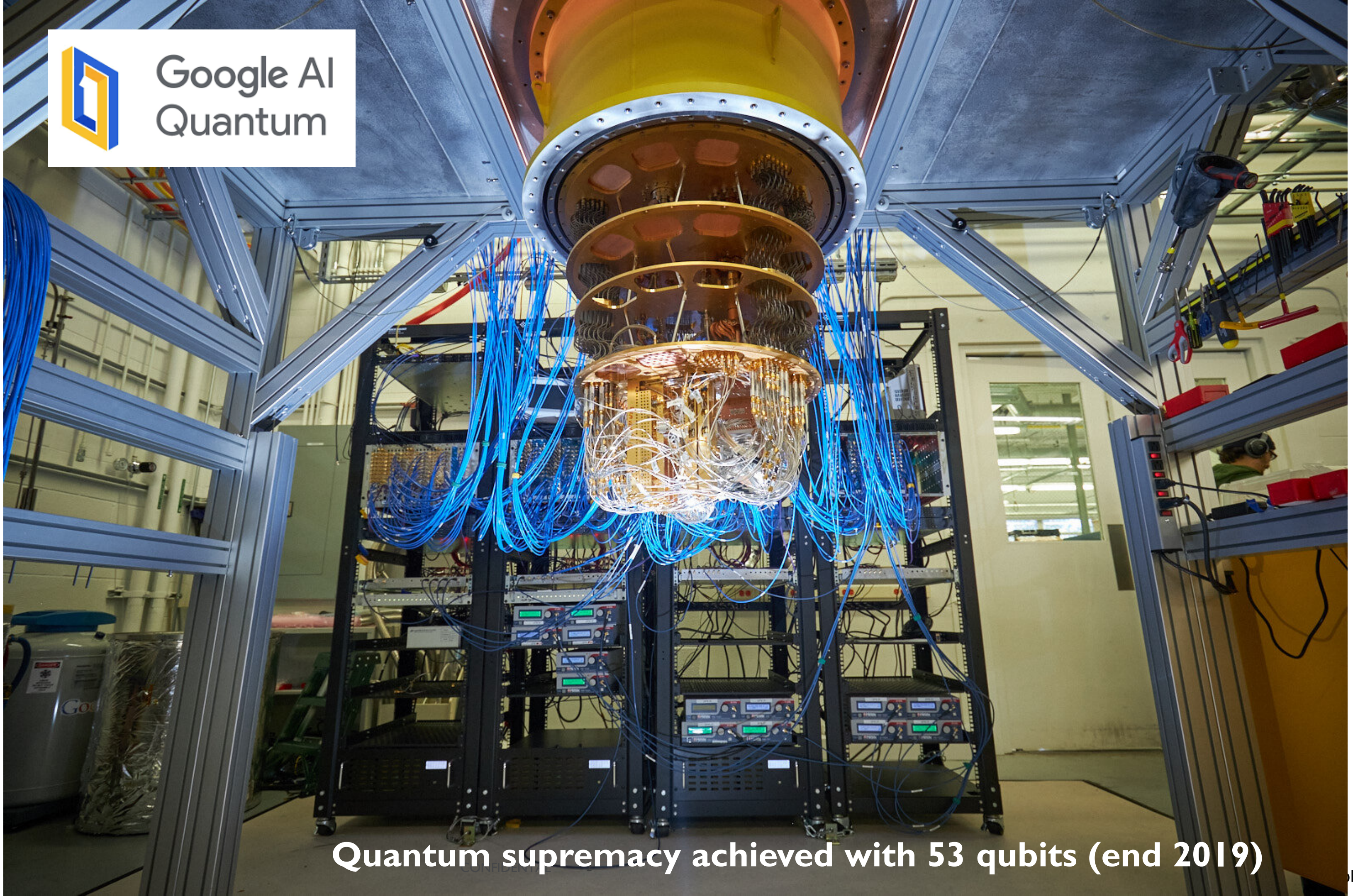
Towards large-scale quantum computing

Anton Potocnik



Quantum supremacy achieved with 53 qubits (end 2019)

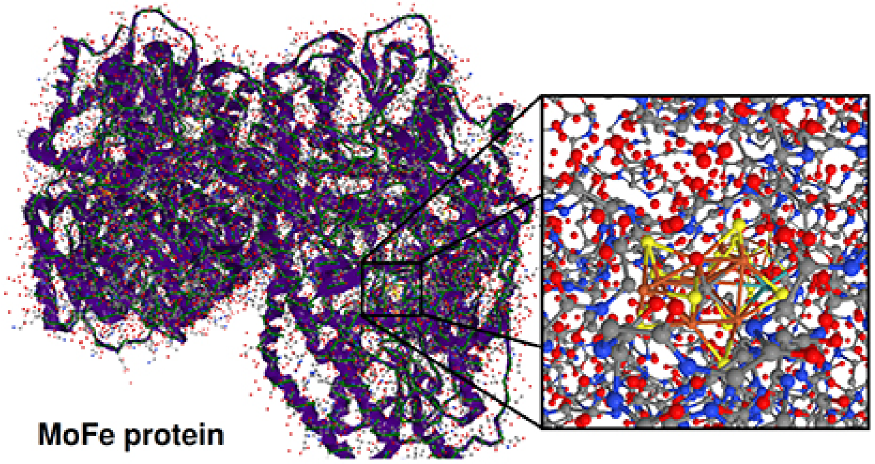
Katere probleme resuje kvanto racunalnistvo?

Logistika

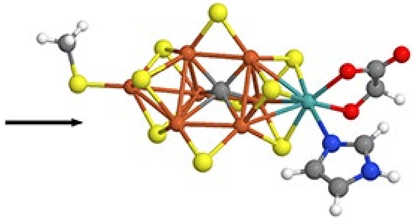
Medicina & Materiali

Strojno ucenje

Kriptografija

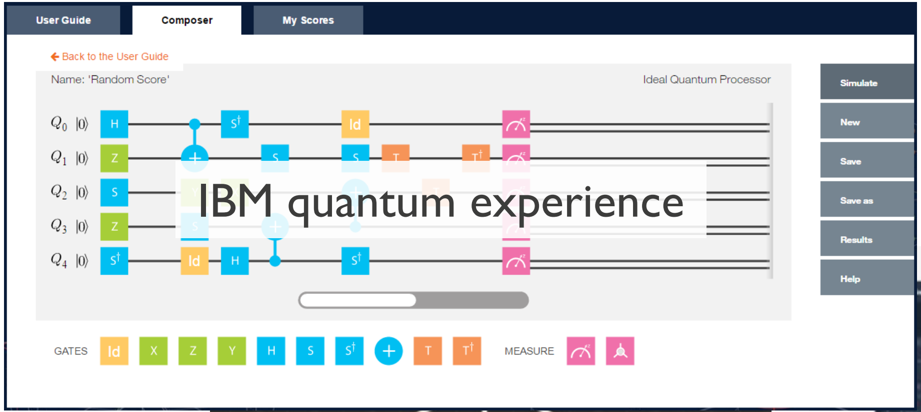


FeMoco

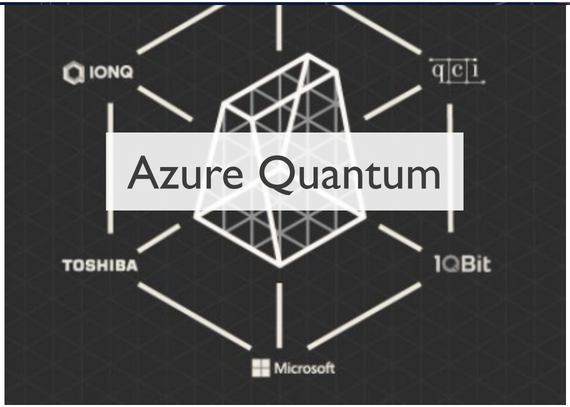


3-5% uporabe zemeljskega plina letno!

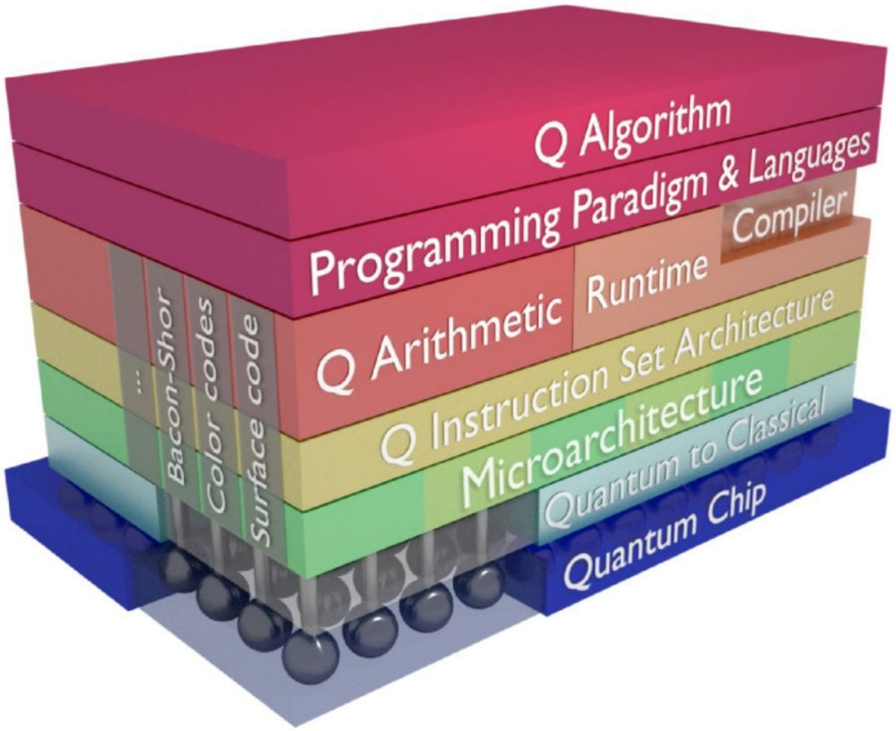
Current applications



Google AI Quantum



Stack/Outlook

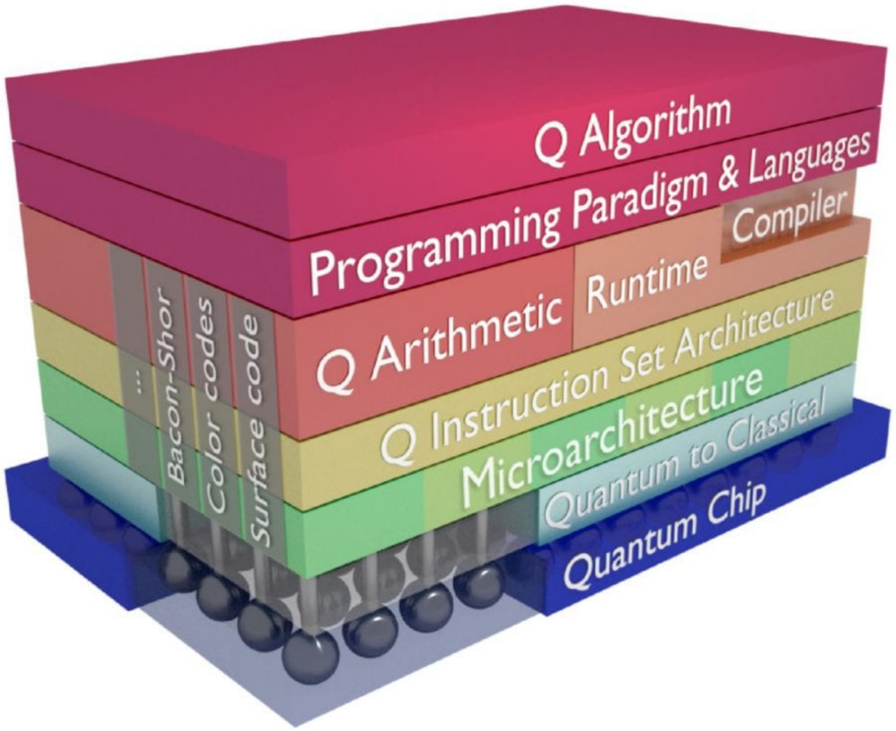


imec

imec
Leuven, Belgium

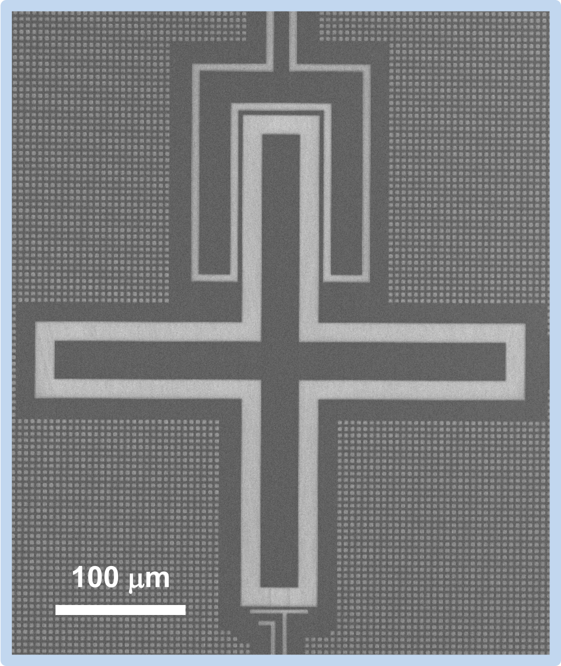
Quantum chip

Stack/Outlook

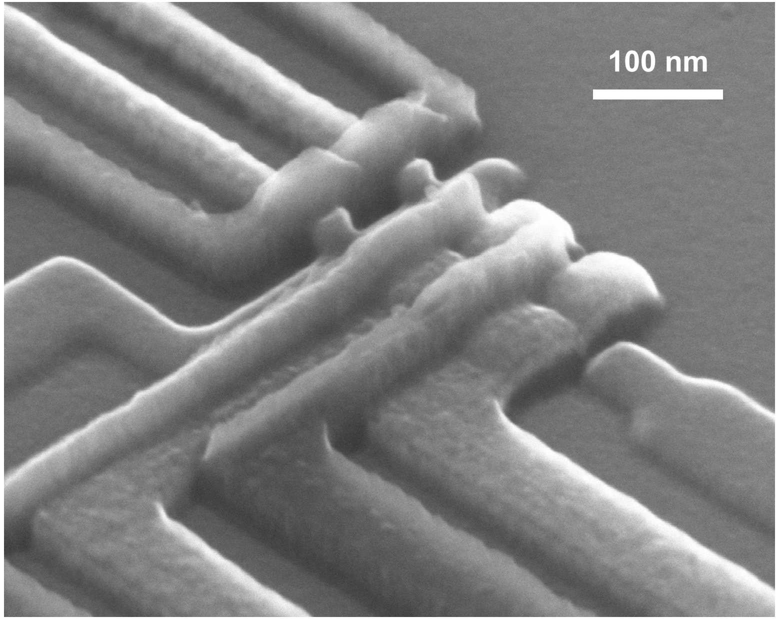


Quantum Chip

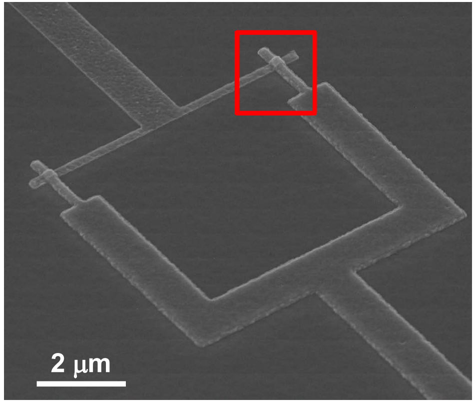
Superconducting qubits

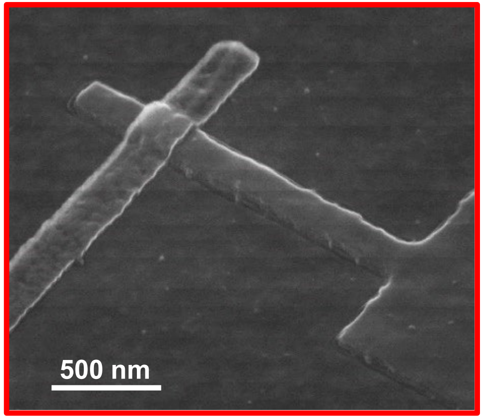


Spin qubits

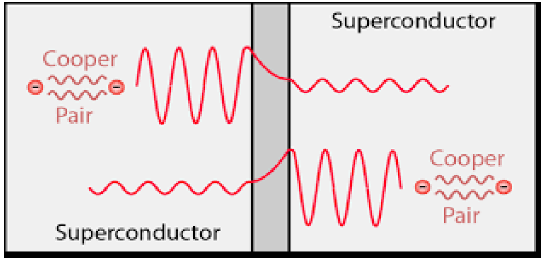


Josephson junction is an S-I-S junction



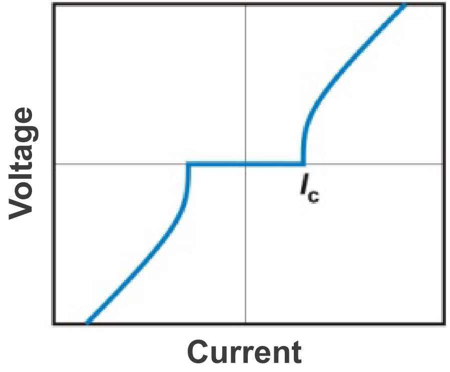


S – I – S



Al	AlO_x	Al
30 nm	1-2 nm	50 nm

Symbol:



Josephson equations:

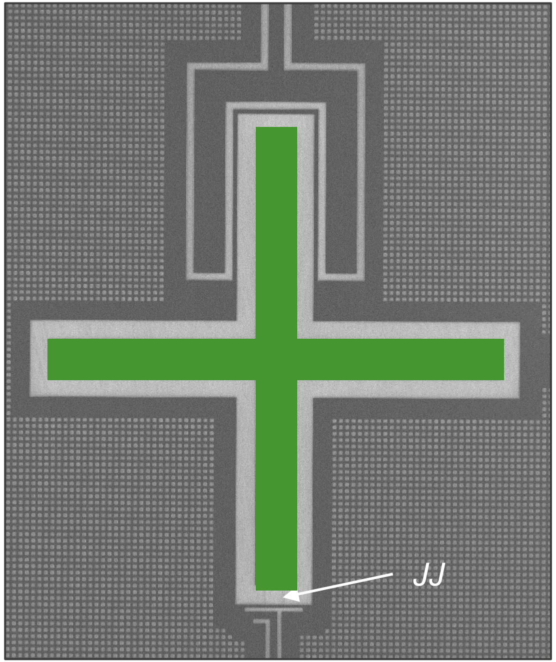
$$I(t) = I_c \sin(\varphi(t))$$

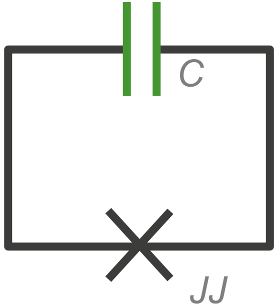
$$\frac{\partial \varphi}{\partial t} = \frac{2eV(t)}{\hbar}$$

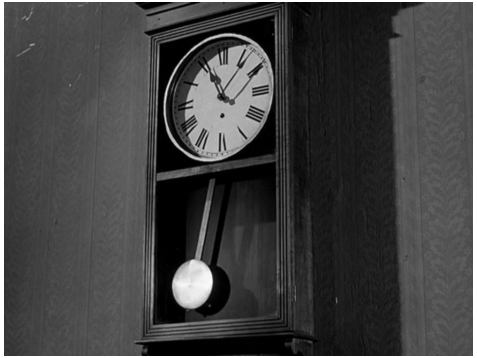
Josephson Energy:

$$H = E_J \sin(\varphi)$$

Qubit is a nonlinear oscillator



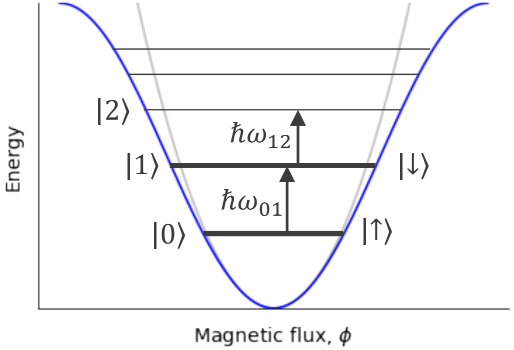




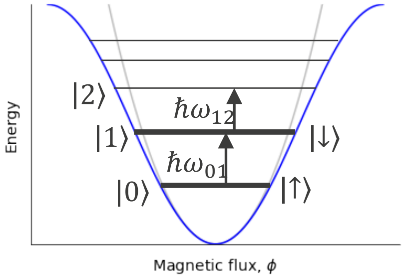
$$H = \frac{1}{2} C \dot{\varphi}^2 + E_J \sin(\varphi)$$

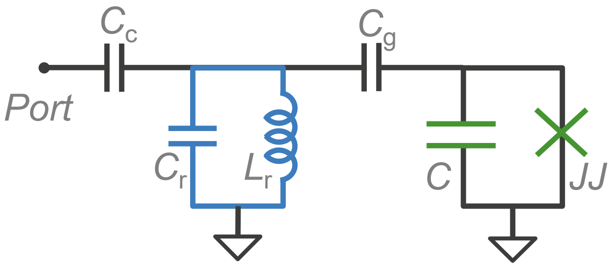
$$H \approx \hbar\omega_q a^\dagger a + K\, a^\dagger a^\dagger a a$$

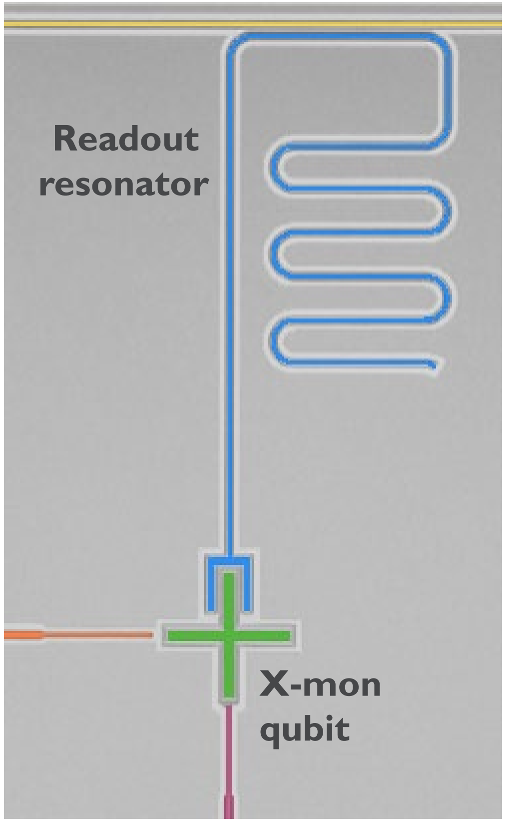
$$H \approx \hbar\omega_q \sigma_z$$

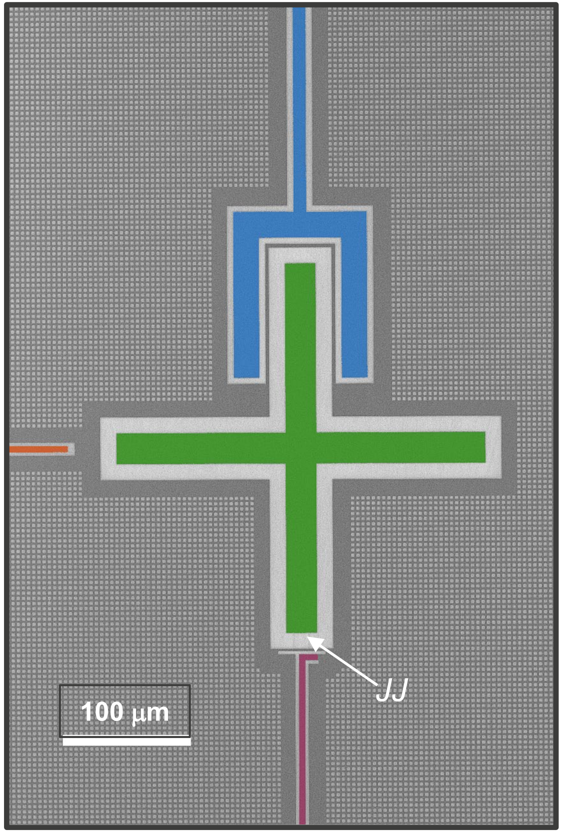


Resonator used for readout and protection







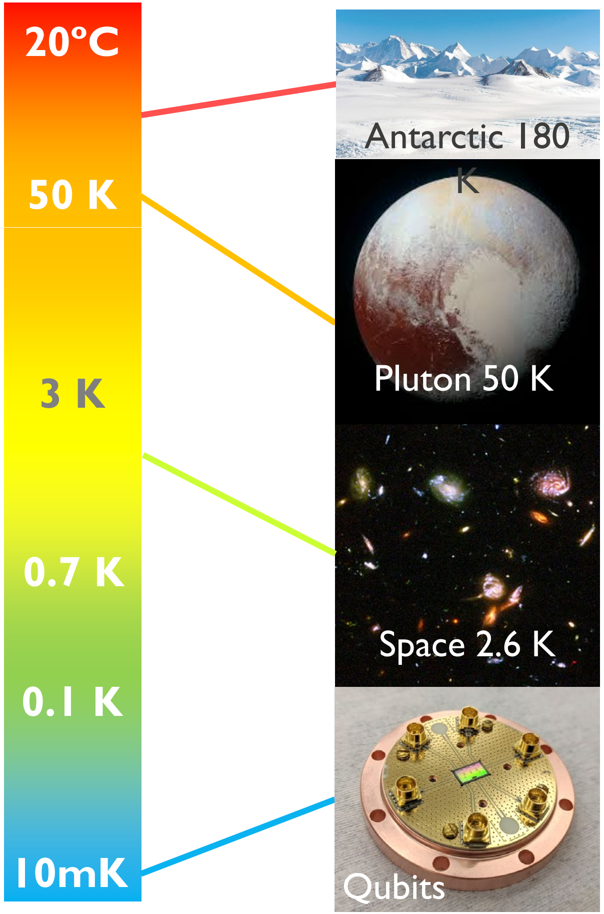


1. Protection against environment
2. Readout: $\nu_r = \nu_{r0} + \chi\langle\sigma_z\rangle$

Periphery

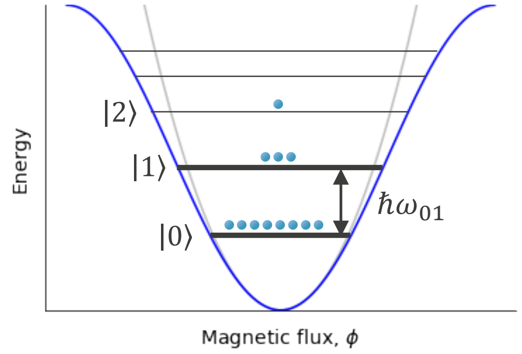
He3/He4 REFRIGERATOR

Control Unit, Gas Handling System, and cryostat in mounting frame.

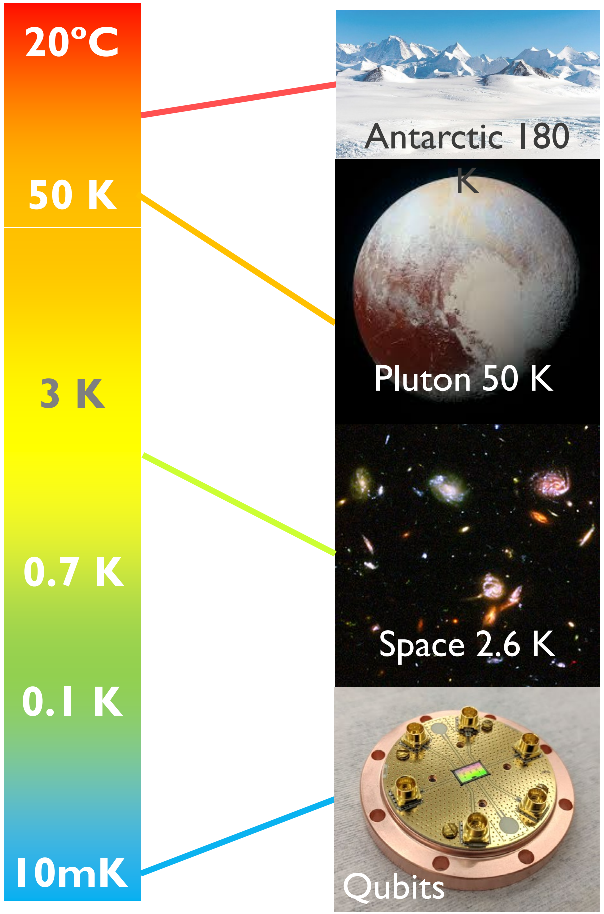


SC Qubits operate at 10 mK

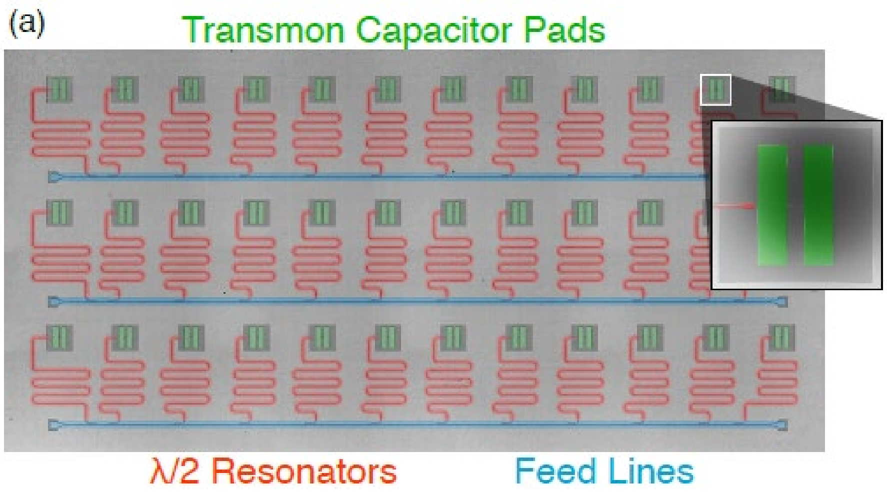
TO MINIMIZE THERMAL EXCITATIONS

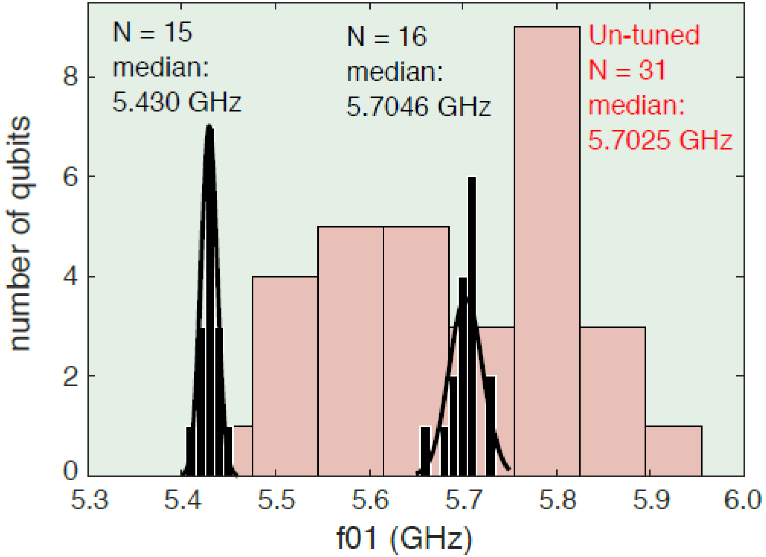


$$\hbar\omega_{01} \approx 6\ \text{GHz}$$
$$\approx 0.3\ \text{K}$$
$$\boldsymbol{T \ll 0.3\ \text{K}}$$



Qubit frequency crowding is a problem

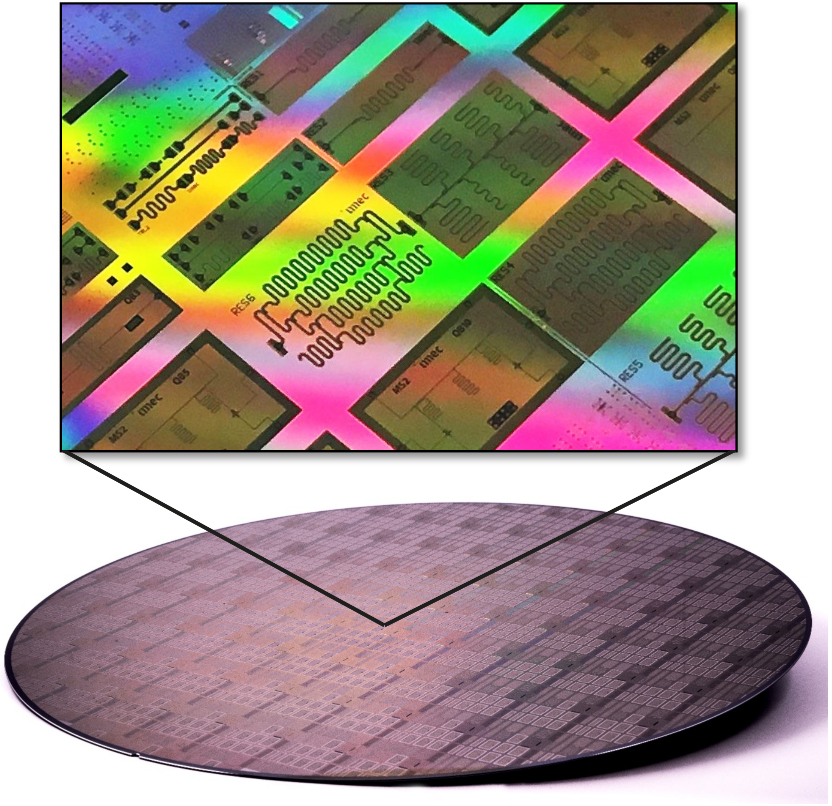


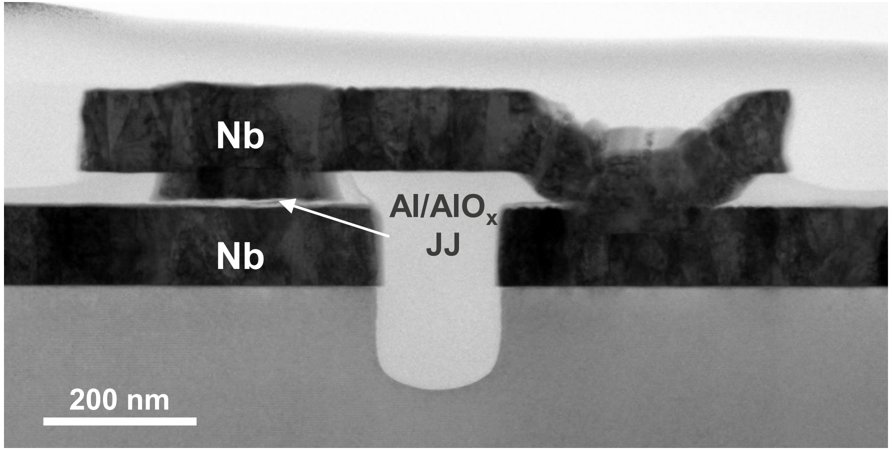


- Bandwidth per qubit: ~300 MHz
- Qubit frequency spread: ~500 MHz (~10%)

Hertzberg *et al.* arXiv 2009.00781v4 (2020).

Shadow evaporation vs Trilayer JJ



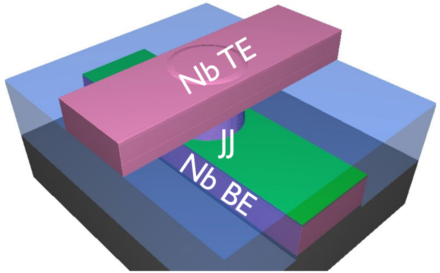


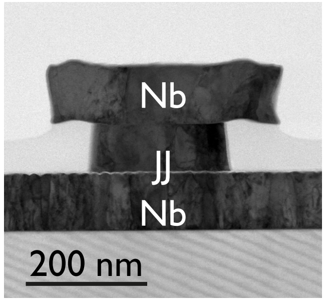
	Shadow ev.	Trilayer
Wafer size	< 200 mm	300 mm
Technology	E-beam	optical
Environment	Laboratory	Industrial
JJ variability	4-10%	~1%*

* Other developed junctions at imec

Room temperature trilayer junction testing

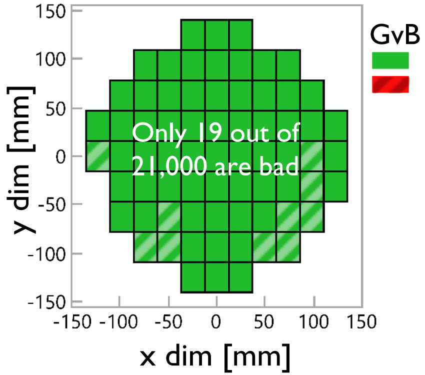
Junction resistance



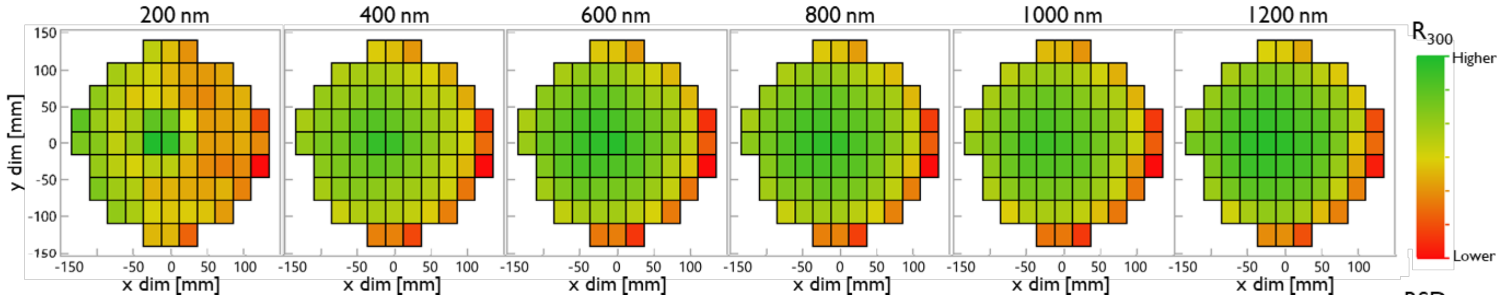


21,000 junctions tested

Junction yield map



Ambegaokar-Baratoff relation: $R_{300K} \propto \sqrt{f_{01}}$

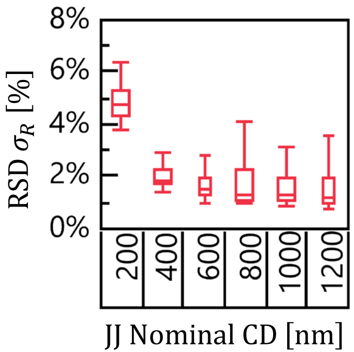


300mm wafer results: high JJ yield > 99.9%

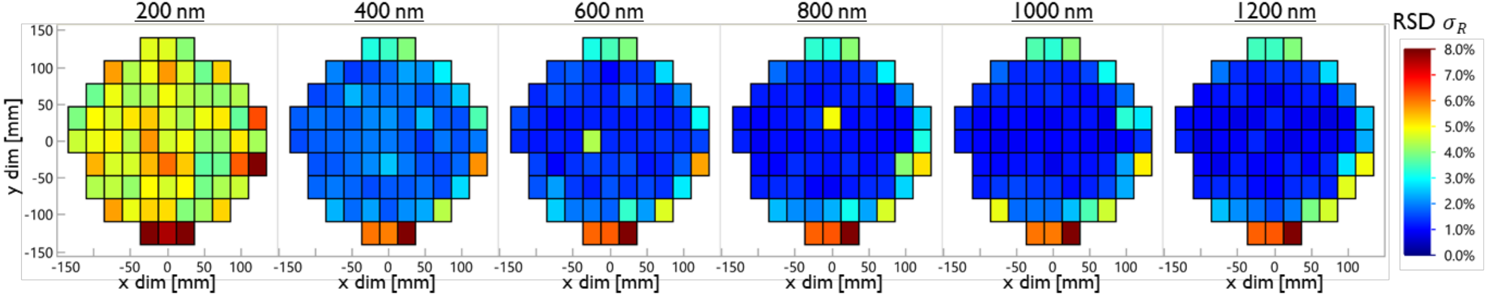
Wan, AP *et al.* JJAP 60 SBBI04 (2021).

Variability in Junction resistance

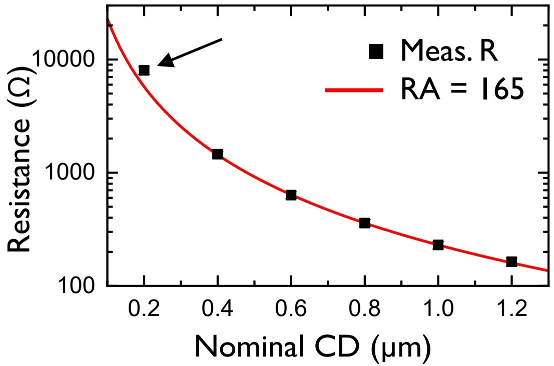
Junction RSD



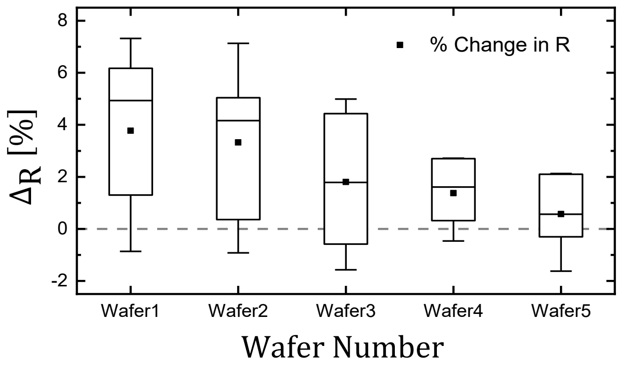
Junction RSD map



Resistance vs nominal CD for RA 165



Resistance stability over 2 months

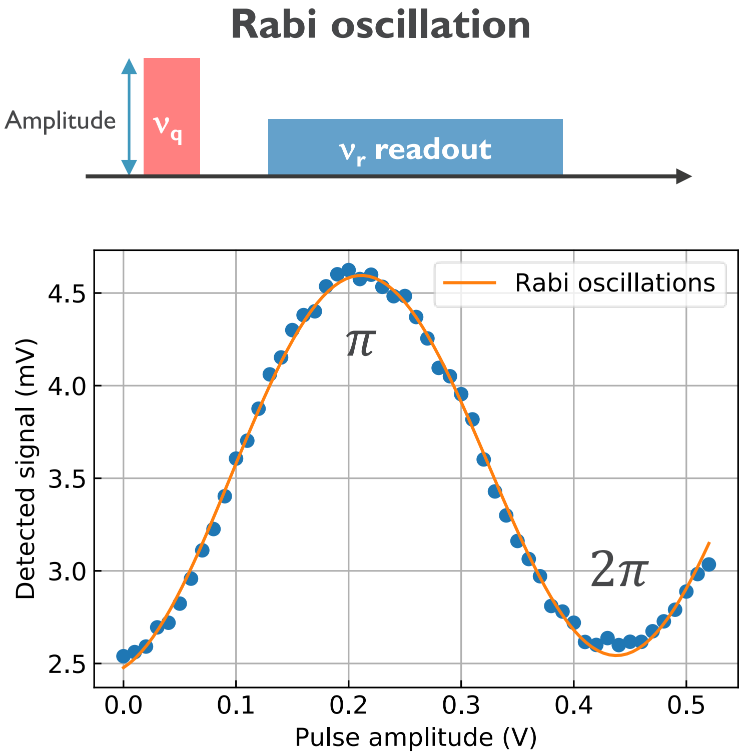


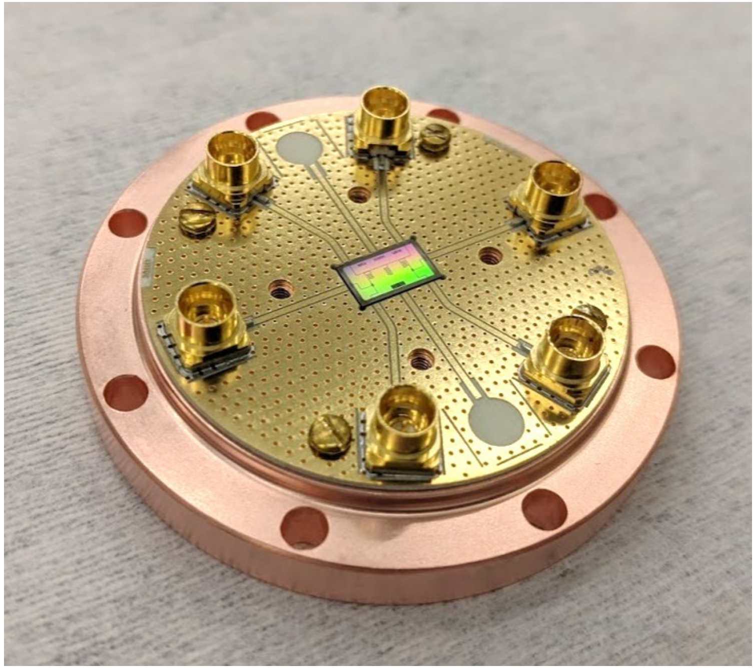
Very low resistance variability <1% measured for single JJs. Smaller CDs perform worse. Resistance is stable and does not change much over time.

Wan, AP *et al.* JJAP 60 SBBI04 (2021).

First 300mm integrated qubit at imec

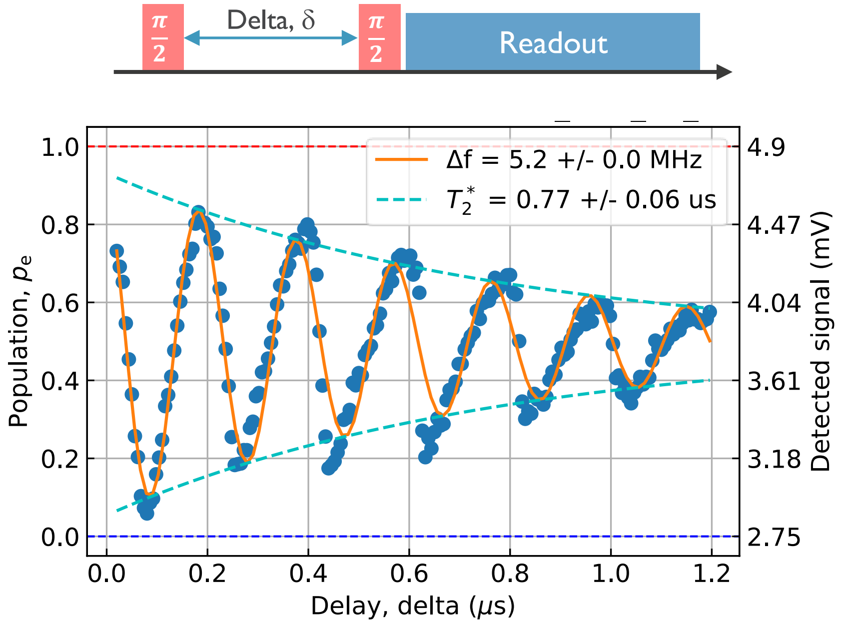
Rabi oscillations: qubit is alive



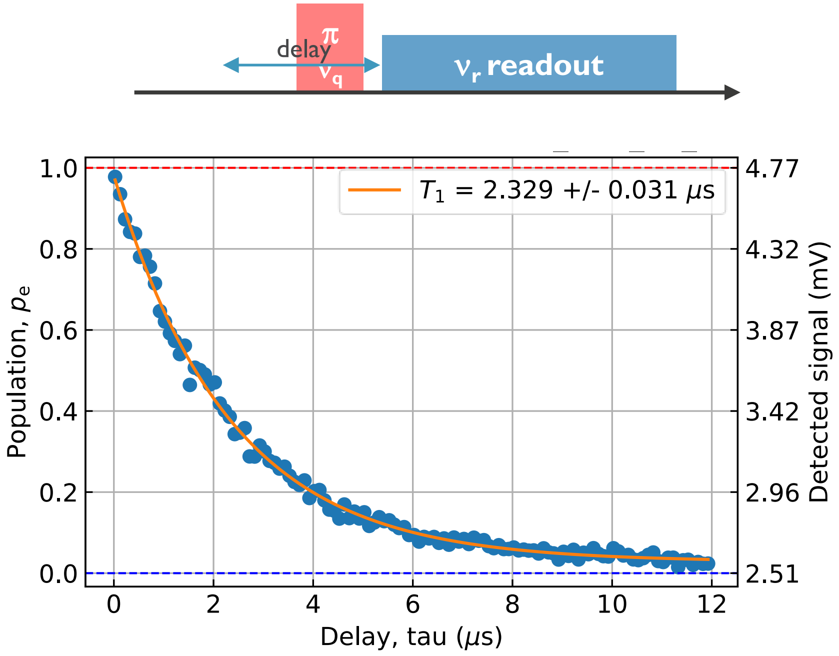


300 mm integrated Transmon qubit

Ramsey, T_2^*

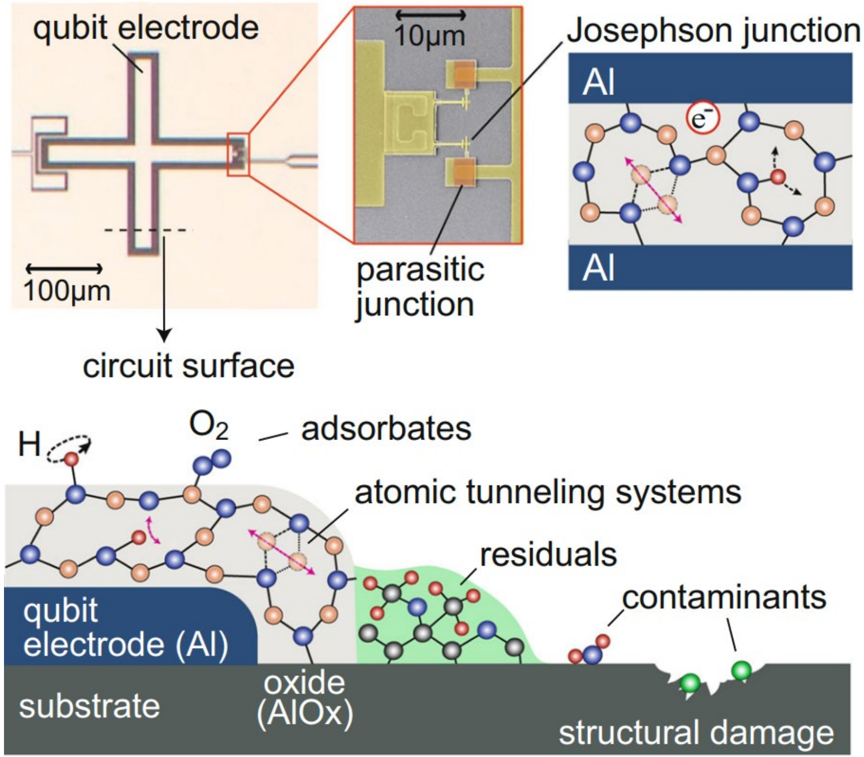


T_1 measurement



Verjauw, AP *et al.* in preparation.

Microwave losses and decoherence

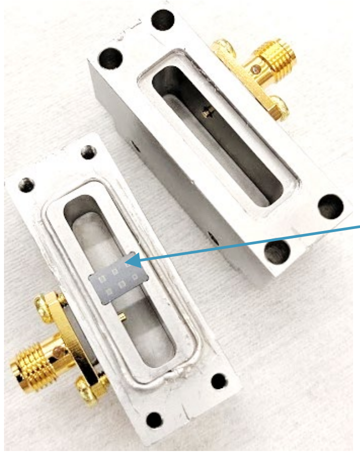


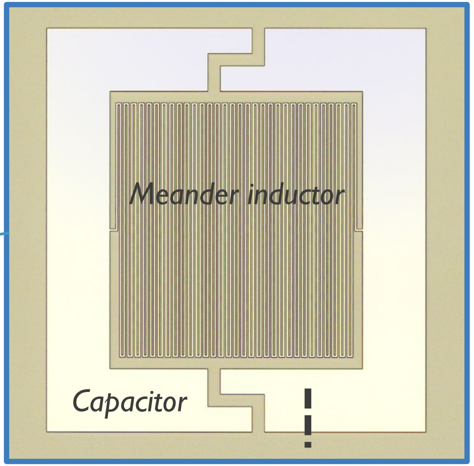
Lisenfeld, *et al.* Npj Quantum Inf. 5, 105 (2019).
Müller *et al.* Rep. Prog. Phys. 82 124501 (2019).

- TLS found in amorphous interfaces are main source of dielectric loss
- Visible <100 mK and low MW powers
- >60% of loss in the capacitor

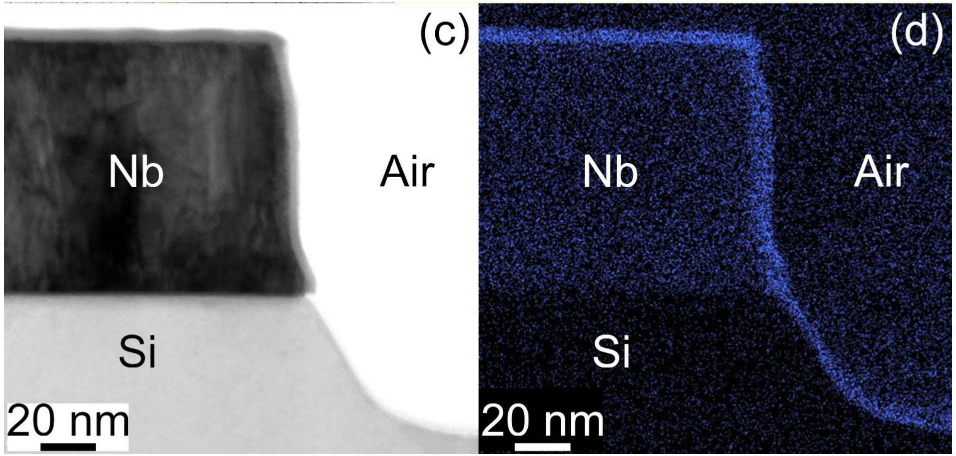
- Search for materials with lowest TLS loss tangent.
- Search for new deposition conditions

Short loop study: LE resonators





TEM & EDS

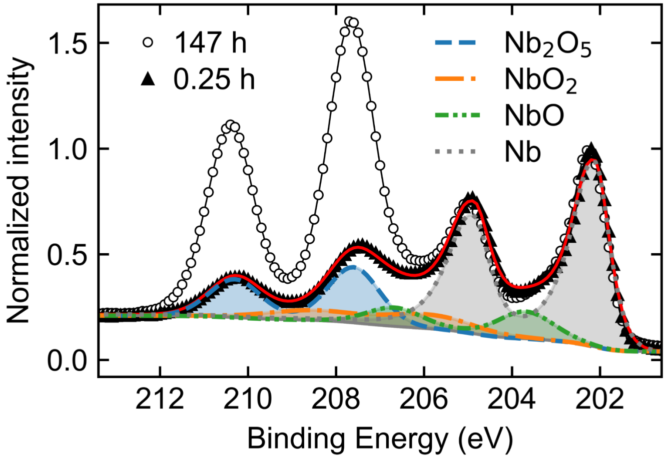


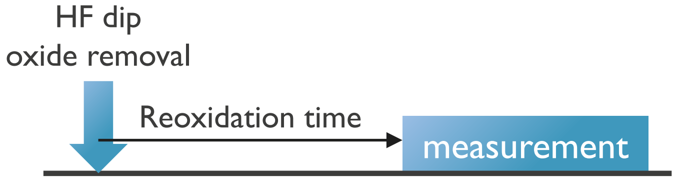
- Fast sample exchange (No wire-bonding)
- Good EM environment
- Perfect superconducting magnetic shielding

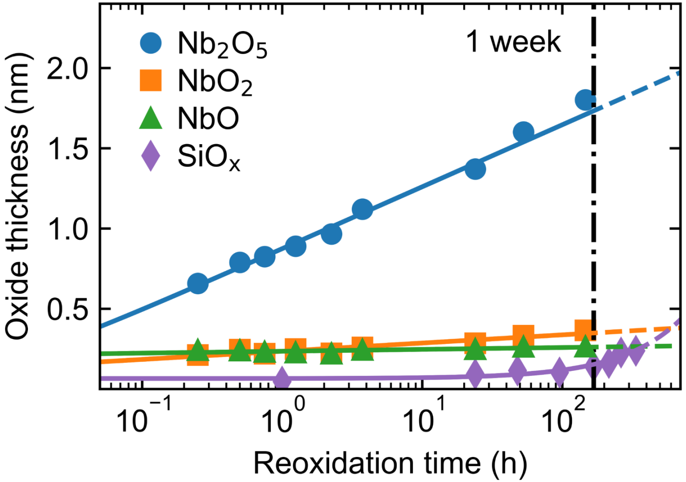
- Oxides at the air interface
- No oxide at the Substrate-Metal interface

Verjauw, AP, *et. al* arXiv 2012.10761 (2020).

Angle resolved X-ray photoelectron spectroscopy (ARXPS)



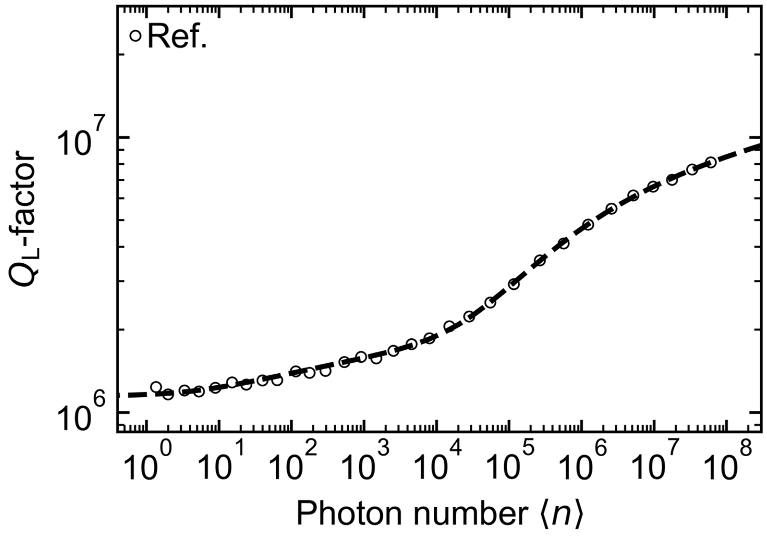


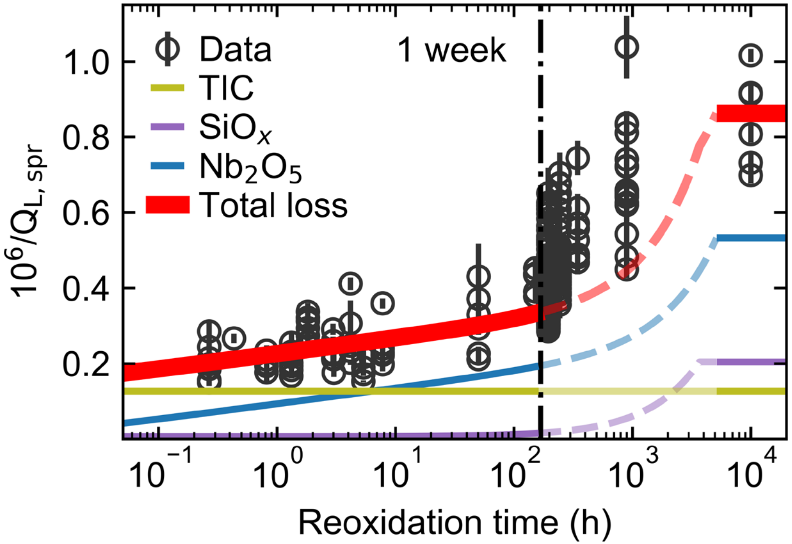


- Surfaces contain NbO_x and SiO_x
- HF dip removes surface oxides and protects Si from oxidation for cca 1 week.
- Nb_2O_5 growth: extended Cambrera-Mott model

Verjauw, AP, *et. al* arXiv 2012.10761 (2020).

Microwave TLS loss



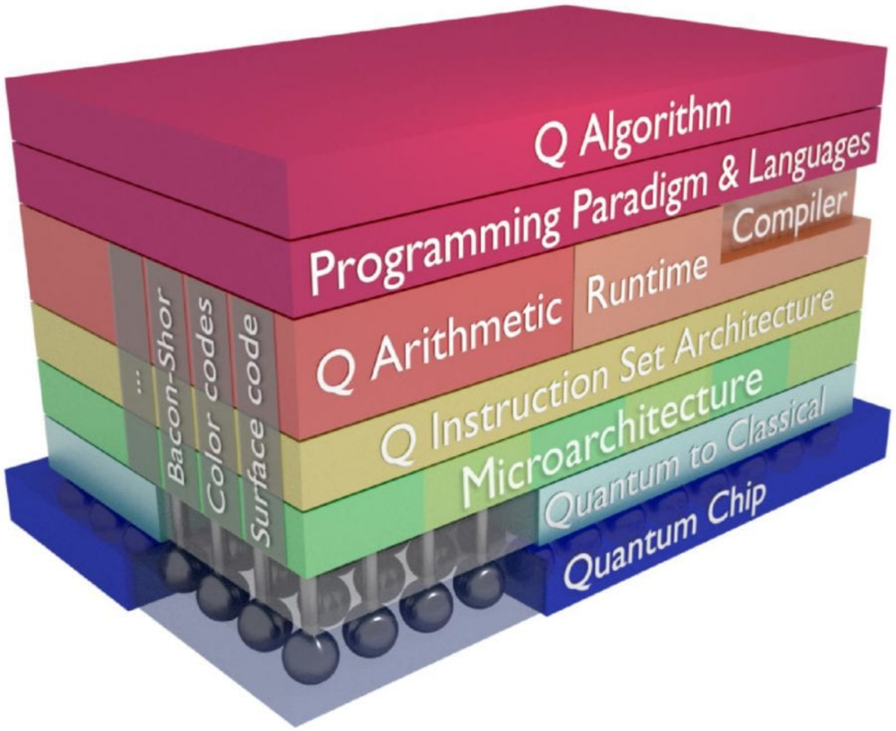


$$\frac{1}{Q_\mathrm{L}} \approx \frac{1}{Q_\mathrm{i}} = \sum_{i=1}^{2} \frac{F_i \tan\delta_i}{\left(1 + \frac{\langle n \rangle}{n_{\mathrm{c},i}}\right)^{\beta_i}} + \frac{1}{Q_\mathrm{r}},$$

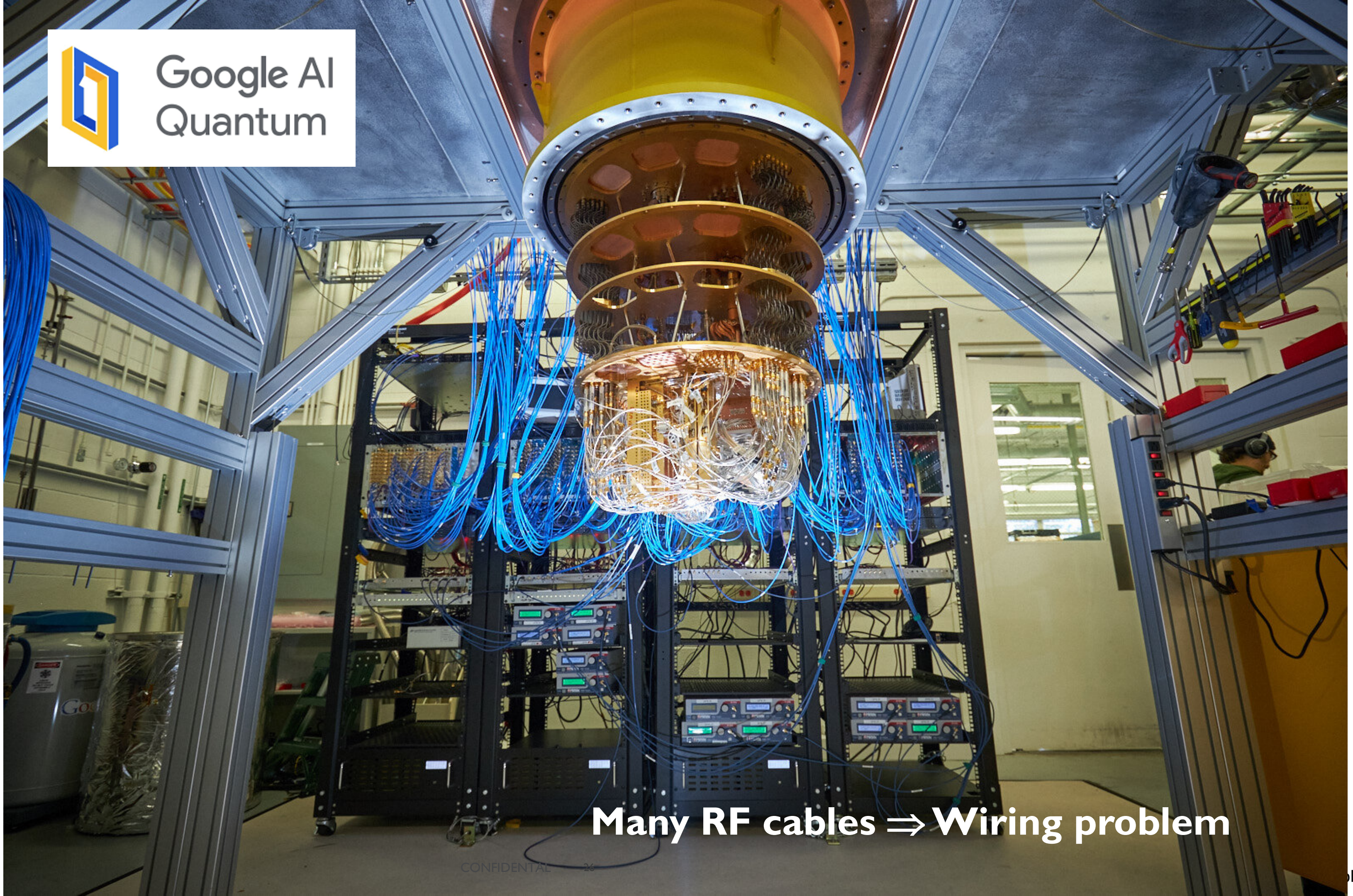
Ref. sample	Loss rate	Percentage
NbO_x	$5.3 \cdot 10^{-7}$	62%
SiO_x	$2.0 \cdot 10^{-7}$	24%
Si and M-S	$1.2 \cdot 10^{-7}$	14%

Verjauw, AP, *et. al* arXiv 2012.10761 (2020).

Stack/Outlook

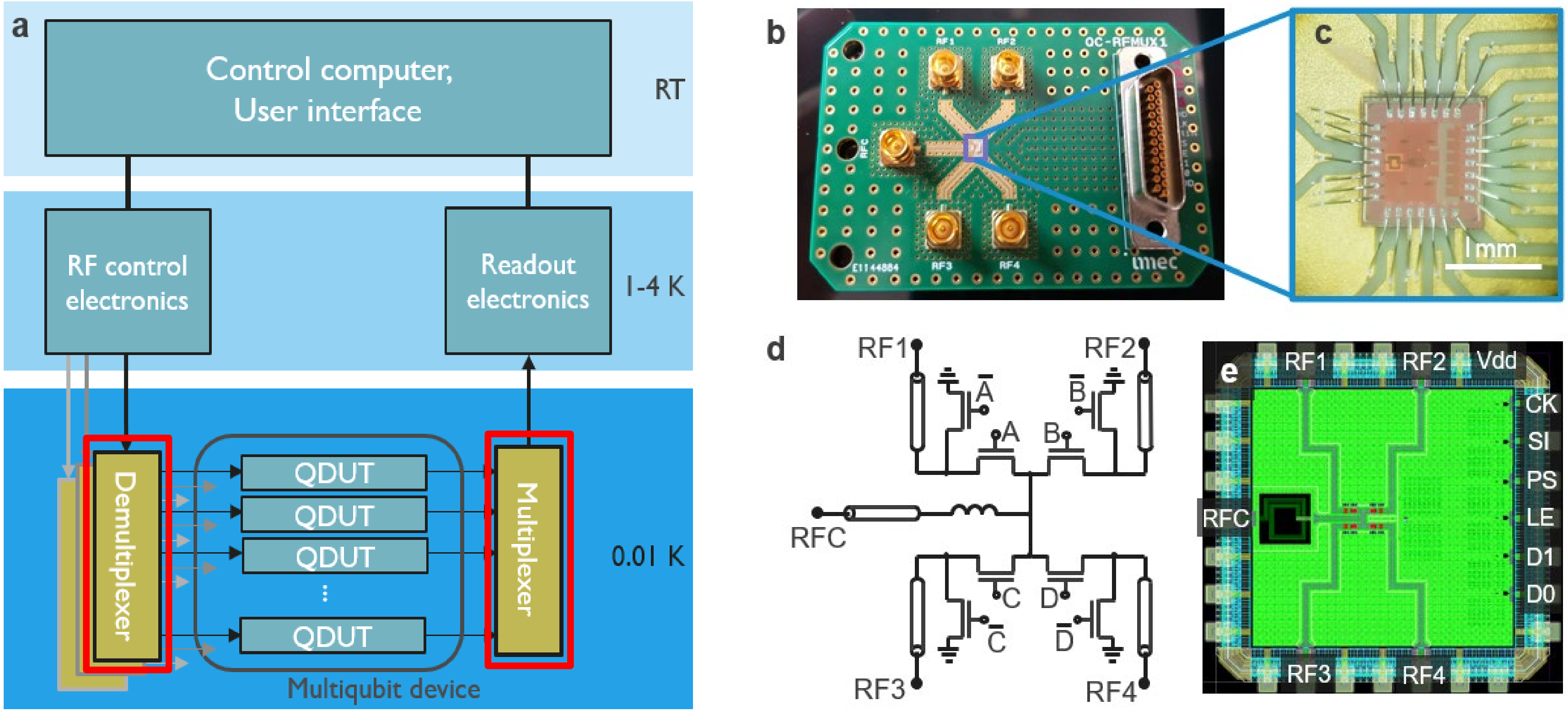


Quantum to Classical



Many RF cables ⇒ Wiring problem

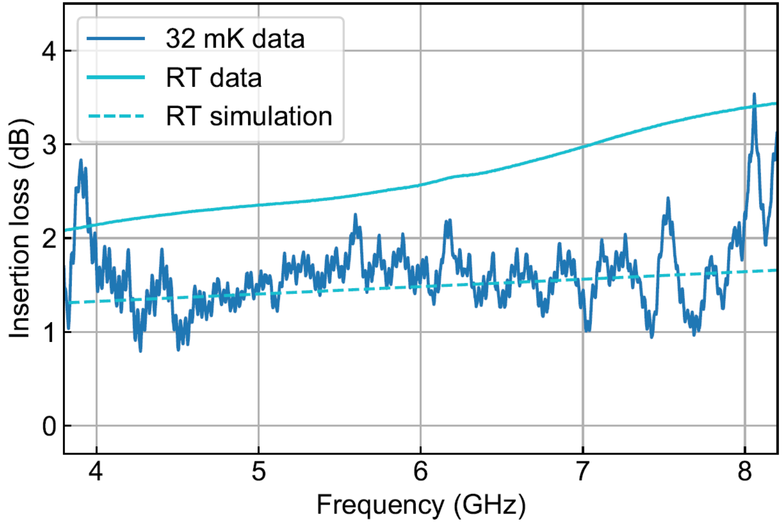
Custom designed Cryo-CMOS multiplexer



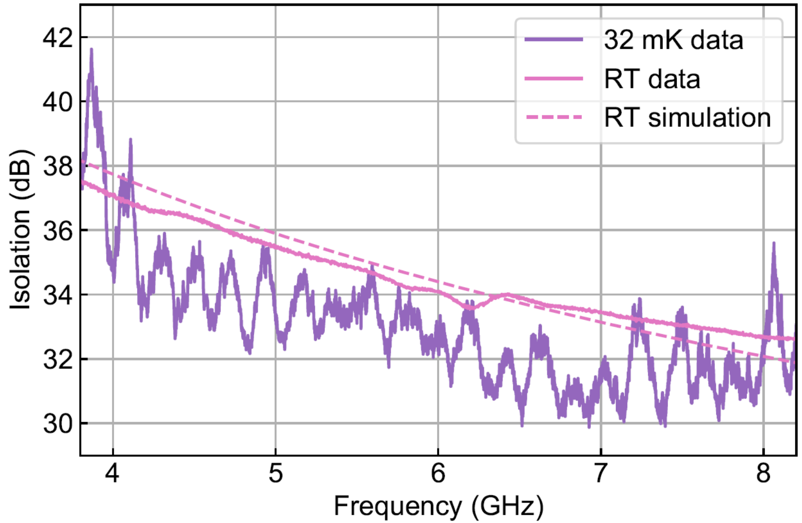
A. Potočnik, S. Brebels, *et. al* arXiv 2011.11514 (2020).

RF PERFORMANCE

Insertion loss (dB)



Isolation (dB)

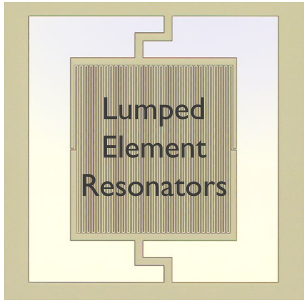


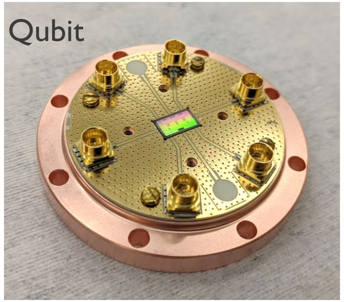
- Operating temperature: 32 mK
- Unprecedented RF performance
- DC – 10 GHz bandwidth

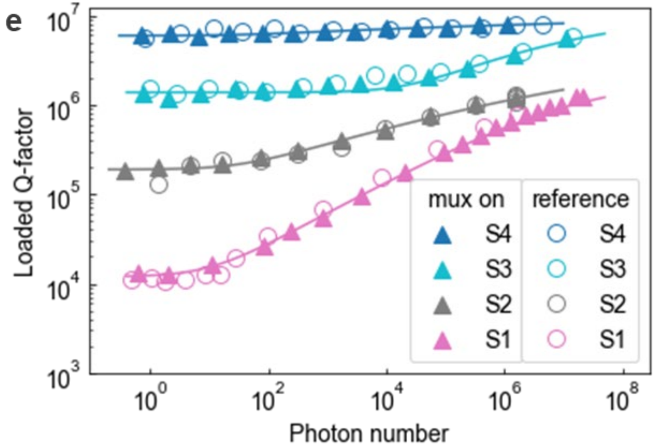
- 1-2 dB insertion loss
- 30-40 dB isolation

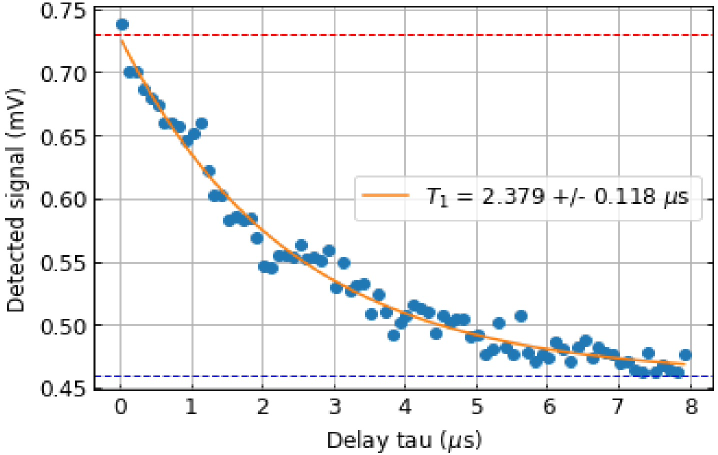
A. Potočnik, S. Brebels, *et. al* arXiv 2011.11514 (2020).

Cryo-CMOS Mux Increases Measurement thruput



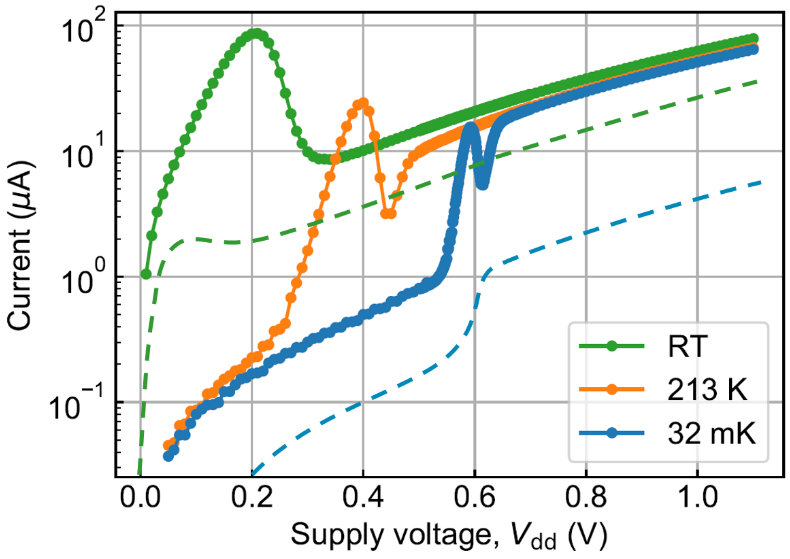


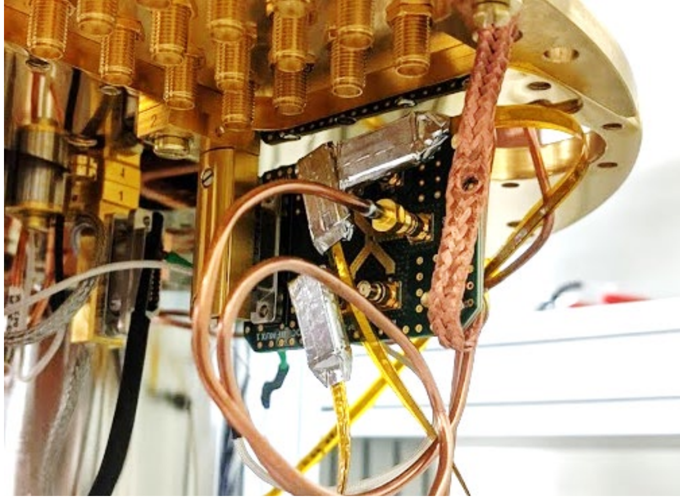




A. Potočnik, S. Brebels, *et. al* arXiv 2011.11514 (2020).

Residual power dissipation could be reduced



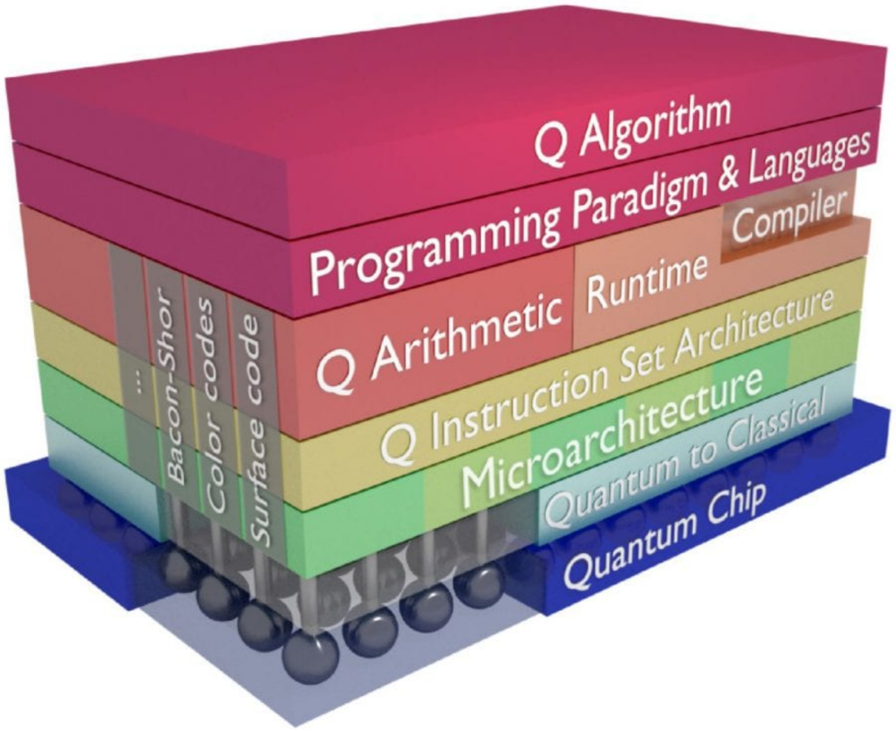


Improved design:
~1 μW dissipation
at 10 mK.

- 36 μW dissipation at 32 mK
  order of magnitude higher than expected
- Dissipation is static,
  leakage in ESD protection
- Resonator thermal population cca. 2 photons
  Not appropriate for qubit control

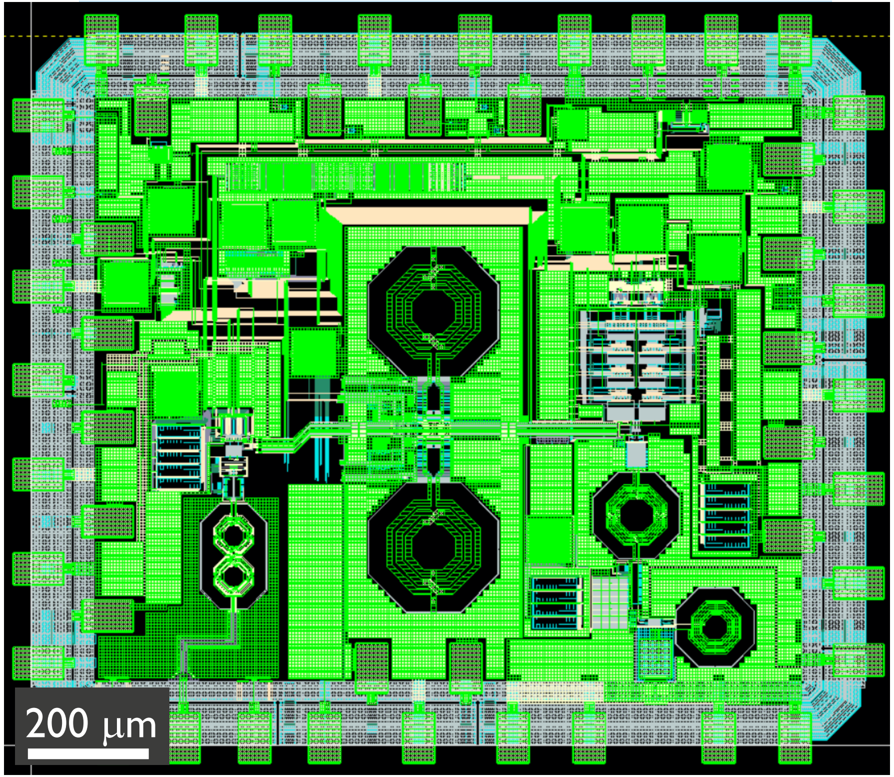
A. Potočnik, S. Brebels, *et. al* arXiv 2011.11514 (2020).

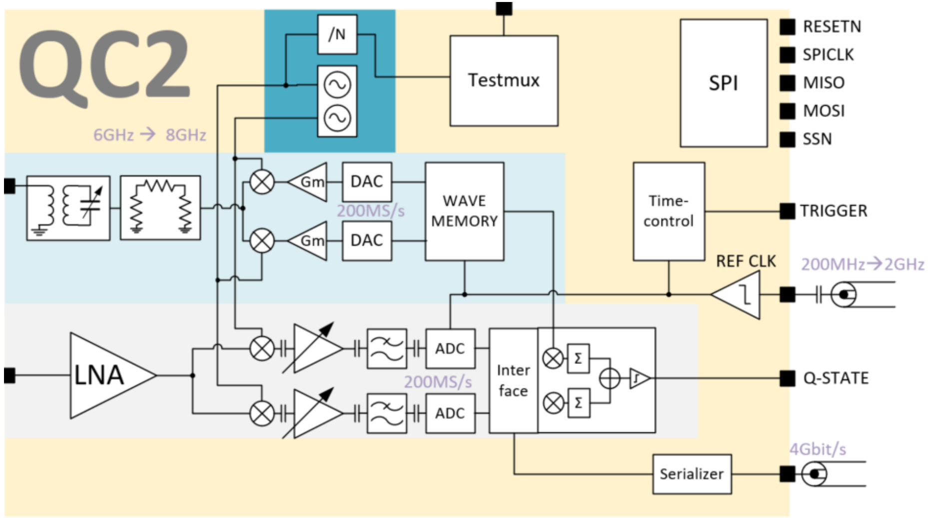
Stack/Outlook



Microarchitecture

Custom designed Cryo-CMOS control and readout

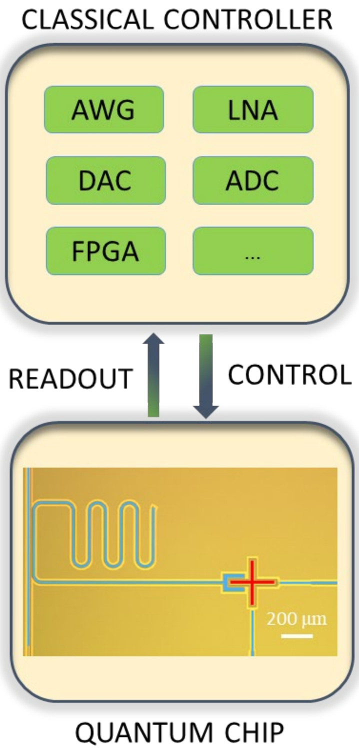




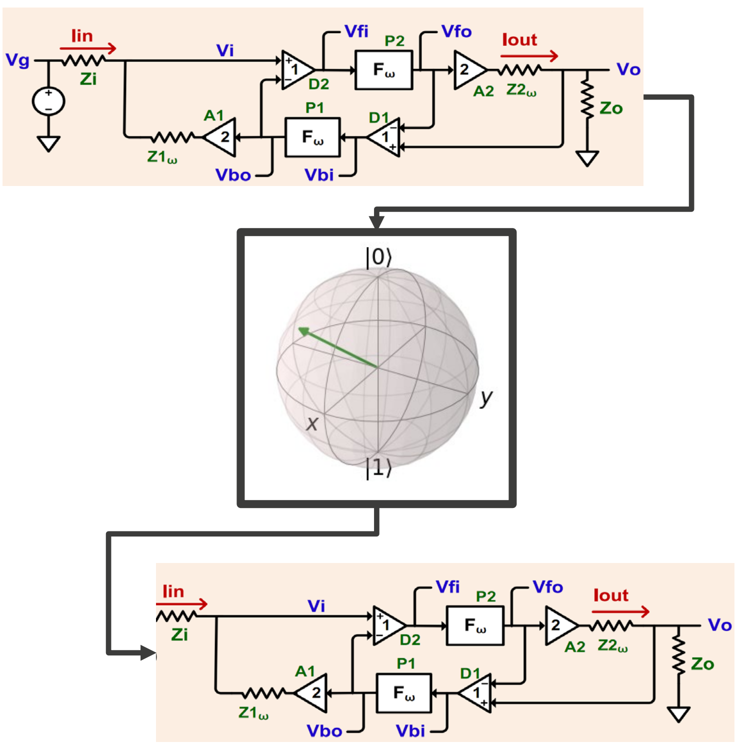
- Lower power consumption per qubit
- Lower latency
- Smaller footprint

J. Craninckx AP et al IEDM (2020)., S. Van Winkel, AP et al. *in preparation*

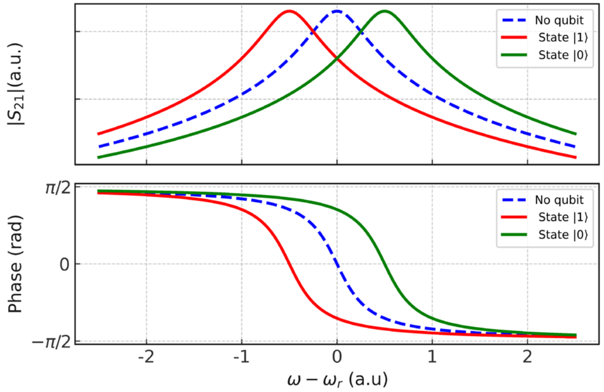
Full qubit compact model



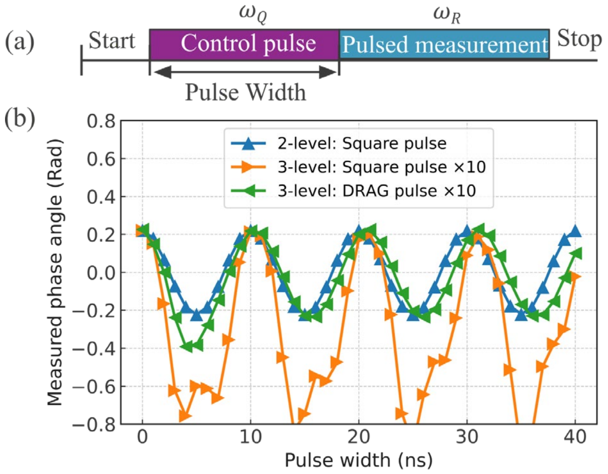
SPICE simulator



Read out

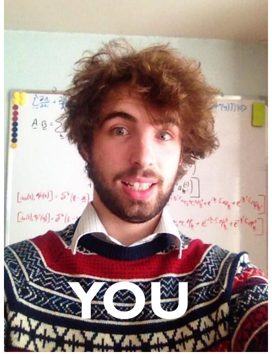


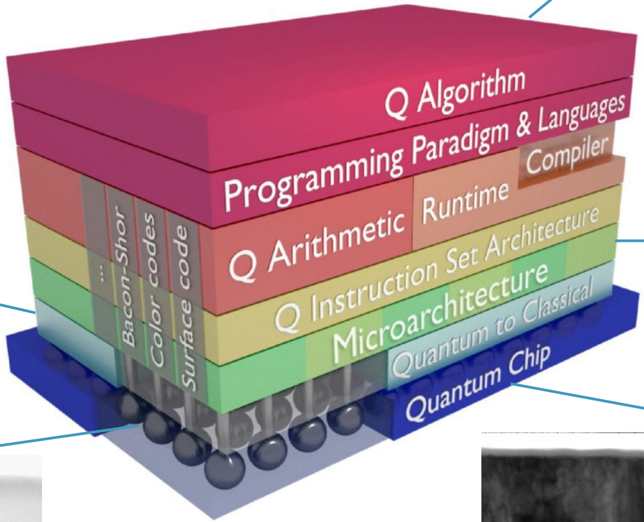
Rabi oscillations

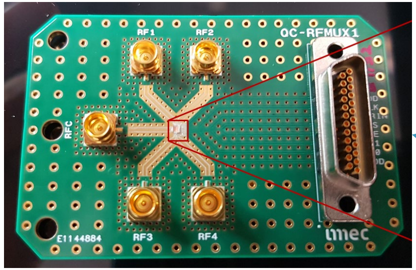


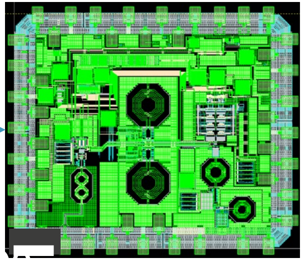
R. Acharya, AP et al. *DATE 2021*.

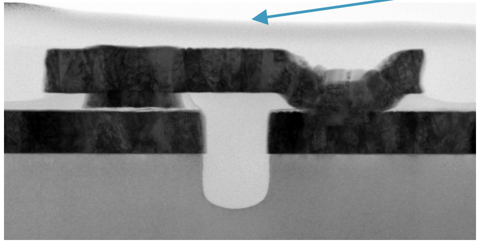
Recap

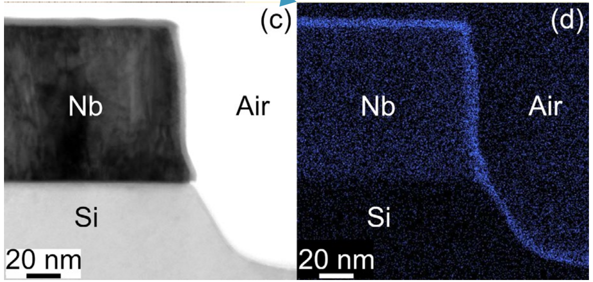

YOU


Q Algorithm
Programming Paradigm & Languages
Compiler
Runtime
Q Arithmetic
Q Instruction Set Architecture
Microarchitecture
Quantum to Classical
Quantum Chip
Bacon-Shor
Color codes
Surface code


QC-RFMUX1
RF1
RF2
RF3
RF4
RFC
E1144884
imec






(c)
Nb
Air
Si
20 nm
(d)
Nb
Air
Si
20 nm

Acknowledgments

- imec's scientific and technical support Staff, especially
  - R. Li, S. Kubicek, N. Dumoulin-Stuyck, A. Elsayed, M. Shehata, M. Mongillo, D. Wan, Ts. Ivanov, J. Verjauw, R. Acharya, F.A. Mohiyaddin, G. Simion, S. Narasimhamoorthy, A. Grill, B. Govoreanu, I. Radu (***QC Program***)
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- imec's Management

- imec's Quantum Computing Program Partners

- External academic research groups, especially
  - EPFL Lausanne (A. Beckers, Group C Enz)

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