SURFACE PREPARATION OF NIOBIUM FOR SUPERCONDUCTING QUBIT APPLICATIONS

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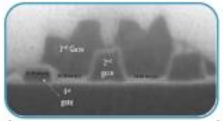
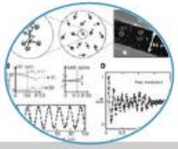
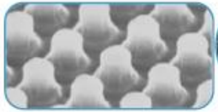
QUBIT DEVICE FOCUS @ IMEC

SEMI- & SUPER-CONDUCTING QB'S

(dark green)	No issue
(light green)	Good enough
(yellow)	Survivable
(orange)	Not clear, difficult
(red)	Showstopper



Qubit Type	NMR	Ion traps/ atoms	semiconductor QD (imec)	N V in diamond+	Superconduct. circuits (imec)	Optical qubits	Gatemon (Majorana)
Coherence/ gate time	OK 2E4	OK 6E7	OK ~E7	OK ~E7	OK 5E7	OK ~E5	OK E5
2D array path	No	likely	Likely with extreme scaling	likely	yes	likely	maybe
Max qb #	14	73	2	2	21 (~2000)	2	0
Fabrication	chemistry	Maybe Si fab likely*	CMOS compatible	Random Single ion	$Al/Al_2O_3/Al$ Si fab OK	OIO platform	CMOS compat Maybe
Device size	molecule	Atom but many lasers	transistor	Not clear	100s of um^2	mm^2	mm^2
other	Requires very large magnets	Requires lasers 4K	25mK	Requires lasers 4K	25mK	Deterministic 1-photon source; 4K	25mK

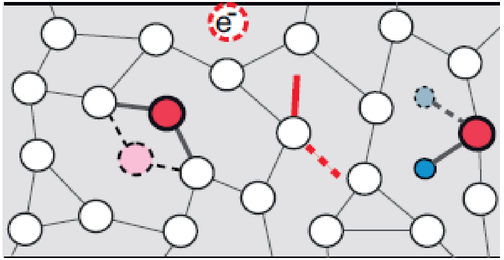
QUBIT COHERENCE

MOORE'S LAW FOR QUANTUM COHERENCE

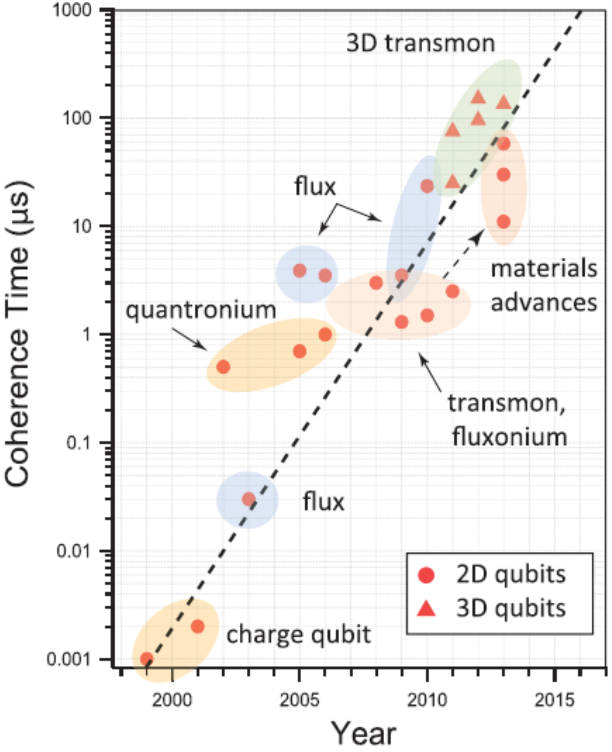
LOW LOSS =
HIGH Q-FACTORS

LONG COHERENCE TIMES

→ REDUCTION OF TWO-LEVEL-SYSTEMS



LISENFELD, SCIENTIFIC REPORTS MARCH 2016

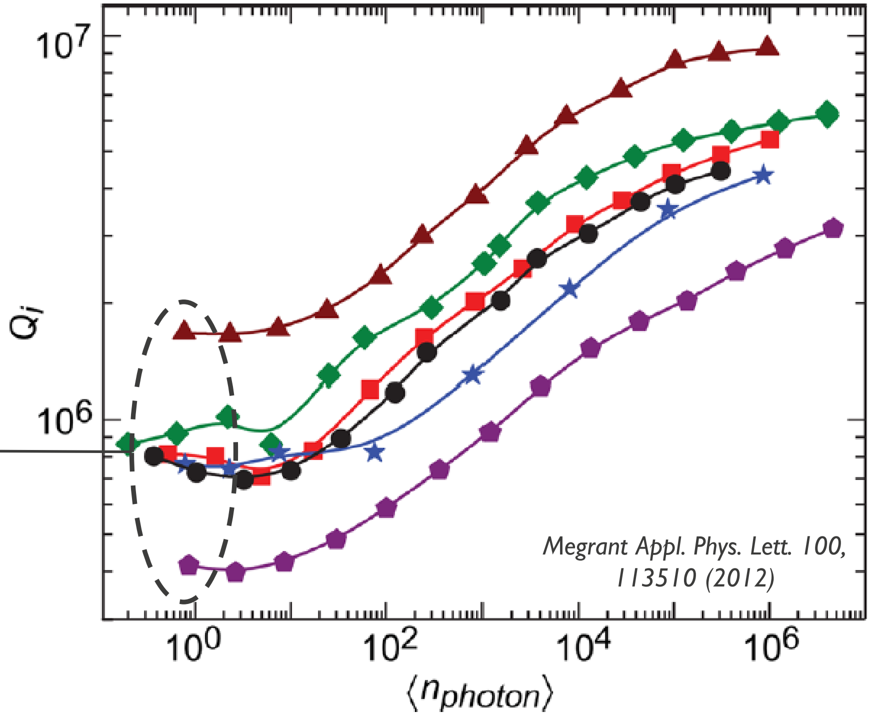


WELANDER, MRS BULLETIN VOL 38 OCTOBER 2013

RESONATORS FOR DETECTION OF TLS'S

POWER DEPENDENCE OF THE INTERNAL QUALITY FACTOR Q_I

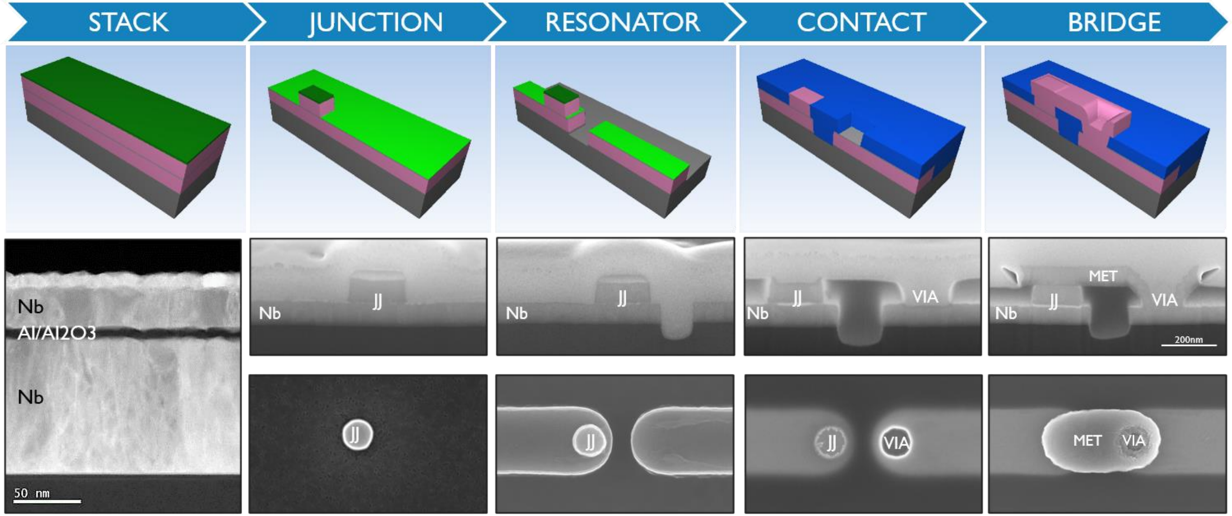
Low power ("single photon") regime is of interest to qubits



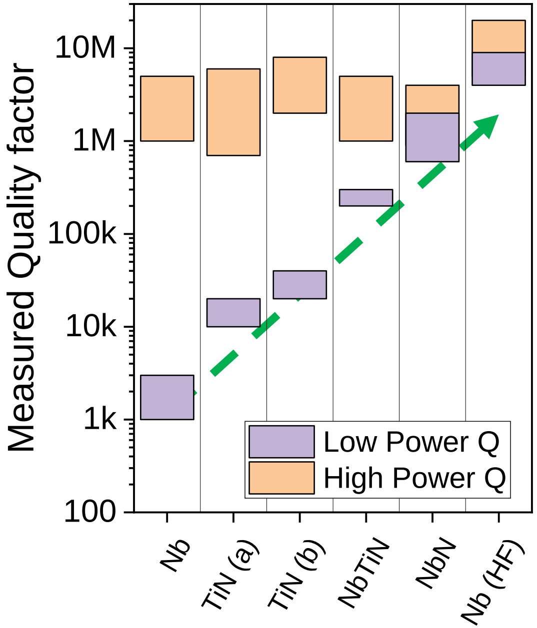
Q_I → measure for *MATERIAL* and *FABRICATION PROCESS* **QUALITY**

QB FABRICATION PROCESSES AND SC METALS

IMEC 300 mm wafer FAB QUBIT PROCESS flow:



FAB PROCESSES have an influence on SURFACES & INTERFACES



STRONG **MATERIAL &**
PROCESS DEPENDENCE

NIOBIUM AS SUPERCONDUCTING METAL

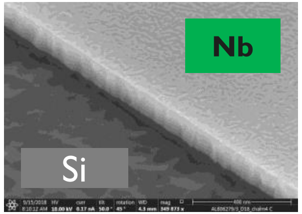
PRO Promising candidate for **VLSI** and high $\mathbf{T_c}$ at **9.2 K.**

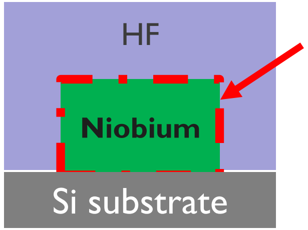
CONTRA forms a **native oxide film once exposed to air** → detrimental TLS‘s

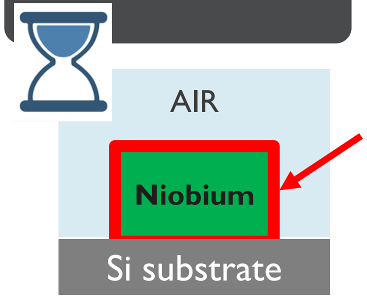
THIS STUDY

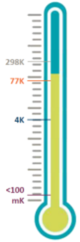
EXPERIMENTAL METHOD:

RESONATOR FAB PROCESS → SURFACE TREATMENT → AGING TIME, REOXIDATION → Q FACTOR & XPS MEASUREMENTS







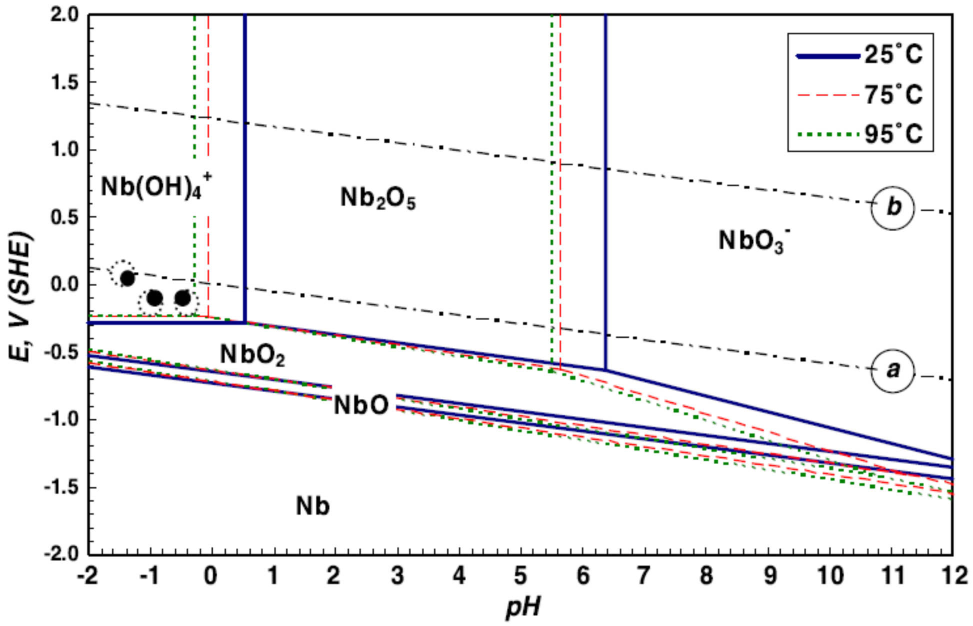


CHEMICAL PROPERTIES OF NIOBIUM

- Noble? **NO**
- Resistant to corrosion? **YES**

→ **EASY** to clean niobium

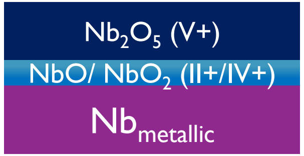
→ **DIFFICULT** to have niobium in its metallic form



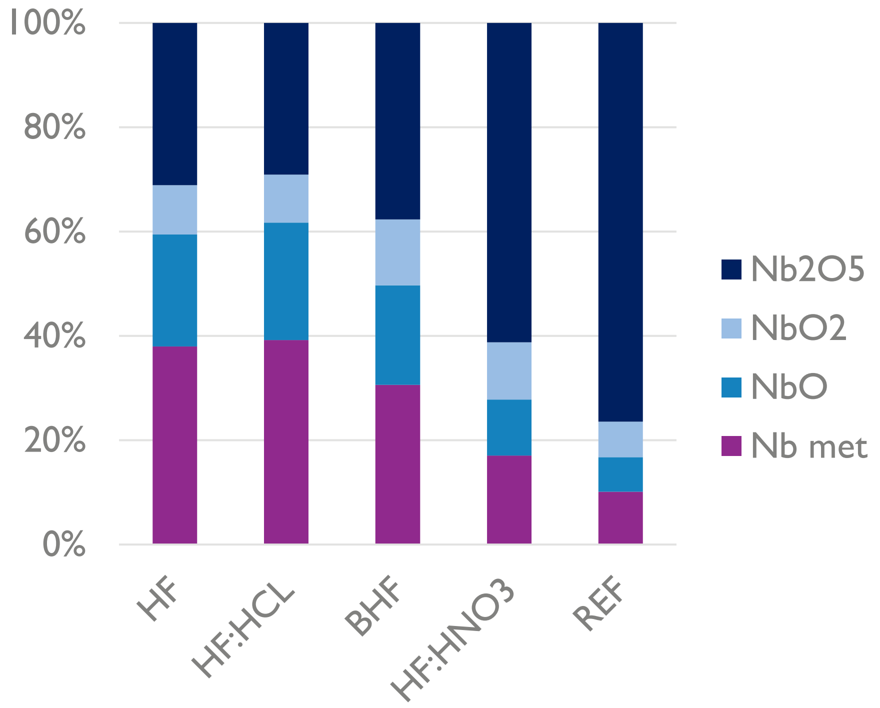
Asselin, E., Ahmed, T.M., and Alfantazi, A. (2007), "Corrosion of Niobium in Sulfuric and Hydrochloric Acid Solutions at 75 and 95 deg. C," *Corrosion Science*, **49**(2), pp 694-710.

CLEANING & ETCHING SOLUTIONS

ETCH RATE AND SURFACE COMPOSITION AFTER ETCH



Solution	Dip time (min)	Film loss (nm)	Etch Rate (nm/min)
HF	10	14.5	1.4
HF:HCl	10	10.4	1.0
BHF	10	2.3	0.2
$HF:HNO_3$	3.5	61.8	17.7

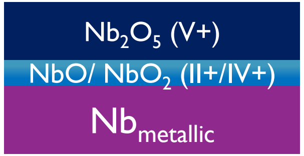


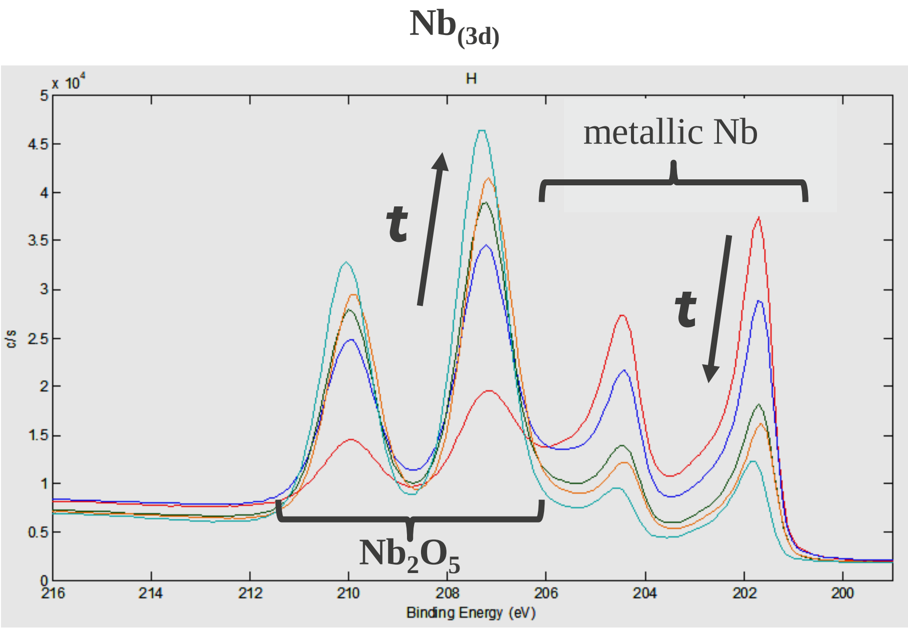
HF-based treatments etch Nb and decrease the Nb_2O_5 oxide.

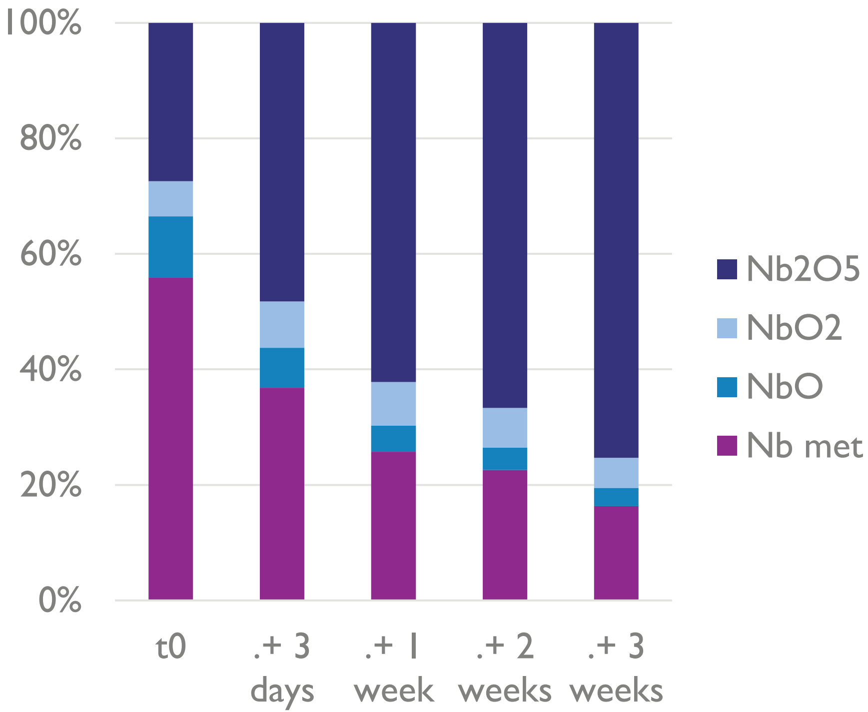
$$Nb_2O_5 + 10F^- + 10H^+ = 2NbF_5 + 5H_2O$$

RE-OXIDATION OF NIOBIUM (LONG TIMES)

SURFACE COMPOSITION MONITORED BY XPS (AFTER HF-TREATMENT)



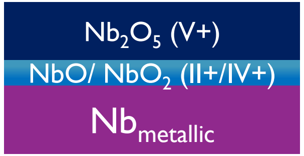




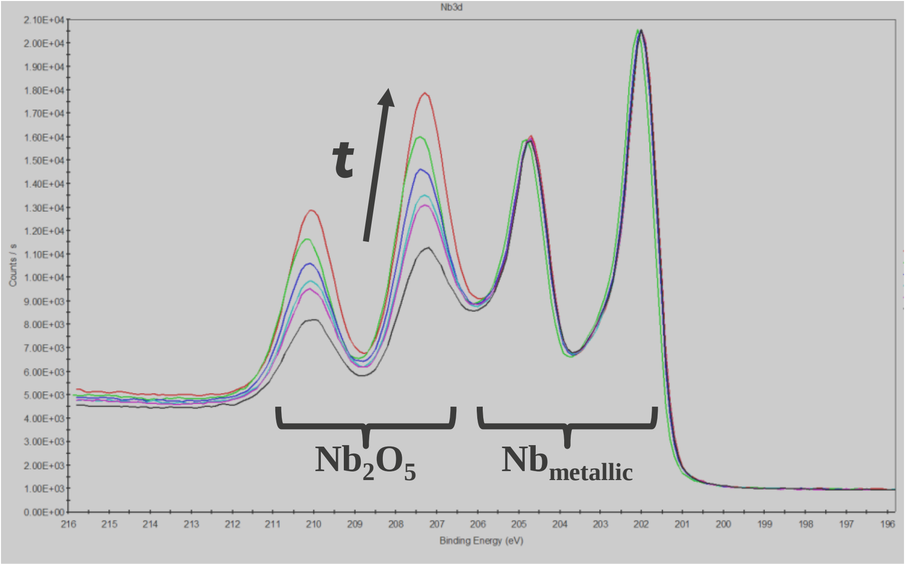
Nb gradually oxidizes to Nb_2O_5 oxide.
Sub-Ox decrease marginally a.f.o. time.

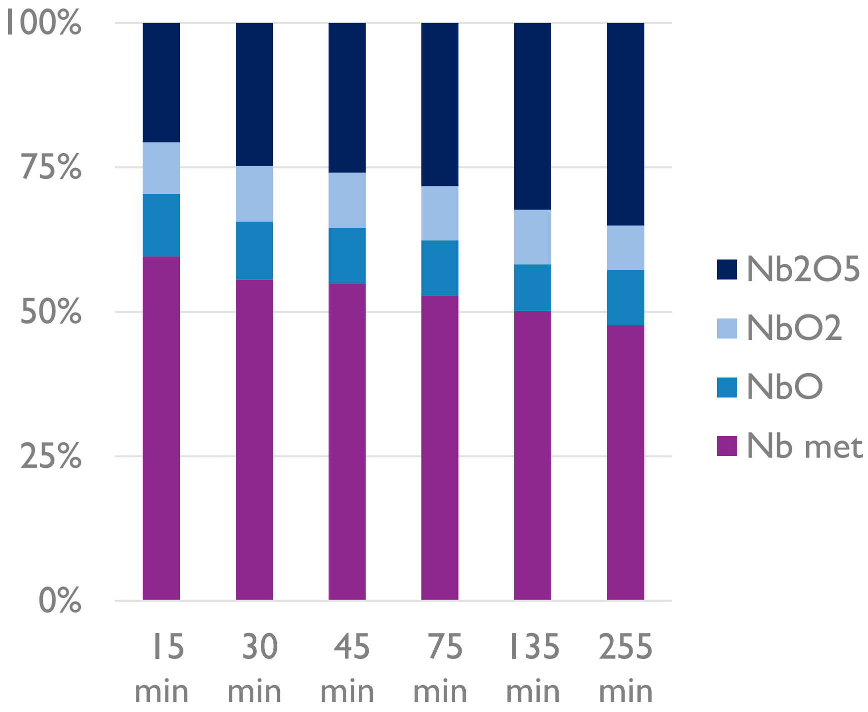
RE-OXIDATION OF NIOBIUM (SHORT TIMES)

SURFACE COMPOSITION MONITORED BY XPS (AFTER HF-TREATMENT)



$Nb_{(3d)}$

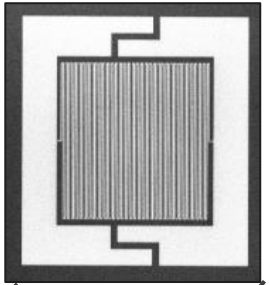


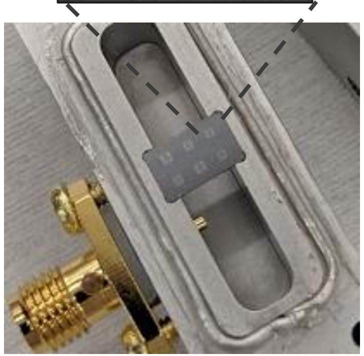


3 oxide types already present after the shortest ageing time !

INTERNAL QUALITY FACTOR MEASUREMENTS

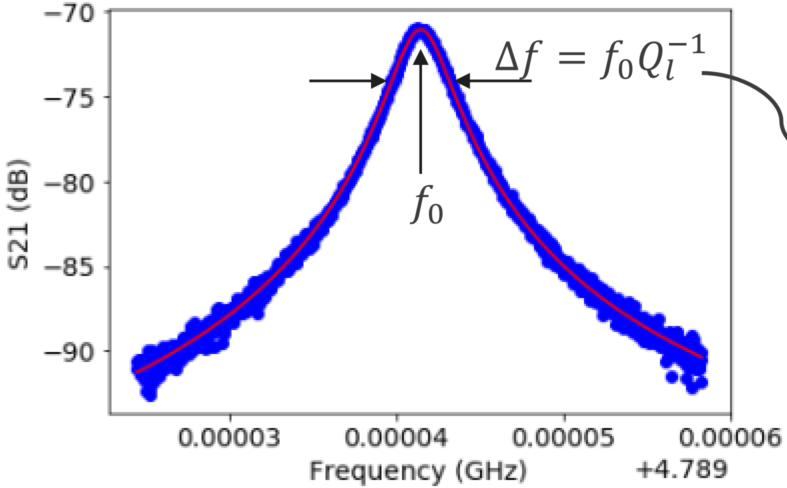
LE resonator





LE resonators in a 3D cavity

one of the LE resonances



Keep small by design

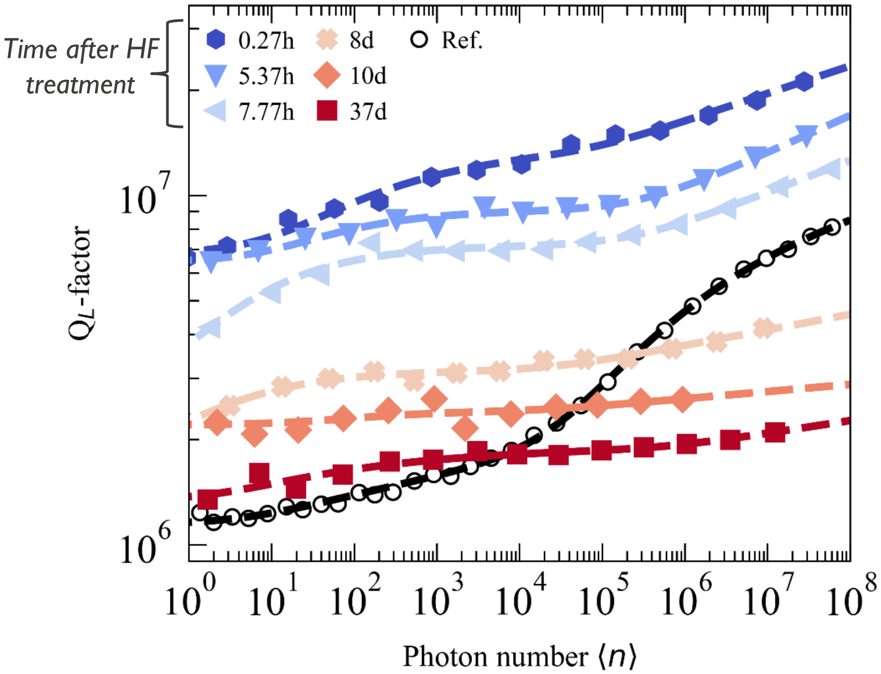
$$\frac{1}{Q_l} = \frac{1}{Q_{\mathrm{ext}}} + \frac{1}{\boldsymbol{Q}_{\mathbf{int}}}$$

Measured

Material dependent term of interest

$$Q_l \sim \boldsymbol{Q}_{\mathbf{int}}$$

DEPENDENCE OF THE Q FACTOR ON RE-OXIDATION TIME

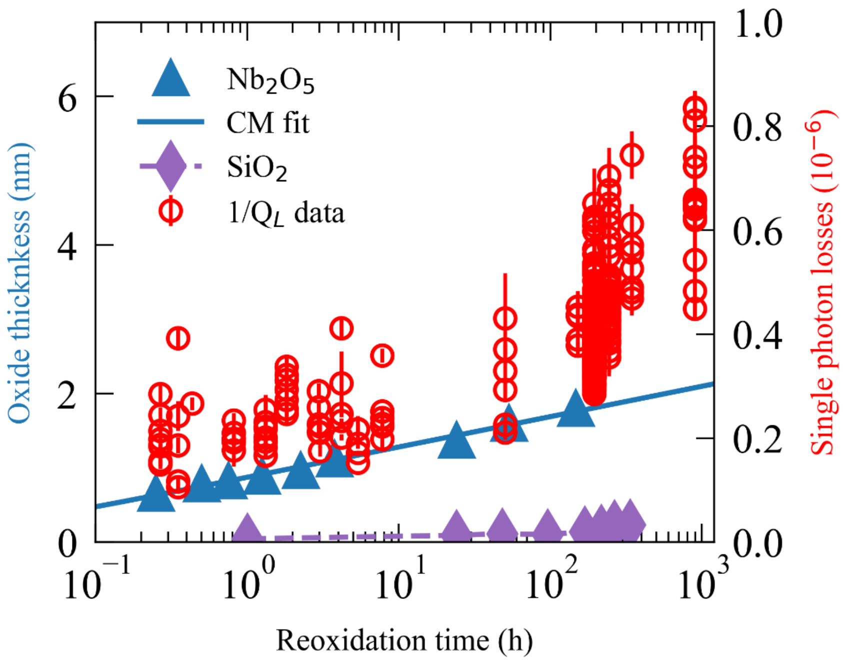


Verjauw J. et al. 300mm fab process for ultra high-quality superconducting resonators. IEDM paper, submitted.

- Q-factors increase after an HF treatment of the niobium resonators.
  - quality factors up to **7 million** in the single photon regime.

    = highest reported for niobium !
- When niobium re-oxidation takes place, the Q-factors reduce again over time.

DEPENDENCE OF THE Q FACTOR ON Nb_2O_5 THICKNESS



Verjauw J. et al. 300mm fab process for ultra high-quality superconducting resonators. IEDM paper, submitted.

- The lower limit of $1/Q_L$ scales with the niobium oxide thickness.

  → Reduction of Nb_2O_5 thickness improves Q factor.

- Nb_2O_5 is the main source of loss in the single photon limit within the first ~200h.

SUMMARY

- An HF treatment partially removes the niobium(V) oxide.
- A decrease in Nb_2O_5 thickness has a huge effect on the quality factor of the niobium resonators:

  Very high quality $Q_{s.ph}$ ~ 7M were measured for the lowest aging (re-oxidation) times.
- Losses increase again with Nb_2O_5 regrowth in time.

ACKNOWLEDGEMENTS

- Surface and Interface Processing Group:
  - Jens Rip, Kurt Wostyn, Efrain Altamirano Sanchez, Frank Holsteyns.
- Superconducting Qubit Integration Team:
  - Jeroen Verjauw, Anton Potocnik, Danny Wan, Massimo Mongillo, Tsvetan Ivanov, Laurent Souriau, Rohith Acharya, Bogdan Govoreanu, Iuliana Radu, Marc Heyns
- Materials & Component Analysis Team
  - Anja Vanleenhove, Thierry Conard, Ilse Hoflijk, Inge Vaesen

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