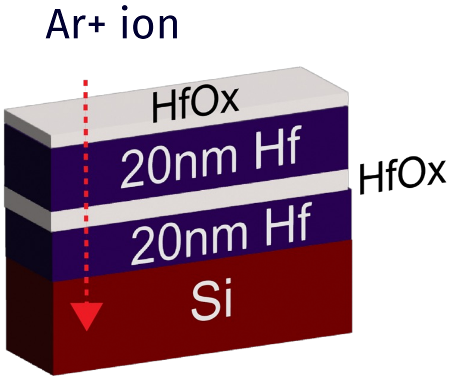
JJ Composition analysis - XPS depth profile

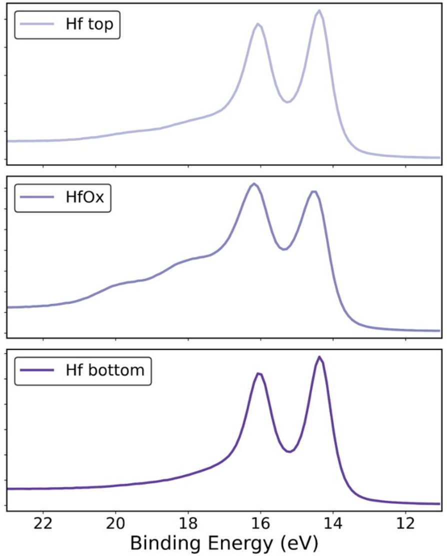


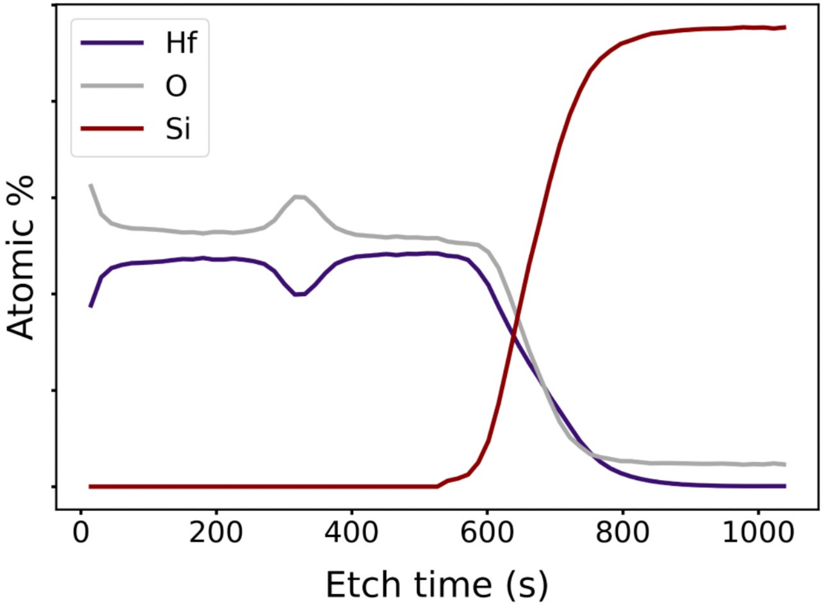


- To identify the oxidation state of Hf within the oxide.
- Increase in oxygen concentration - Decrease in Hf concentration

JJ Composition analysis - XPS depth profile







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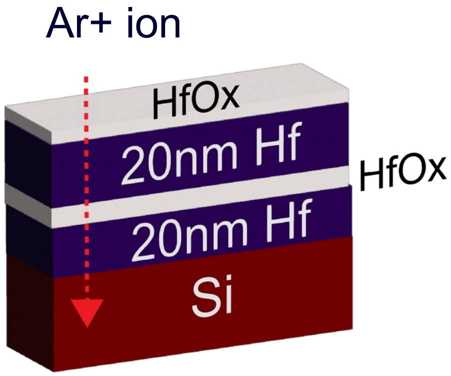

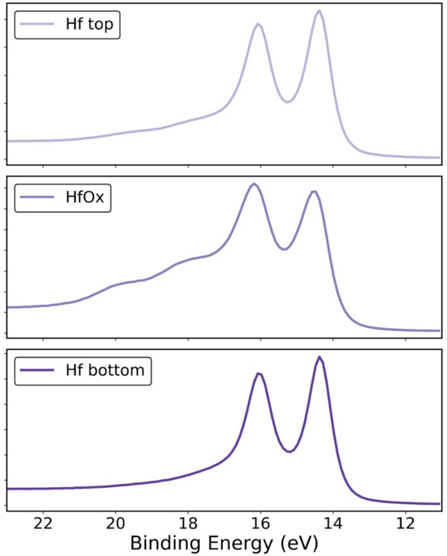

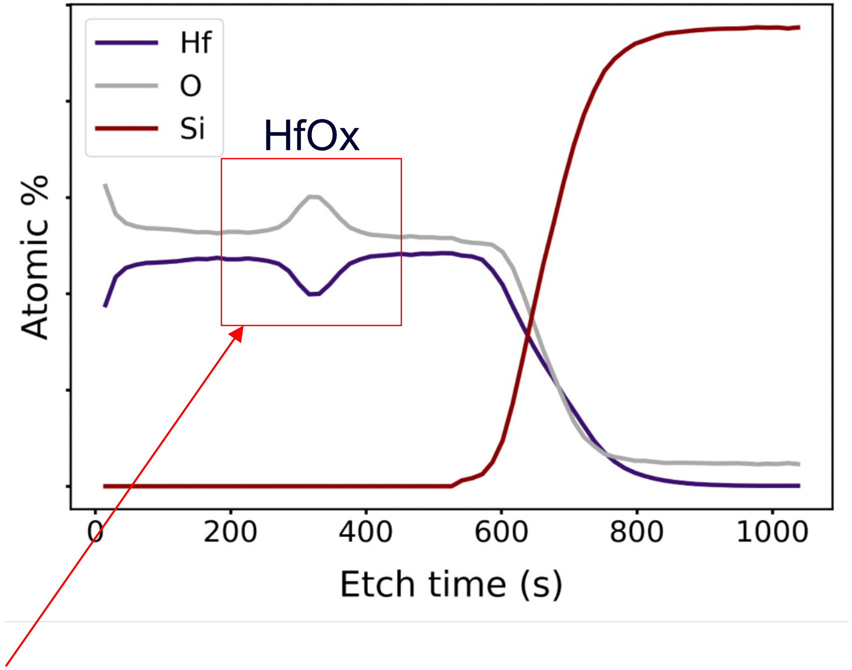

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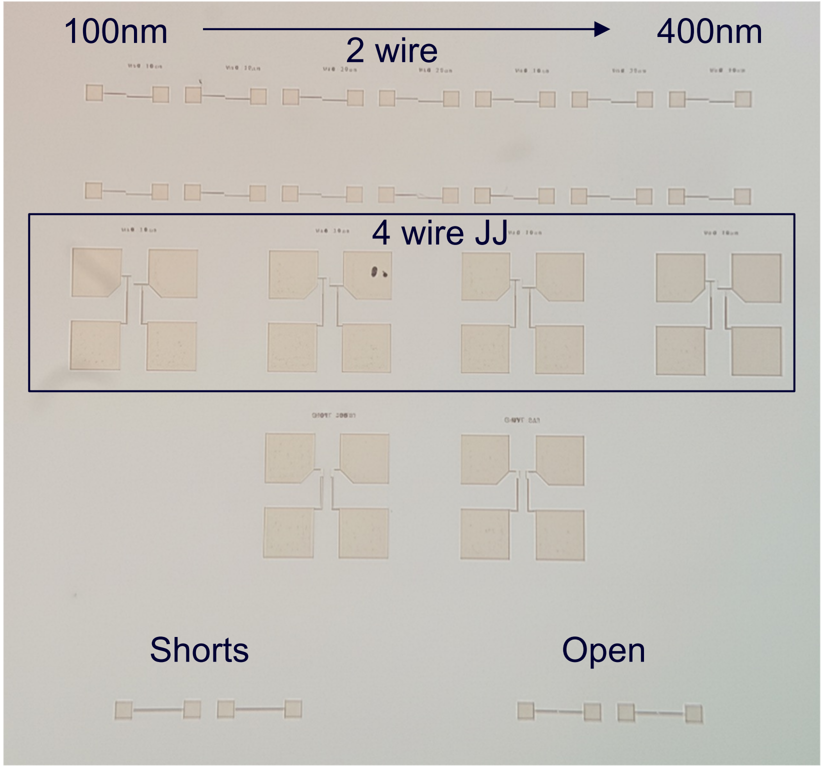
Test structure Layout

Optical image after liftoff



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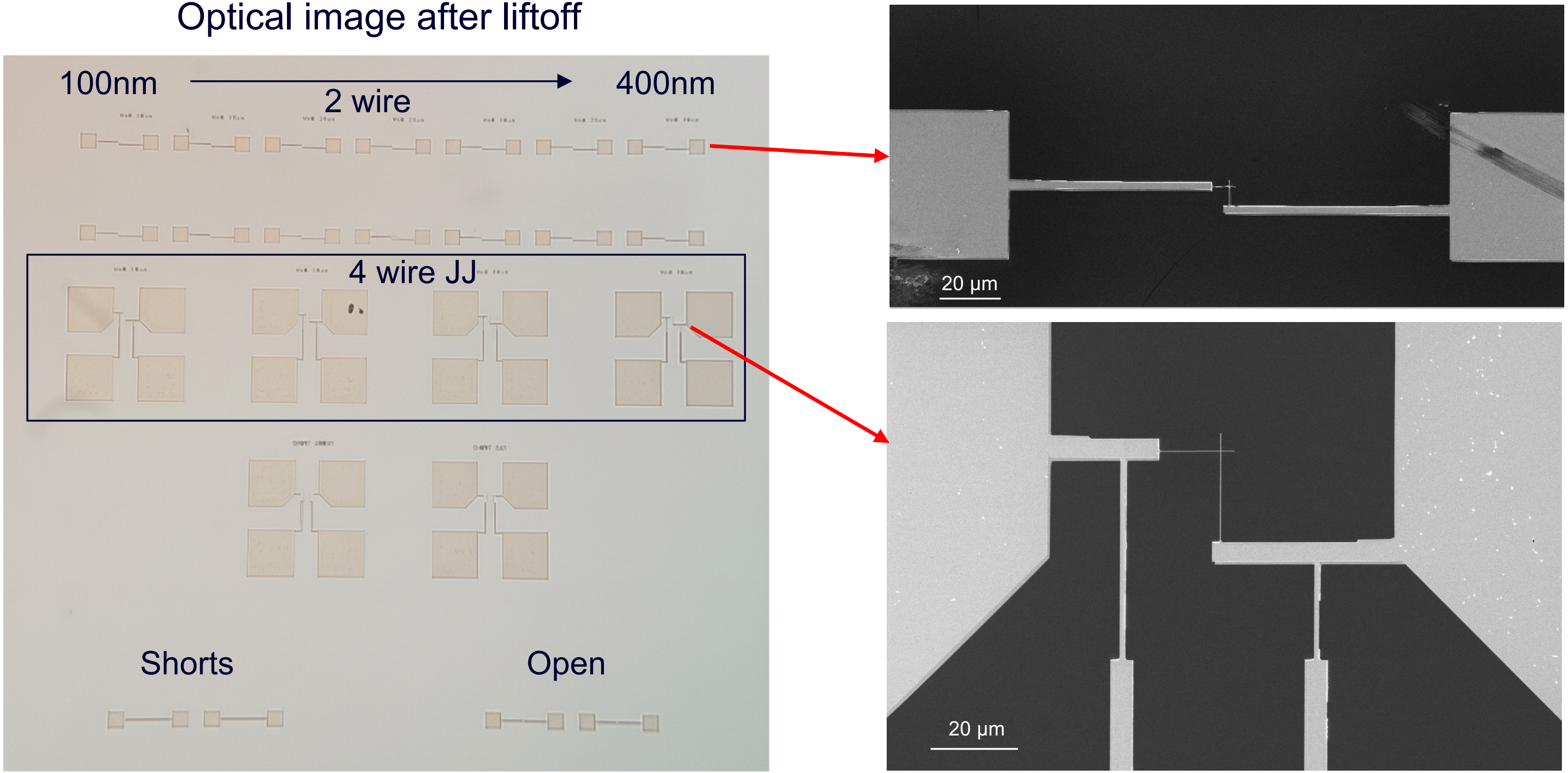
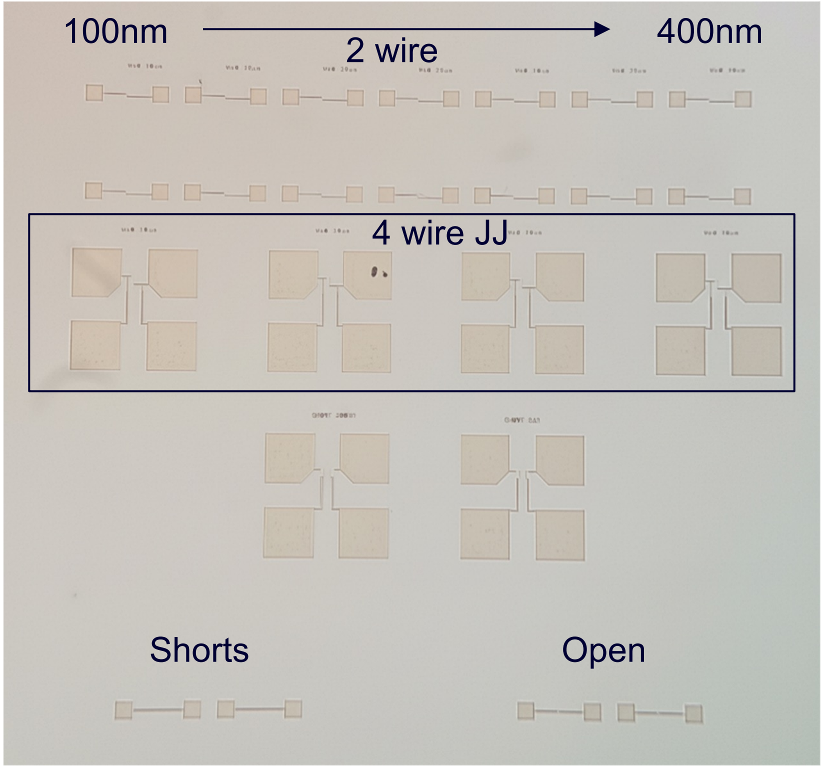
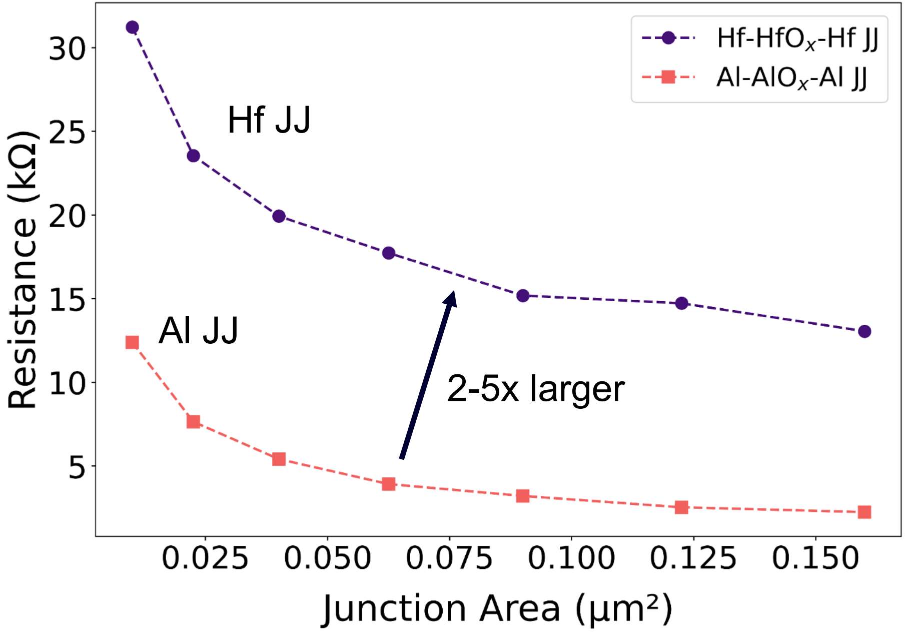


Room temperature measurements

Optical image after liftoff

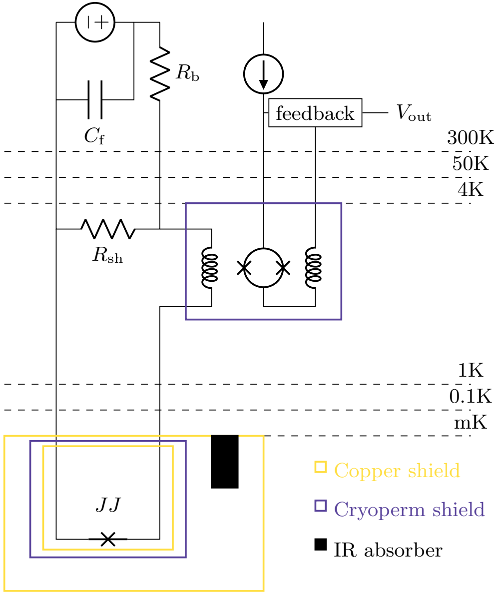


Room temperature DC measurements



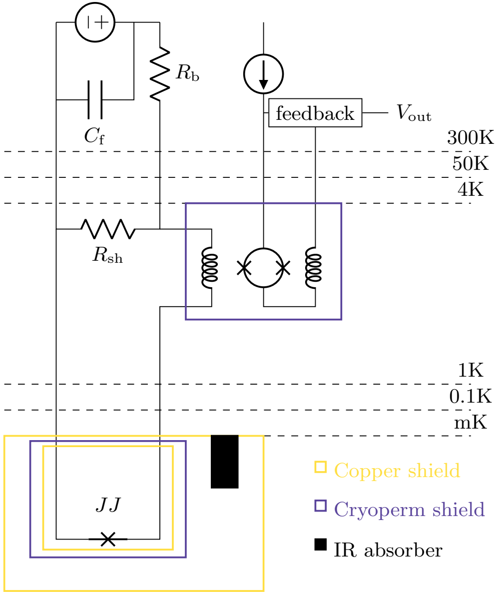
Comparison of Hf JJ with Al JJ resistance

Measurement setup

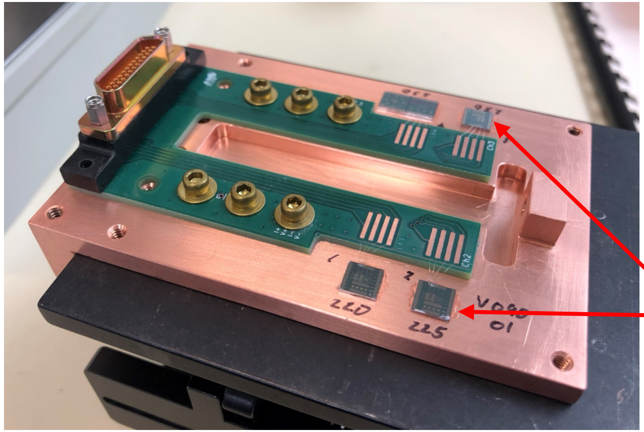


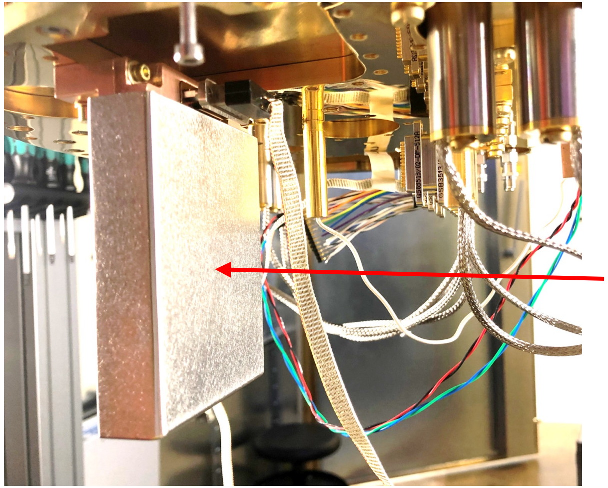
- Voltage divider to minimize parasitic series resistance.
- DC SQUID system to readout JJ current

Measurement setup



Tc Box

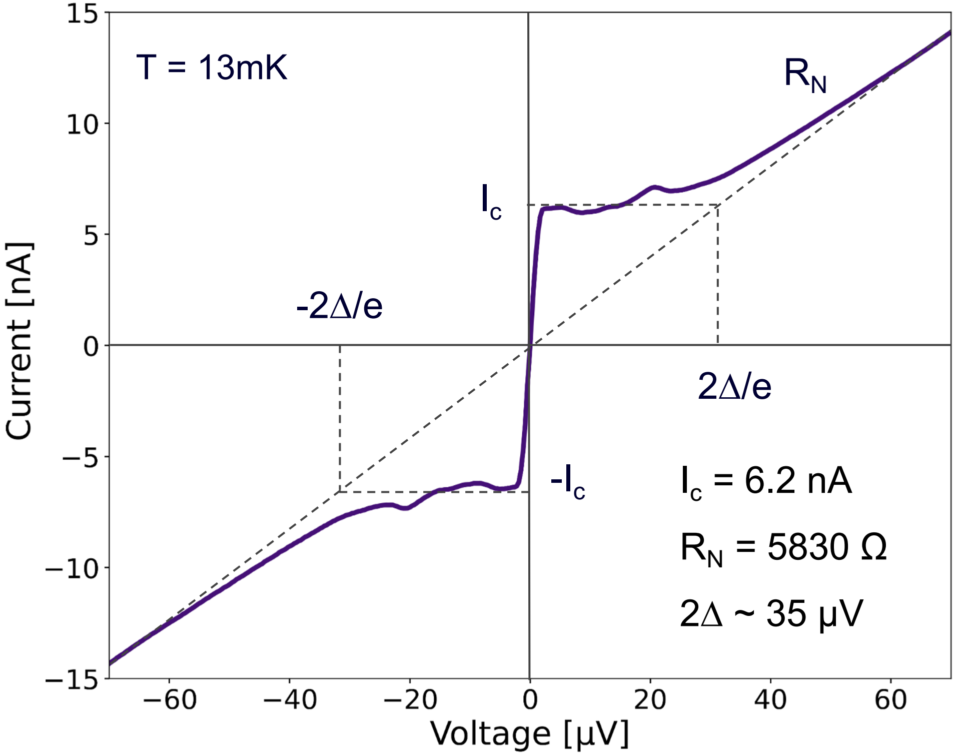

Samples


Magnetic shield

- Voltage divider to minimize parasitic series resistance.
- DC SQUID system to readout JJ current

Measurement setup

I-V curve of 400 nm x 400 nm lead JJ



Hf JJ show supercurrent behavior!

Measurement setup

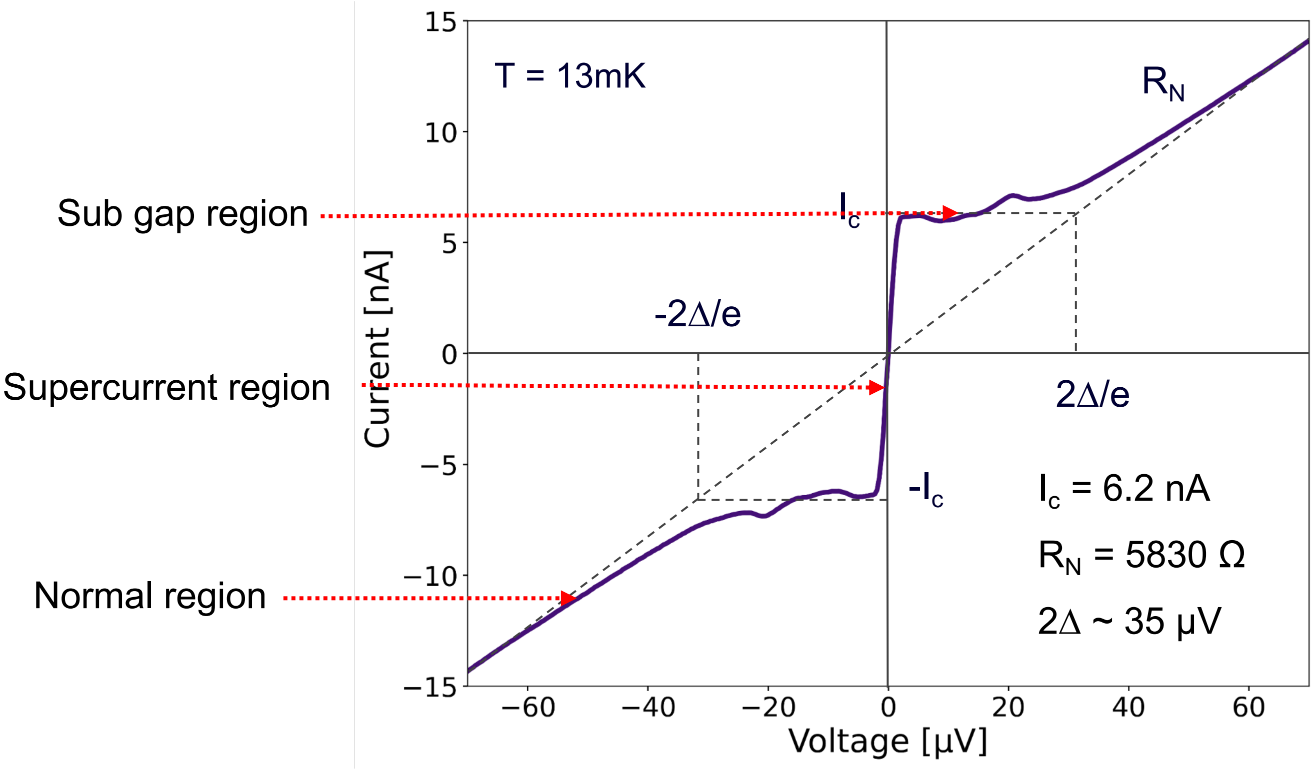
AB relation to extract Δ

$$I_c R_N = \frac{\pi\Delta}{2e}\tanh\left(\frac{\Delta}{2k_\mathrm{B}T}\right)$$

Δ_{AB} ~ 22 μV

Δ_{meas} ~ 17.5 μV

Presence of subgap states



Sub gap region

Supercurrent region

Normal region

T = 13mK

I_c = 6.2 nA

R_N = 5830 Ω

2Δ ~ 35 μV

Measurement setup

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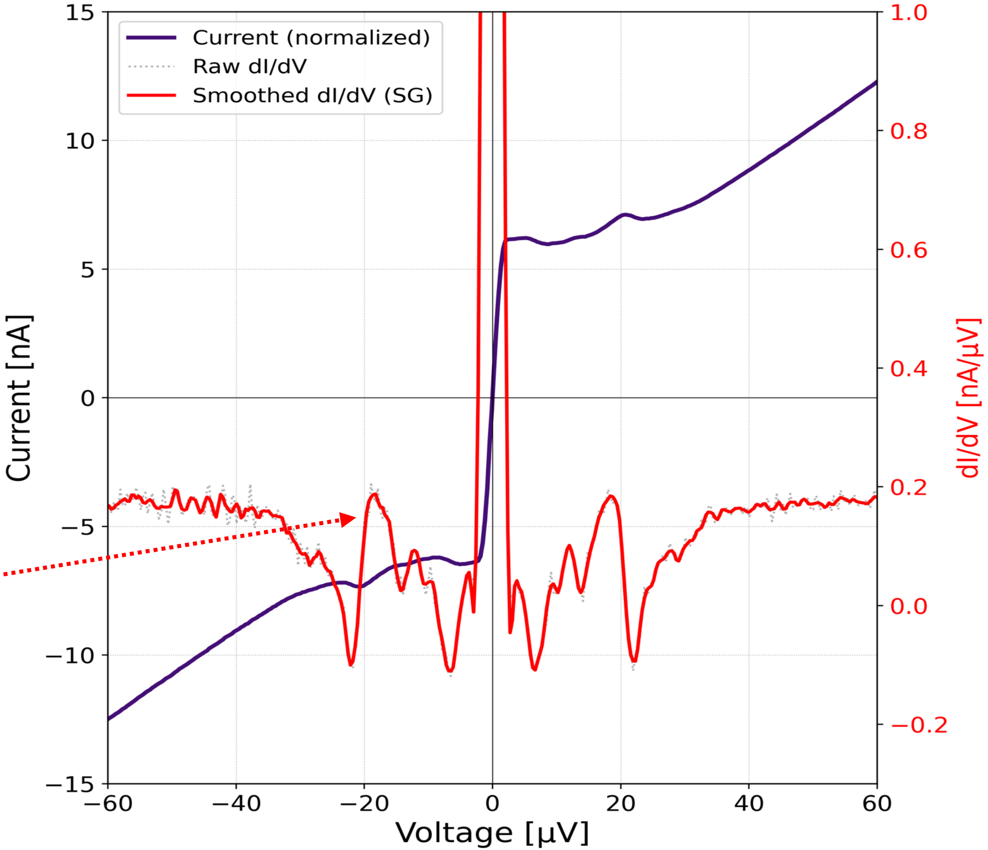
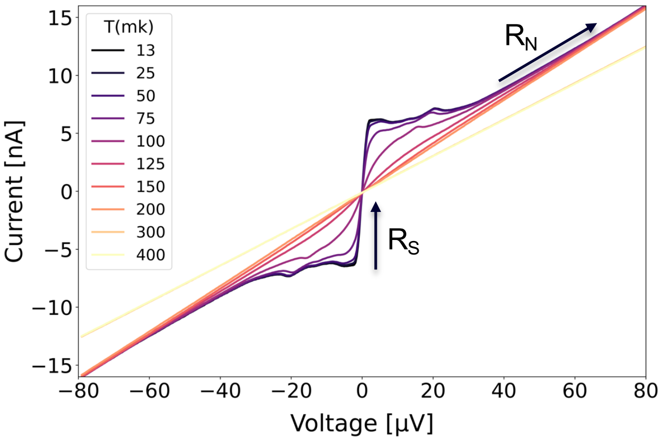
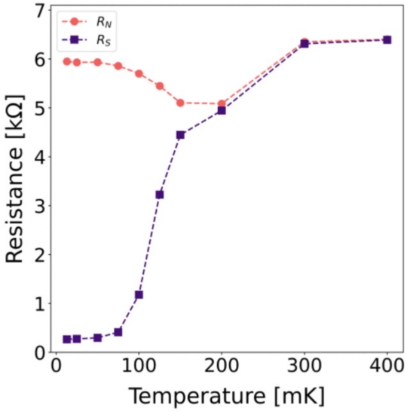


IV Characteristics – Temperature dependence

Supercurrent resistance increases with increasing temperature.





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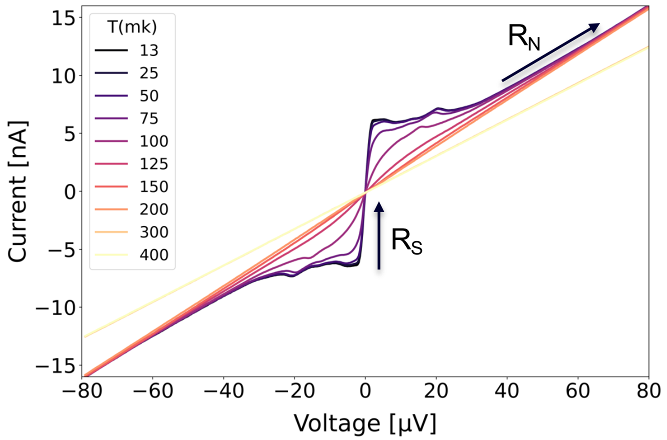
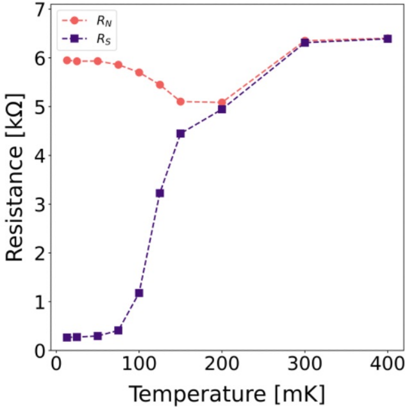
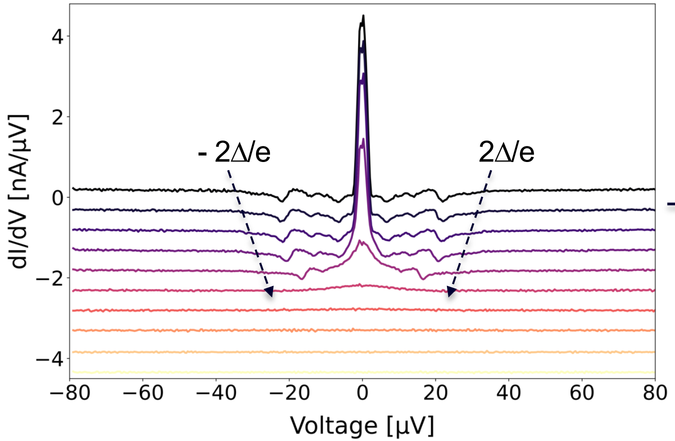
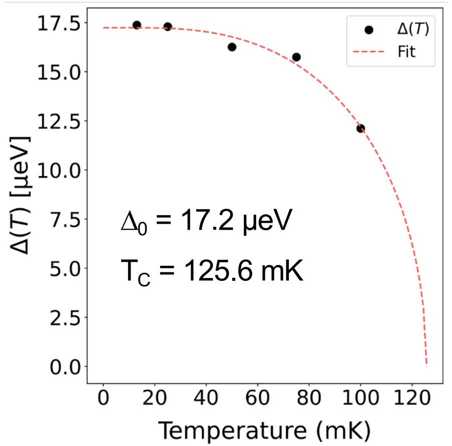




Extract superconducting gap and Tc





Conclusion

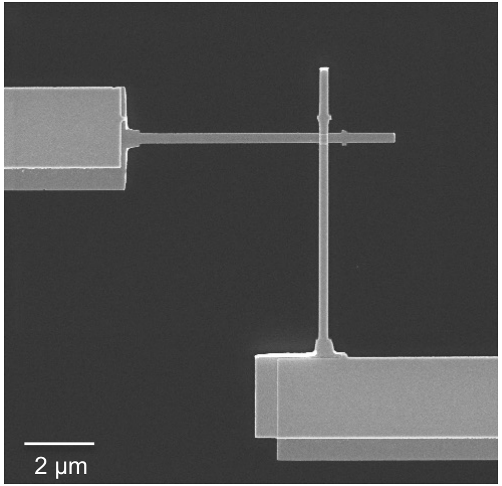
- Demonstrated Hf JJ as a viable platform for Low – Tc qubit based detectors.

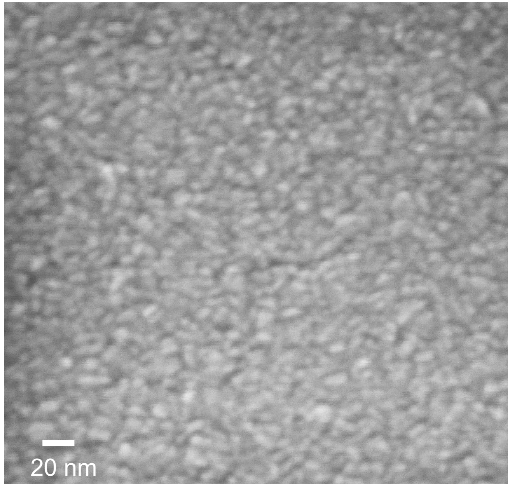
- Ongoing JJ fab and optimization – study Hf JJ barrier

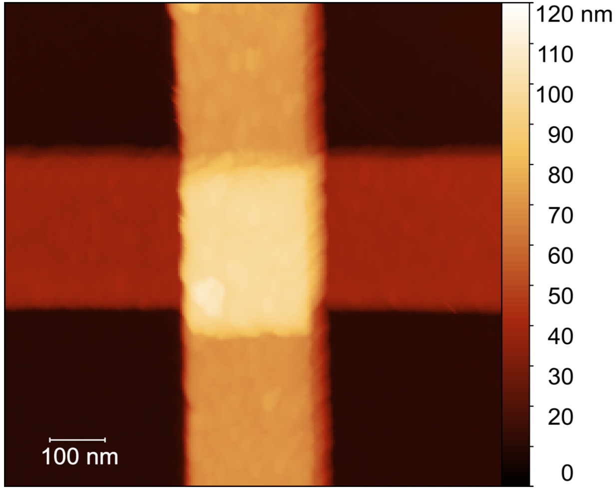
- Understand Qubit parameters.

- Implement Hf JJs in SQUATS

Thank you!


2 µm


20 nm


100 nm
120 nm
110
100
90
80
70
60
50
40
30
20
0

Device Characterization