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Novel Materials for High Coherence Superconducting Quantum Devices

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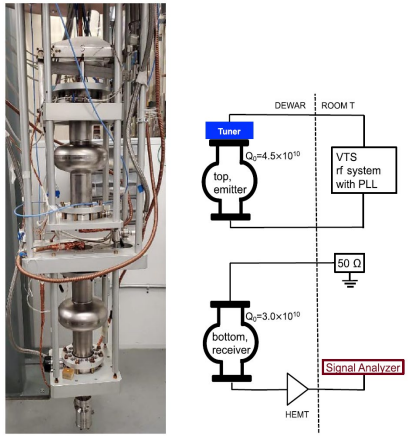
Fermilab

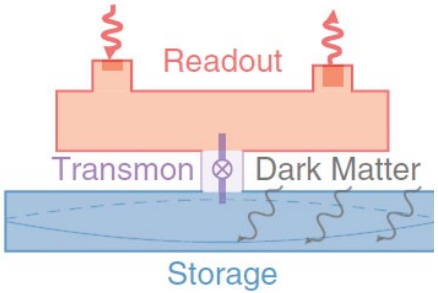
This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Superconducting Devices for Dark Matter Experiments

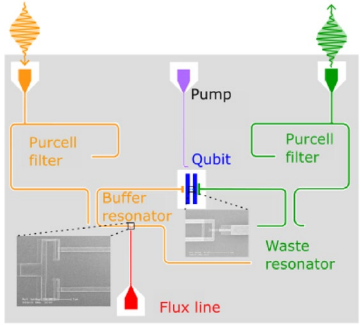
- SRF Cavities
- Qubits
- JJ based Single Photon Counters
- Quantum Limited Amplifiers
- Microwave Kinetic Inductance Detectors (MKIDs)
- Transition Edge Sensors
-



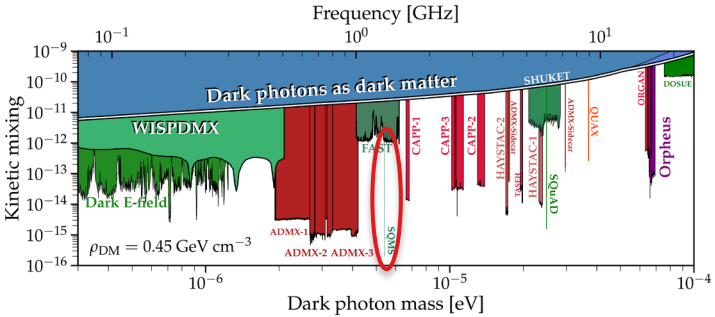
A. Romanenko et al, PRL **130**, 261801 (2023)



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)

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

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}

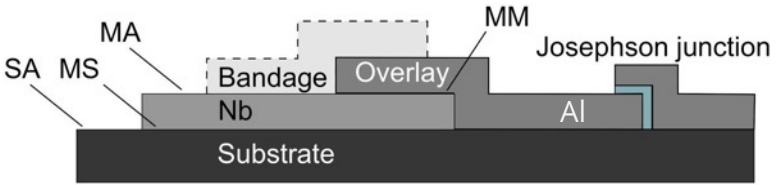
$$\gamma = \sum_i \gamma_i + \Gamma = \omega \sum_i p_i \tan\delta_i + \Gamma$$

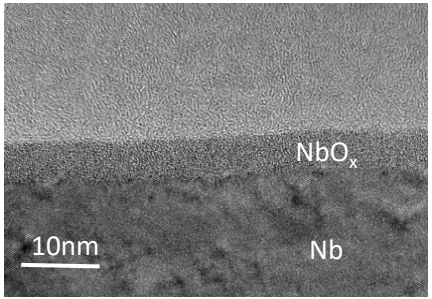
Lossy elements with known E_{stored}/E_{total}

Qubit frequency

Loss tangent

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





Each channel bounds T1:

$$T_1 \leq 1/\gamma_i$$

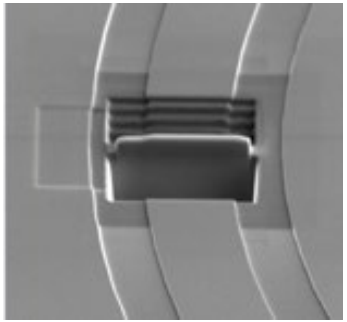
Looking for changes channel-by-channel:

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

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

Cryogenic TEM, AFM, MFM

Northwestern University

NUANCE Northwestern University Atomic and Nanoscale Characterization Experimental Center

Cryo XRD, XRR

Cryogenic TOF-SIMS

AMES LABORATORY

SIF SENSITIVE INSTRUMENT FACILITY

Atom Probe Tomography

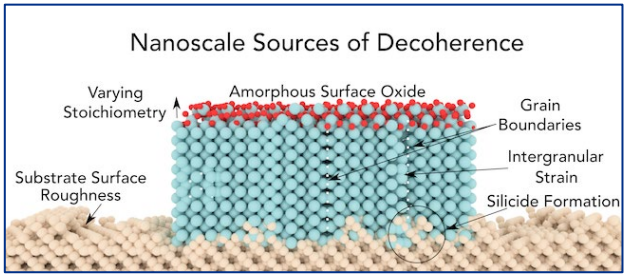
THz spectroscopy

Magneto Optical Imaging

Fermilab

β-NMR, μSR

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

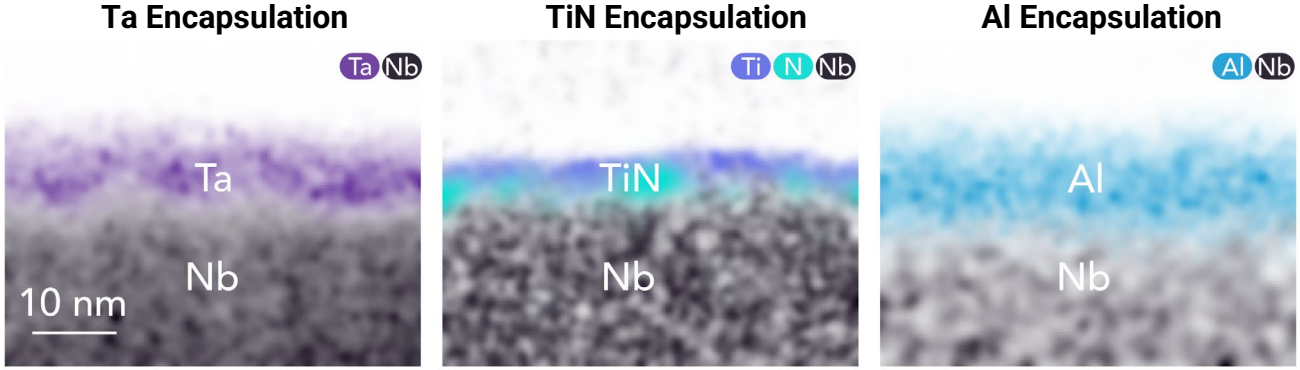


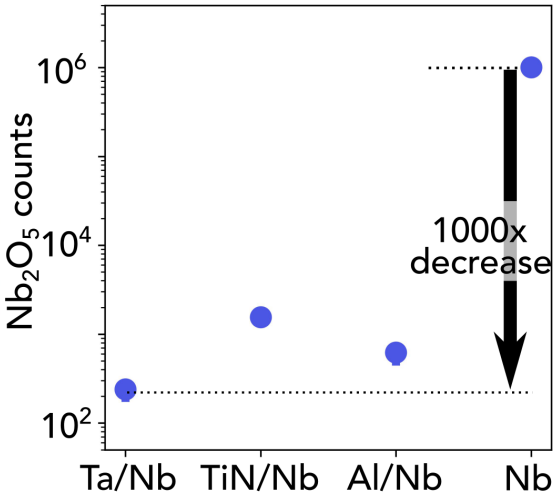
A. A. Murthy et al, ACS Nano **16**, 17257 (2022)

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

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



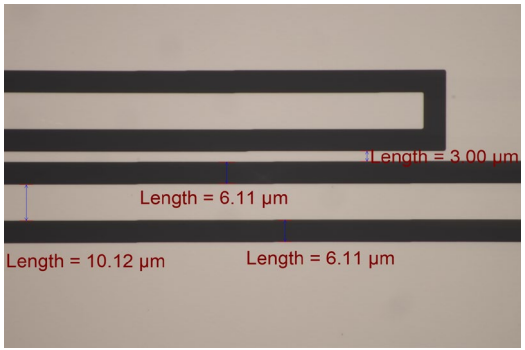


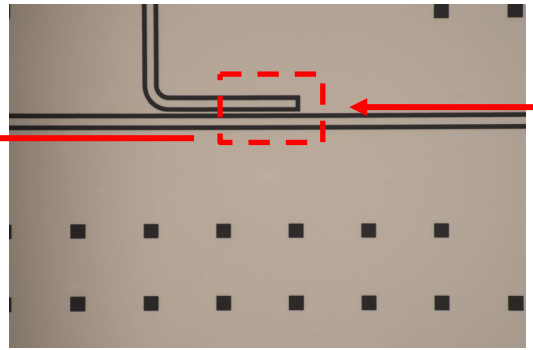
Process Flow to Define Qubit Circuitry on Sapphire

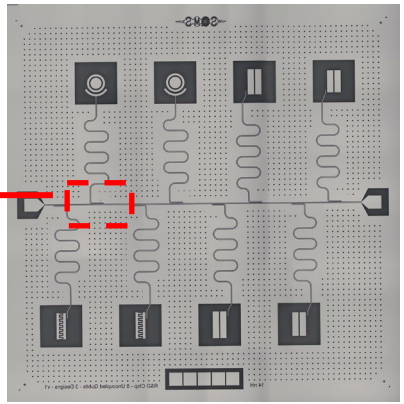
Substrate Preparation
- Solvent Clean
- RCA SC-1 Clean

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



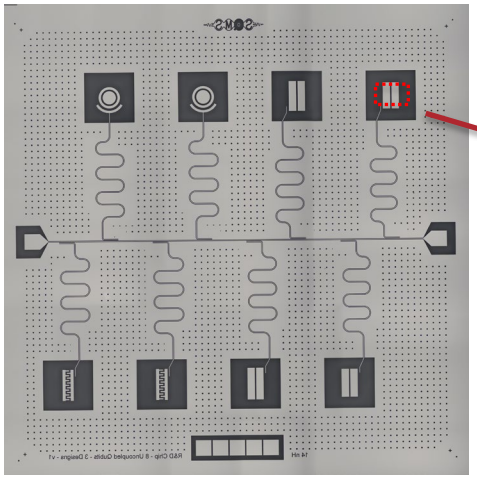




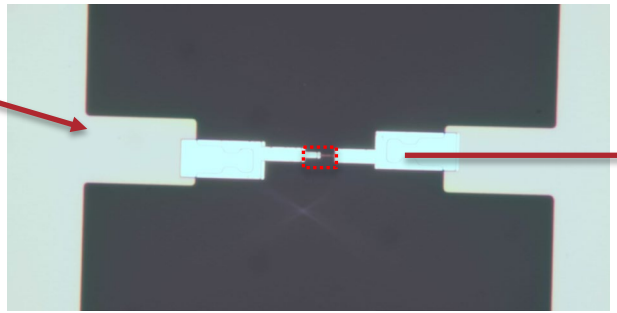
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Josephson Junction Fabrication

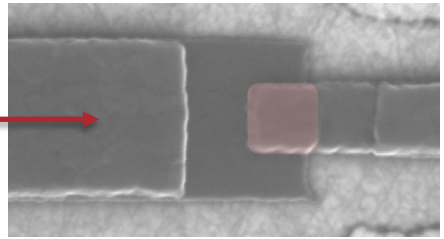
- Al/AlOx/Al Junctions are deposited at +22 / -22 degree angles relative to the normal of the substrate.
- 2’15” (45”/45”/45” at +60/0/-60 degree) Ar ion milling to remove oxide on Nb.
- Bottom/Top electrode thicknesses are 40 nm/90 nm.
- The Oxidation is 20 mBar for 12 minutes (Ar/O2 (85/15) mixture)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



7.5 mm

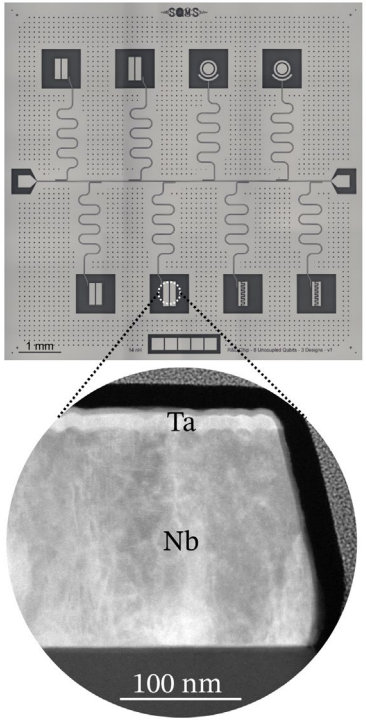


20 μm

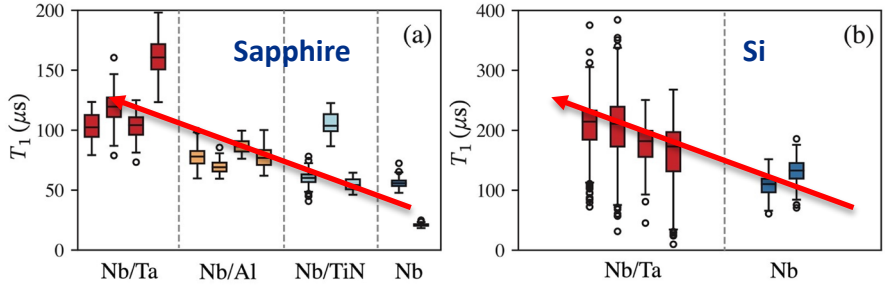


500 nm

Qubit Coherence Results



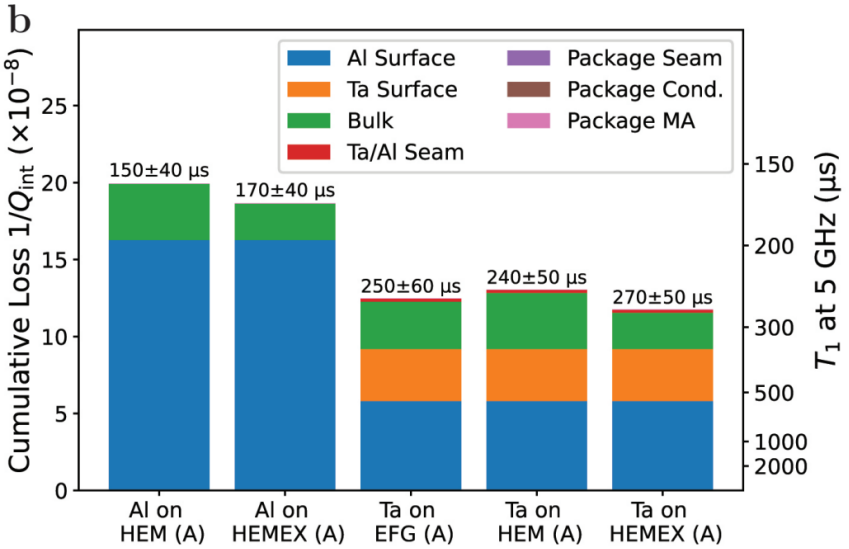
M. Bal et al, arXiv:2304.13257 (2023)



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**

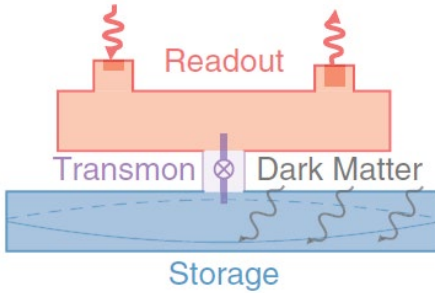
Elimination of Surface Losses Critical for T1 beyond ms time scales

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

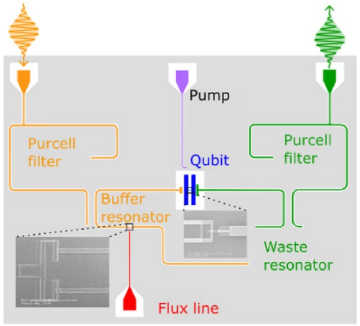


S. Ganjam et al, arXiv:2308.15539 (2023)

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.

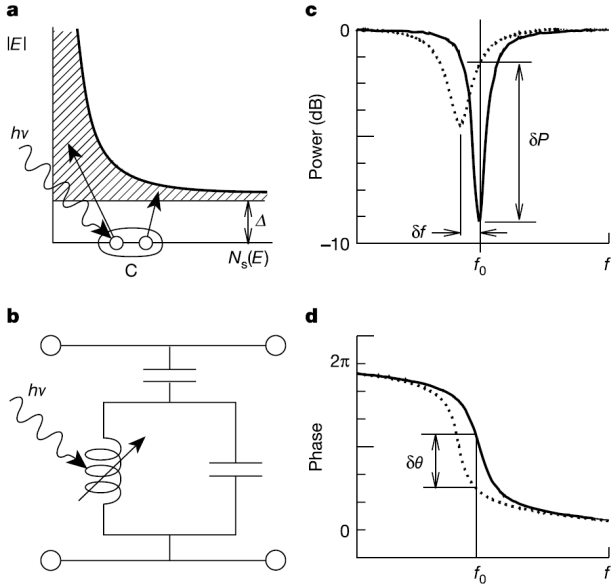
MKIDs

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)

Acknowledgments

Fermilab

Akshay A. Murthy
Francesco Crisa
Sabrina Garattoni
Shaojiang Zhu
Xinyuan You
Ziwen Huang
ZuHawn Sung
Jaeyel Lee
Daniel Bafia
David van Zanten
Ivan Nekrashevich
Tanay Roy
Yulia Krasnikova
Roman Pilipenko
Alexander Romanenko
Anna Grassellino

rigetti

Cameron J. Kopas
Ella O. Lachman
Duncan Miller
Josh Y. Mutus
Matthew J. Reagor
Hilal Cansizoglu
Jayss Marshall
David P. Pappas

NIST
National Institute of Standards and Technology
U.S. Department of Commerce

Florent Q. Lecocq
Michael R. Vissers
David Olaya
Jose Aumentado
Joel N. Ullom
Peter Hopkins

Northwestern University

Dominic P. Goronzy
Carlos G. Torres-Castanedo
Graham Pritchard
Vinayak P. Dravid
James M. Rondinelli
Michael J. Bedzyk
Mark C. Hersam
Jens Koch

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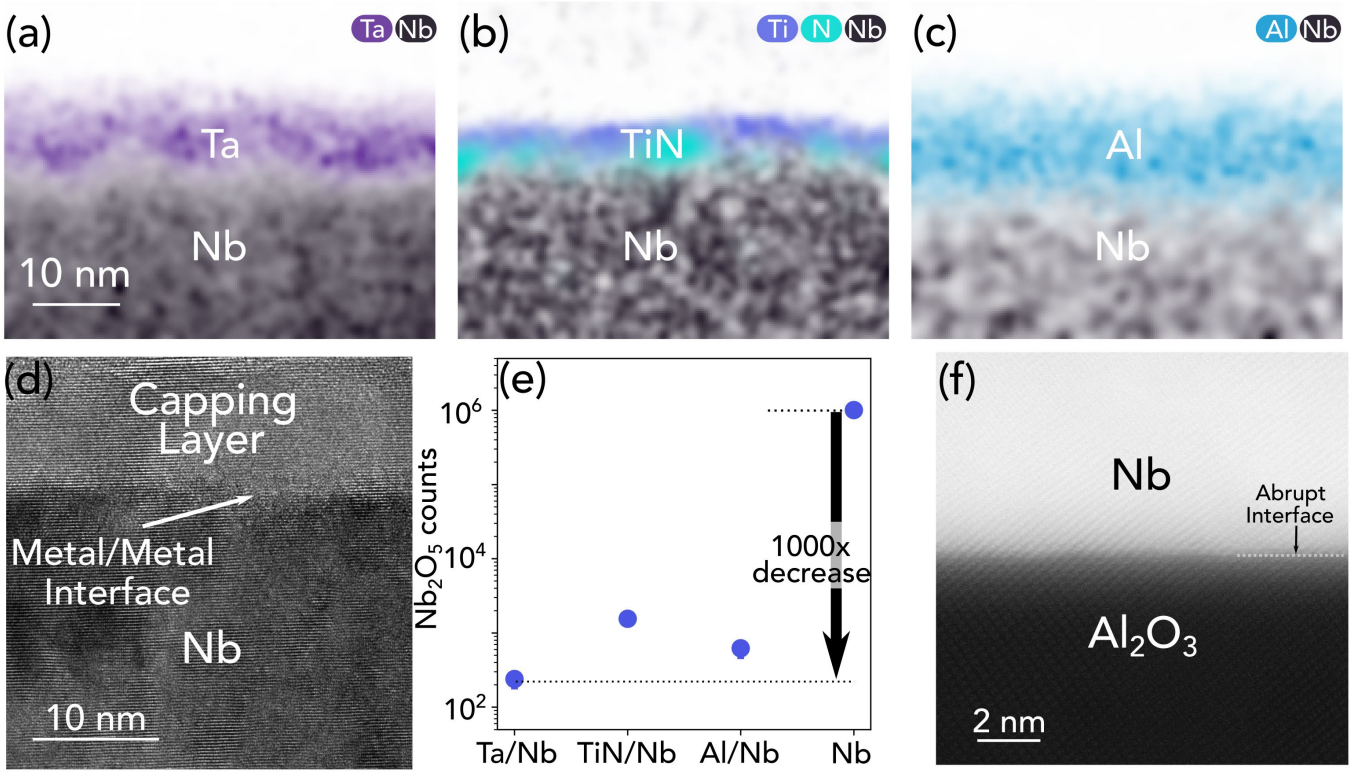
Effectiveness of Passivation



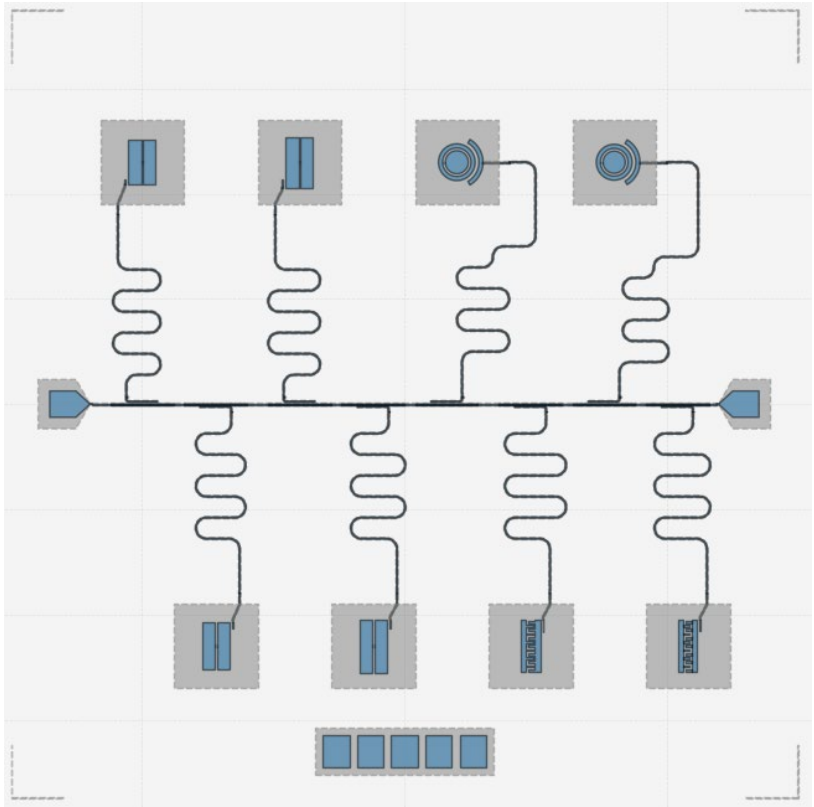
Design parameters and device layout

14pH, Sapphire=10.0

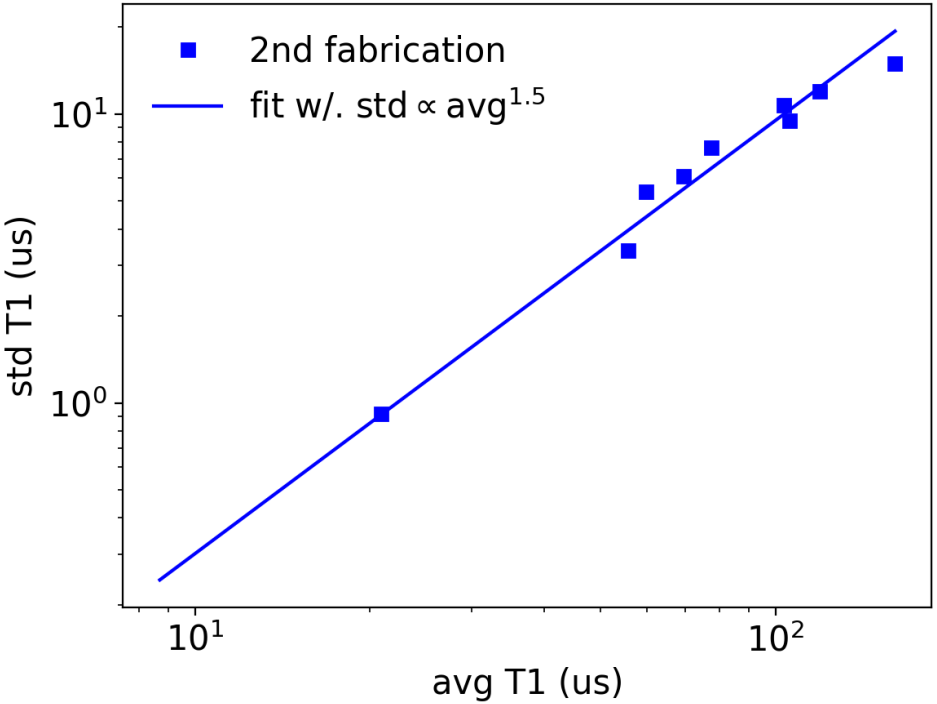
	L	f_r	f_{01}	χ	α	g	κ	Q_c	γ
0	4047.0	7505.0	5055.0	0.46	308.0	88.0	0.75	10000	0.0010
1	4151.0	7327.0	4914.0	0.47	290.0	91.0	0.73	10000	0.0010
2	4260.0	7147.0	4784.0	0.49	274.0	94.0	0.71	10000	0.0011
3	4376.0	6965.0	4663.0	0.50	259.0	95.0	0.70	10000	0.0012

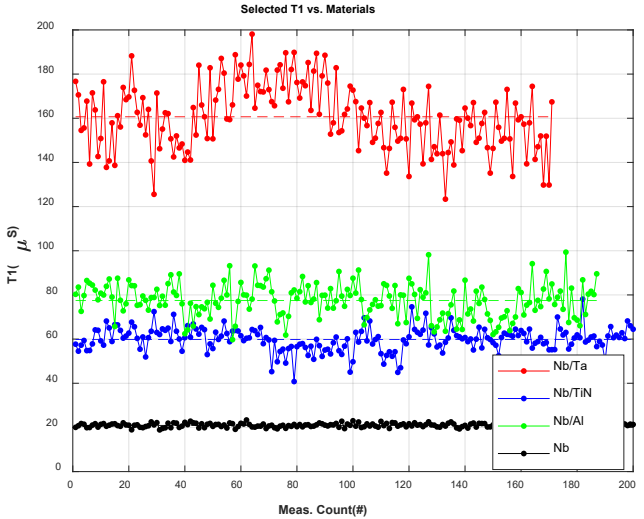
	L	f_r	f_{01}	χ	α	g	κ	Q_c	γ
0	4497.0	6760.0	4526.0	0.5	242.0	96.0	0.68	10000	0.0012
1	4626.0	6571.0	4410.0	0.5	229.0	95.0	0.66	10000	0.0013

	L	f_r	f_{01}	χ	α	g	κ	Q_c	γ
0	4762.0	6093.0	4364.0	0.66	225.0	88.0	0.61	10000	0.0016
1	4906.0	5934.0	4250.0	0.50	213.0	76.0	0.59	10000	0.0012



T1 variation due to TLS





Average T1 vs. Standard variation T1

$$\langle T_1 \rangle = \frac{1}{\kappa^2 N M^2 \omega \pi} \qquad \sigma_{T_1} = \frac{G}{2\gamma_\phi^{\frac{3}{2}} \kappa^2 N^{\frac{3}{2}} M^2 \omega^{\frac{3}{2}} \pi^{\frac{3}{2}}}$$

Assume variation due to number of TLS

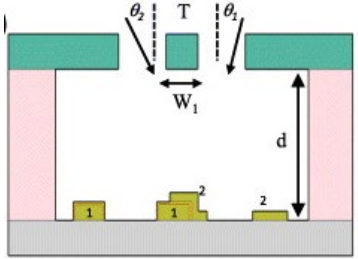
$$\sigma_{T_1} \propto \langle T_1 \rangle^{3/2}$$

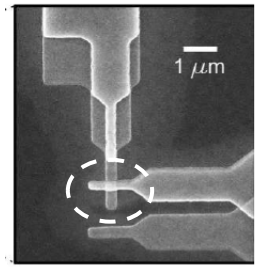
X. You, et al., Phys. Rev. Appl. ***18****, 044026 (2022)*

Liftoff Process to Fabricate Submicron Al/AlOx/Al Junctions

Shadow evaporation with tilt, "Dolan bridge" – Single pattern step, single pumpdown

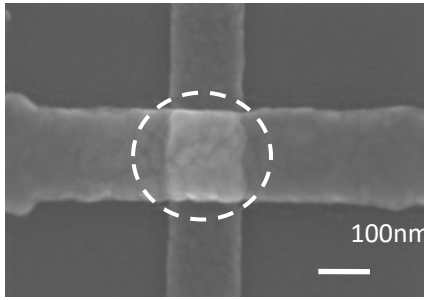
1) Pattern, deposit 1st layer, oxidize, tilt, deposit 2nd layer





Overlap junction - 2 patterns, pumpdowns

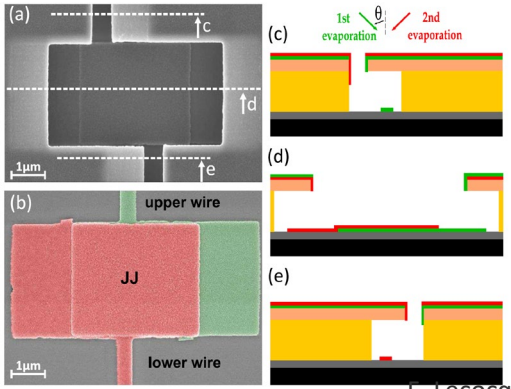
1) Pattern
   pumpdown
   LO BE
2) Pattern
   pump down
   mill BE & oxidize
   LO TE

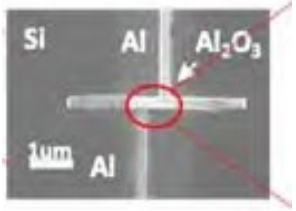


X. Wu, et. al APL (2017)

M. Steffen et. al, PRL97, 050502 (2006)

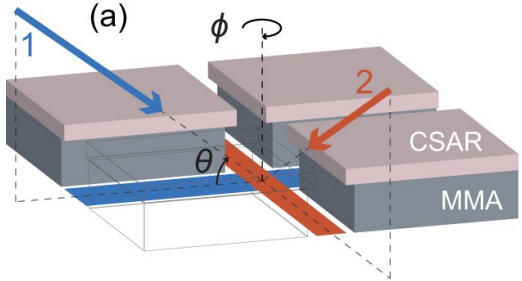
"Bridgeless" – shadow evaporatioin high aspect tilt

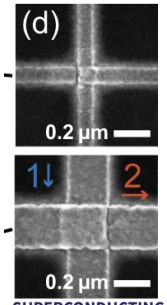




F. Lecocq et al Nanotechnology (2011)

"Manhattan style" – shadow evaporation
Use rotation between the two depostions and oxidation





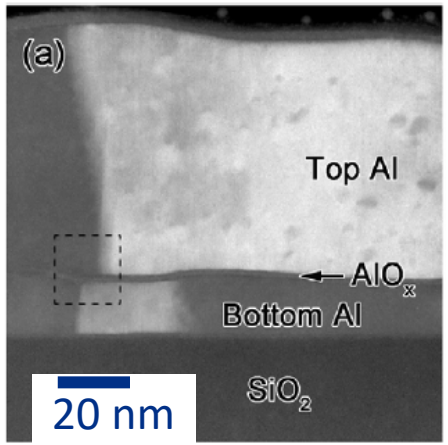
J M Kreikebaum *et al* 2020 *Supercond. Sci. Technol.* **33** 06LT02

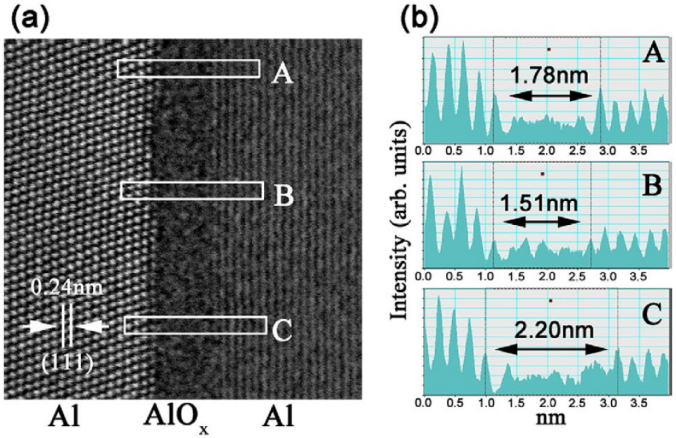
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Josephson junctions - sensitive to atomic-level defects

- Aluminum oxidation is conformal, ~ 1.8 nm thick Al/AlOx/Al
- Thickness variations with exponential dependence of current
  - Less than 10% of total barrier active
  - Strong inhomogeneity of tunnel current across junction
- Amorphous materials are lossy – make junctions small

Cross-section TEM

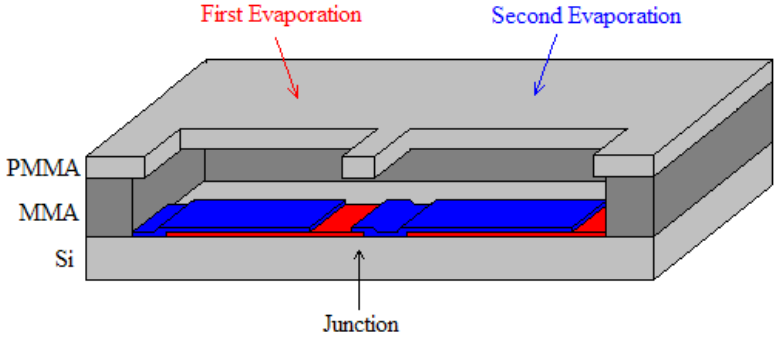




Zeng, J. Phys. D: Appl. Phys. **48** (2015) 395308

Dolan Bridge Double Angle Shadow Evaporation

Raith EBPG5200 E-Beam lithography system (100 kV)



t1: thickness of 1st resist layer
t2: thickness of 2nd resist layer
m1: 1st metal deposition thickness
m2: 2nd metal deposition thickness
θ_1 : 1st deposition angle
θ_2 : 2nd deposition angle
b: bridge width