SRF Thin Films: Not just for Cavities

SRF 2023 GRAND RAPIDS

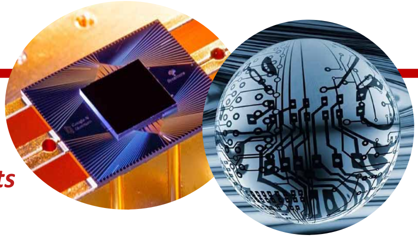
21st International Conference on Radio-Frequency Superconductivity

25-30 June 2023
Amway Grand Plaza Hotel

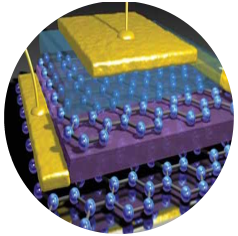
A-M VALENTE-FELICIANO

Outline

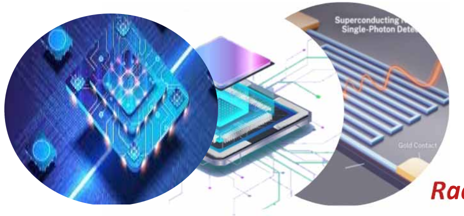
Outline



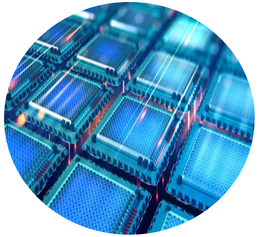
Quantum Systems - Qubits



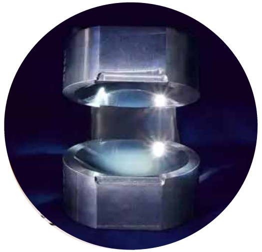
Superconducting Metamaterials



Radiation-hard Sensing

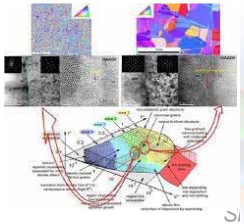


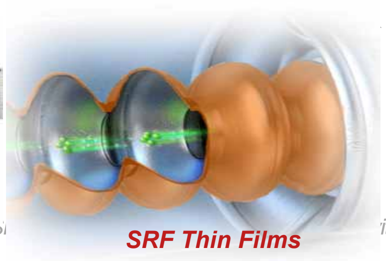
Next Generation Electronics



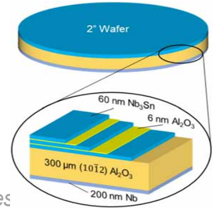
QCD Experiments

SRF Ancillaries

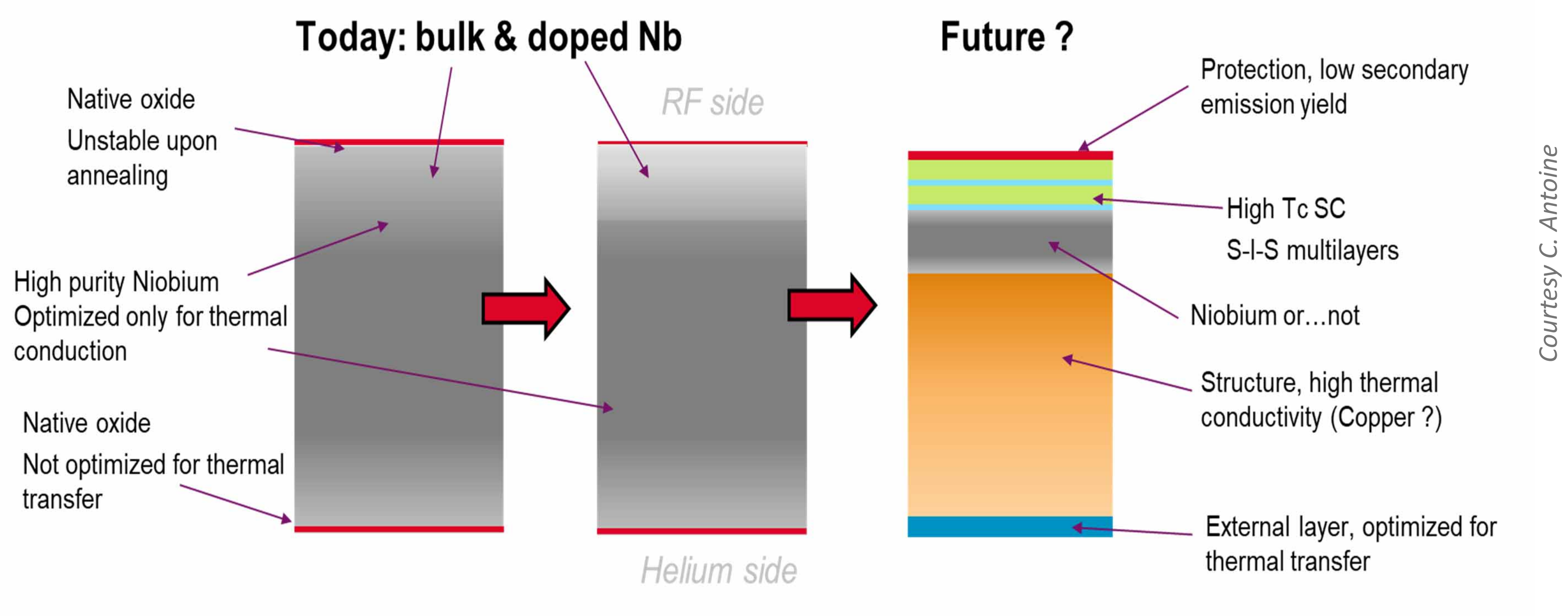




SRF Thin Films



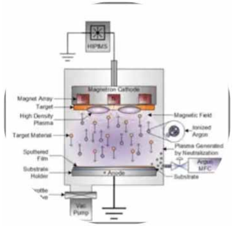
SRF Thin Films for Next-Generation Cavities



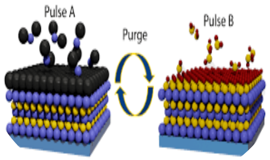
MOTIVATION

- Recent years have seen renewed interest and activities in developing SRF cavity materials based on thin film technologies.

ECR



HiPIMS



ALD

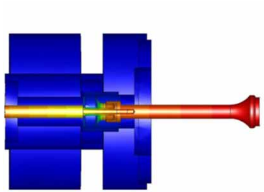
- Beyond cavity applications, the developments in SRF thin film technologies find a variety of applications in the fields of superconducting metamaterials, electronics, sensors and quantum devices.

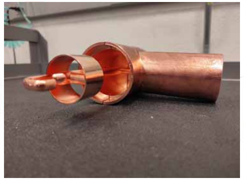
- **Unifying theme across these technologies is that the same physics and material properties such as extreme low loss, stability, and manufacturability are required.**

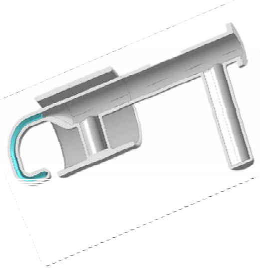
ANCILLARIES FOR ACCELERATORS

3D Cu printed ancillaries with improved cooling with ECR, HiPIMS or ALD coatings (Nb, NbTiN, Nb_3Sn….)

C. Ledford, NCSU







HOM Probe coating with Nb_3SN or NbTiN
on Nb/Cu Antennas – P. Plattner, Helmoltz-Institut Mainz, TFSRF2022

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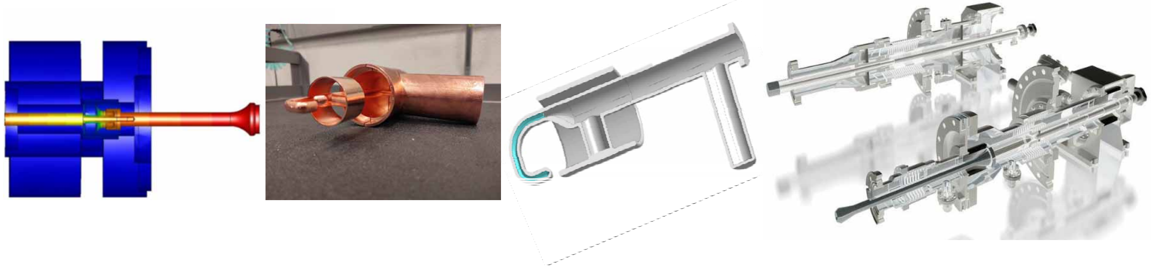

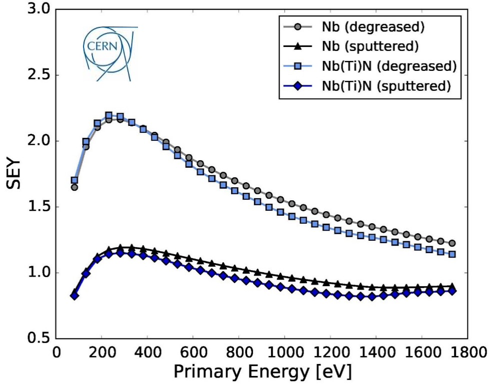

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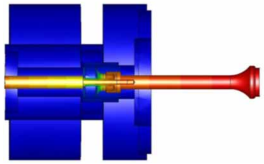
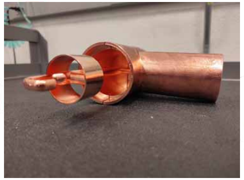
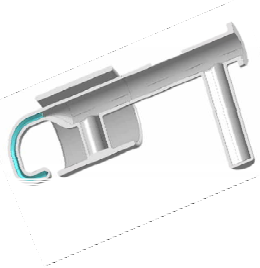
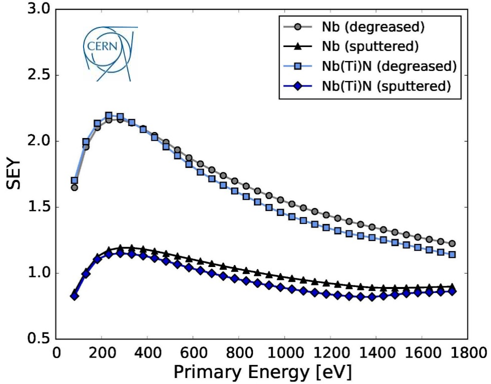






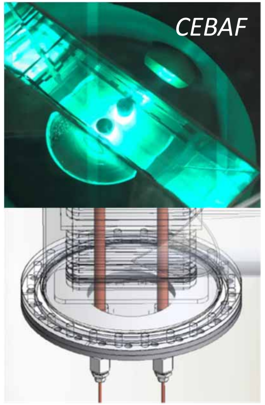


HOM Probe coating with Nb_3SN or NbTiN on Nb/Cu Antennas – P. Plattner, Helmoltz-Institut Mainz, TFSRF2022

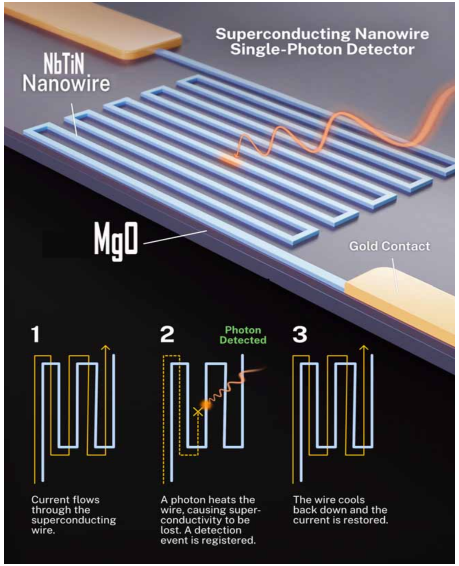
HiPIMS application to Cu on stainless steel bellows without Ni strike layer

Reliable, reproducible method, improved aspect ratio on convolutions

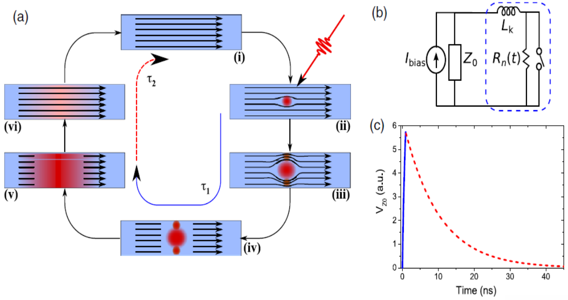
SBIR-II project, Starfire & JLab



Radiation Hard Detectors

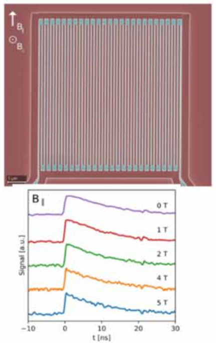


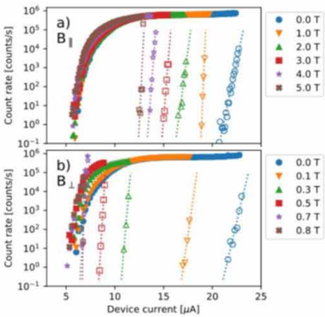
Chandra M Natarajan et al 2012 Supercond. Sci. Technol. ***25*** *063001*

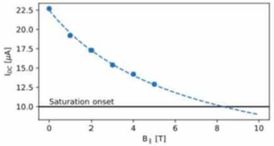


- ❑ Photon energy thresholds as low as ~100 meV
- ❑ Timing jitter 20–40 ps easily achieved (current record 3 ps)
- ❑ Reset times can be as low as 5-10 ns (potentially <1 ns)
- ❑ Pixels on the order of 10x10 μm^2 to 30x30 μm^2
- ❑ Fast, granular, high-rate pixel detector → low occupancies
- ❑ Photon detection efficiencies >90%
- ❑ Expected to very radiation hard (more on this later)
- ❑ Can be fabricated with different geometry or pixel dimensions

Highest performing detectors available from the ultraviolet to the mid-infrared

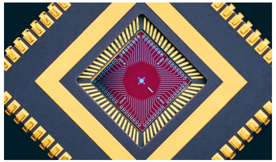






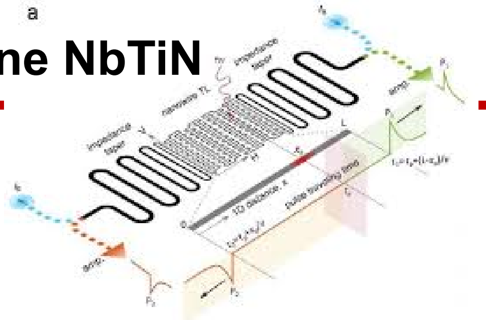
Can operate on strong magnetic fields with nearly zero dark count

- ❑ *EIC-related Detector R&D, Active Polarized Neutron Target Concept for CLAS12, Superconducting Magnet integrated particle detector, rapid SFQ electronics, beam loss monitors….*
- ❑ *Optical communications (large mid-IR focal plane arrays of SNSPD for exoplanet transit spectroscopy for the Origins Space Telescope. UV SNSPD are being integrated with ion trap chips for quantum computing applications.*



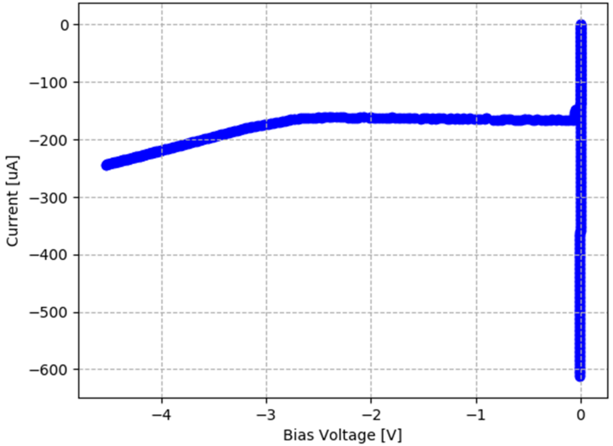
Matt Shaw, JPL

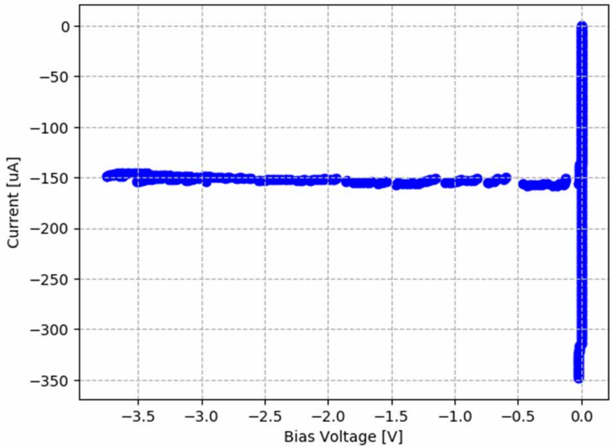
SNSPD Applications - Preliminary Results with crystalline NbTiN



- SNSPD patterned from 10 nm thick film
  - T_c=14.15± 0.5 K
  - Too thick yet to be photon sensitive

M.D, Shaw, A.D. Beyer, B.A. Korzh, B. Bubbler



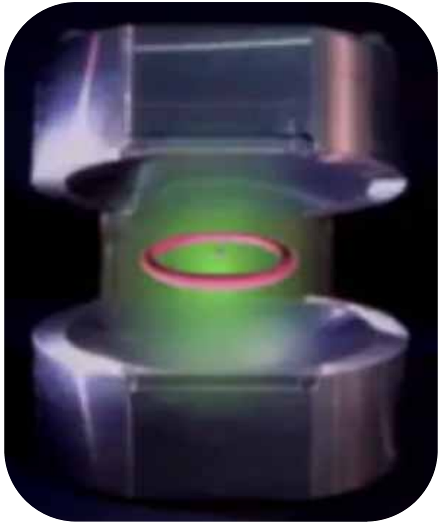


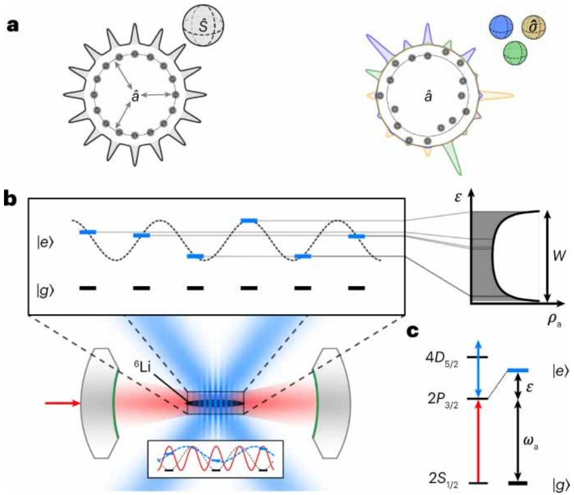
switching current of 300 µA (~30 higher than usual JPL NbTiN recipe), re-trapping current of 150 µA

Open the way to detection without amplification

QCD Experiments

High-finesse, near-concentric optical resonator enables strong and long-range interactions among atomic spins.





ECR Nb/Cu, 180 eV nucleation

D. Vitali, et al., Journal of Modern Optics, 54:11, 1551-1567 .(2007)
Haroche, S., Brune, M. & Raimond, J.M. Nat. Phys. 16, 243–246 (2020)

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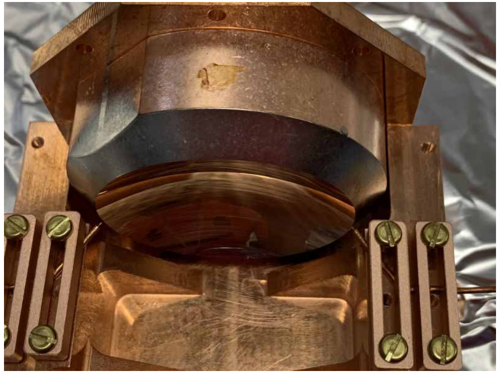
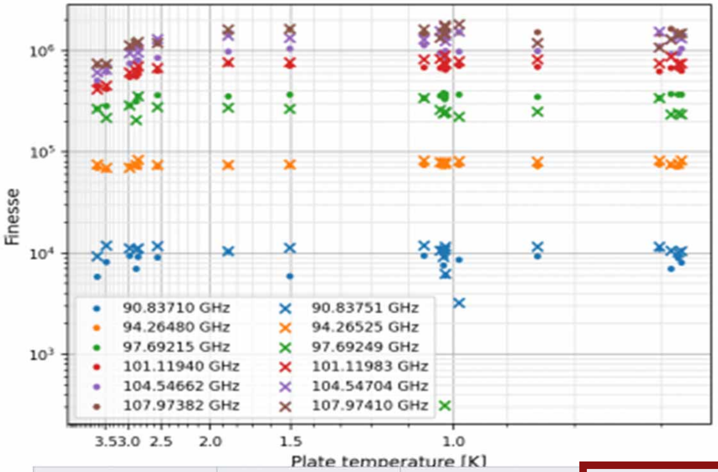
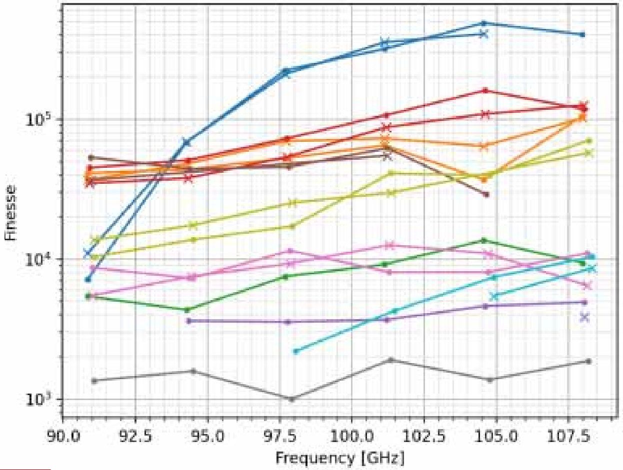
ECR Nb Films for Studies of Highly Entangled States of Laser-Cooled Atoms

High-finesse measurements in near-confocal Fabry–Perot geometry enable strong and long-range interactions among atomic spins







Courtesy T. Zhang, M. Schleier-Smith et al.

Polarization	Center frequency (GHz)	Linewidth (kHz)	*Q*	Finesse
s	107.97381668(2)	2.3(1)	46.9(2.0) M	**1.49(6) M**
p	107.97422315(5)	2.15(20)	50(5) M	**1.59(15) M**

At 4.2 K, TEM00 modes improved with frequency, suggesting limitation by diffractive loss.
At 700 mK, TEM00 modes barely improved, modest improvement for higher frequency ones
Best modes : 2 orthogonal polarizations of TEM(31, 0, 0) at 107.974 MHz, with **Q ~ 5x 10^7**

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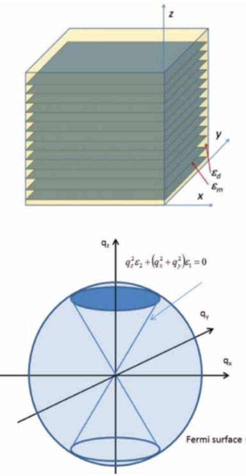
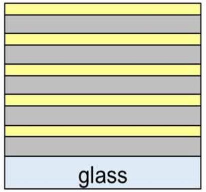
Metamaterials Developments

Meta-materials for functional surfaces

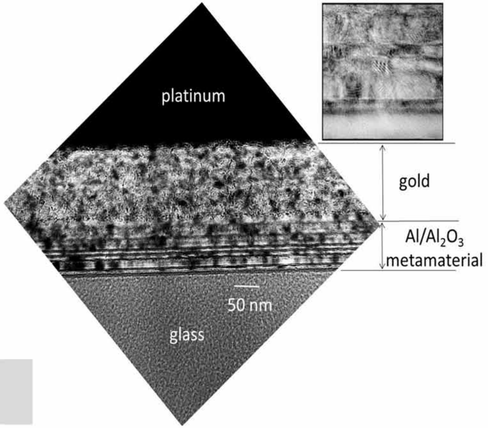
Nature Scientific Reports 6, Article number: 34140 (2016)



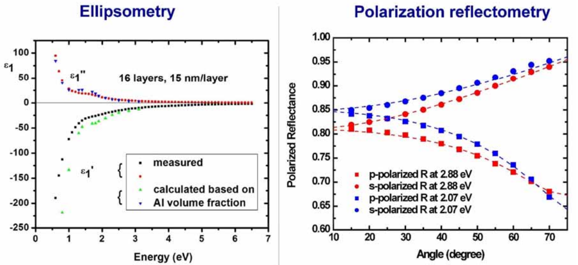


thermal evaporation of Al
followed by 1 hour oxidation in air
forming Al2O3 (1-2 nm)

thickness of Al and number of layers were varied



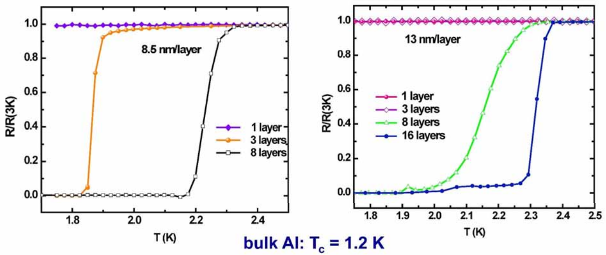
Hyperbolic character of Al/Al_2O_3 multilayers
($\varepsilon_{1\,(in\ plane)} < 0$; $\varepsilon_{2\,(out\ of\ plane)} > 0$)



- $\varepsilon_{1\,(in\ plane)} < 0$
- good agreement with calculated values based on Al volume fraction

ε_1 = -7.17 and ε_2 = 1.56, at 2.07 eV (600 nm)
ε_1 = -2.15 and ε_2 = 1.30 at 2.88 eV (430 nm)

Effect of the number of layers on T_c of the Al/Al_2O_3 hyperbolic metamaterial samples



bulk Al: T_c = 1.2 K

Metamaterial (multilayer) is needed for T_c enhancement

Applications: compact RF resonator application, THz SIS Receivers, RF-SQUID arrays, MRI (magnetic resonance imaging) and near field imaging

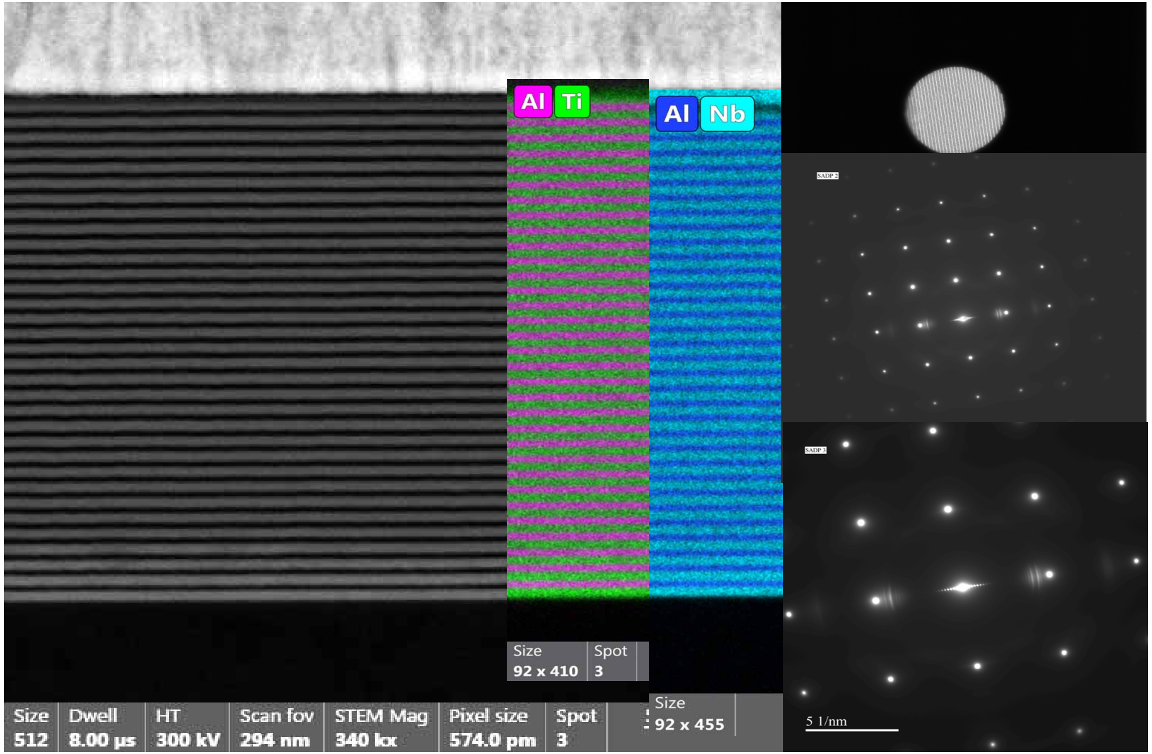
For example, Metamaterials on MgB_2 could get superconducting structures at LN_2 temperatures

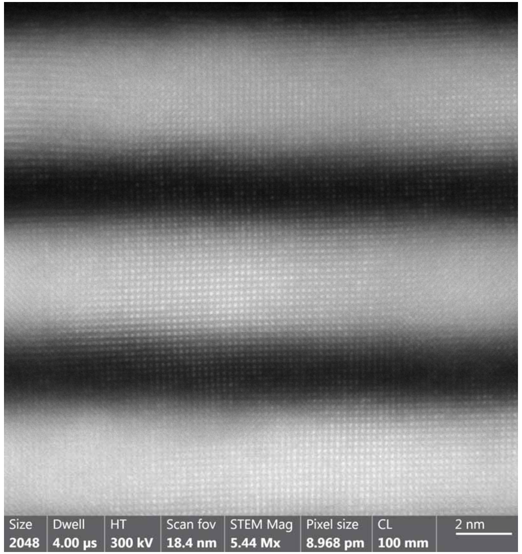
Materials Research Foundations 132 (2022) 194-210

Metamaterials based on NbTiN

Meta-materials for functional surfaces

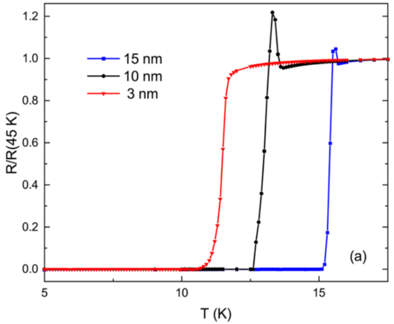
- Multilayer structure of NbTiN = 3.6/3/2 nm and AlN = 2/1.5/1 nm.
  N bilayers deposited on NbTiN/MgO



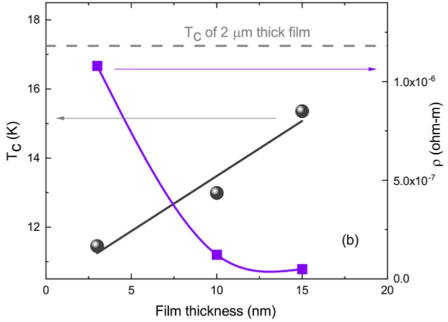


NbTiN/AlN Metamaterials Developments

Effect of Thickness on Critical Temperature

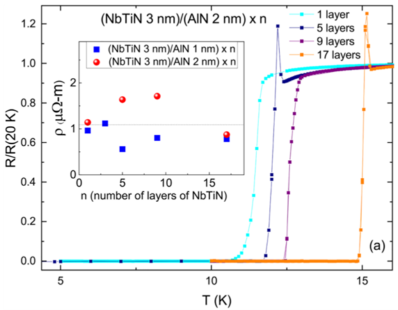


Normalized temperature dependence of the resistance of standalone NbTiN films as a function of thickness.

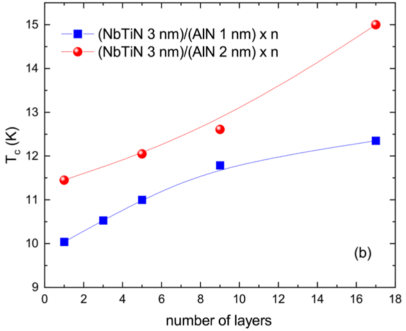


Thickness dependence of T_c and resistivity at T = 20 K for the standalone films (lines are guides for the eye).

Effect of Number of Layers on Critical Temperature

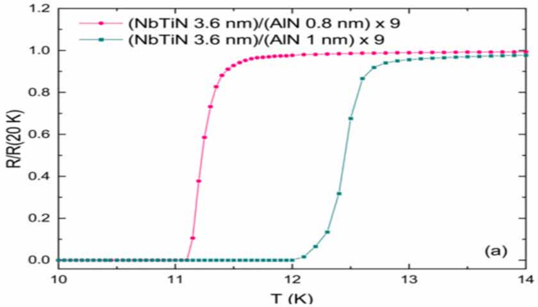


Normalized temperature dependence of the resistance of (NbTiN 3 nm)/(AlN 2 nm) × n films for the varying number of layers, n. The inset shows the resistivity of (NbTiN 3 nm)/(AlN 2 nm) × n and (NbTiN 3 nm)/(AlN 1 nm) × n multilayers as a function of n. The dashed line is the average resistivity of the multilayers, 1.1 Ω m.

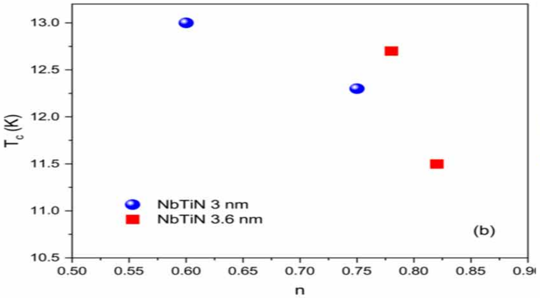


Dependence of the Tc on n for (NbTiN 3 nm)/(AlN 2 nm) × n and (NbTiN 3 nm)/(AlN 1 nm) × n multilayers. The Tc of these metamaterials is up to 32% higher than the Tc of a single ultrathin NbTiN layer (lines to guides the eye).

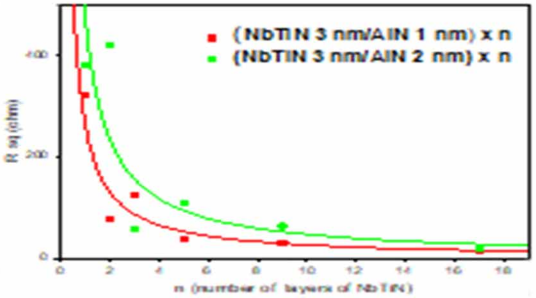
Effect of Volume Fraction of the Metal



Normalized temperature dependence of the resistance of the (NbTiN 3.6 nm)/(AlN 0.8 nm) × 9 and (NbTiN 3.6 nm)/(AlN 1 nm) × 9 films, which have different volume fractions of metal.



Tc dependence on the volume fraction of metal for the 8 bi-layer NbTiN/AlN structures.



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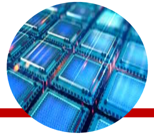
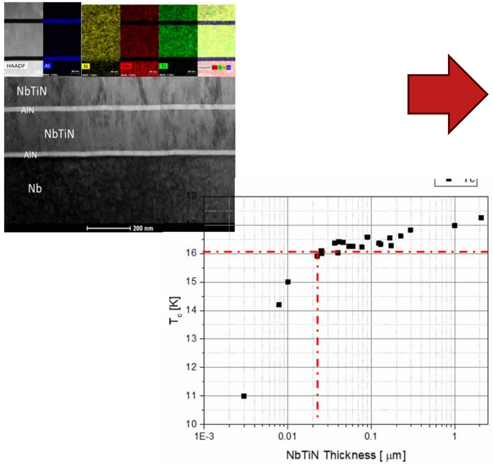
Jefferson Lab

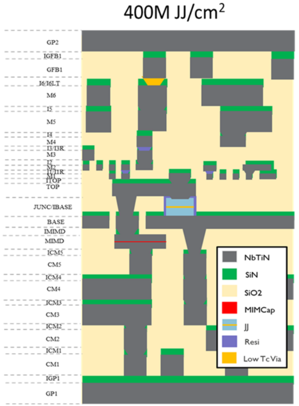
Superconducting Digital Logic

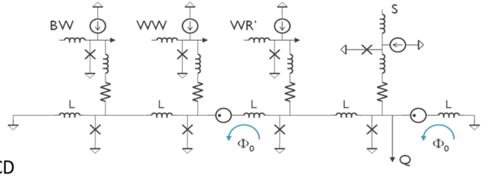


	CMOS 7 nm	Superconducting 30 nm
Speed	1.4 GHz	17x
Memory	500 MB/cm² (SRAM)	0.01x
Device density	1T devices/cm²	0.1x
Interconnects	1.6 Gb/line @ 1 pJ/bit	120x, 1000x
Power efficiency	1 TOPS/W	50x



Fabrication Stackup + JSRAM Schematic = Memory Unit Cell

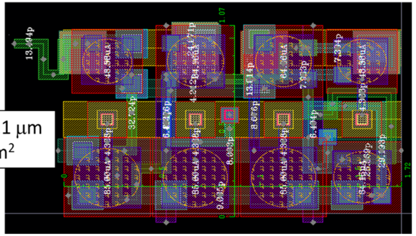




50nm CD

3 routing layers
1 layer for flux initialization

1.75μm x 1.1 μm
5 MB/cm²



Courtesy Q. Herr, imec

- *Fabrication stackup for digital logic with 16 superconducting NbTiN layers, self-shunted a-silicon barrier Josephson Junctions (JJs), and low loss, high-k tunable HZO capacitors to enable 400 MJJ/cm² device density*
- *Energy efficiency, high computational density, and high interconnect bandwidth.*
- *Uniquely enable real-time AI training models and improved security by distributing to edge systems compute power that currently must be deployed in a centralized data center*

ACTIVE CONTROL AT THE EDGE HAS SEVERAL APPLICATIONS

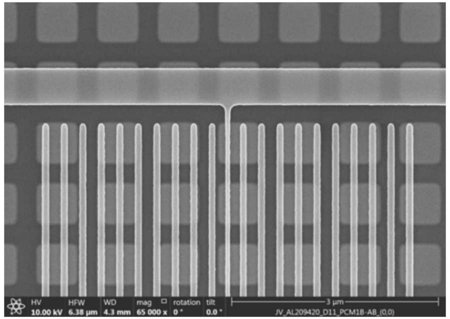
AUTOMOTIVE	ROBOTICS	MOBILITY MANAGEMENT	BIOPROCESSES
• Update autonomous car models based on sensory fleet input • Optimize car's local control policy to time of day, location, etc.	• Multi-task cobot interaction • Train a cobot for task A today, re-train for task B next 2 hours	• Central control of traffic lights & signage • Optimize for time of day, weather, incidents, etc.	• Personalized medicine • Control a recipe for process X and re-train for process B in next 2 hours

And several others:
- Distributed control of smart grids (planning of car charging, balancing production vs consumption)
- Port management of ships
- Healthcare, etc.

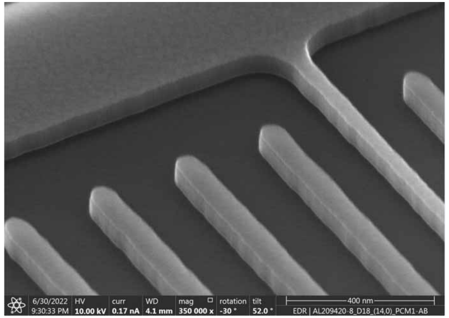
Courtesy Q. Herr, imec

Potential to provide a sustainable solution for large-scale compute applications positioned between mature CMOS and long-horizon quantum computing.

Superconducting Digital Logic

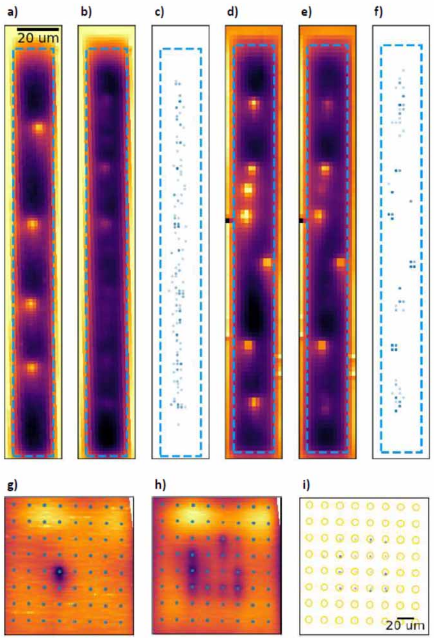


2 metal layers with 50 nm critical dimension.

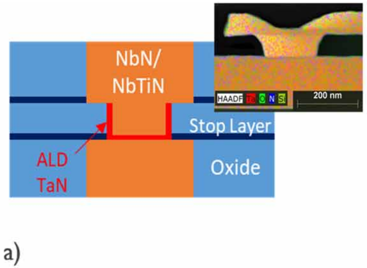


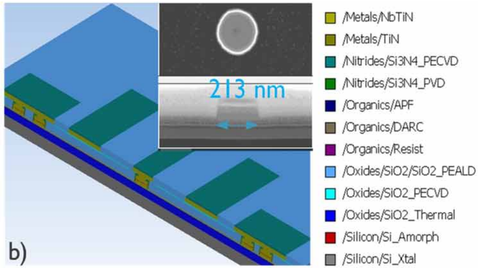
Courtesy A. Herr, imec

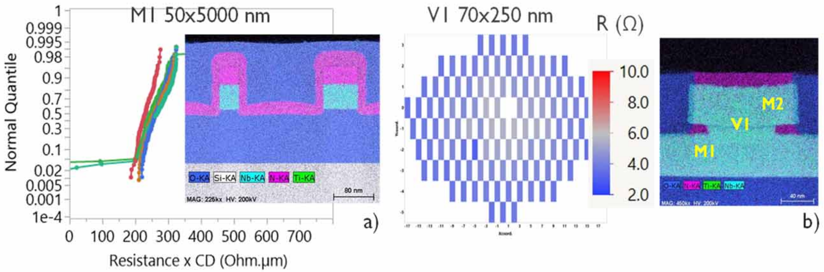
Courtesy K. Nowack, Cornell U.

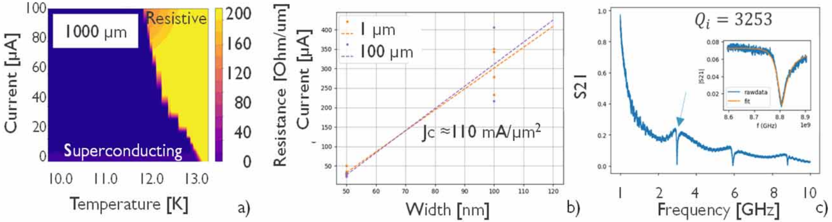


Magnetic imaging of field-cooled patterned NbTiN ground planes showing vortex location.
20 mm strip fabricated from a 100 nm thick film cooled in 12 -14 µT fields.









T_c=12.5 K j_c=110 mA/µm^2 @ 4.2 K

Courtesy A. Herr, imec

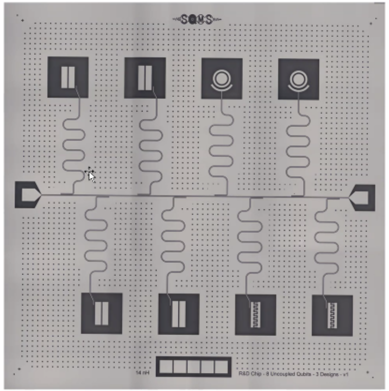
Quantum Information Systems

QIS NP Funding — Jefferson Lab, University of Waterloo, Fermilab *within* SQMS — Superconducting Quantum Materials & Systems Center

Exploit JLab high quality films deposited by ECR for qubit optimization

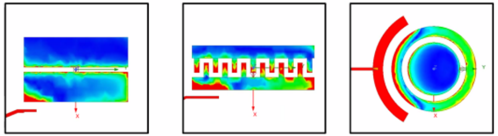
- *Optimization of Nb/Al_2O_3 films in the thickness range of 150-200 nm specific for qubits*
- *Development and optimization of Nb/Si*
- *Investigation of other superconducting materials*
- *Optimization of transmon & flux qubits coherence time*
- *Optimization of 2D and 3D design concepts*

2D SQMS R&D Qubit Chip – v1

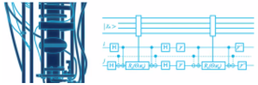


Standardized qubit chip

- 8 fixed frequency uncoupled transmons ~ 4 – 5 GHz
  - 4 w/ double capacitive pads (for statistics)
  - 2 w/ interdigitated capacitive pads (most sensitive)
  - 2 w/ concentric capacitive pads (most insensitive)
- Anharmonicity ~ 220 MHz
- Readout resonators ~ 6 – 8 GHz
- Frequency multiplexing on single feedline



E-field distribution of different transmon geometries

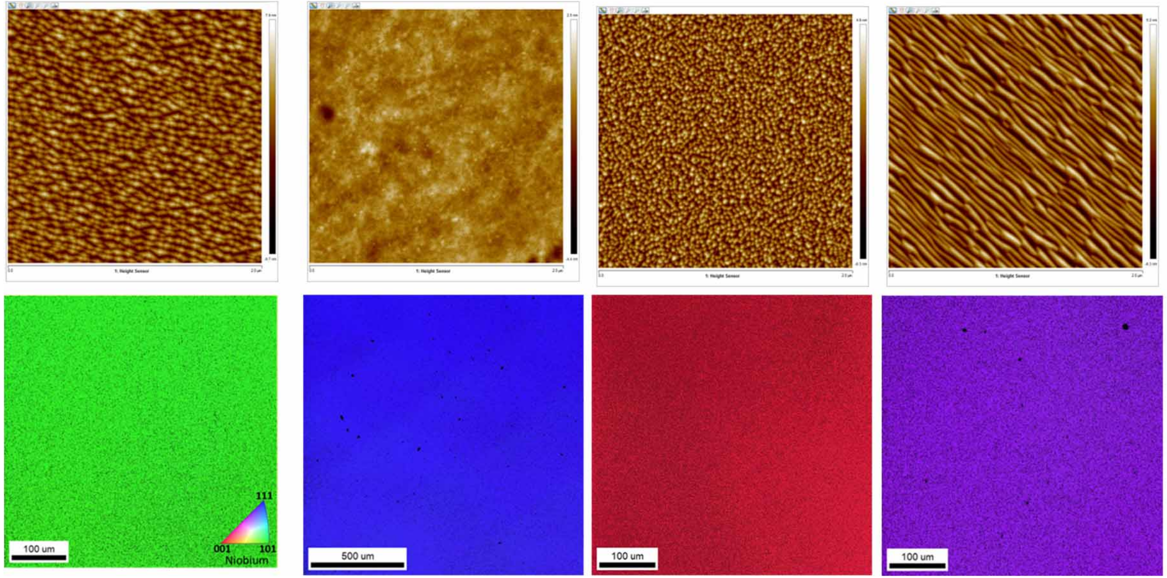


SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

High quality Nb films for Qubits

150 - 200 nm ECR Nb films nucleated at 304 eV, subsequent growth at 64 eV

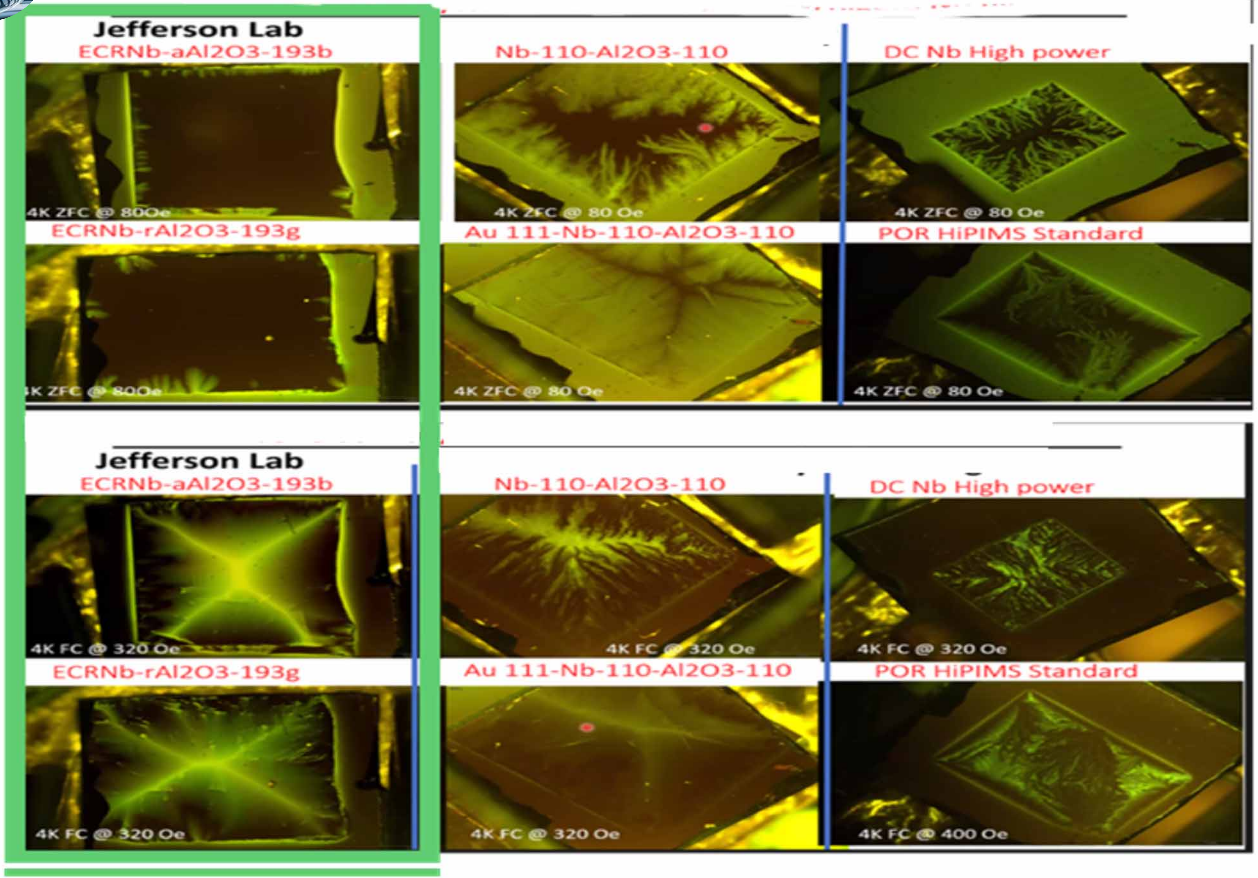
Nb/ Al_2O_3(11-20) | Nb/ Al_2O_3(0001) | Nb/ Al_2O_3(1-120) | Nb/ Al_2O_3(10-10) | Nb/ fused silica



	Al_2O_3					Fused Silica
R_a [nm]	(11-20)	(0001)	(1-120)	(10-10)	ceramic	
2 um	*1.54*	*0.28*	*1.03*	*1.35*		*1.81*
5 um	*1.52*	*0.34*	*1*	*1.31*		*1.86*
10 um	*1.5*	*0.47*	*0.89*	*1.17*		*1.84*
50 um	*0.95*	*0.55*	*0.66*	*0.46*		*1.69*
T_c [K]	9.33	9.33	9.32	9.28	9.29	9.24
ΔT_C [K]	0.07	0.06	0.04	0.05	0.06	0.26
RRR	75.60	79.00	83.00	68.00	39.00	14.00

Preliminary work : collaboration with JLab, FNAL, Ames Lab, Temple University

High quality Nb films for Qubits



Magneto-optical Measurements

R. Prozorov et al (Ames)

AMES NATIONAL LABORATORY

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Preliminary

SUMMARY

***Many Applications of SRF Thin Films beyond Cavities** :*

Ancillaries, Metamaterials, Novel Electronics and Sensors, Quantum Devices

Developments of high performing, low-loss SRF Thin Films

- *Truly synergistic with benefits for both SRF and Applications*
- *Allow more in-depth studies or out-of-the box developments*
- *Potential for transformational developments with benefits for society at large*