Novel Materials for High Coherence Superconducting Quantum Devices

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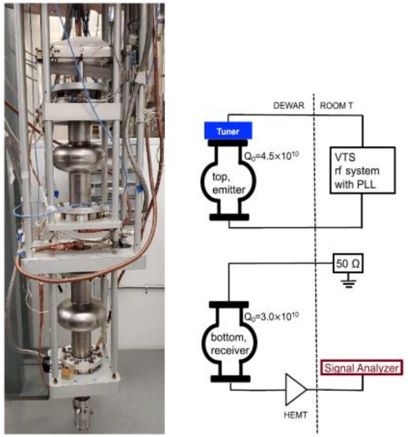
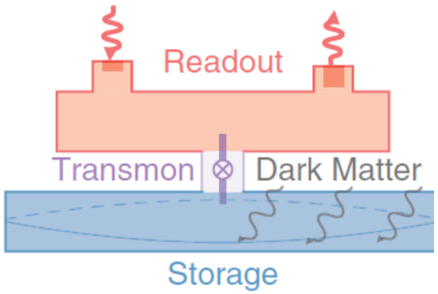
Superconducting Devices for Dark Matter Experiments

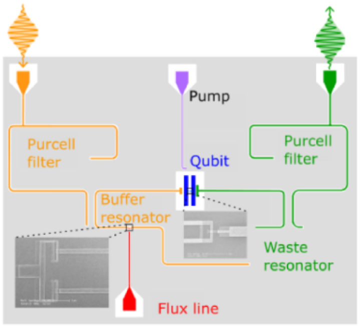
- SRF Cavities
- Qubits
- JJ based Single Photon Counters
- Quantum Limited Amplifiers
- Microwave Kinetic Inductance Detectors (MKIDs)
- Transition Edge Sensors
-



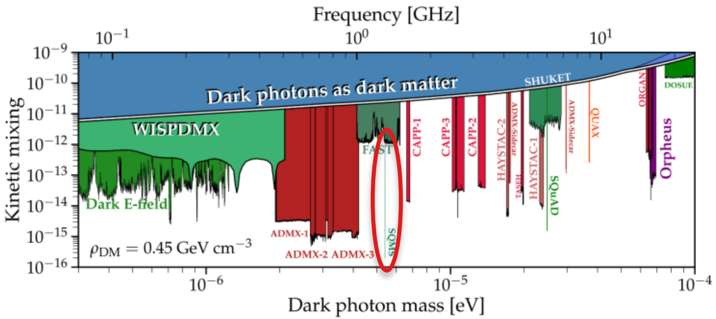
A. Romanenko et al, PRL **130**, 261801 (2023)



A. V. Dixit et al, PRL **126**, 141302 (2021)



L. Balembois et al, arXiv:2307.03614 (2023)



R. Cervantes et al, arXiv:2208.03183 (2022)

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Decoherence channels in 2D superconducting qubits:

two-level systems, bulk substrate losses, quasiparticles, …

Total decay rate [1,2,3]

Other channels (e.g. radiative decay)

Participation ratio E_{stored} /E_{total}

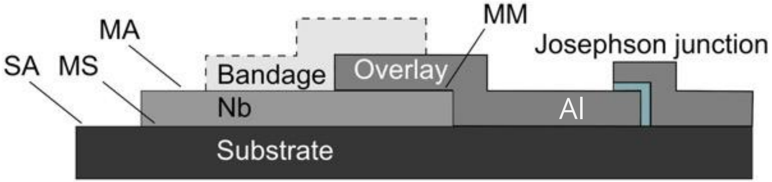
$$\gamma = \sum_i \gamma_i + \Gamma = \omega \sum_i p_i \tan \delta_i + \Gamma$$

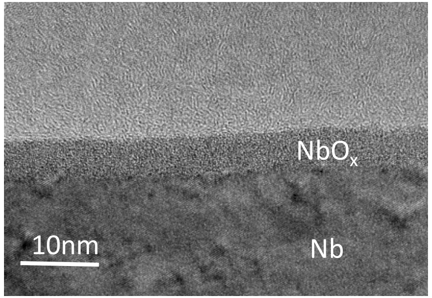
Lossy elements with known E_{stored} /E_{total}

Qubit frequency

Loss tangent

MS: Metal-Substrate | SA: Substrate-Air | MA: Metal-Air | MM: Metal-Metal





Each channel bounds T1:

$$T_1 \leq 1/\gamma_i$$

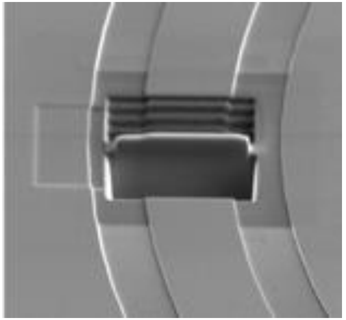
Looking for changes channel-by-channel:

$$\Delta\gamma = \sum_i \delta\gamma_i$$

1. Koch, J. *et al.* Physical Review A **76**, 042319 (2007)
2. Wenner, J. *et al.* Applied Physics Letters **99**, 113513 (2011)
3. Wang et al. Appl. Phys. Lett. 107, 162601 (2015)
4. Calusine, G. *et al.* Applied Physics Letters **112**, 062601 (2018)

SQMS innovative approaches quantum materials and devices characterization

Dissecting and studying fragments of characterized devices



rigetti

- Leveraging DOE and SQMS academic partners user facilities capabilities to identify sources of decoherence

Cryogenic TEM, AFM, MFM

Northwestern University NUANCE Northwestern University Atomic and Nanoscale Characterization Experimental Center

Cryo XRD, XRR

Cryogenic TOF-SIMS

Atom Probe Tomography

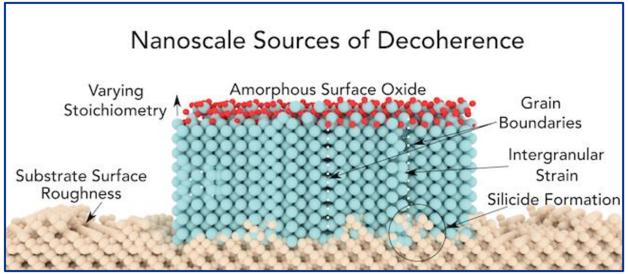
AMES LABORATORY SENSITIVE INSTRUMENT FACILITY

THz spectroscopy

Magneto Optical Imaging

Fermilab

β-NMR, μSR



A. A. Murthy et al, ACS Nano **16**, 17257 (2022)

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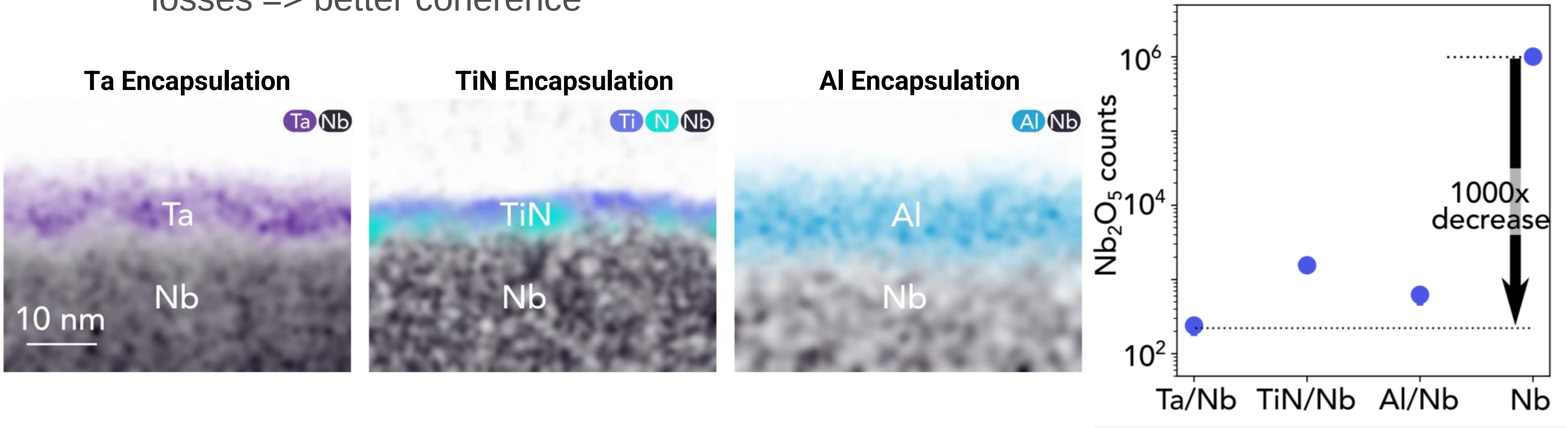
Novel Surface Encapsulation as Mitigation Strategy to eliminate Nb_2O_5

- Avoid niobium oxidation by stable surface **encapsulating layer**
  - Thin (~5-10 nm) => small contribution to conductive losses
  - But TLS-hosting dissipative surface Nb_2O_5 is absent => reduction of the TLS dielectric losses => better coherence



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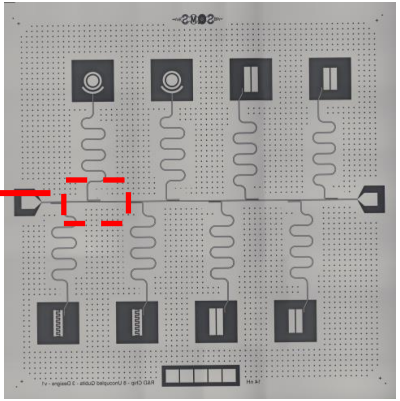
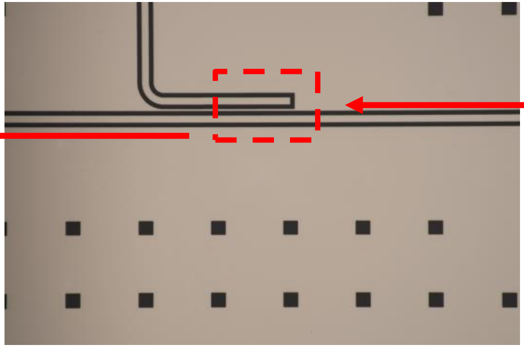
Process Flow to Define Qubit Circuitry on Sapphire

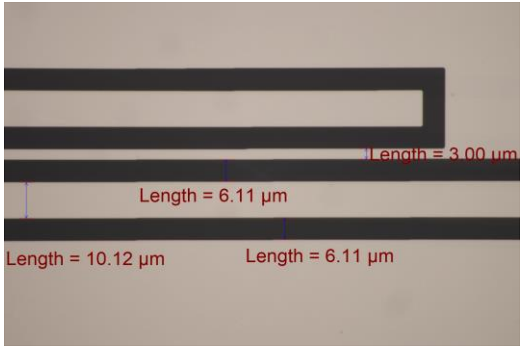
Substrate Preparation
- Solvent Clean
- RCA SC-1 Clean

Film Deposition
- Sputter Nb film
- Deposit 5-10 nm encapsulation layer
  - Ta & Al encapsulation in situ (sputter)
  - TiN encapsulation ex situ (ALD)

Patterning Film
- Photolithography
- Dry Etch







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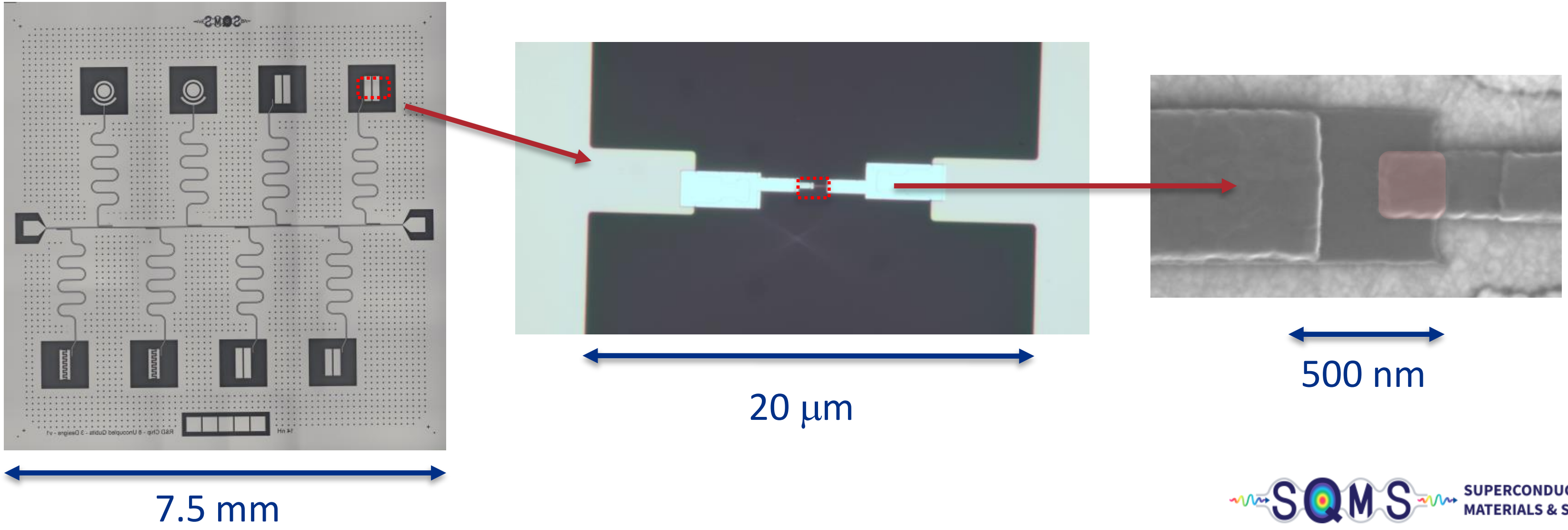
Josephson Junction Fabrication

- Al/AlOx/Al Junctions are deposited at +22 / -22 degree angles relative to the normal of the substrate.
- 2’15” (45”/45”/45” at +60/0/-60 degree) Ar ion milling to remove oxide on Nb.
- Bottom/Top electrode thicknesses are 40 nm/90 nm.
- The Oxidation is 20 mBar for 12 minutes (Ar/O2 (85/15) mixture)
- Typical Junction area is approximately 200 nm x 200 nm



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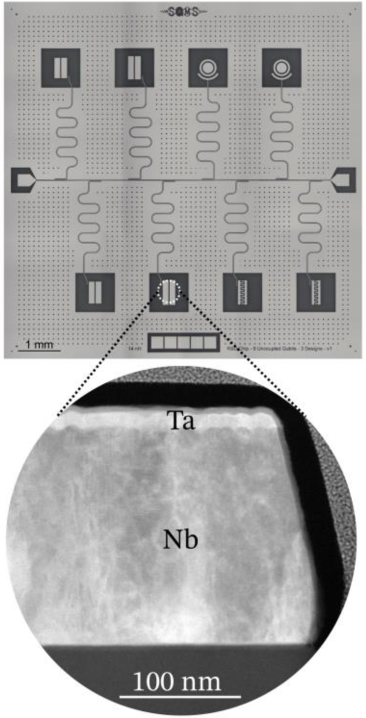
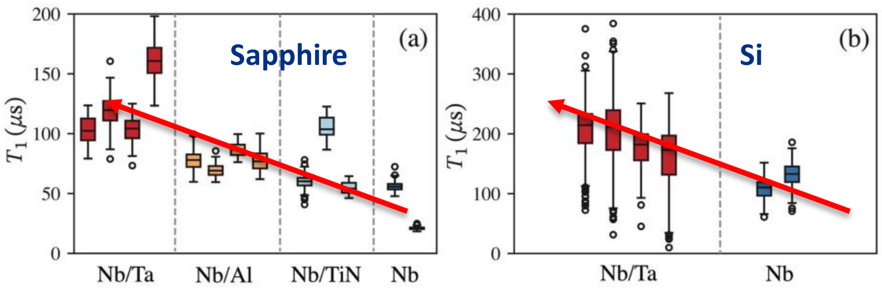
Qubit Coherence Results



M. Bal et al, arXiv:2304.13257 (2023)



Group	Best T_1 (μs)	Freq. (GHz)	Substrate	Primary Material	Publication Year
Yu	503	3.8-4.7	Sapphire	Ta, dry etch	2022
SQMS	**451**	**4.5-5**	**Silicon**	**Ta/Nb, dry etch**	**2023**
Houck	360	3.1-5.5	Sapphire	Ta, wet etch	2021
IBM	340	~4	Silicon	Nb, dry etch	2022
IBM	234	3.808	Silicon	Al, dry etch	2021
SQMS	**198**	**4.5-5**	**Sapphire**	**Ta/Nb, dry etch**	**2023**

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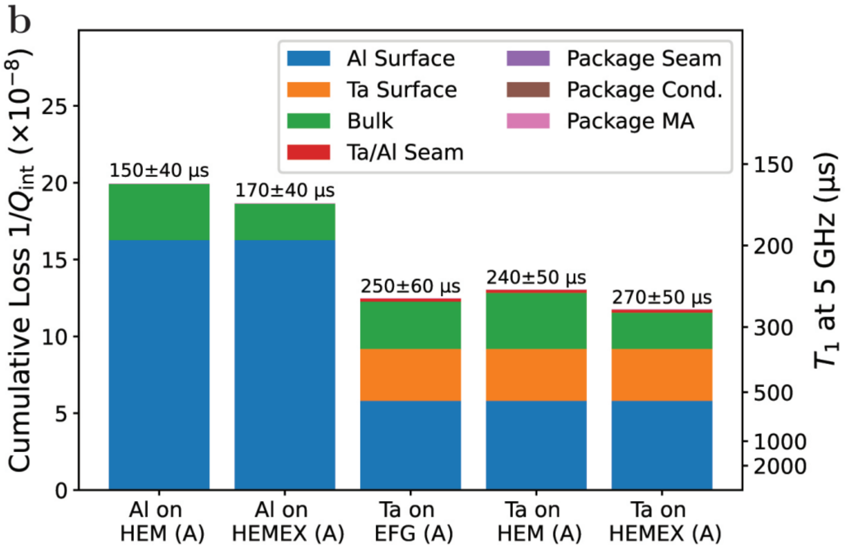
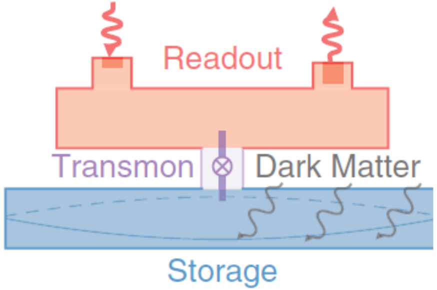
Elimination of Surface Losses Critical for T1 beyond ms time scales

- **Explore novel surface encapsulations (Au, PdAu, NbN,…)**
  - **Nb/Au – 181 +/- 15 us**
- Different SC materials (Ta, TiN, NbTiN,…)
- Reduce bulk dielectric losses (Annealing, impurities,…)

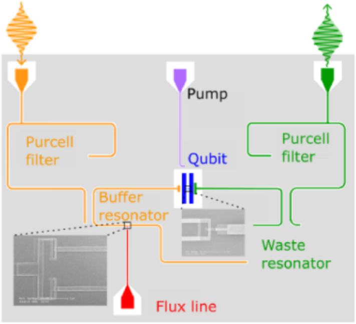


S. Ganjam et al, arXiv:2308.15539 (2023)

Qubits for Dark Matter Search



A. V. Dixit et al, PRL **126**, 141302 (2021)



L. Balembois et al, arXiv:2307.03614 (2023)

Experiments to use these devices for Axion search.

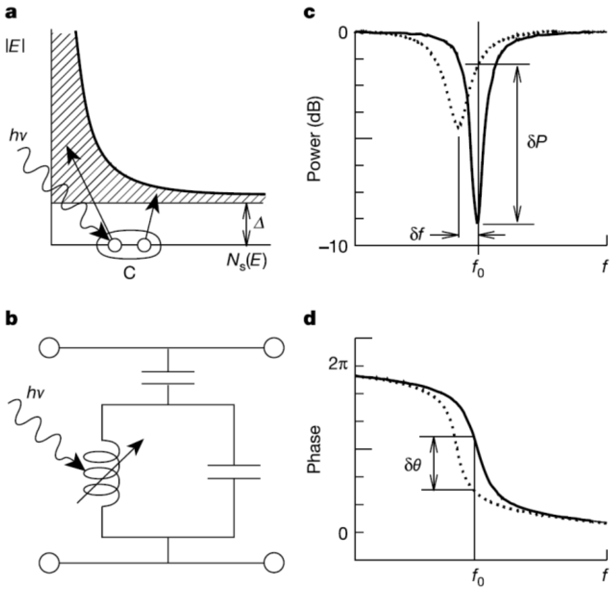
MKIDs

Applications include:

- Observational Astronomy
- Dark Matter Search
- Neutrino Detection
- QIS

Noise Sources:

- TLS noise
- Shot noise from the generation and recombination of quasiparticles
- Amplifier noise



P. K. Day et al, Nature **425**, 817 (2003)

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Acknowledments

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