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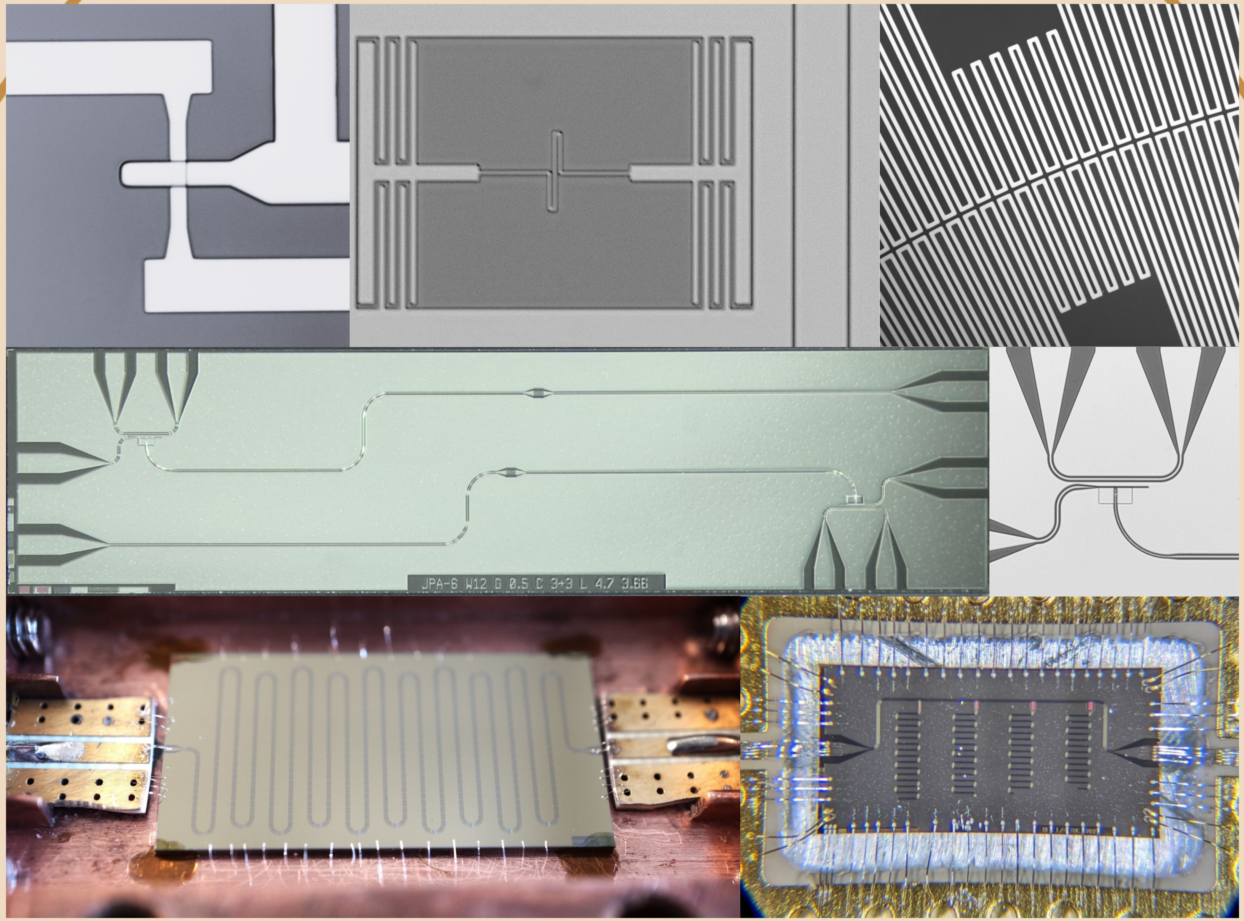
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
NQSTI National Quantum Science and Technology Institute

From **single** ***superconducting components*** to **integrated** ***qubit circuits***:

Vertical **Josephson junctions**, low-loss **superconducting resonators** and **high-kinetic inductance** films



Felix Klaus Ahrens

Fondazione Bruno Kessler (Trento)
Centre for Sensors and Devices

fahrens@fbk.eu
www.fbk.eu

FONDAZIONE BRUNO KESSLER SENSORS AND DEVICES

First NQSTI Congress, 15-16 January 2024, Rome

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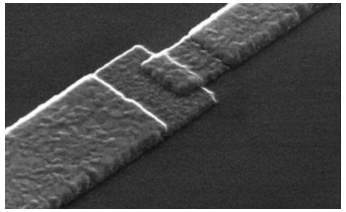
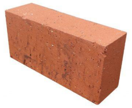
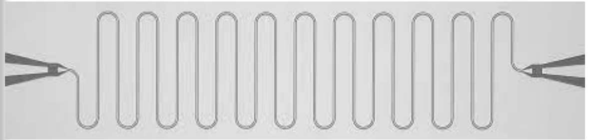
Superconducting electronics - from building blocks to integrated circuits

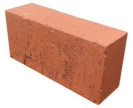
Josephson junctions



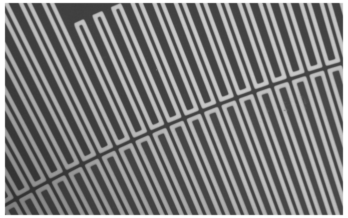


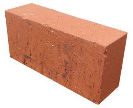
Superconducting resonators





High kinetic inductance films





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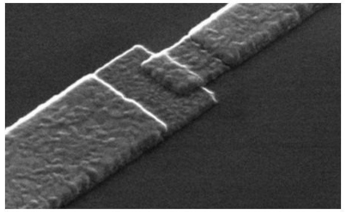
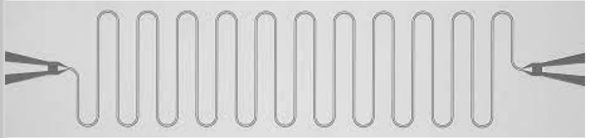
Superconducting electronics - from building blocks to integrated circuits

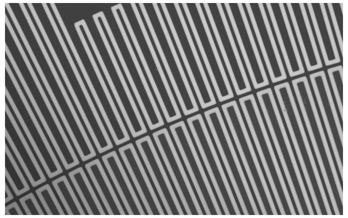
Josephson junctions



Superconducting resonators



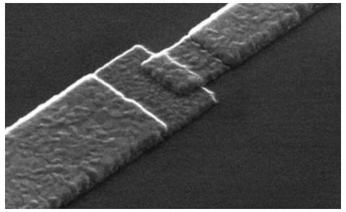
High kinetic inductance films



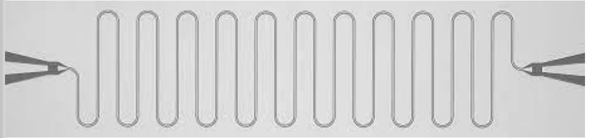
SQUIDs | Parametric Amplifiers | Qubits | Cryogenic detectors | Microwave multiplexers | ...

Superconducting electronics - from building blocks to integrated circuits

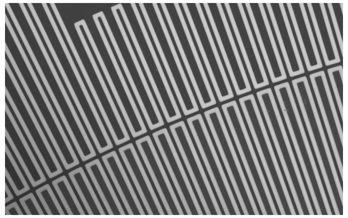
Josephson junctions



Superconducting resonators



High kinetic inductance films



SQUIDs | Parametric Amplifiers | Qubits | Cryogenic detectors | Microwave multiplexers | ...

Multi-qubit systems with read-out limited by quantum noise | Multiplexed read-out of superconducting photon counters | ...

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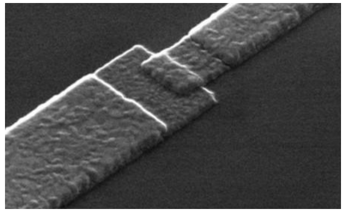

Superconducting resonators

High kinetic inductance films

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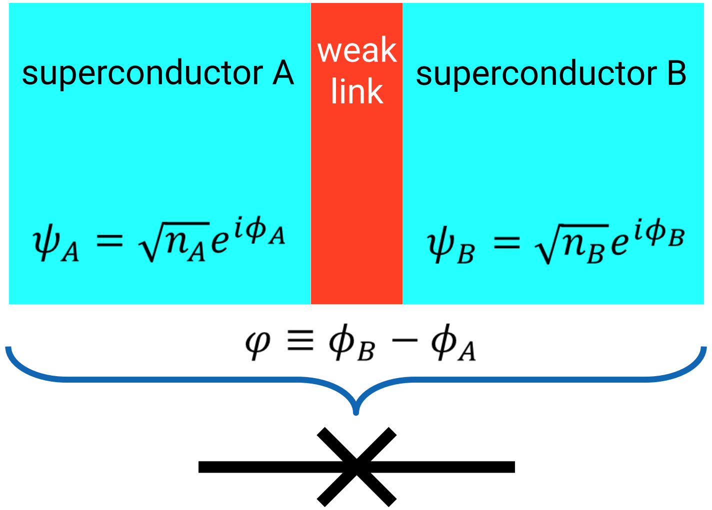
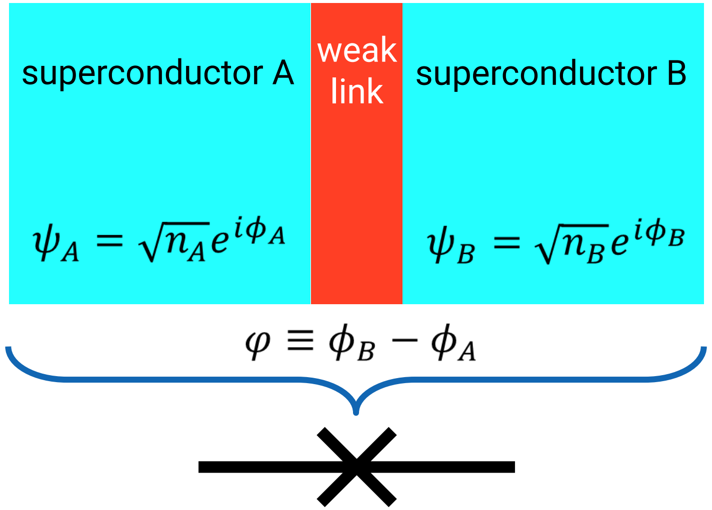
Josephson junctions

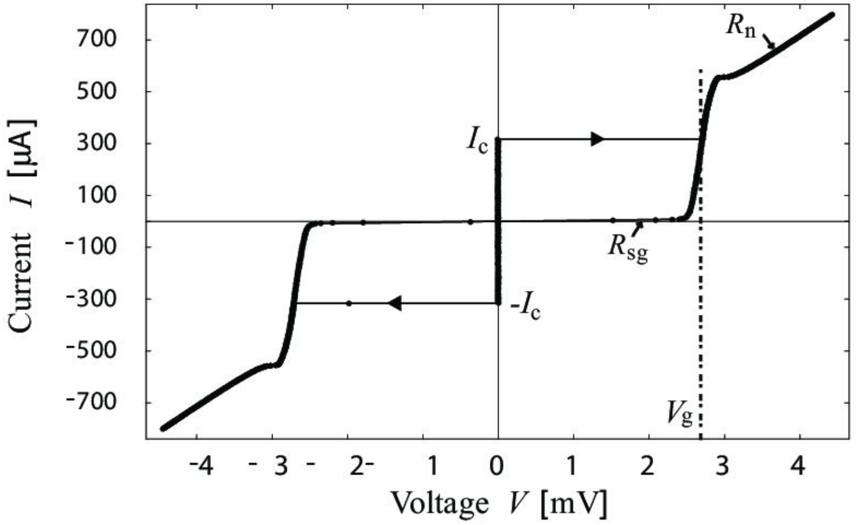


Brian Josephson

Josephson junctions



Brian Josephson



Josephson equations

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

$$\frac{\partial \varphi}{\partial t} = \frac{2e\,V(t)}{\hbar}$$

$$V = \frac{\Phi_0}{2\pi \cdot I_c \cdot cos\varphi} \cdot \frac{dI}{dt} = L_J(\varphi) \cdot \frac{dI}{dt}$$

→ non-linear and tunable inductance

Cross Josephson junctions at FBK

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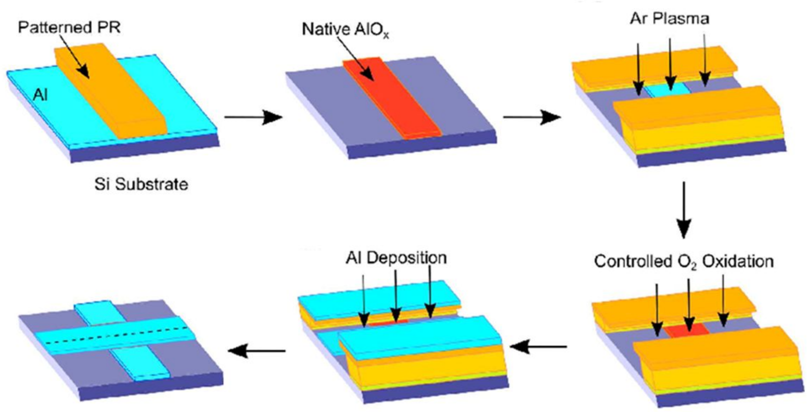
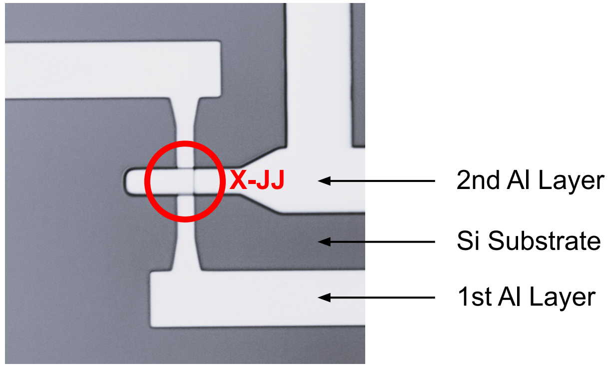




Advantages
- High control on areas (and on junction parameters)
- Two-layers process

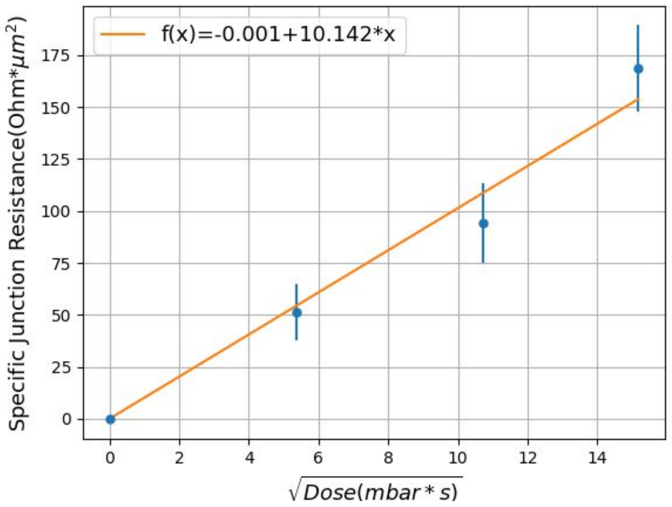
Challenge
- Develop an efficient Ar plasma cleaning
- Optimise the second lithographic step (lift-off)

Cross Josephson junctions at FBK - 1st generation

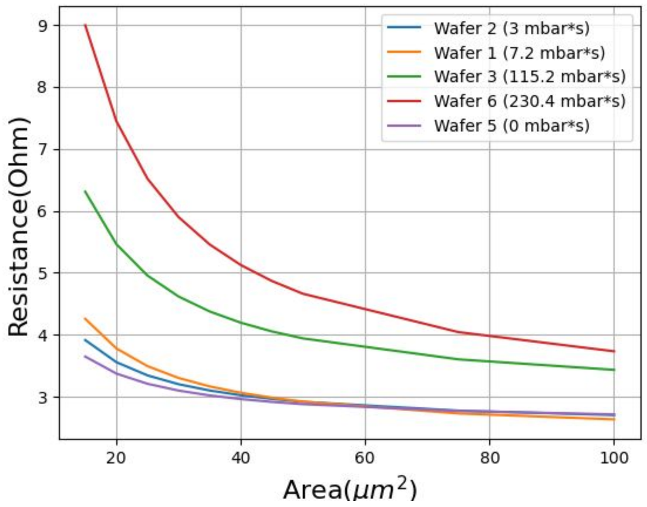
The junction normal resistance R_N is related to the critical current I_c :
$I_c R_N = (\pi/4) \cdot V_g$

Resistance measurements at T = 300 K

Junction resistance vs √oxidation dose

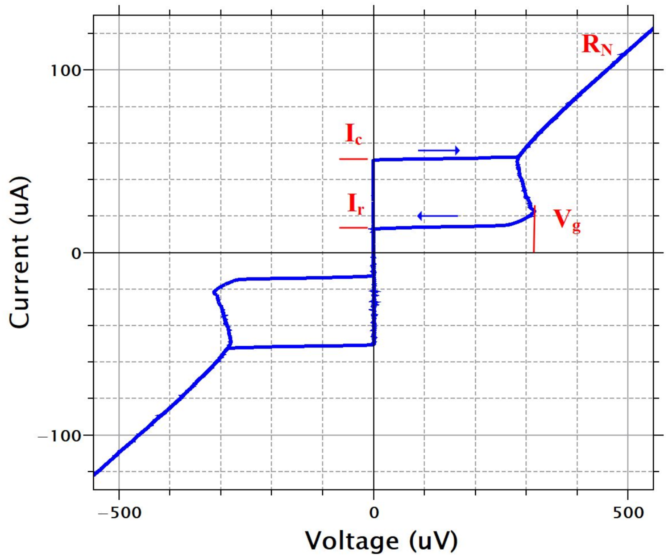


Junction resistance vs junction area (for different oxidation doses)



Cryo measurements at T = 20 mK

IV characteristics



Cross Josephson junctions at FBK - 2nd generation

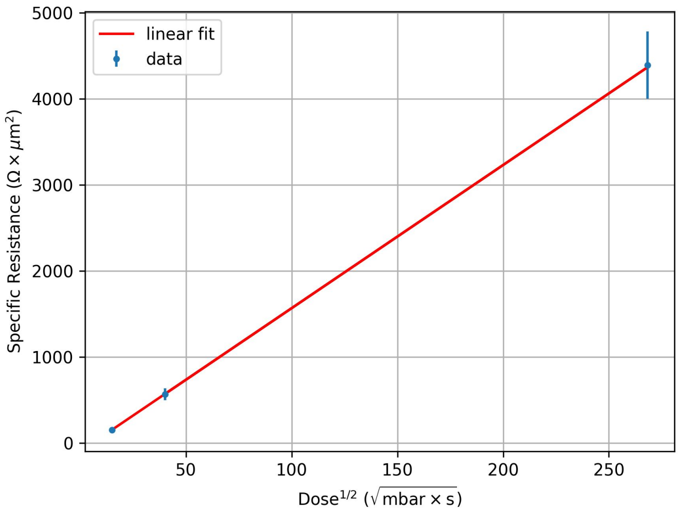
Quantum Science and Technology in Trento

The junction normal resistance R_N is related to the critical current I_c :

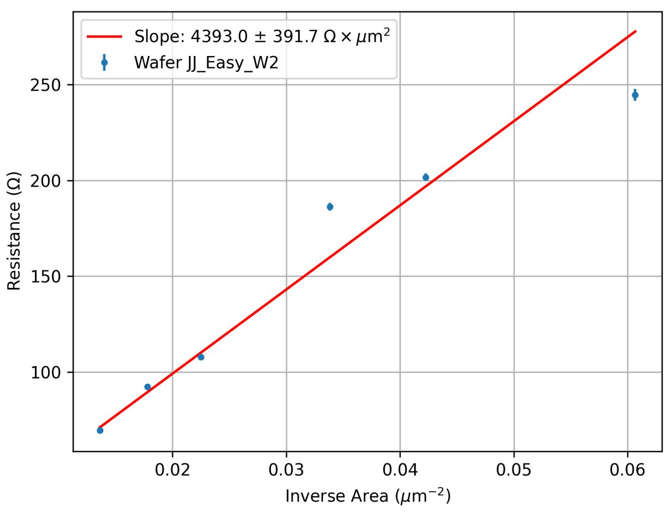
$$I_c R_N = (\pi/4) \cdot V_g$$

Resistance measurements at T = 300 K

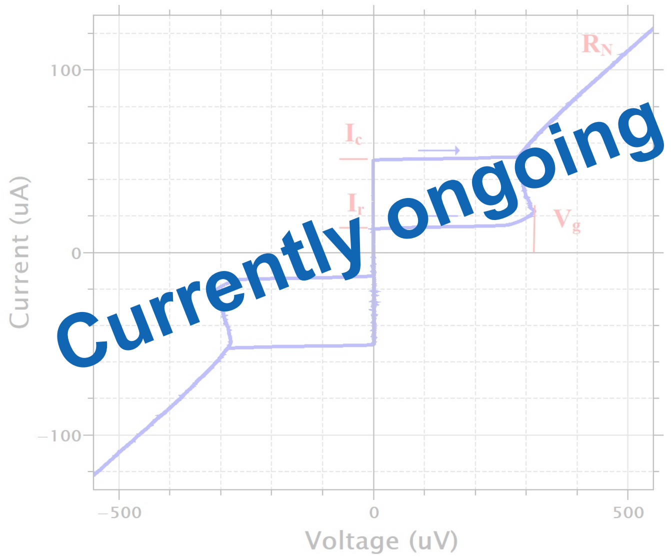
Junction resistance vs √oxidation dose



Junction resistance vs junction area



Cryo measurements at T = 20 mK



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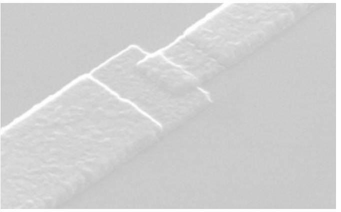
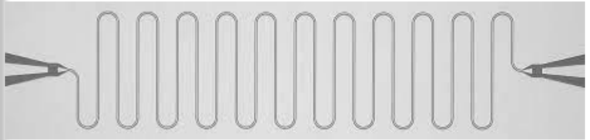
Superconducting electronics - from building blocks to integrated circuits

Josephson junctions



Superconducting resonators



High kinetic inductance films

SQUIDs

Parametric Amplifiers

Qubits

Cryogenic detectors

Microwave multiplexers

...

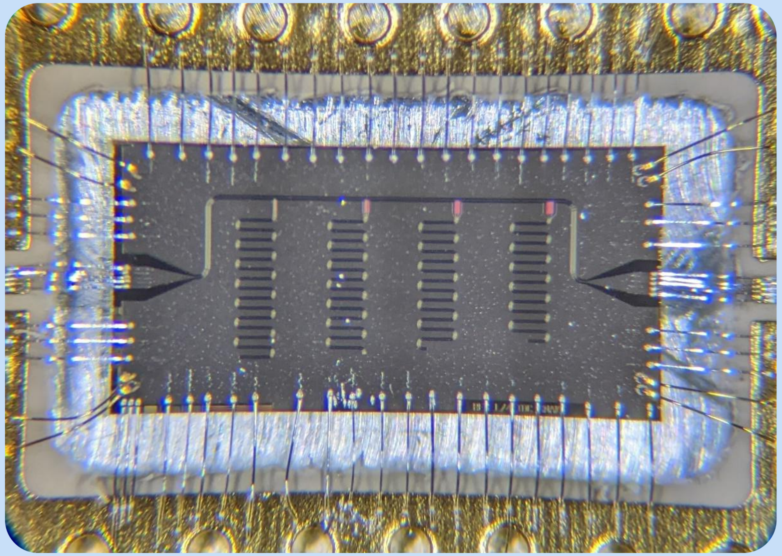
Multi-qubit systems with read-out limited by quantum noise

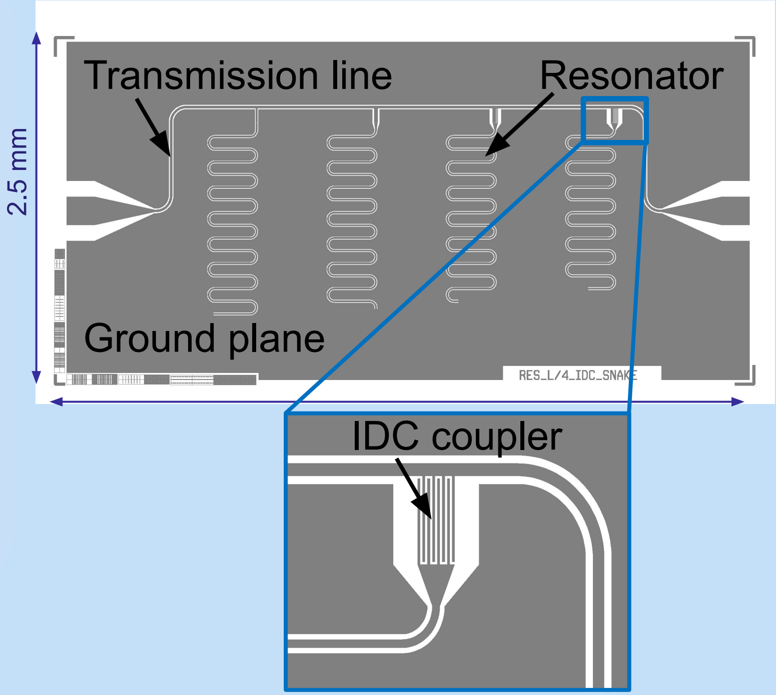
Multiplexed read-out of superconducting photon counters

...

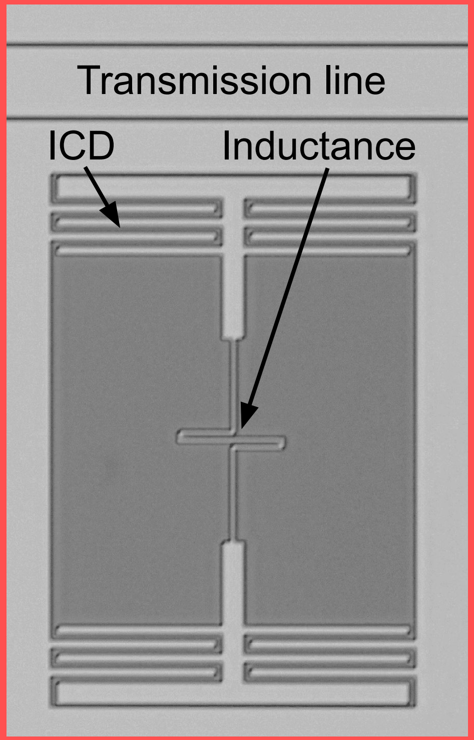
Superconducting microwave resonators

CPW quarter-wave resonators





Lumped element resonators



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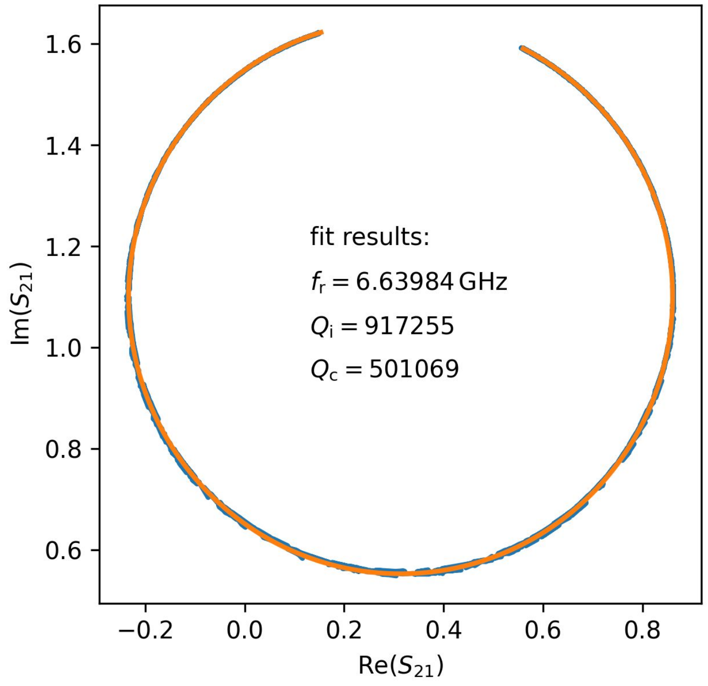
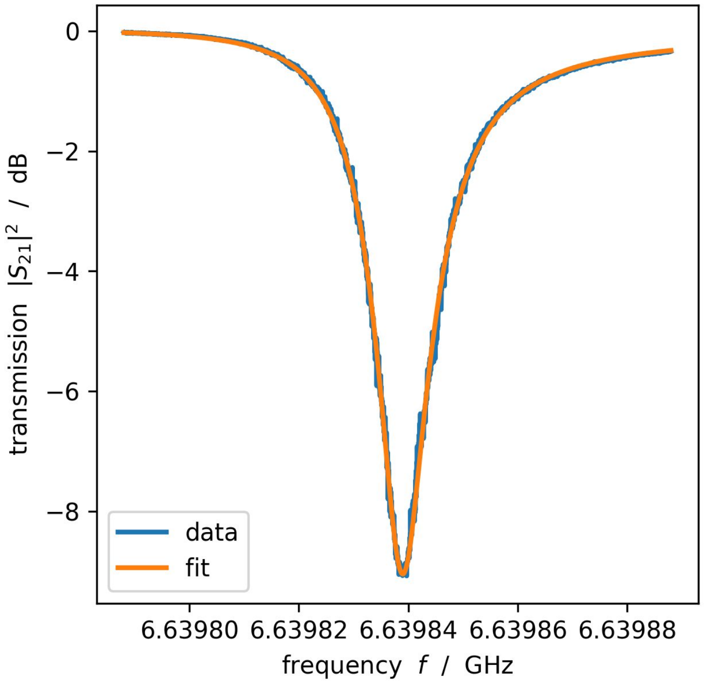
Superconducting microwave resonators

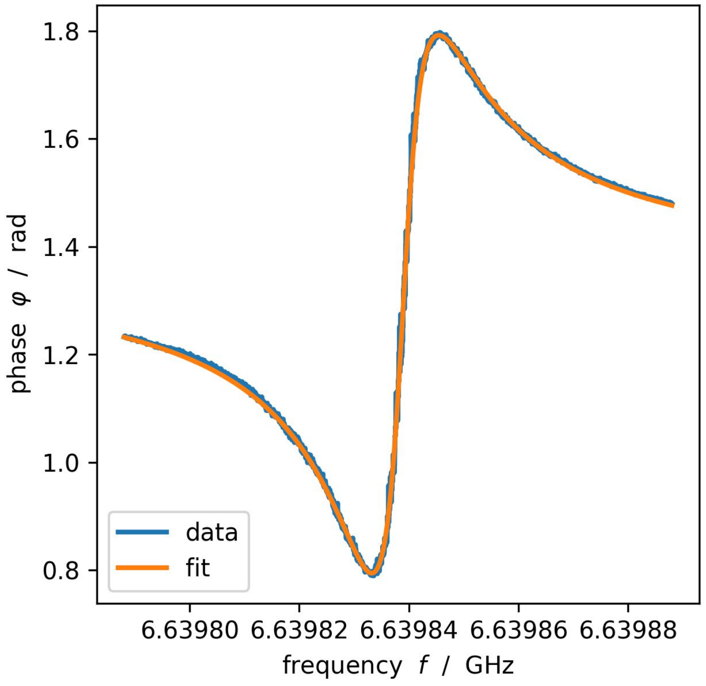
Most recent results with aluminium based lumped element resonators



Fit in complex S_{21} plane



Transmission $|S_{21}|^2$



Phase arctan2[Im(S_{21}), Re(S_{21})]

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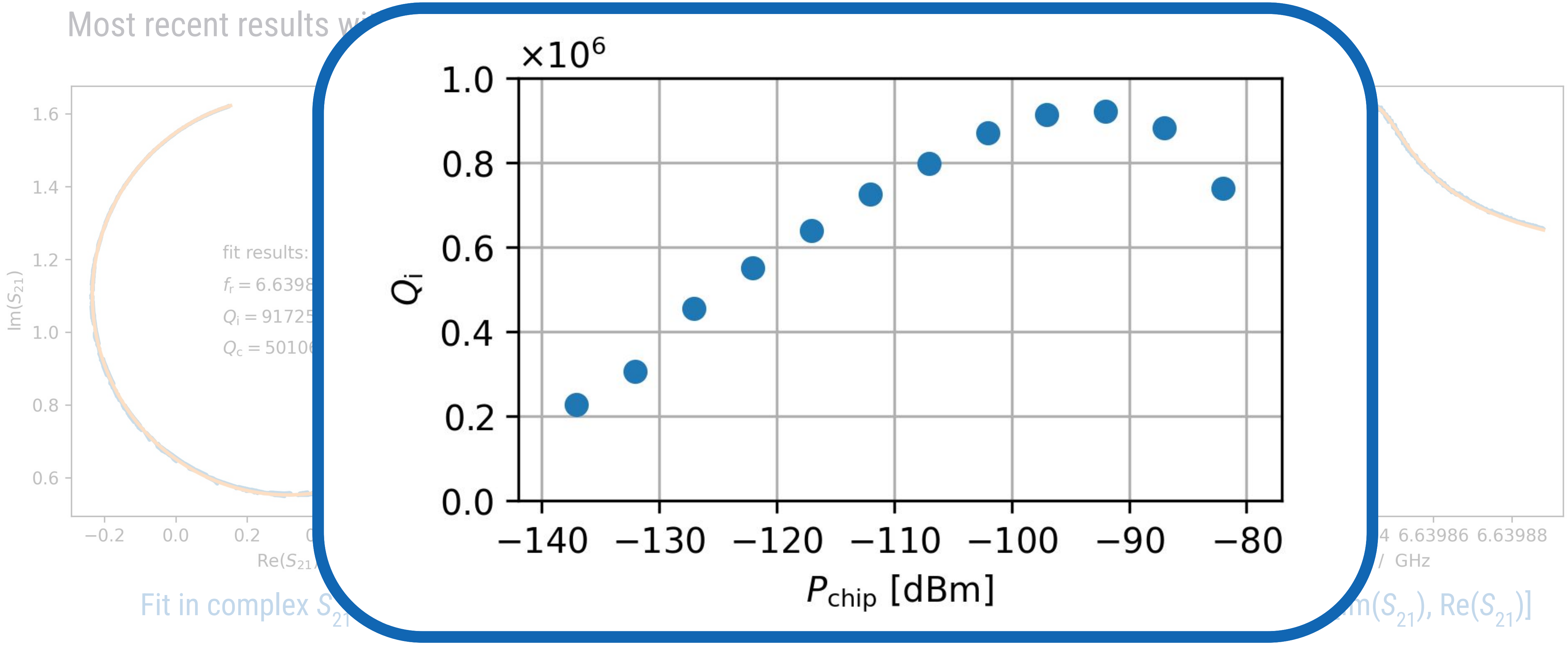
Superconducting microwave resonators

Most recent results wi



Fit in complex S_{21} ... $m(S_{21})$, $Re(S_{21})$]

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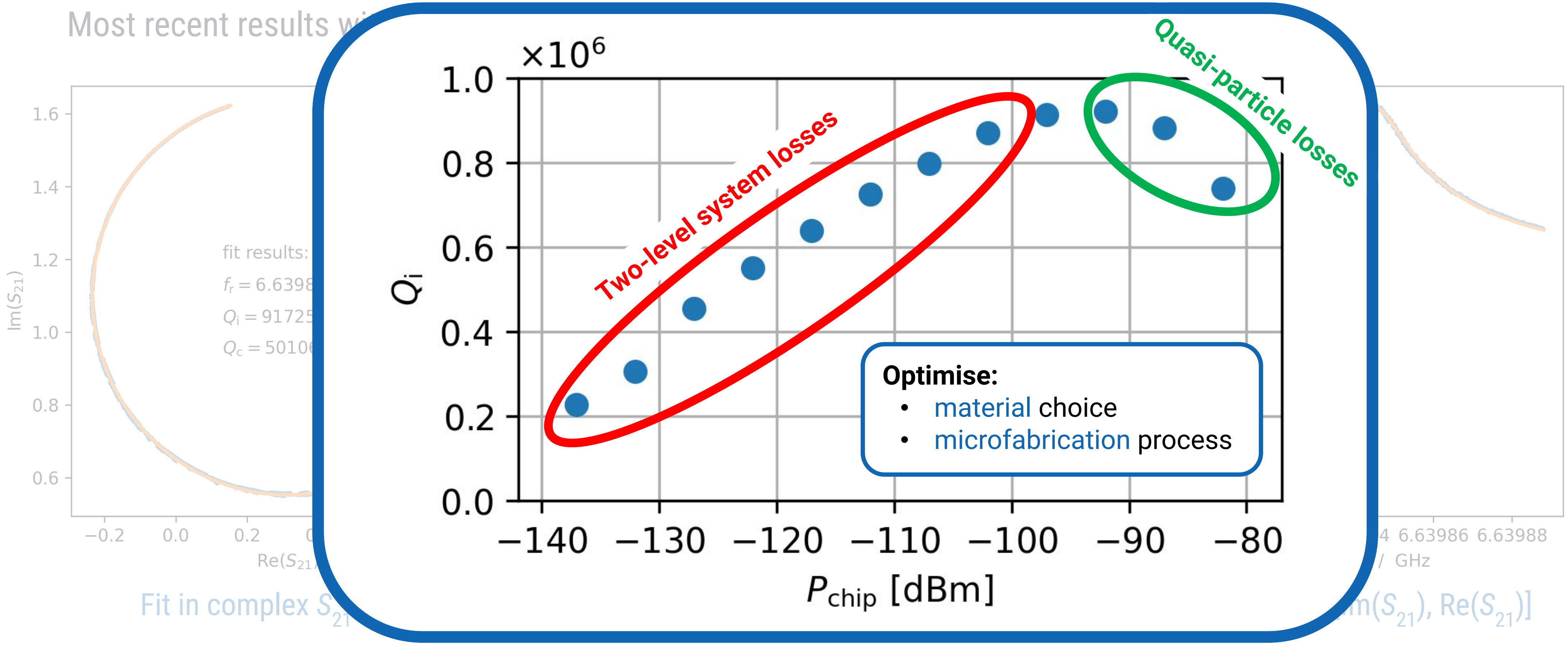
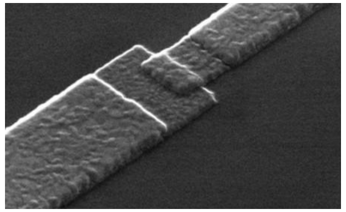
Superconducting microwave resonators

Most recent results wi

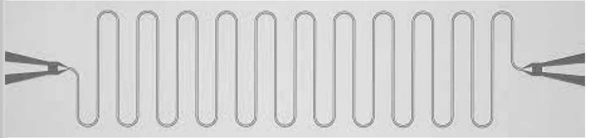


Superconducting electronics - from building blocks to integrated circuits

Josephson junctions



Superconducting resonators

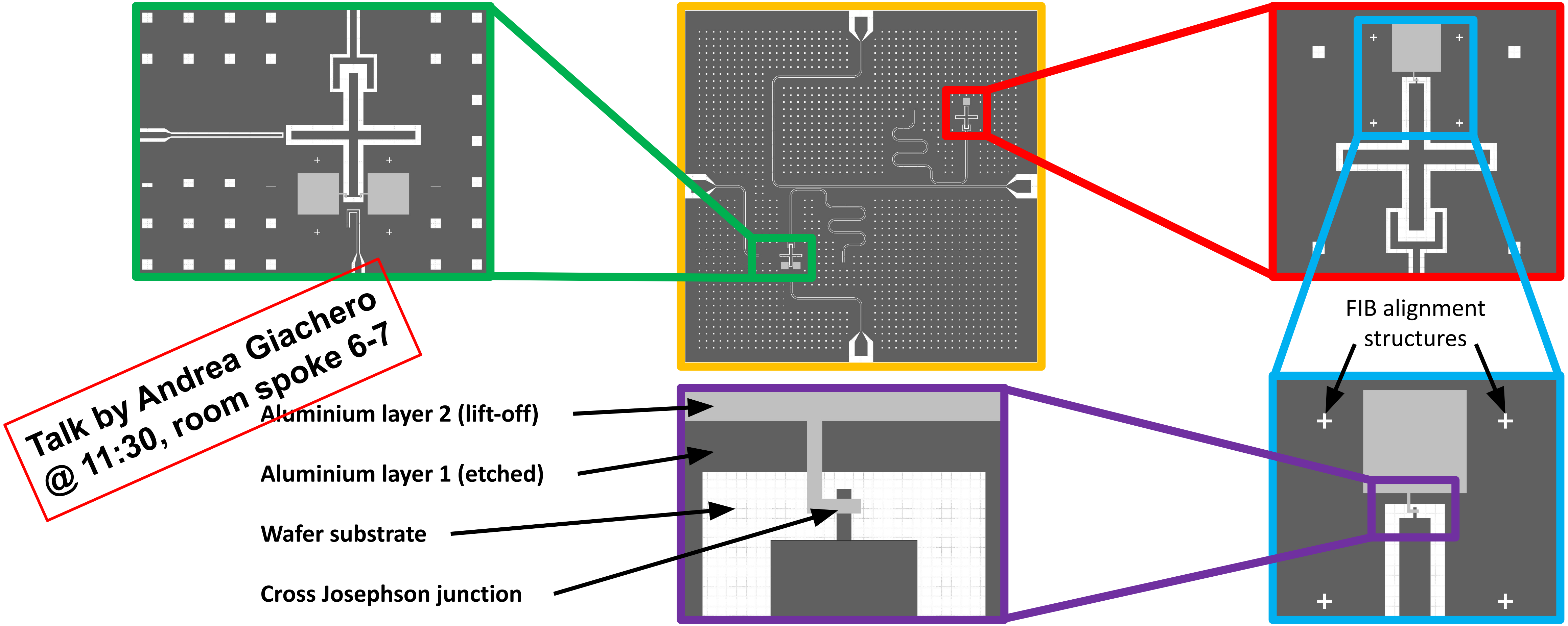


High kinetic inductance films

- SQUIDs
- Parametric Amplifiers
- Qubits
- Cryogenic detectors
- Microwave multiplexers
- ...

- Multi-qubit systems with read-out limited by quantum noise
- Multiplexed read-out of superconducting photon counters
- ...

Microfabrication of qubits



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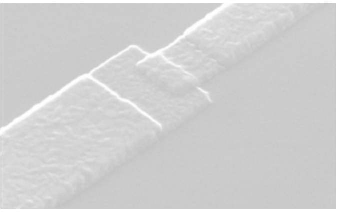
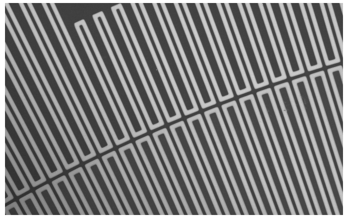


Superconducting resonators

High kinetic inductance films



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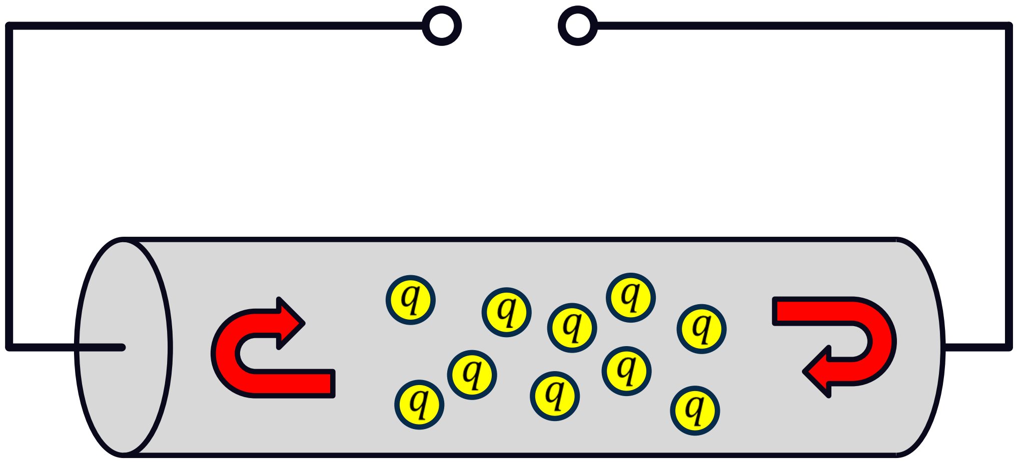
Multi-qubit systems with read-out limited by quantum noise

Multiplexed read-out of superconducting photon counters

...

High kinetic inductance films

$U = U_0 e^{i\omega t}$



$$\sigma = \frac{nq^2\tau}{m(1 + i\omega\tau)}$$

Kinetic inductance:
- large collision time τ
- high frequency ω

Superconductor:

$\tau \to \infty, \quad m = 2m_e, \quad q = 2e$

Cooper pair density $n = n(I)$

$$\Rightarrow \quad L(I) \approx L_0 \cdot \left(1 + \frac{I^2}{I_*^2}\right)$$

$$L_0 = \frac{R_S \hbar}{\pi \Delta} \qquad I_* \propto 1/\sqrt{R_n}$$

High kinetic inductance films

- Interesting materials:
  high-resistivity superconductors

- Our choice: **NbTiN**
  → high resistivity (~100−200 mΩcm)
  → high critical temperature (~12-13 K)

Superconductor:

$\tau \to \infty, \quad m = 2m_e, \quad q = 2e$

Cooper pair density $n = n(I)$

$$\Rightarrow \quad L(I) \approx L_0 \cdot \left(1 + \frac{I^2}{I_*^2}\right)$$

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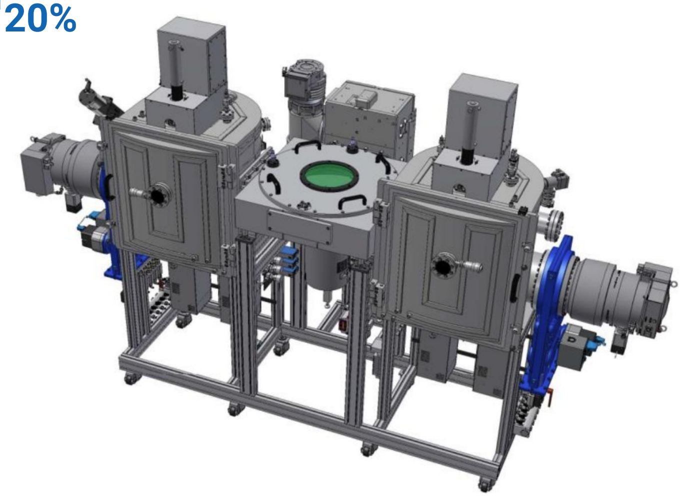
Optimisation of NbTiN thin films: parameter exploration

- Sputter system:
  PVD Kenosistec 800 C

- Sputter target:
  $Nb_{80\%}Ti_{20\%}$

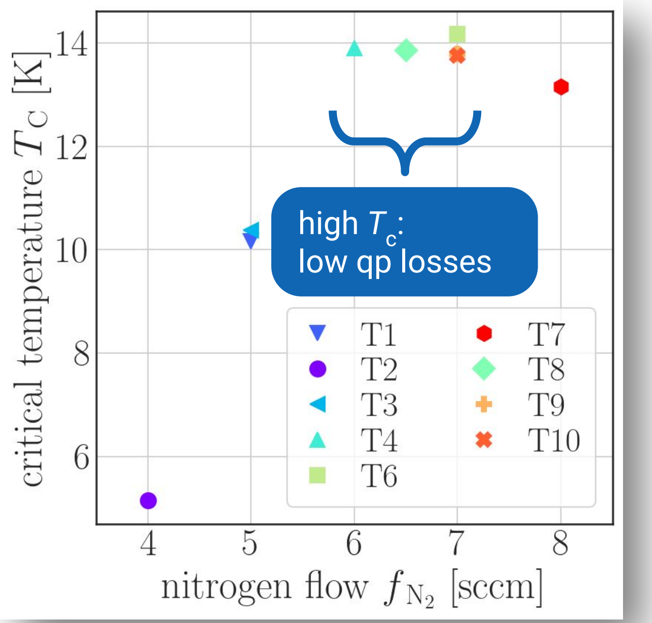


Fabrication run *R1*				
Wafer	P/W	p/mbar	f_{Ar}/sccm	f_{N_2}/sccm
T1	700	2e-3	50	5
T2	700	3e-3	50	4
T3	700	3e-3	50	5
T4	700	3e-3	50	6
T5	1200	3e-3	50	5
T6	700	3e-3	50	7
T7	700	3e-3	50	8
T8	700	3e-3	50	6.5
T9*	700	3e-3	50	7
T10	600	3e-3	50	7

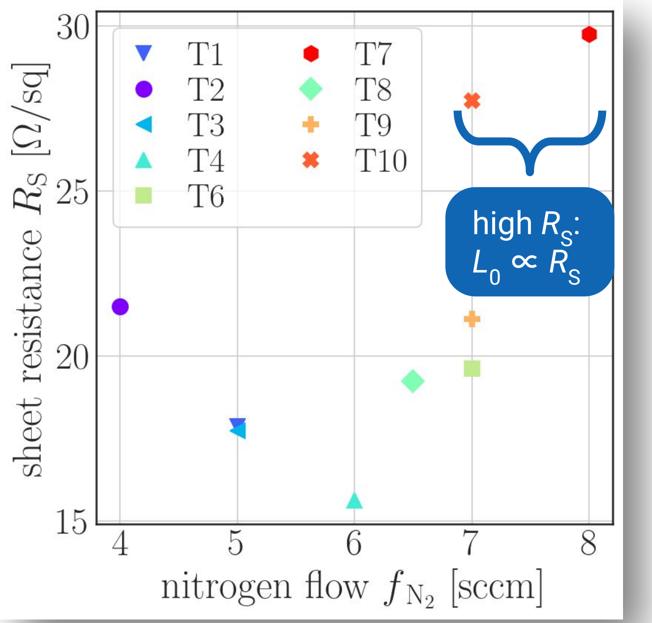
*$T = 300\,°C$

Optimisation of NbTiN thin films: parameter exploration

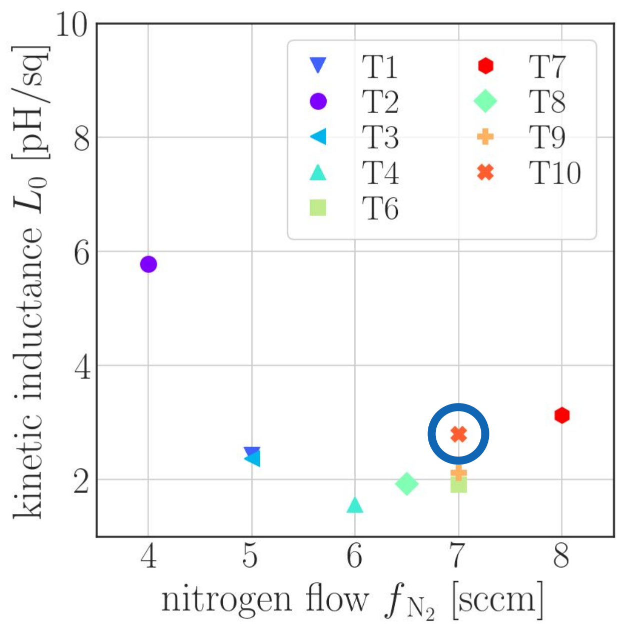
Measured T_c:



Measured R_s:



$$L_0 = \frac{R_S \cdot \hbar}{\pi \cdot T_C \cdot k_B \cdot 1.762}$$



→ Recipe T10: high T_c and sufficiently high R_S

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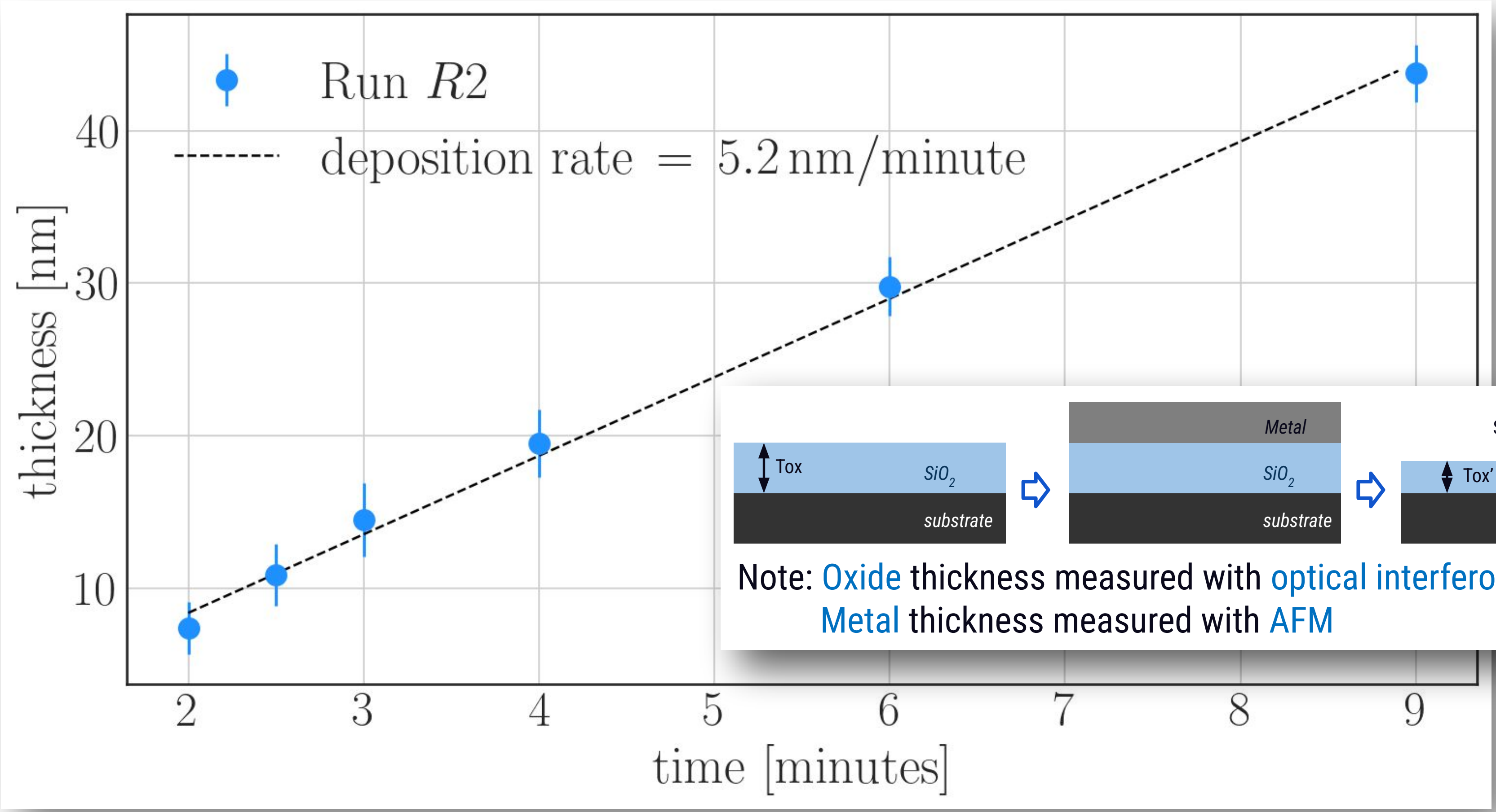
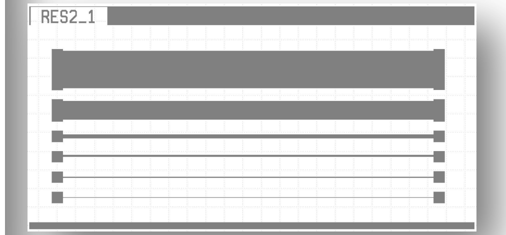
Calibration of NbTiN deposition rate



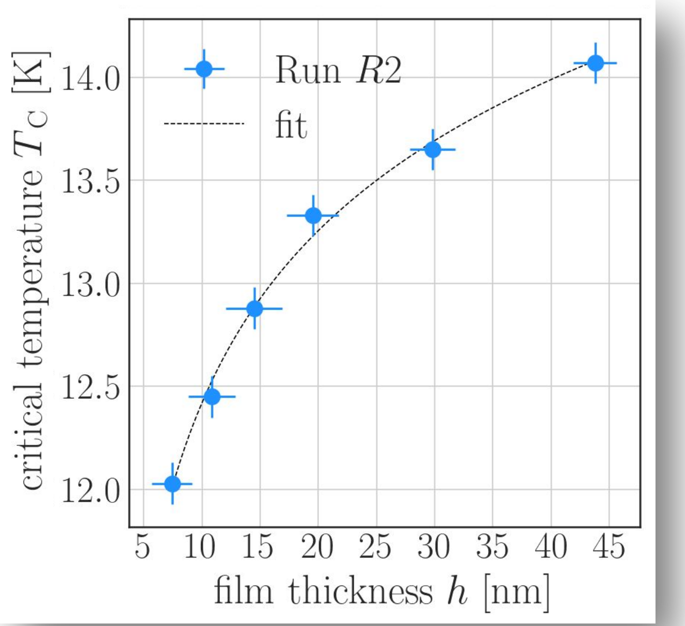
Test chip:



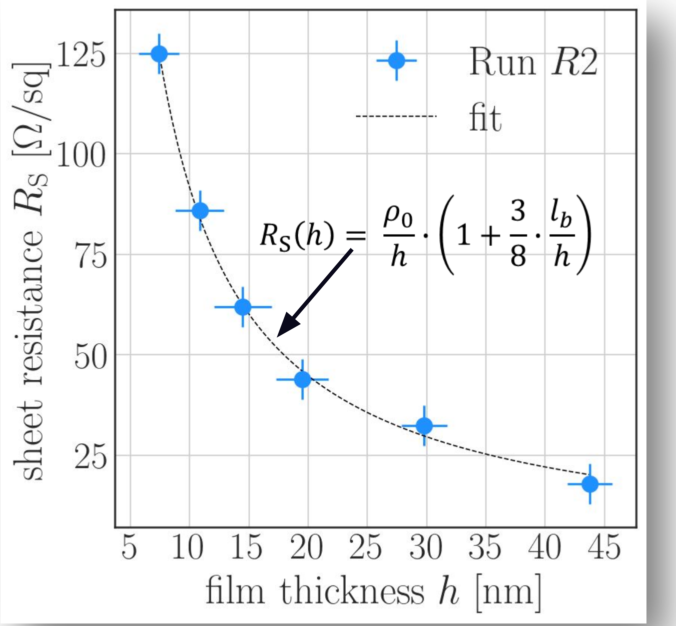
Note: Oxide thickness measured with optical interferometer
Metal thickness measured with AFM

Calibrate film thickness *h* vs kinetic inductance L_0

Measured T_c:

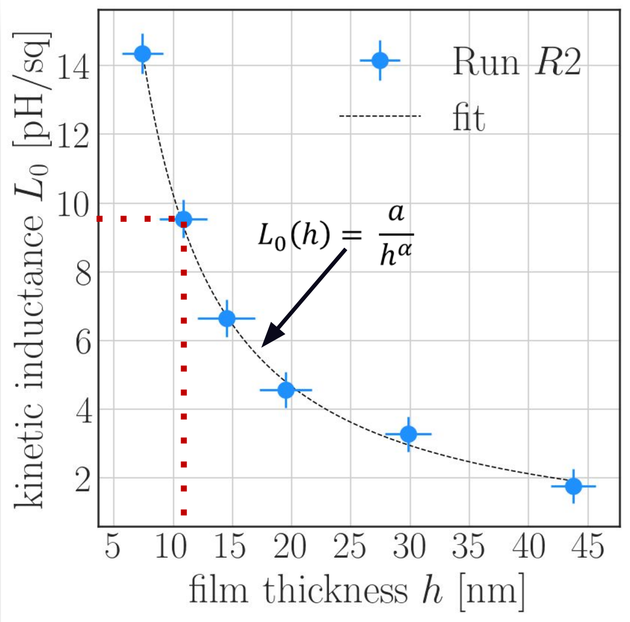


Measured R_s:



Fuchs' model (doi: 10.1017/S0305004100019952)

$$L_0 = \frac{R_S \cdot \hbar}{\pi \cdot T_C \cdot k_B \cdot 1.762}$$



Phenomenological model

→ Use film thickness *h* as L_0 tuning parameter

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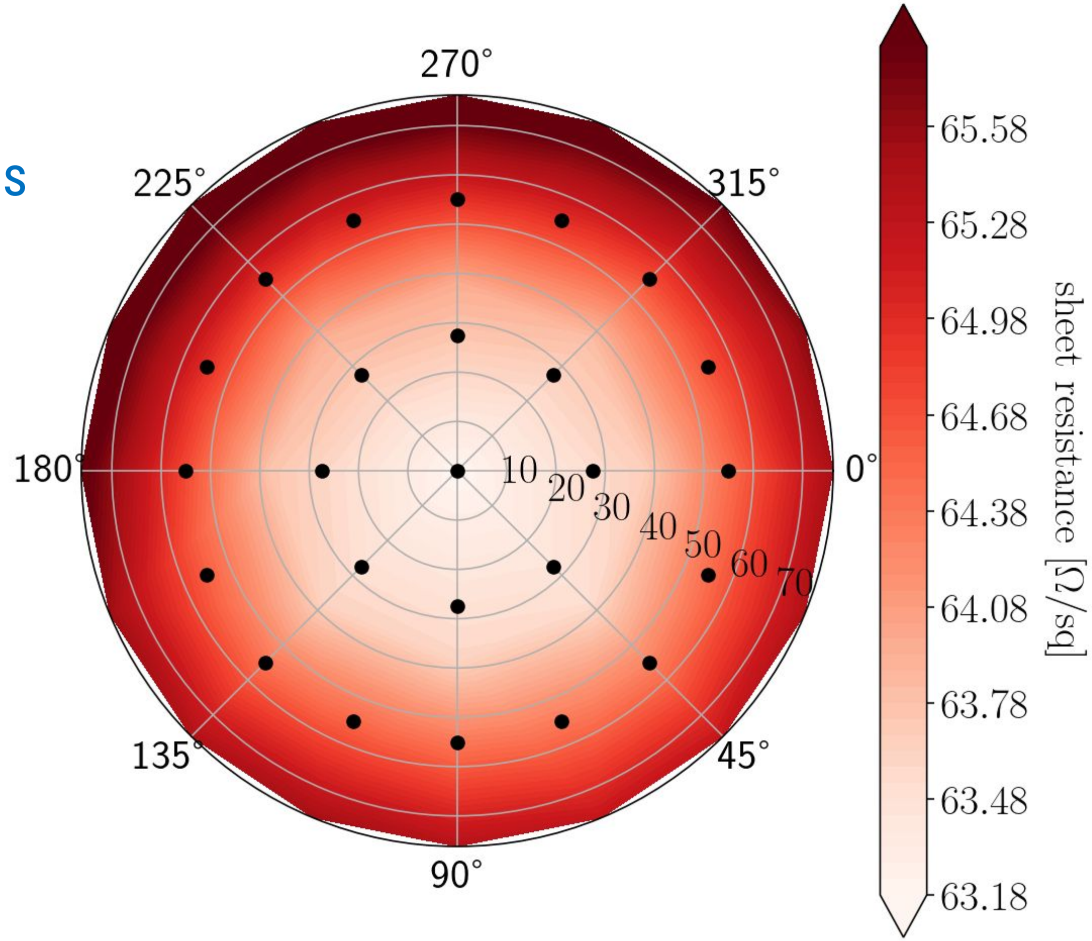
Uniformity on wafer scale

Estimation of the uniformity of the film thickness

→ Measurement of the sheet resistance (25 points over the 6 ″ wafer)

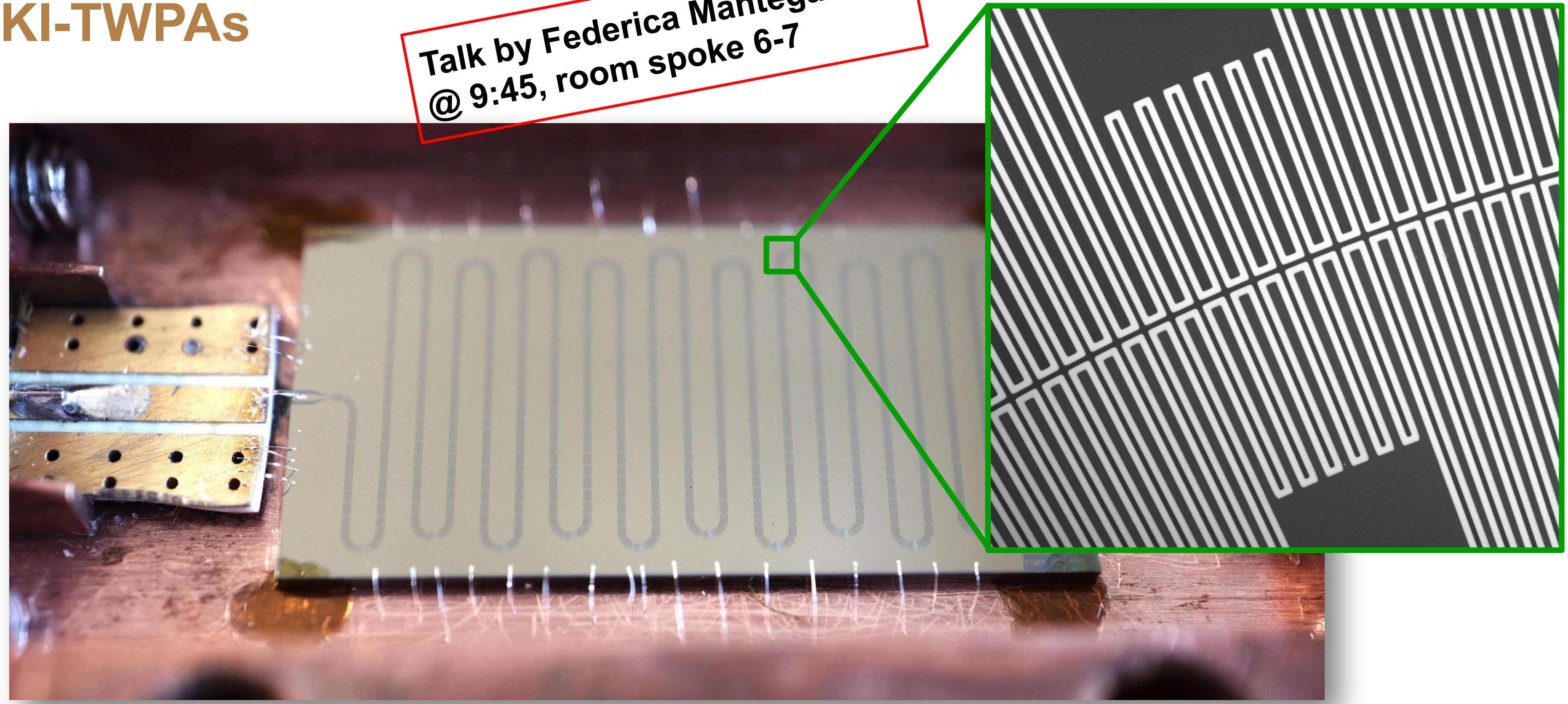
→ Variation is about 4%

→ Radial gradient (thinner film at the edge)



KI-TWPAs

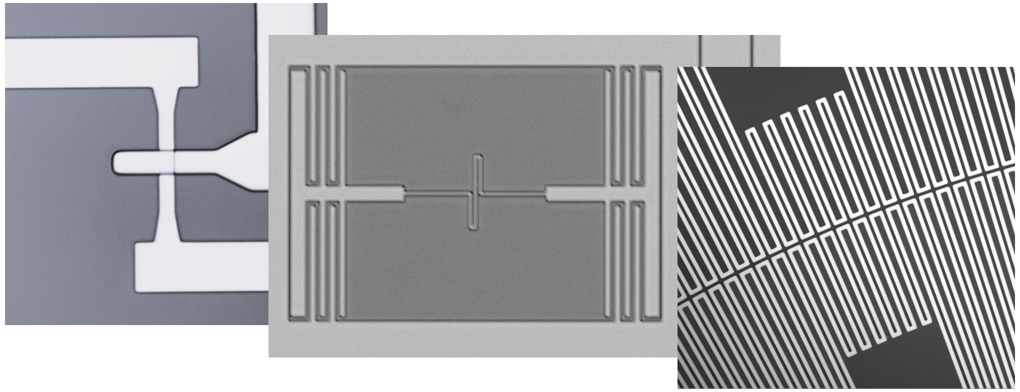
Talk by Federica Mantegazzini @ 9:45, room spoke 6-7



Conclusion

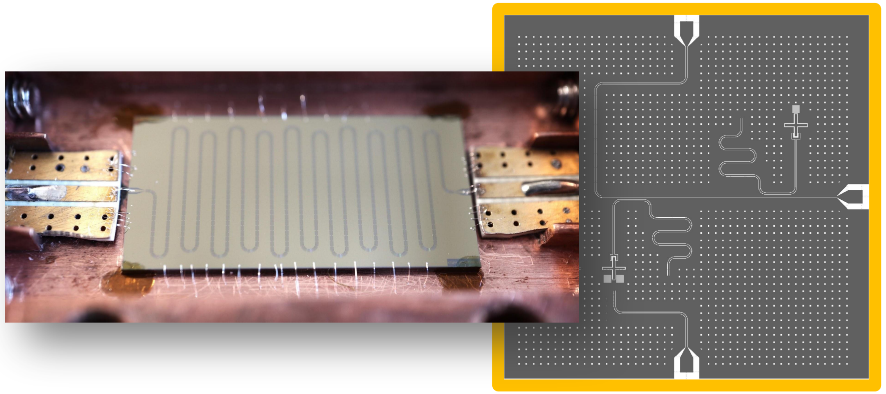
Building blocks ready:

- Josephson junctions ✓
- Microwave resonators ✓
- High kinetic inductance films ✓



Currently ongoing:

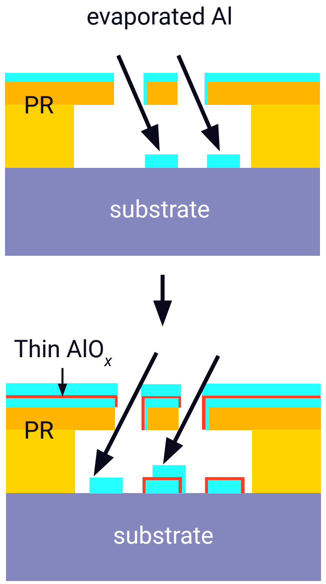
- Further improvement of building blocks
- Integrating building blocks into circuits



How to microfabricate Josephson junctions

Dolan technique (aka shadow evaporation)

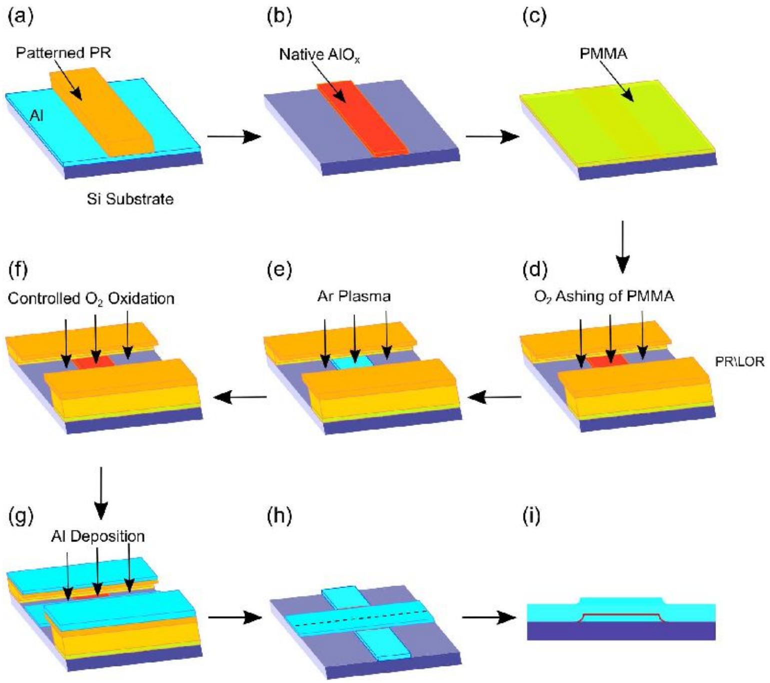
Al/AlOx/Al



Cord B. et al (2006) 10.1116/1.2375090

Cross junctions

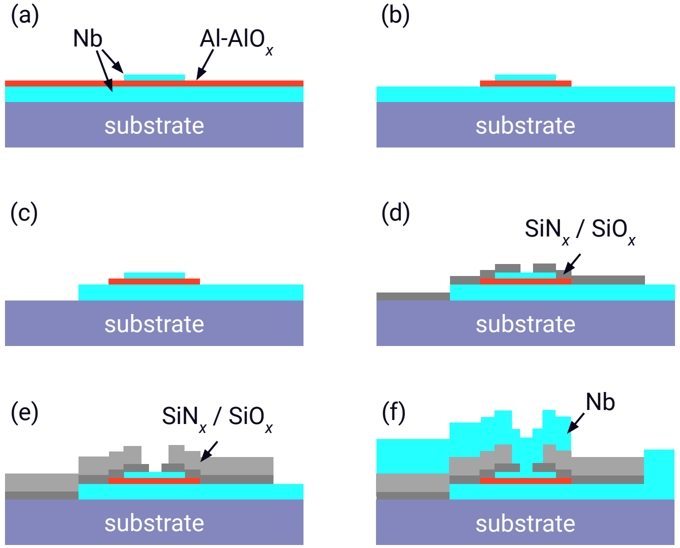
Al/AlOx/Al



Bal M. et al (2021) 10.1063/5.0048621

Window-type / Trilayer

Nb/Al-AlO$_x$/Nb



Kempf S. et al (2013) 10.1088/0953-2048/26/6/065012