Development of Quantum Processor with Fluxonium Superconducting Qubits

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2022/8/26 2022 QST Workshop @NTU

Previous funding agencies

Current funding agencies

nature

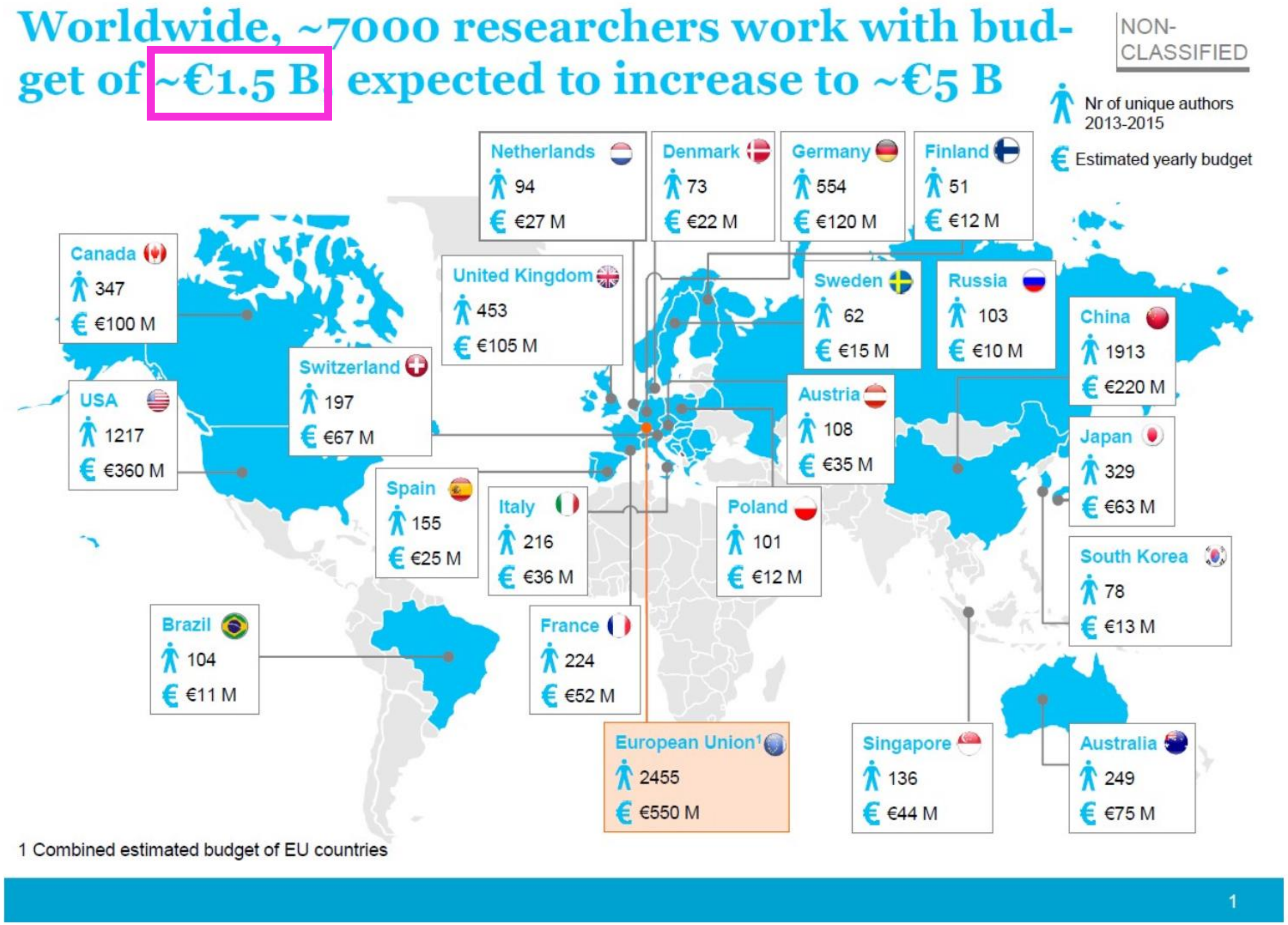
NEWS FEATURE | 02 October 2019

Quantum gold rush: the private funding pouring into quantum start-ups

A *Nature* analysis explores the investors betting on quantum technology.


USA
CALIFORNIA GOLD RUSH 1849

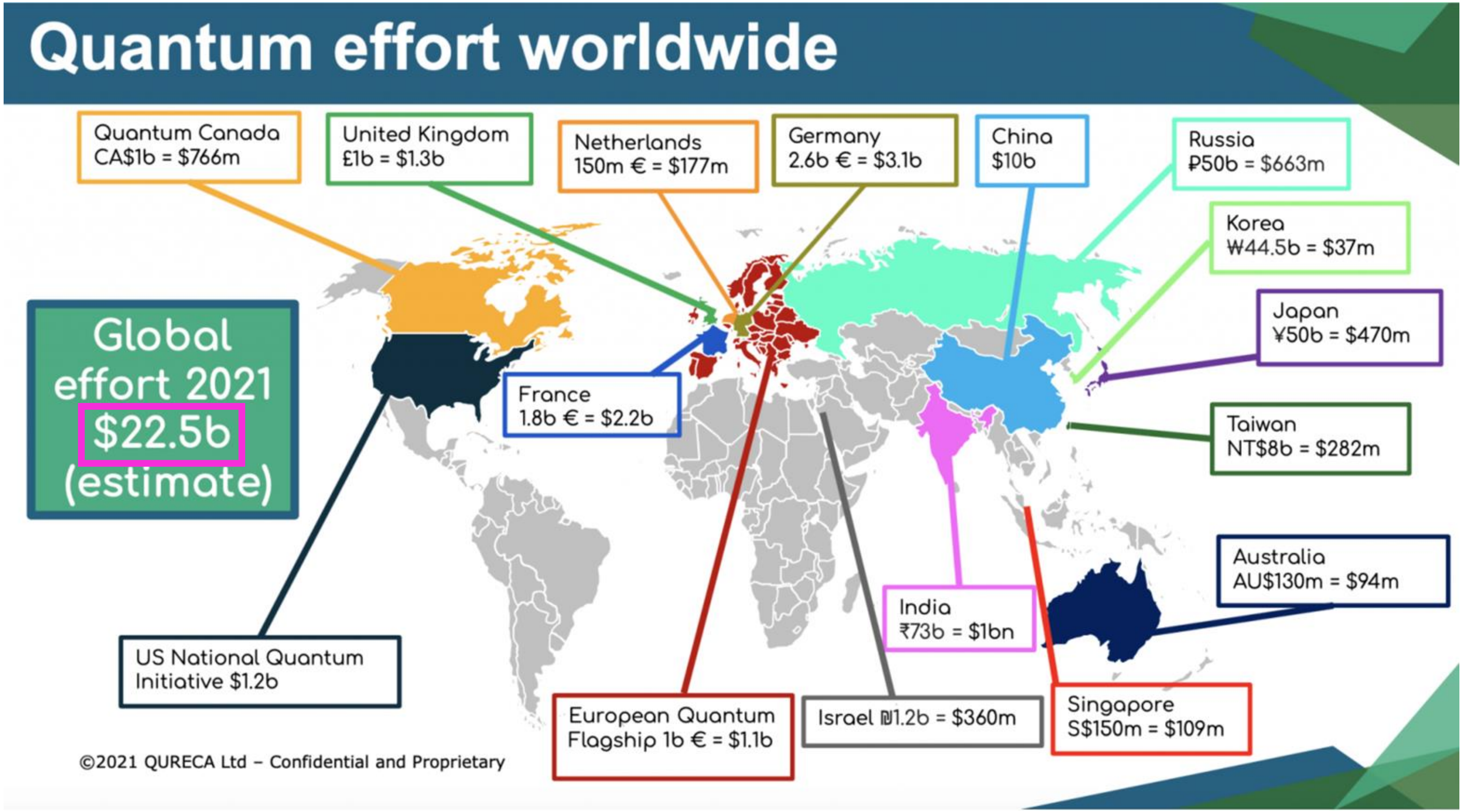
Research Budget for Quantum Technology 2015



Source: Quantum Europe 2016

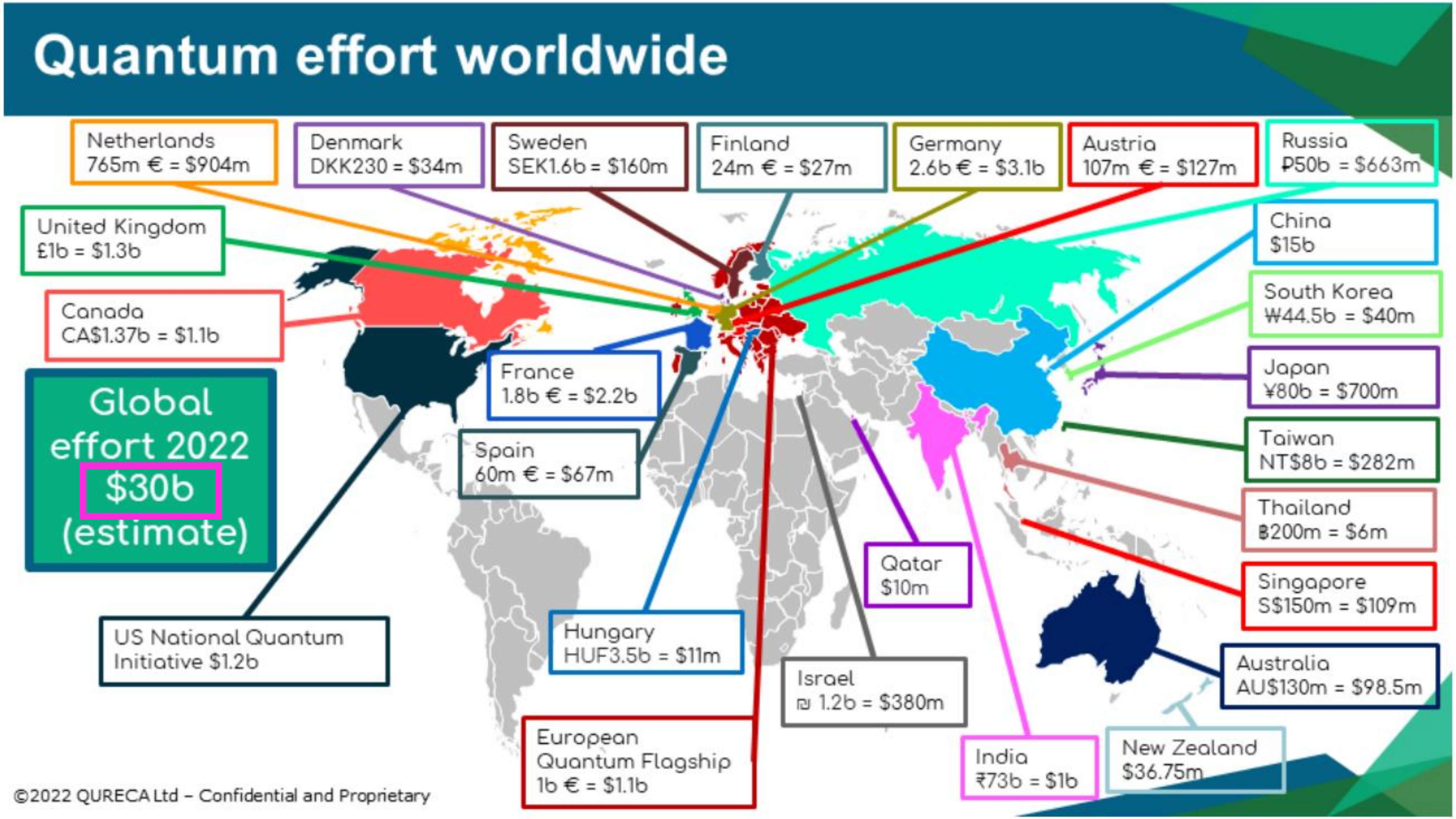
https://medium.com/@ASMLcompany/start-your-engines-the-race-to-quantum-computing-is-on-14c3076a5c47

Research Budget for Quantum Technology 2021



https://www.qureca.com/overview-on-quantum-initiatives-worldwide/

Research Budget for Quantum Technology 2022



Overview of public funding in quantum technologies.

https://qureca.com/overview-on-quantum-initiatives-worldwide-update-2022/

Quantum Hardware R&D by Private Companies!

Superconducting

- Alibaba Group
- Microsoft
- Alice & Bob
- qci
- QRDLAB
- D-Wave The Quantum Computing Company™
- Raytheon BBN Technologies
- Google
- rigetti
- IBM
- RIKEN
- 本源量子 Origin Quantum
- imec
- intel
- IQM
- seeqc

Trapped Ions

- infineon
- IONQ
- Honeywell
- AQT

Quantum Dots

- FUJITSU
- NEC
- TOSHIBA
- Silicon Quantum Computing

Photonic

- NTT
- PsiQ
- XANADU
- QuiX
- AegiQ

NV-centers

- QUANTUM BRILLIANCE
- 国仪量子 CIQTEK

NMR

- hp

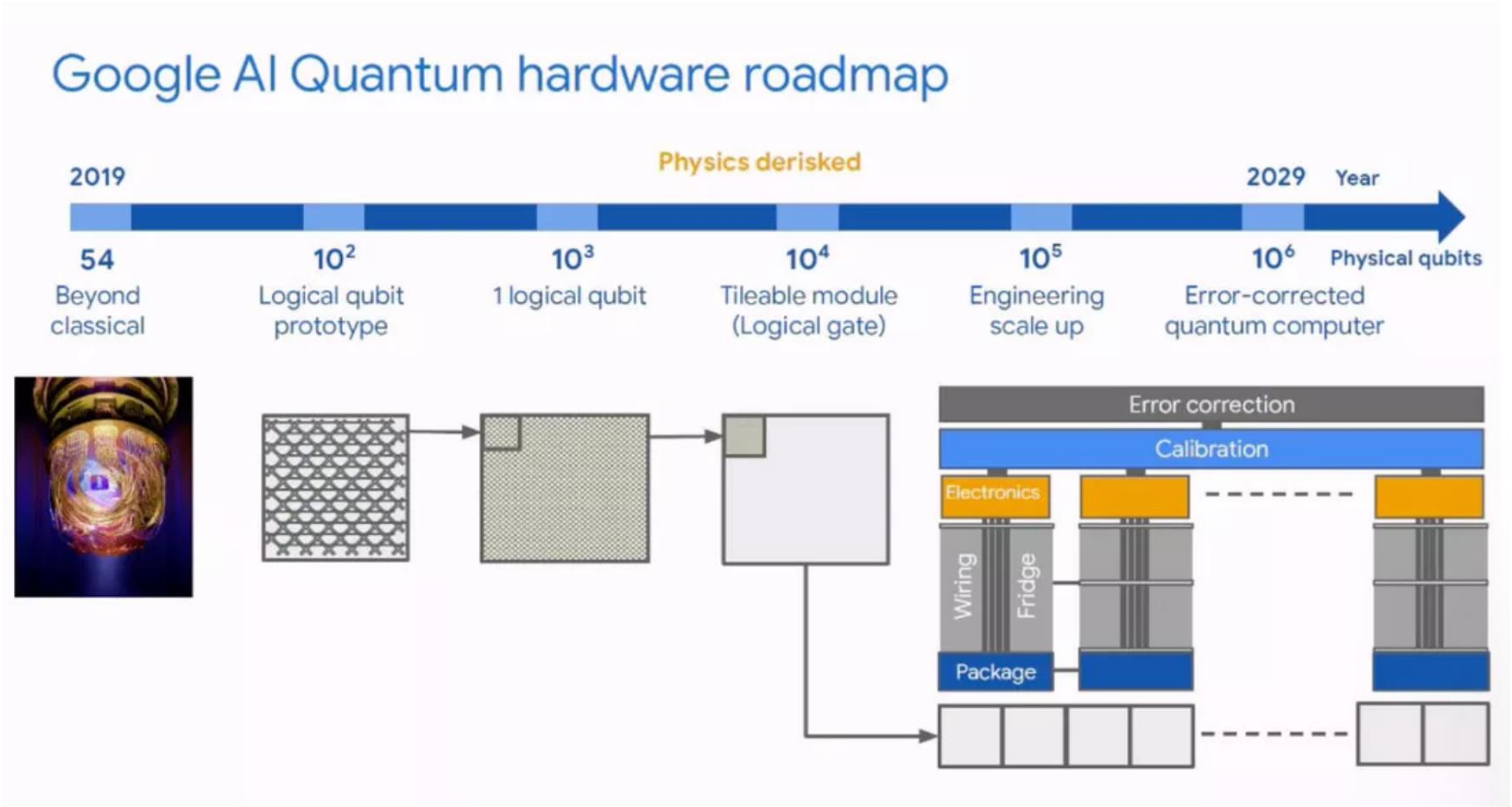
CMOS

- HITACHI

Not a complete list…

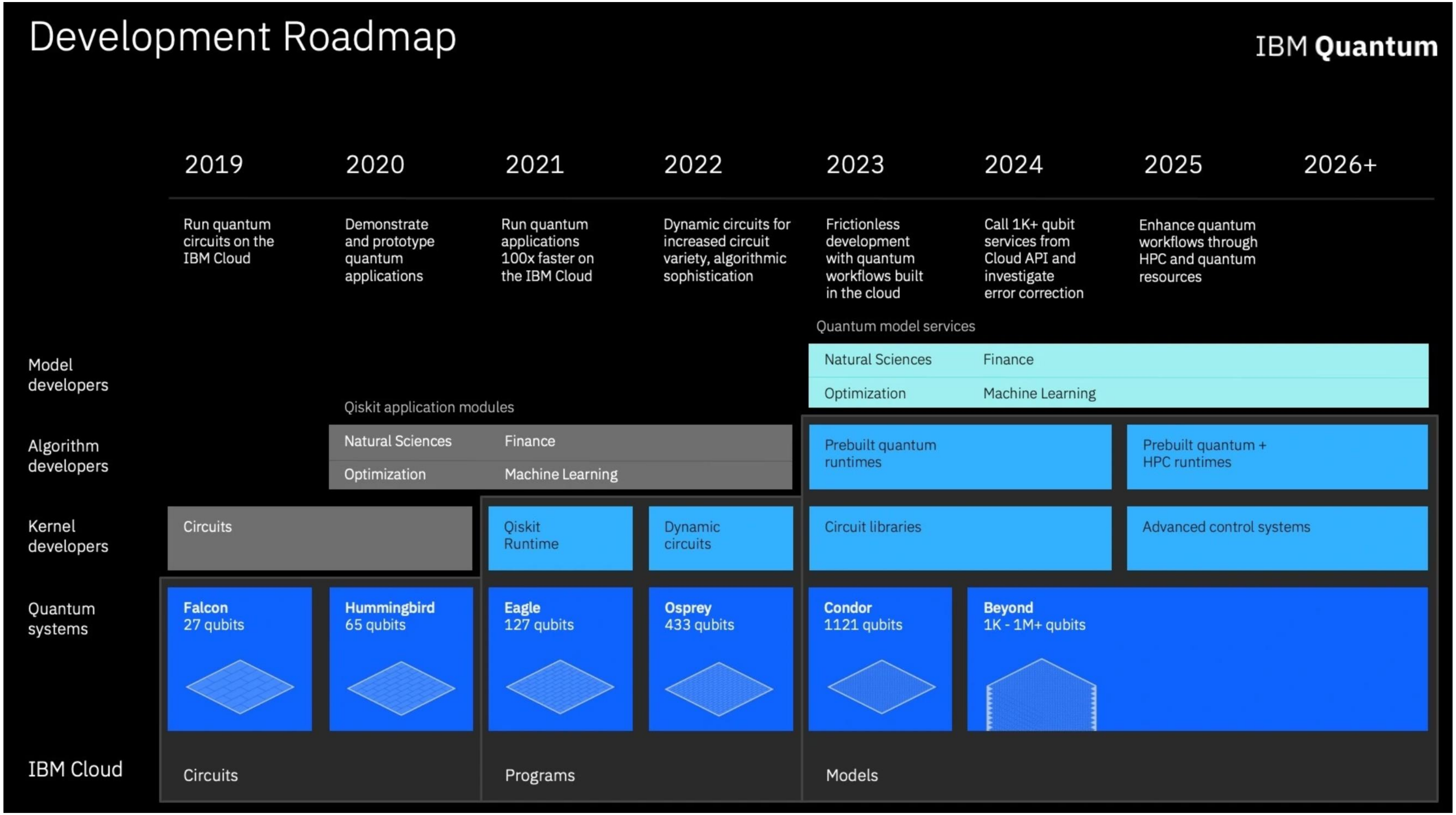
https://en.wikipedia.org/wiki/List_of_companies_involved_in_quantum_computing_or_communication

Google's Roadmap for Quantum Computer



https://www.cnet.com/tech/computing/quantum-computer-makers-like-their-odds-for-big-progress-soon/

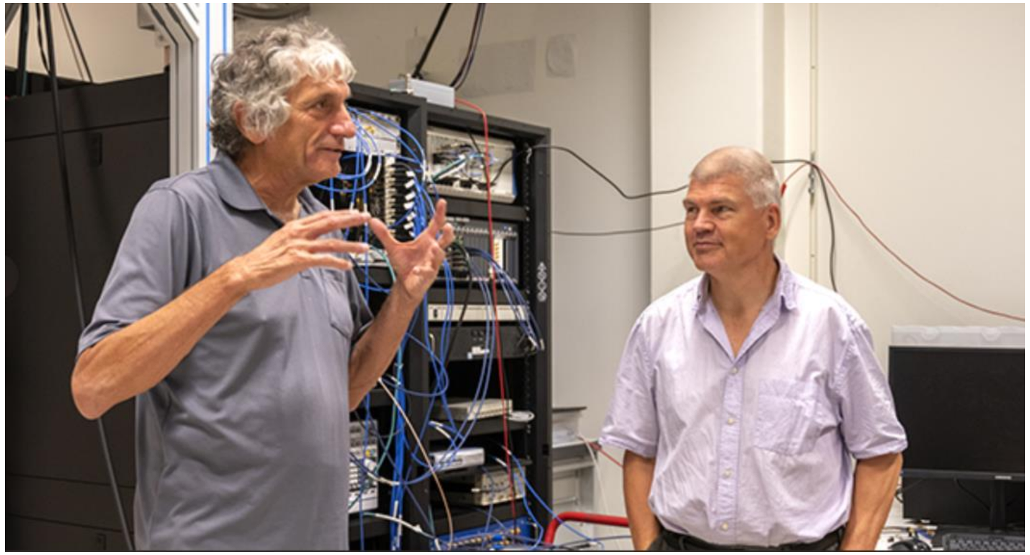
IBM’s Roadmap for Quantum Computer



https://venturebeat.com/wp-content/uploads/2021/02/IBM-quantum-development-roadmap-slide-1.jpeg?strip=all

What can we (as small groups) do for superconducting qubits quantum computer?

Making Better Qubits



"Today people tend to focus on how many qubits you have. In my opinion, one needs to go back and improve the qubits before scaling up. I've been thinking quite deeply on how to make superconducting qubits better"

- John Martinis, Professor UCSB, former Chief Scientist of Google Quantum AI

https://www.chalmers.se/en/departments/mc2/news/Pages/Quantum-computer-project-boosted-by-visiting-superstar.aspx

"How many qubits can you make?"

"How long is your qubits' coherence time?"

Making High Coherence Qubit

$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

Coherence time

Relaxation time

Dephasing time

Key to improve Coherence time T2:

- Enhance T1

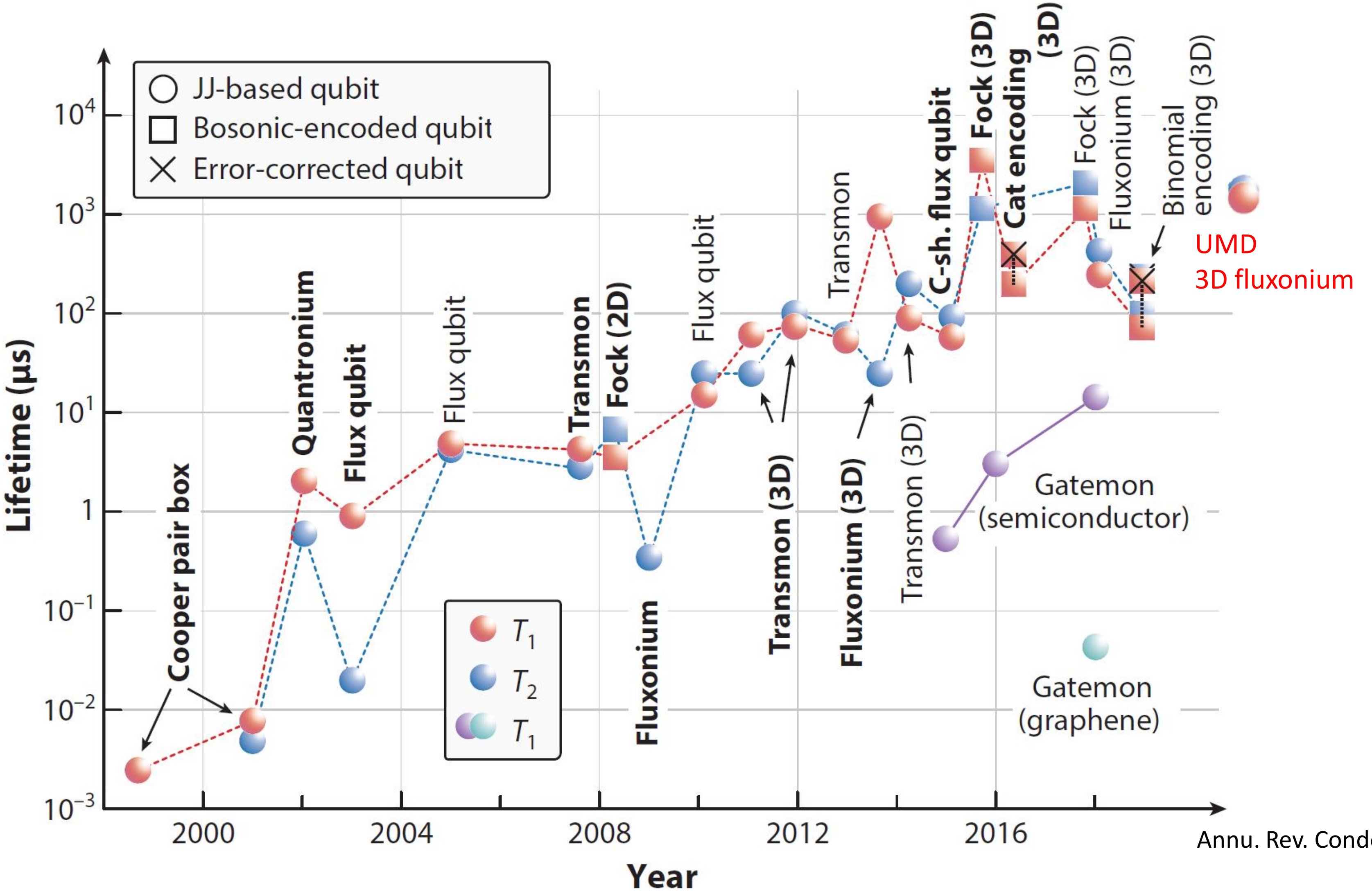
Reduce energy loss to environment

- Enhance Tϕ

Reduce frequency fluctuation of energy transitions

Coherence Time Improvement

Error rate is directly related to coherence time of qubits!



Annu. Rev. Condens.Matter Phys. 2020. 11:369–95

arXiv 2103.08578 (2021)

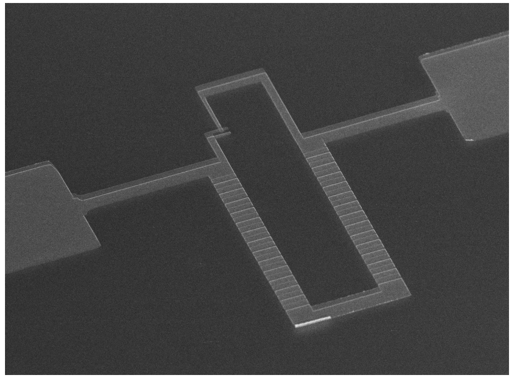
What is a fluxonium superconducting qubit?

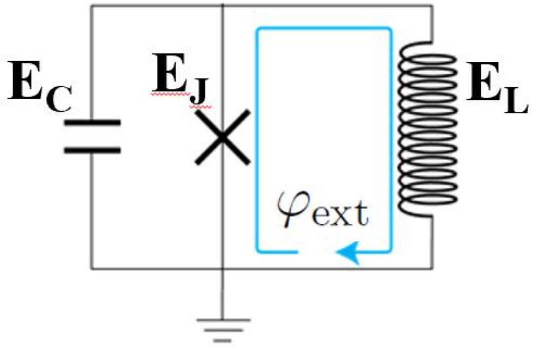
What is a superconducting qubit?

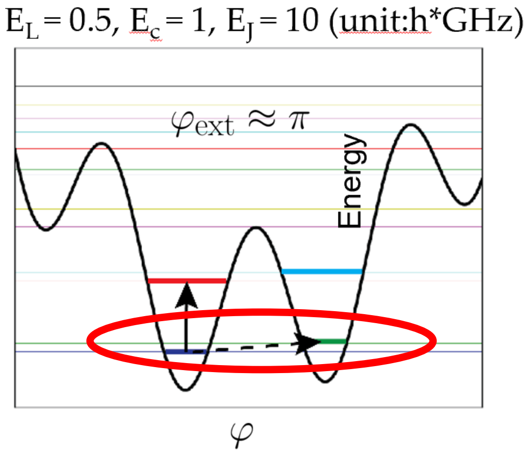
Superconducting Qubits(Short description)

- What is a superconducting qubit(in short)?

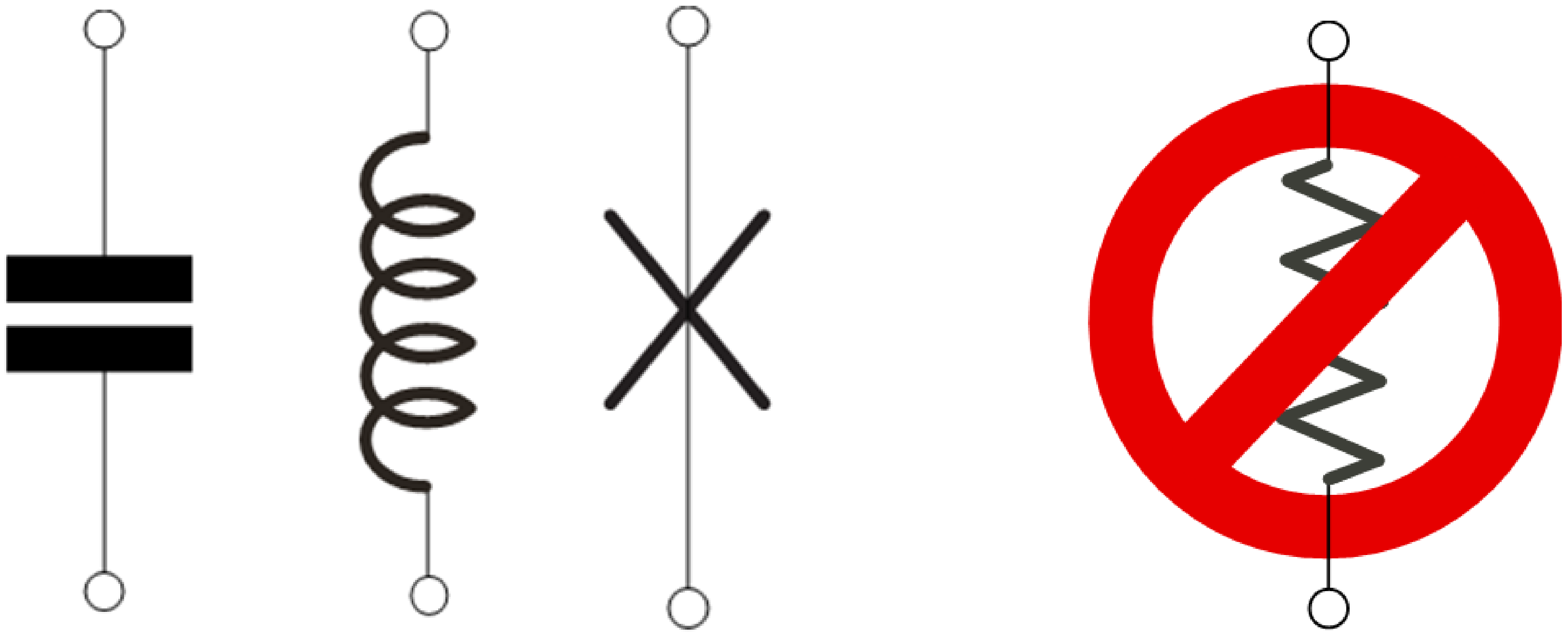
A superconducting electronic circuit forms distinct quantum multi-energy-levels (typically named an artificial atom and the dynamics confined in two levels.





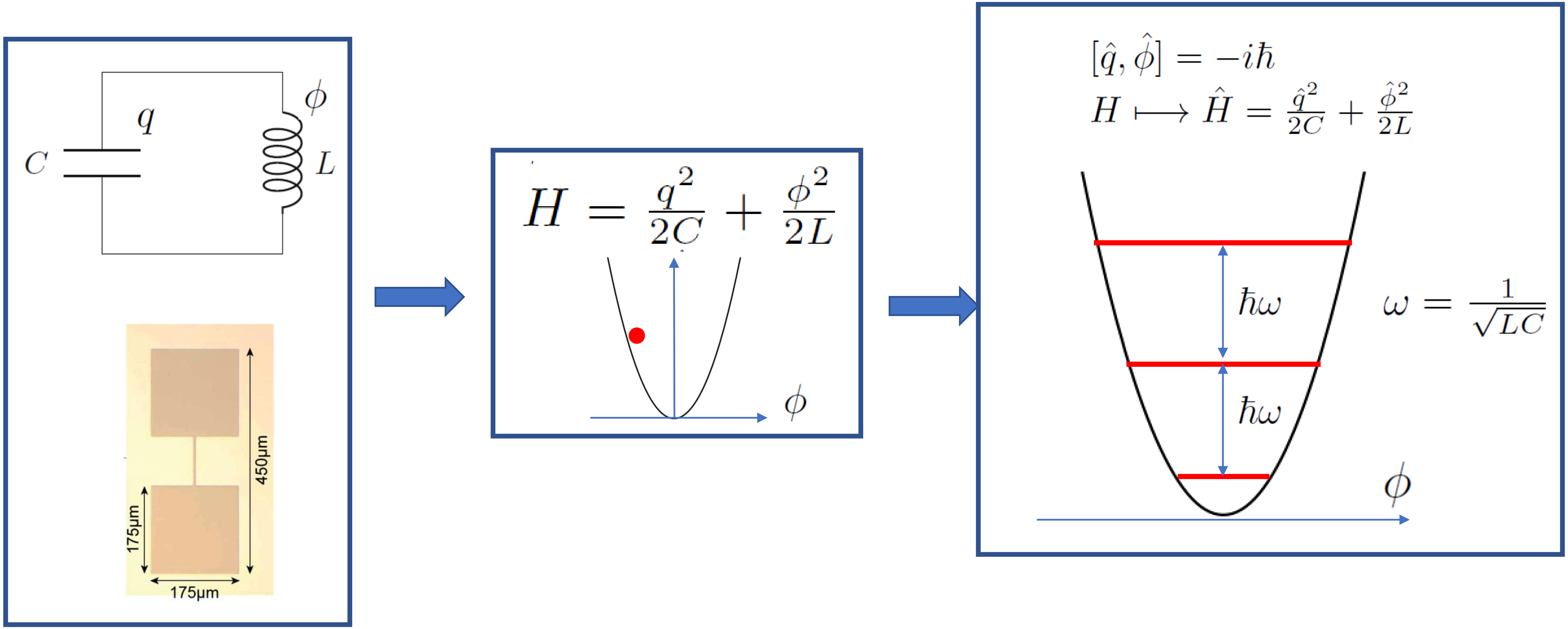


Building Blocks of Superconducting Qubits



quantum LEGO set

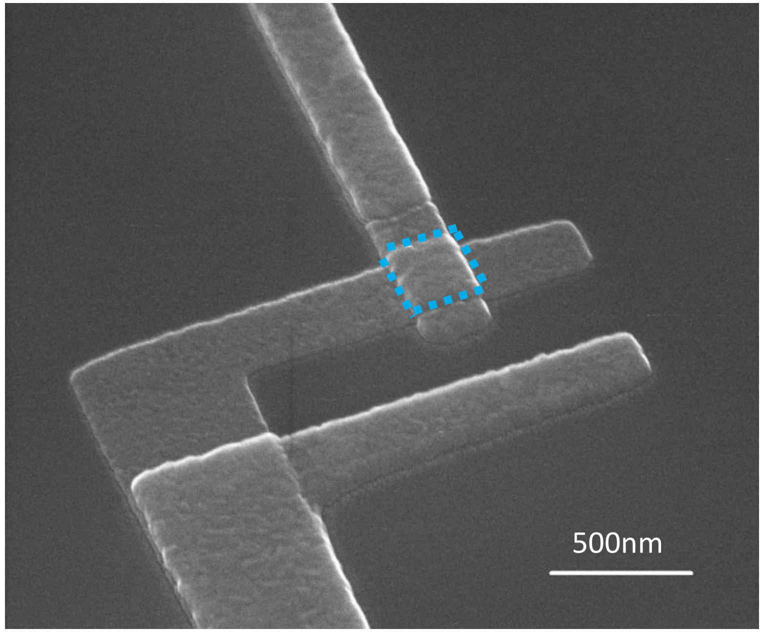
Quantum LC Circuit: Harmonic Oscillator

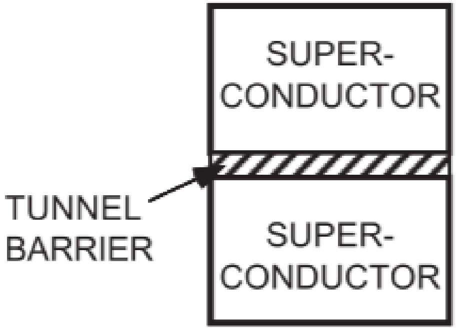


Hard to confine the state within two levels!

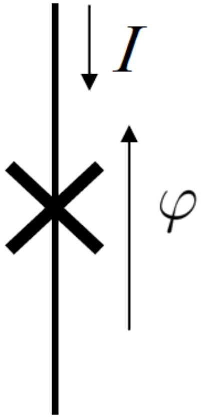
Need Josephson Junctions!

Josephson Al/AlOx/Al Tunnel Junction: a Nonlinear Dissipationless Inductor





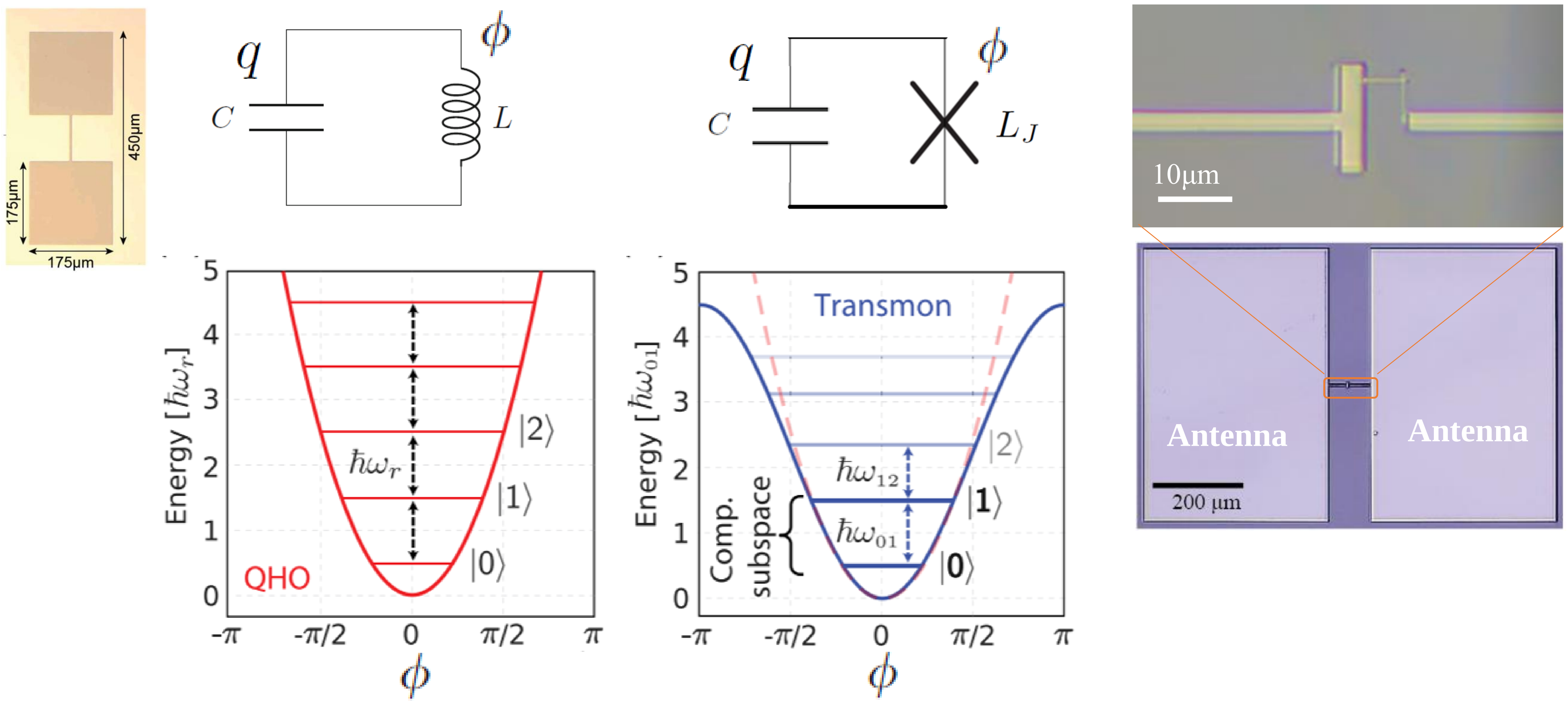
ω_p ~20GHz



$$L_J(\varphi) = \frac{\phi_0}{I_c cos\varphi} = \frac{L_J(0)}{cos\varphi}$$

$$E(\varphi) = \frac{I_c \Phi_0}{2\pi}(1 - cos\varphi) \equiv E_J(1 - cos\varphi)$$

Josephson Al/AlOx/Al tunnel junction: a nonlinear dissipationless inductor

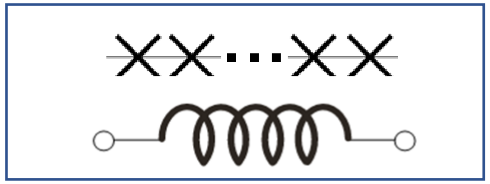


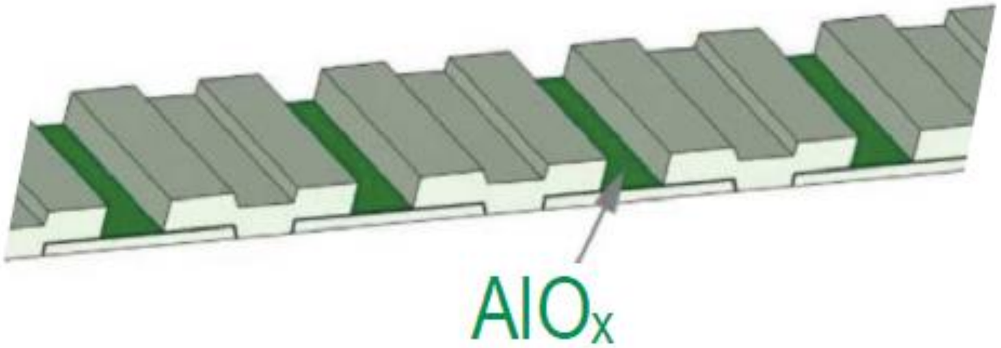
P. Krantz et al, Appl. Phys. Rev. 6, 021318 (2019);

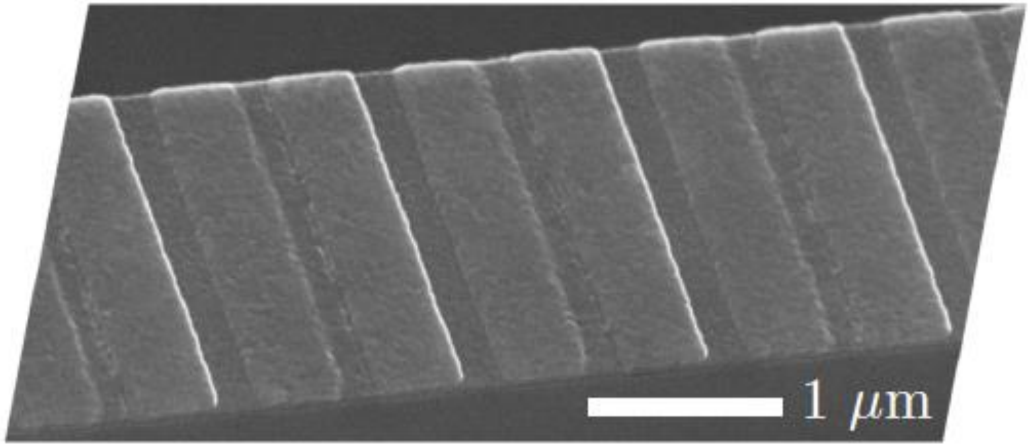
Josephson Junction Chain: superInductor

$$L_J/\sqrt{A} > 10^4\mu_0$$

enormous (kinetic) inductance!

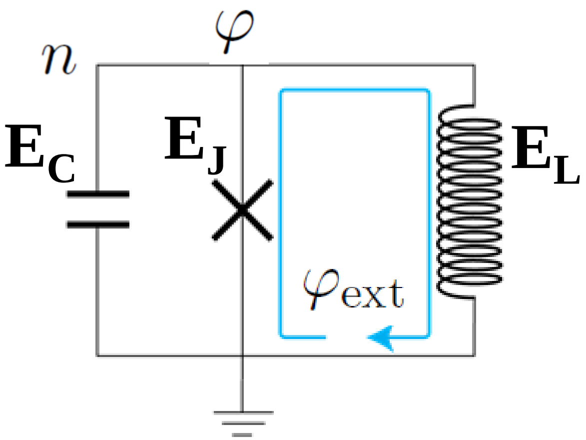






Lin et al. Phys. Rev. Lett. 120, 150503 (2018)

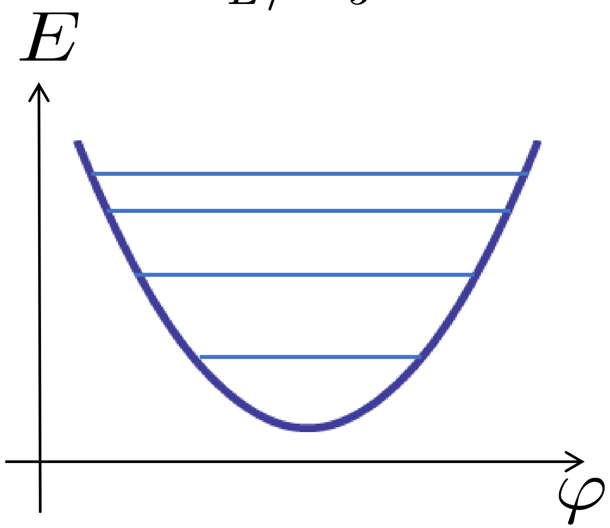
Particle in a box physics: Design box!



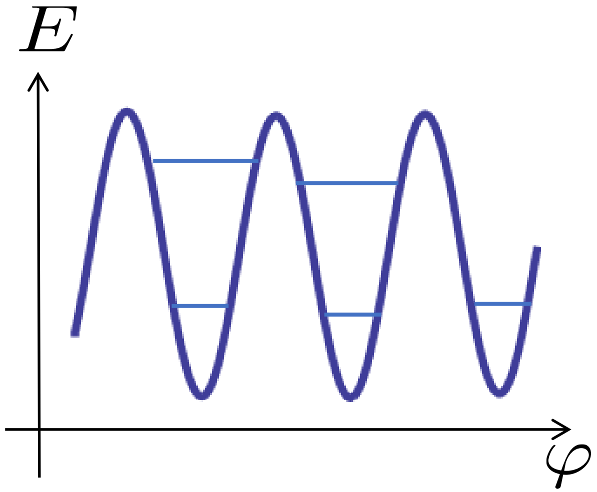
$$\hat{H} = 4E_c(\hat{n} - n_g)^2 - E_J cos\hat{\varphi} + \frac{1}{2}E_L(\hat{\varphi} - \varphi_{ext})^2$$

$$[\hat{\varphi}, \hat{n}] = i$$

$E_L/E_J = 10$



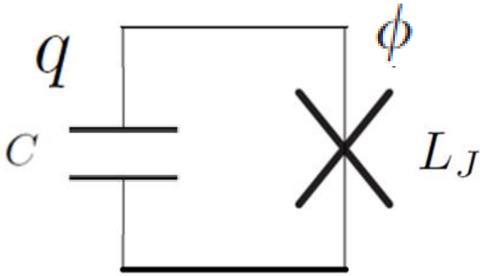
$E_L/E_J = 10^{-3}$

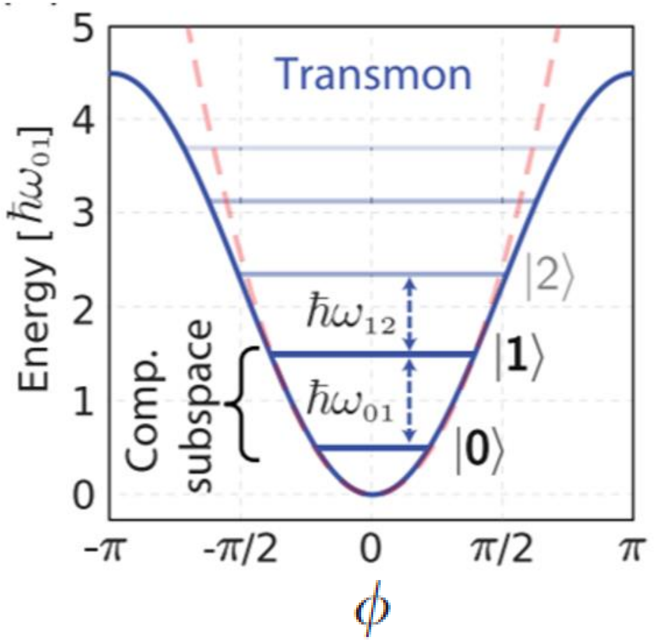


Artificial atoms: engineerable energy states and transitions

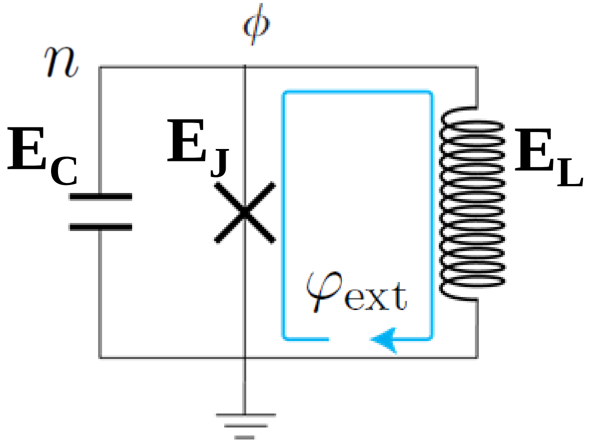
Transmon vs Fluxonium Superconducting Qubits

Transmon

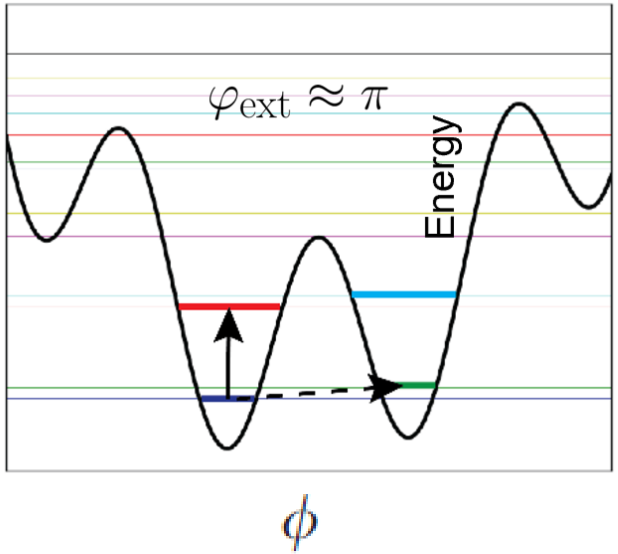




Fluxonium

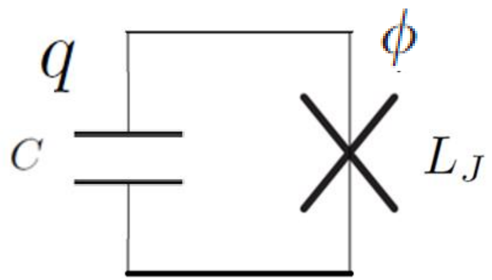


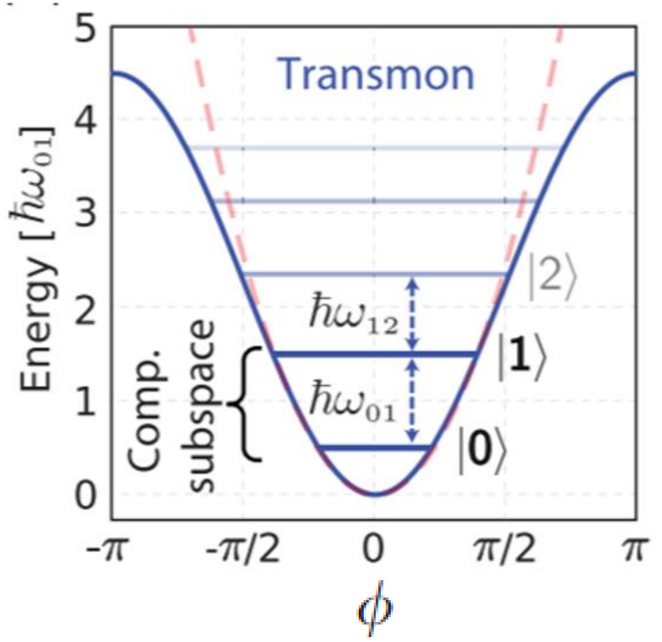
$E_L = 0.5$, $E_c = 1$, $E_J = 10$ (unit:h*GHz)



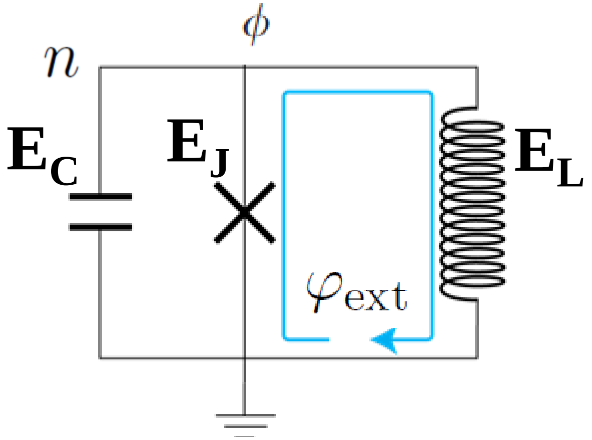
Transmon vs Fluxonium Superconducting Qubits

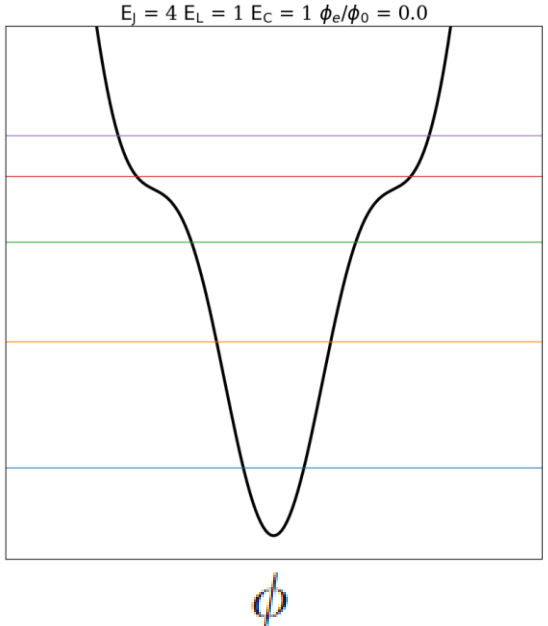
Transmon





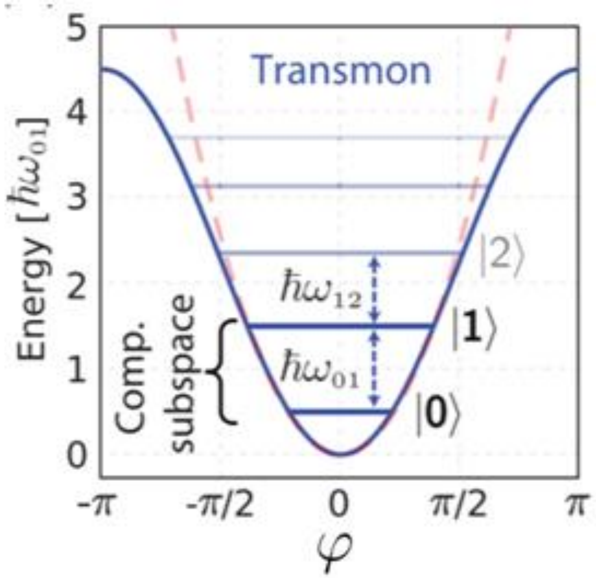
Fluxonium





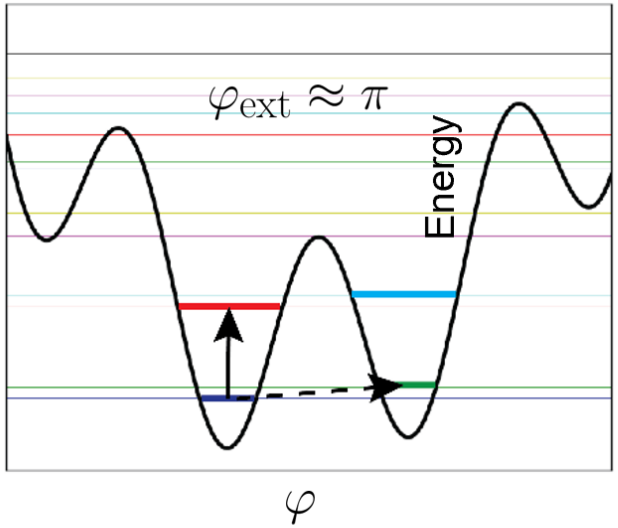
Transmon vs Fluxonium Superconducting Qubits

Transmon



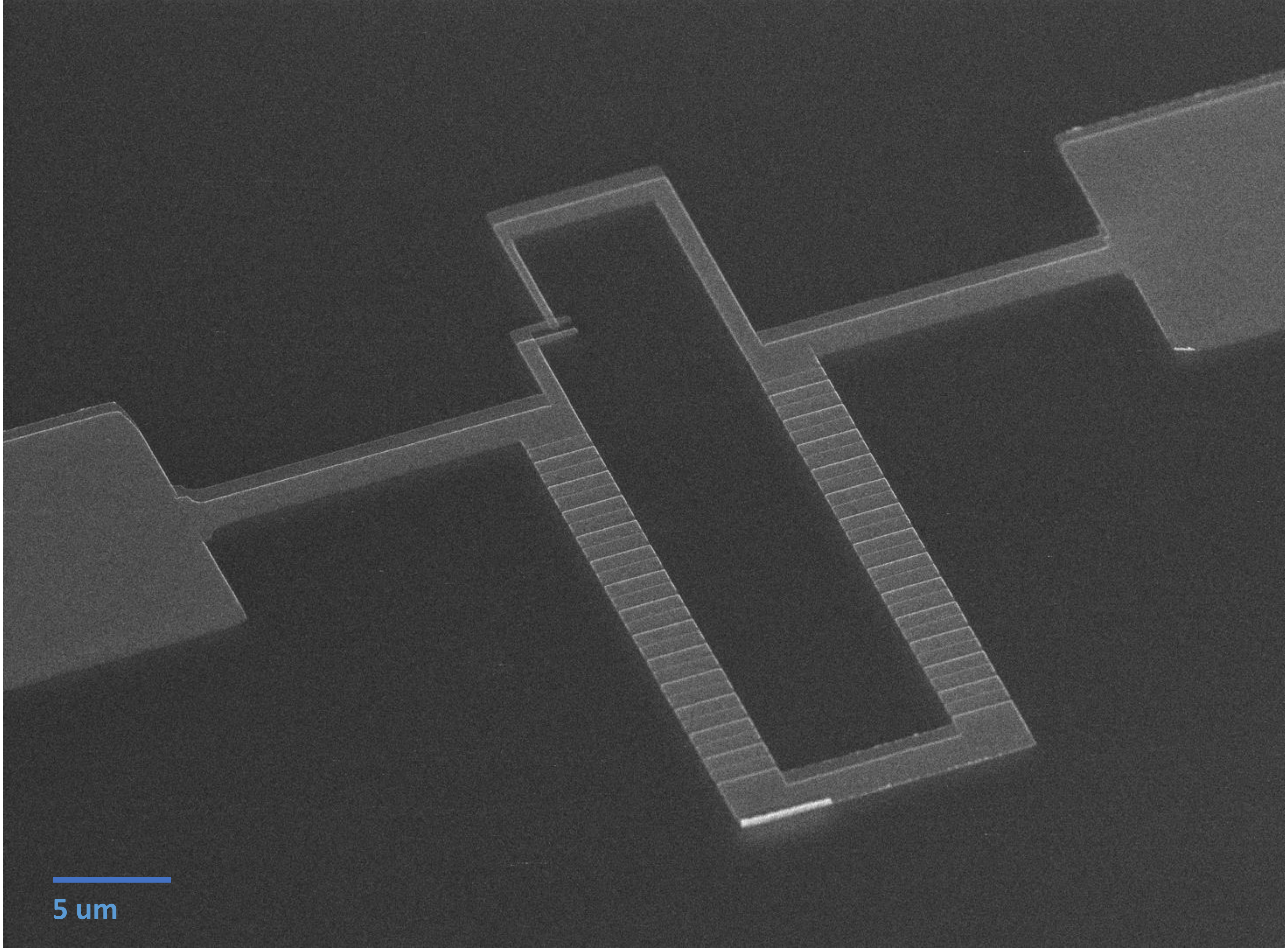
Fluxonium

$E_L = 0.5$, $E_c = 1$, $E_J = 10$ (unit:h*GHz)

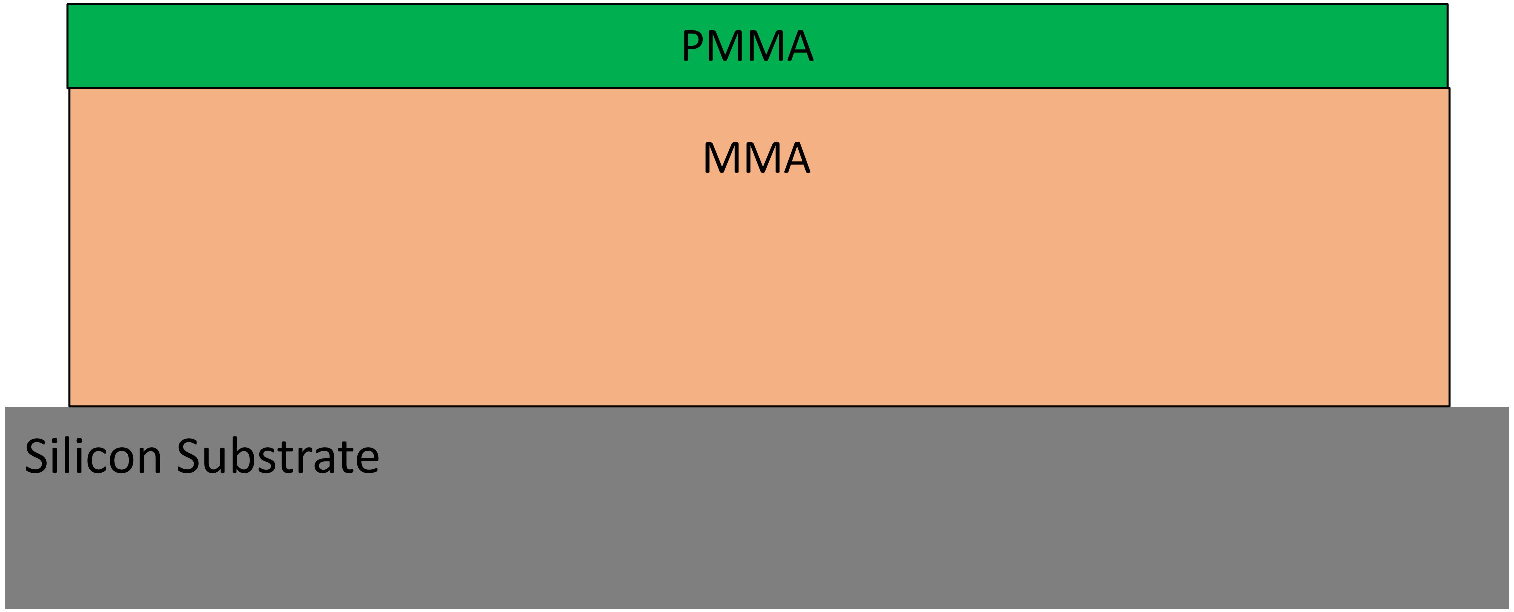


- Qubit transition frequency: 4~8GHz vs 10MHz~8GHz.
- Anharmonicity: ~100MHz vs ~1GHz
- Transition spectrum: Simple vs Rich

How to fabricate fluxonium qubits?


5 um

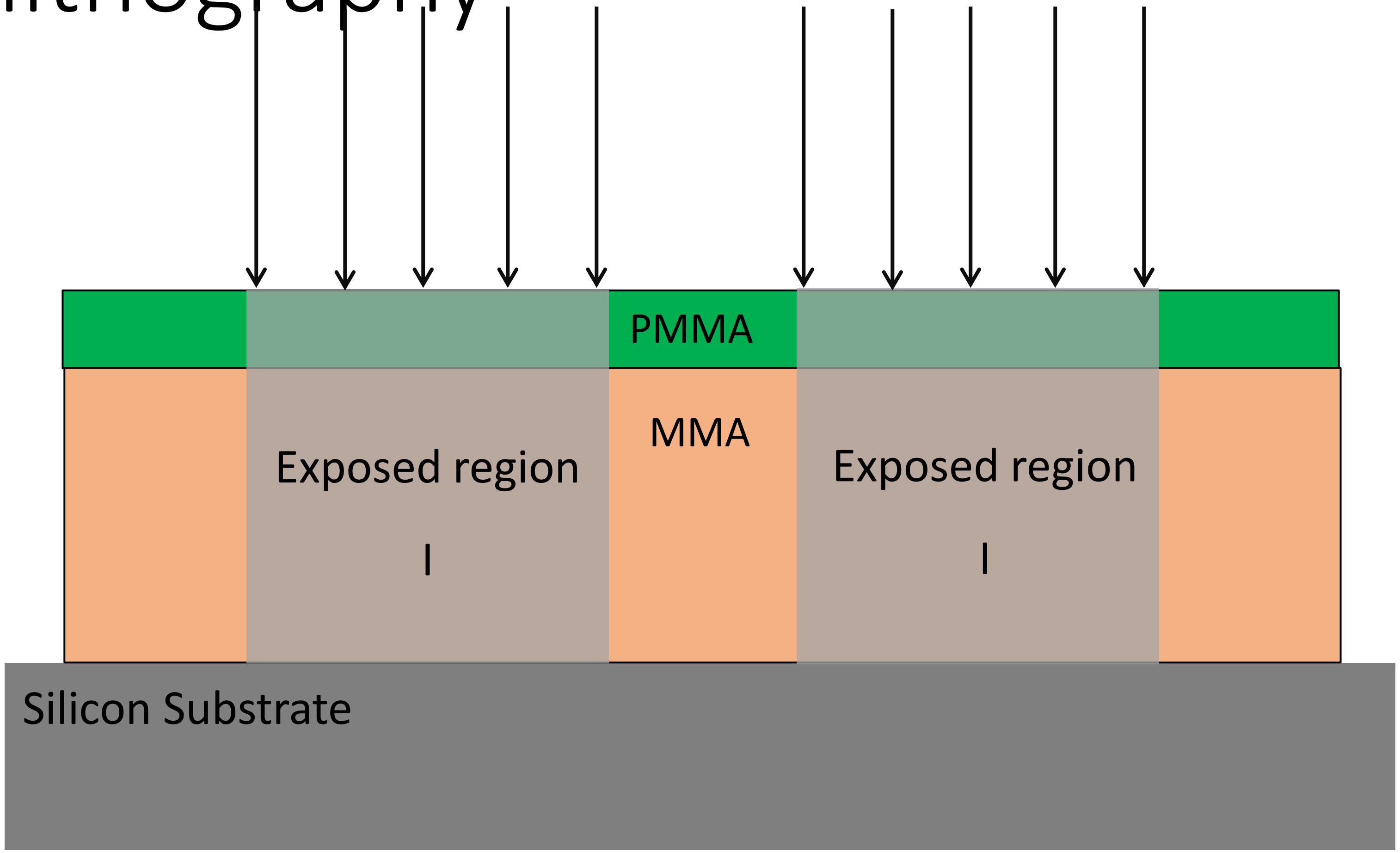
Example of Superconducting Qubits Fabrication in NTHU



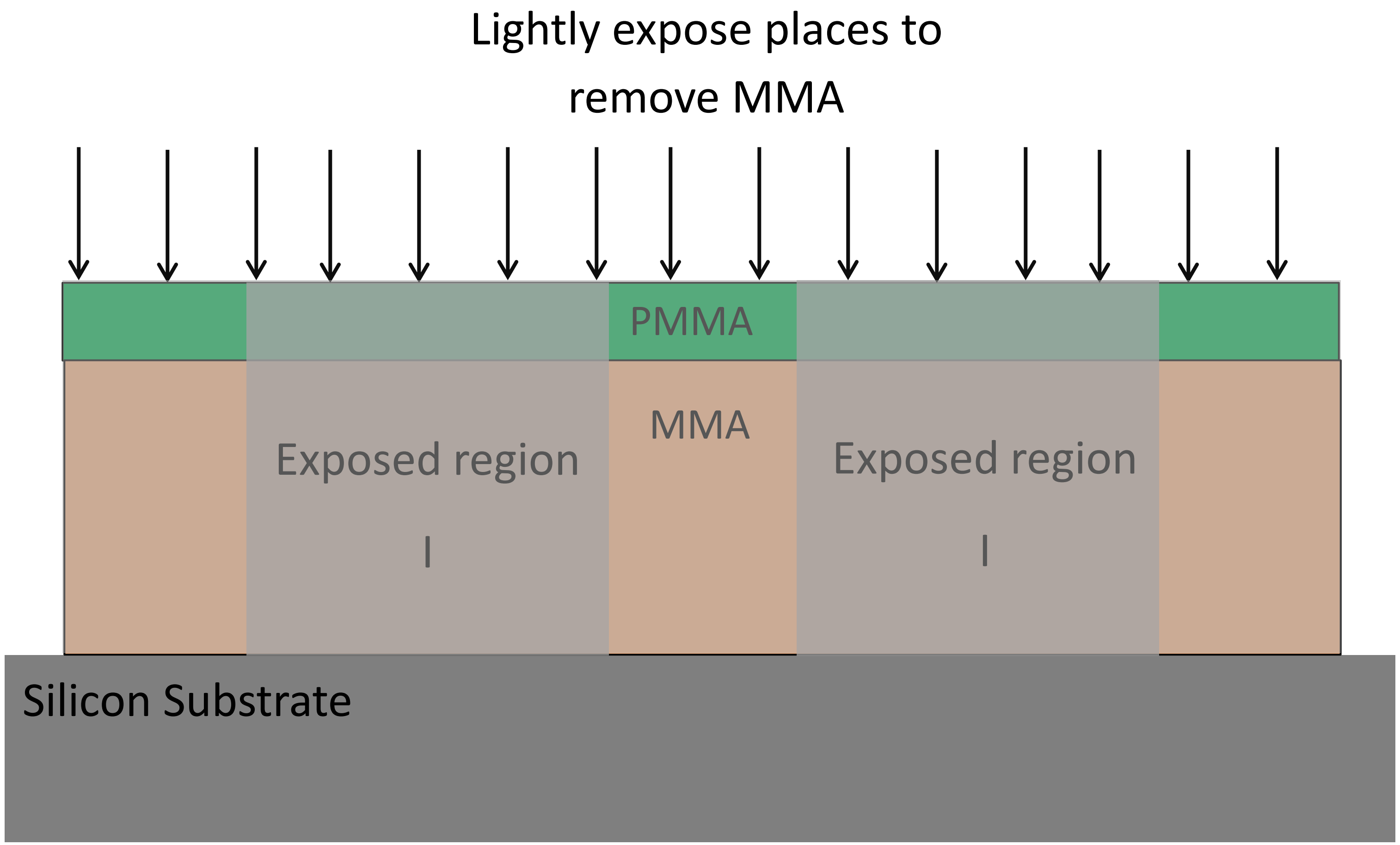
- Cite original Dolan bridge paper 1977

Example of Josephson Junction and Array Fabrication

E-beam lithography

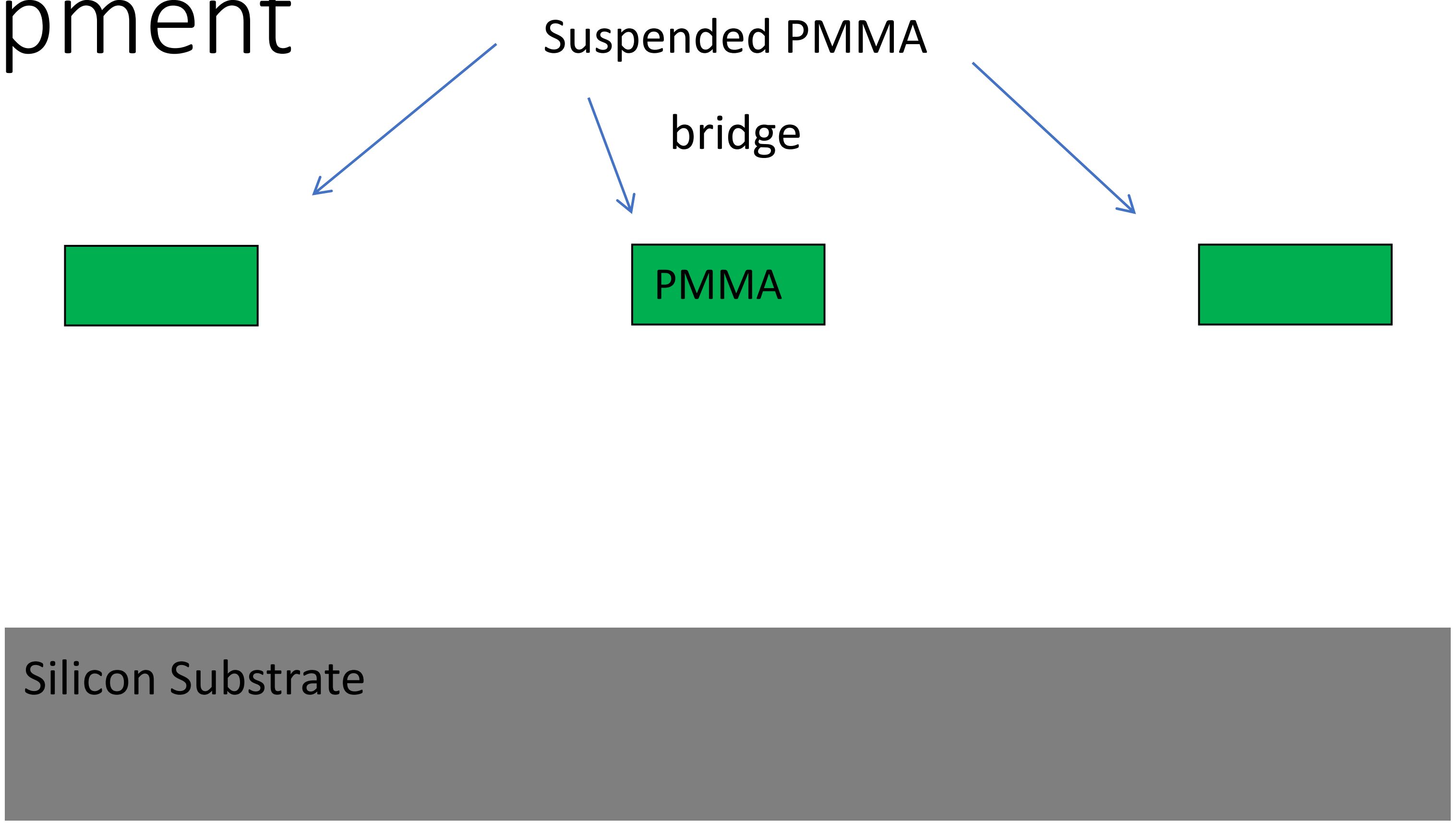


Example of Josephson Junction and Array Fabrication



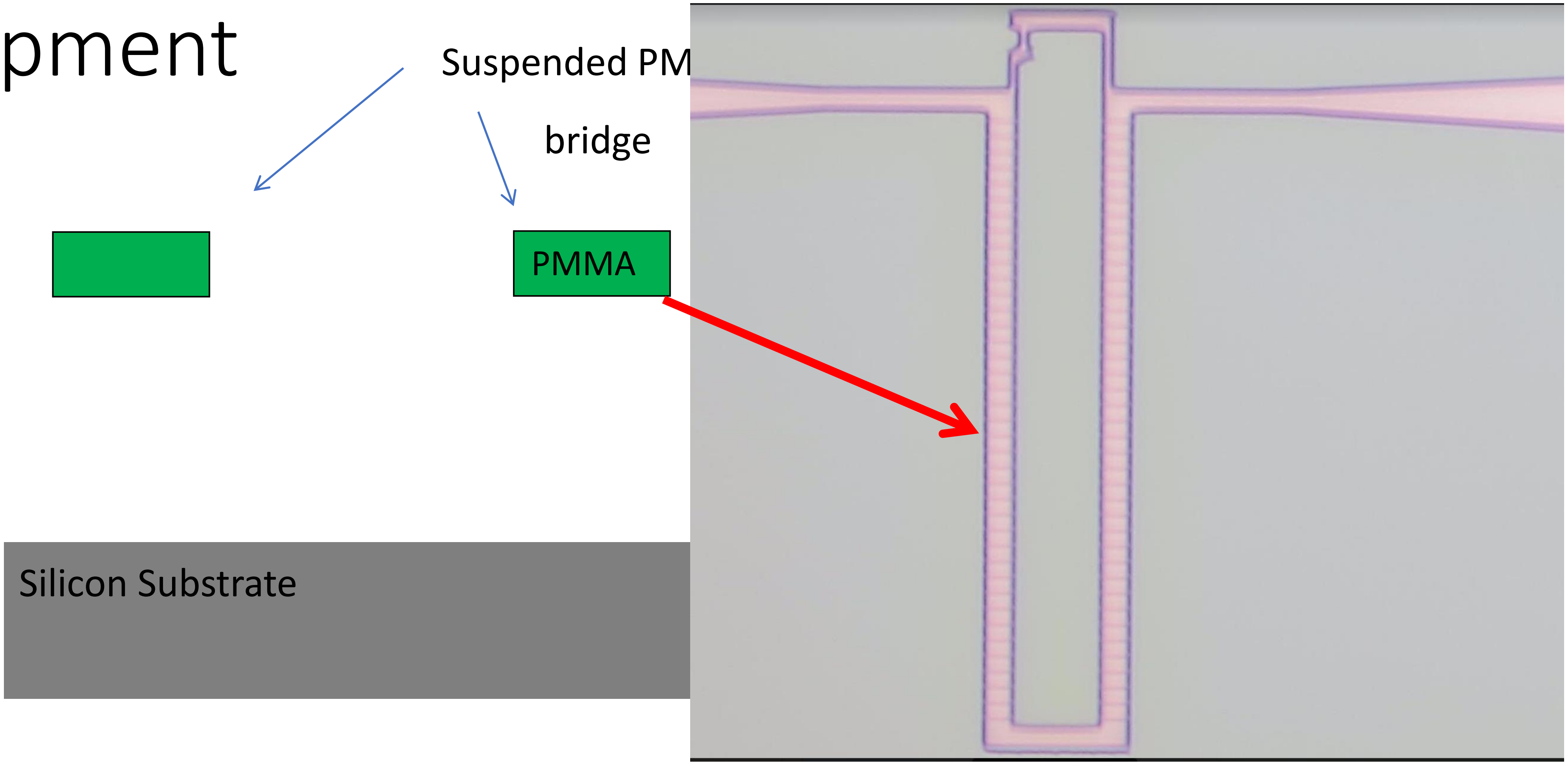
Example of Josephson Junction and Array Fabrication

Development



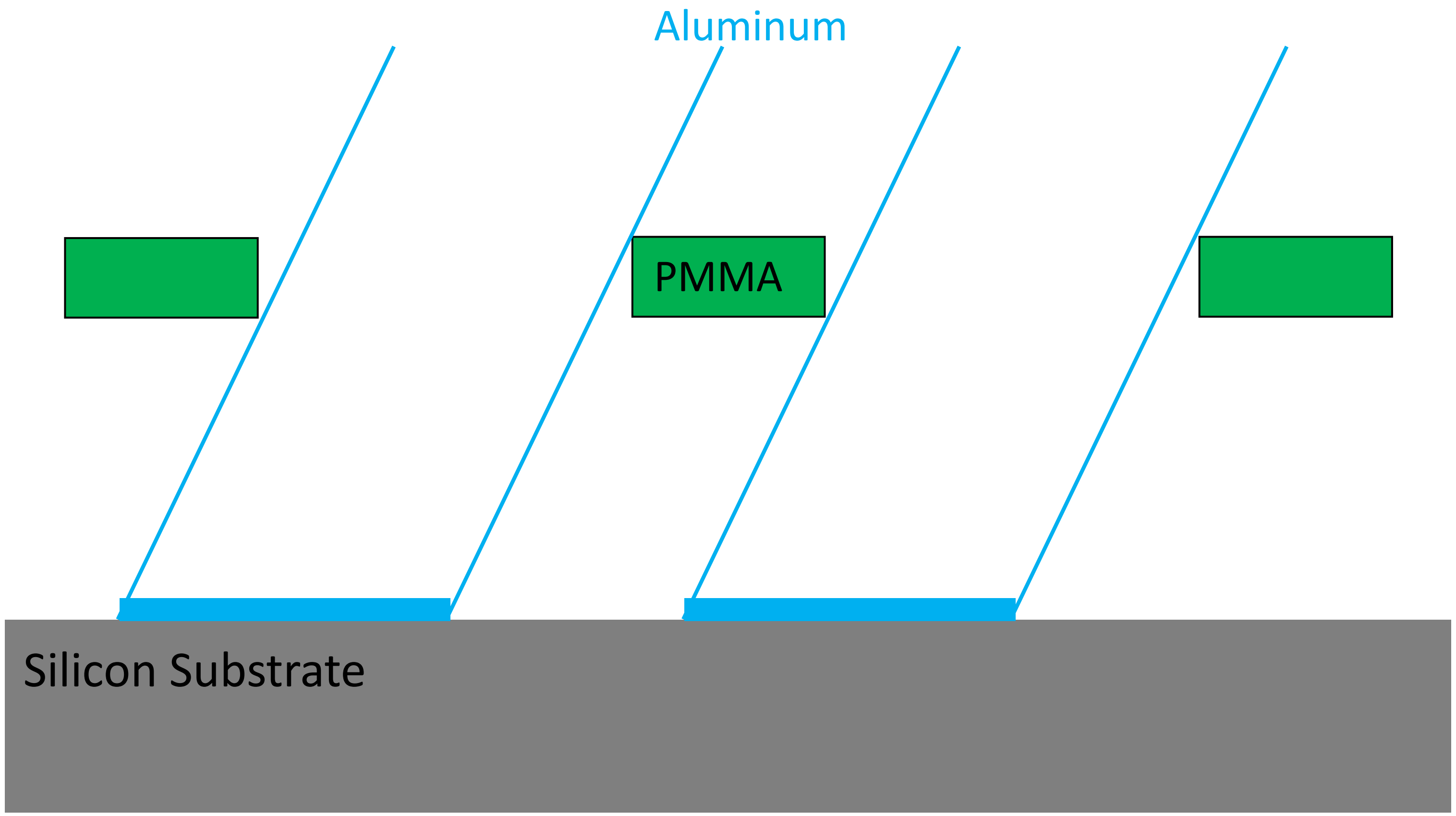
Example of Josephson Junction and Array Fabrication

Development



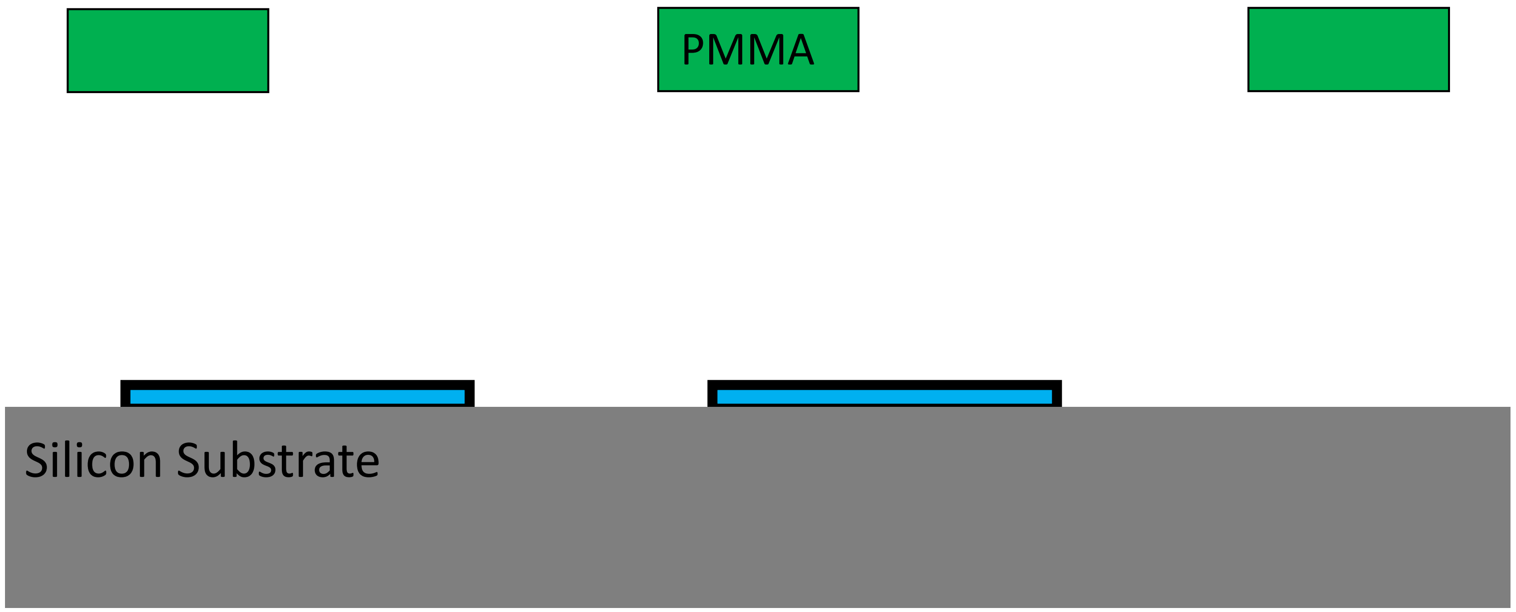
Example of Josephson Junction and Array Fabrication

Shadow evaporation



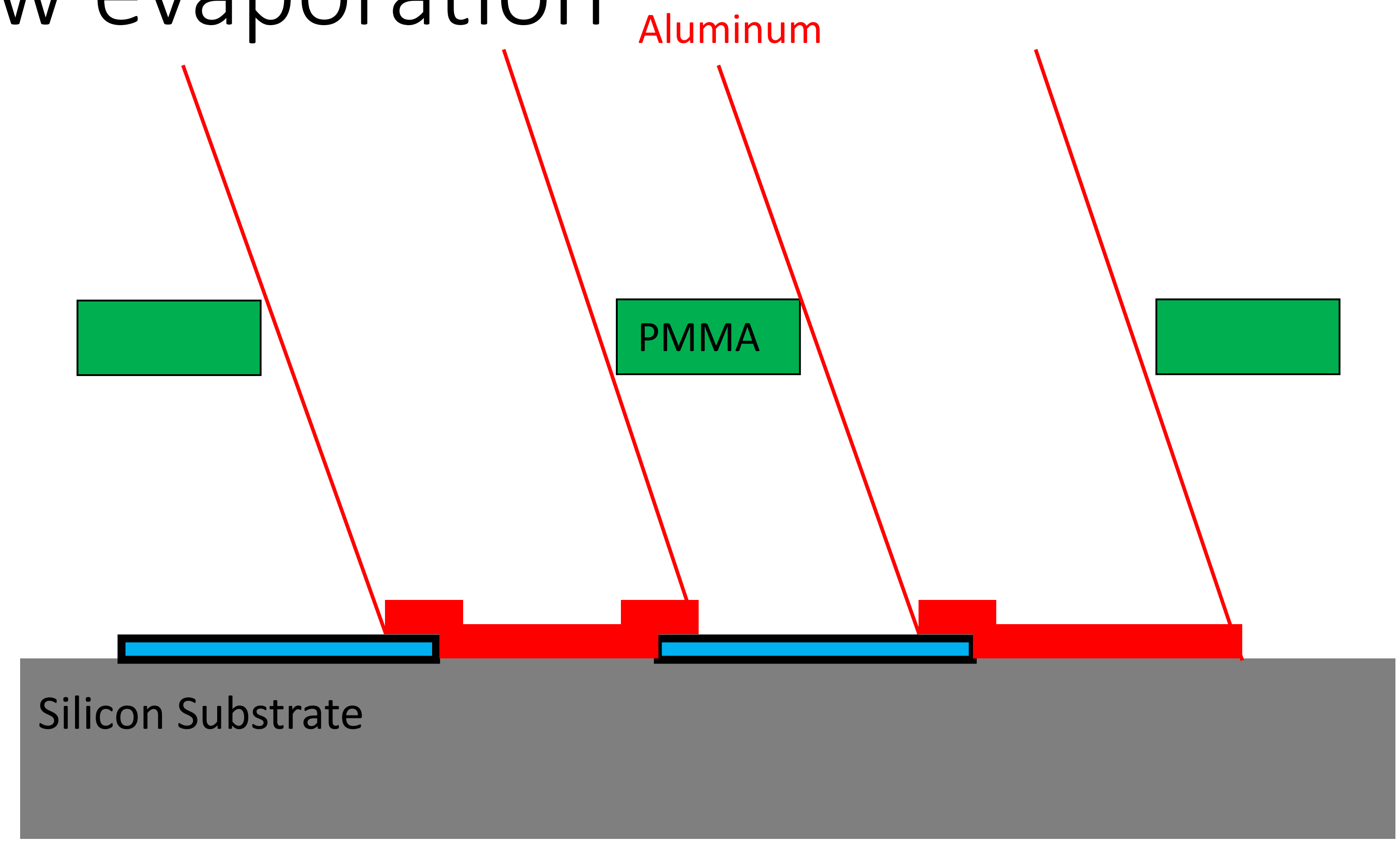
Example of Josephson Junction and Array Fabrication

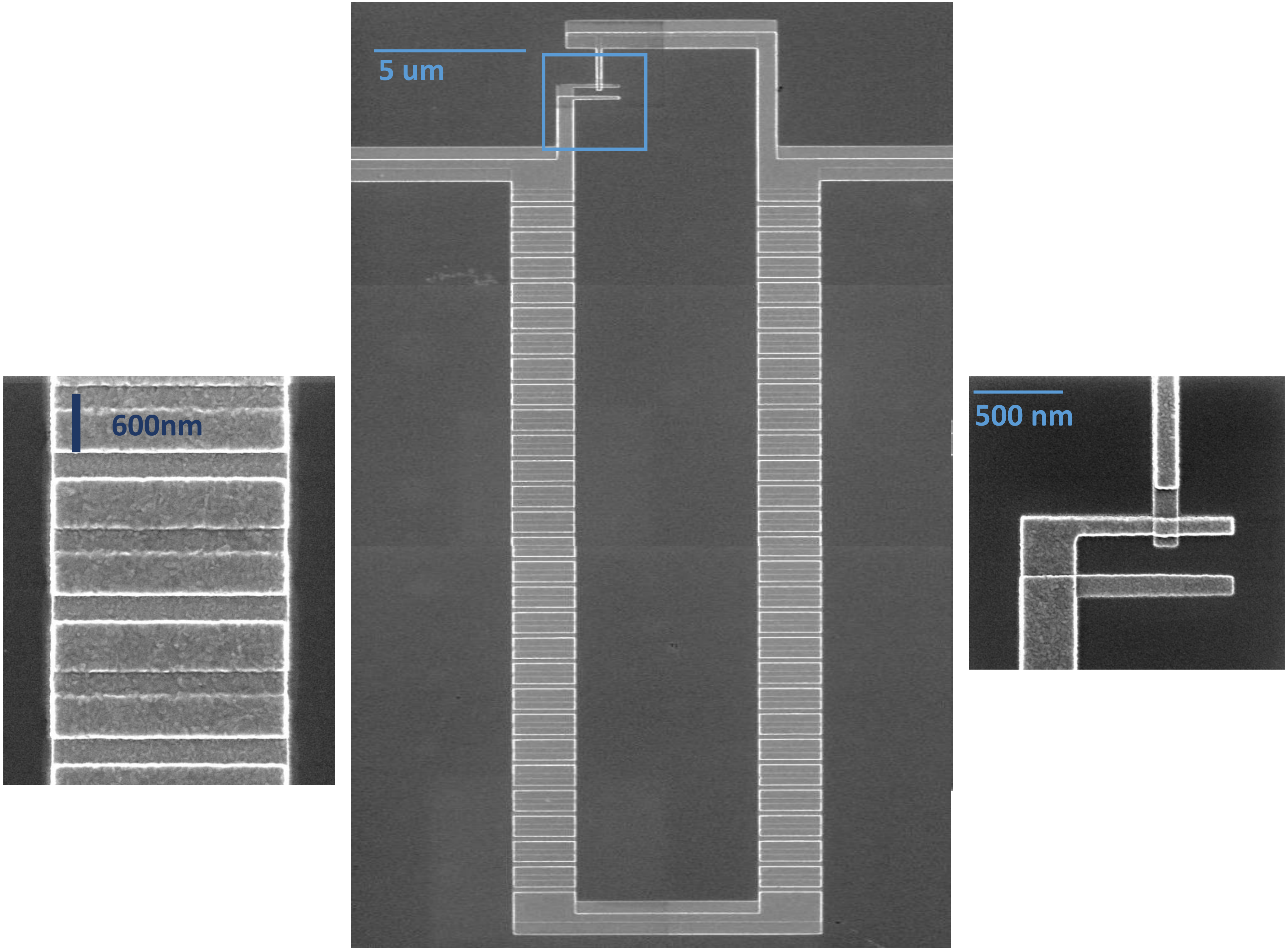
In-situ oxidation

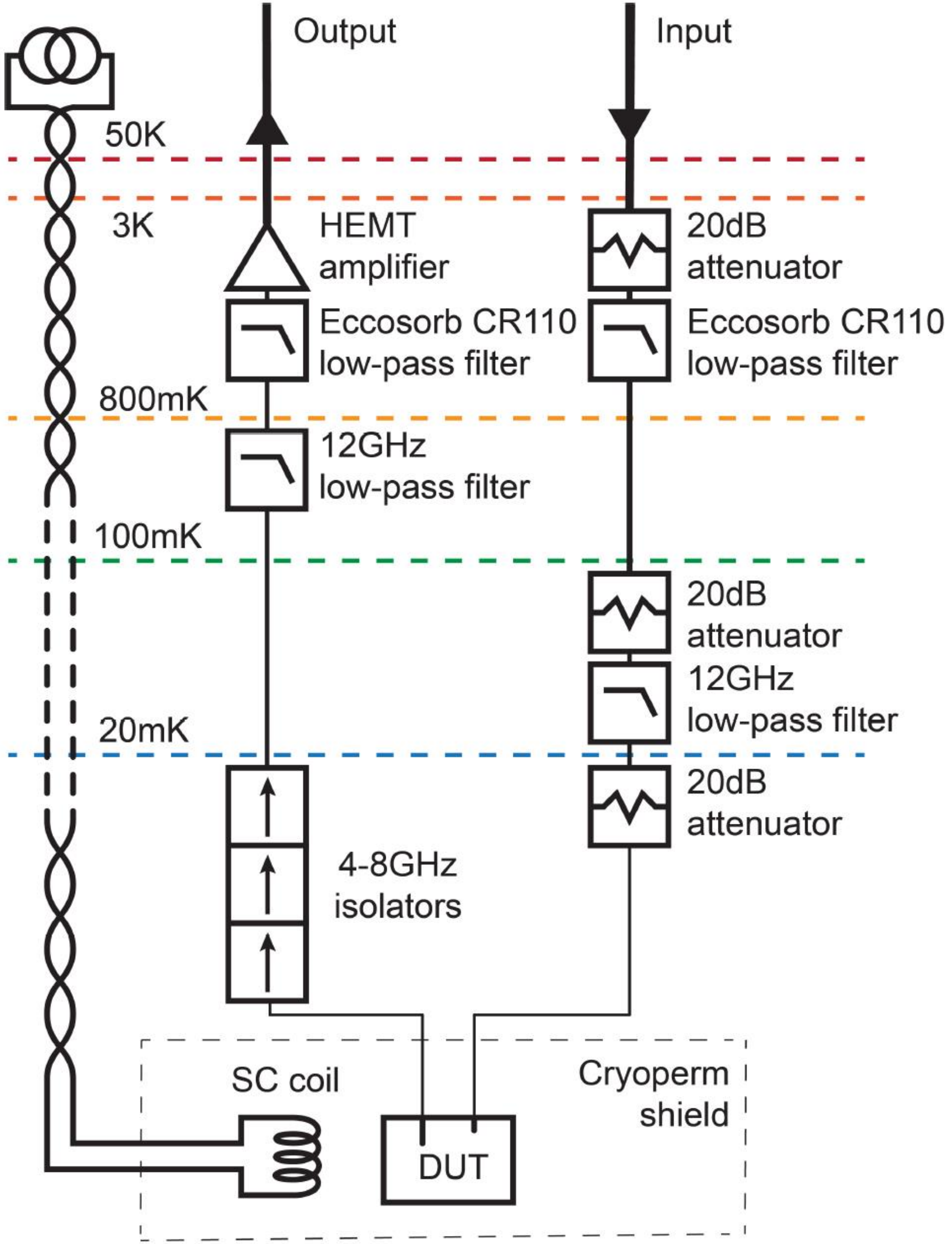


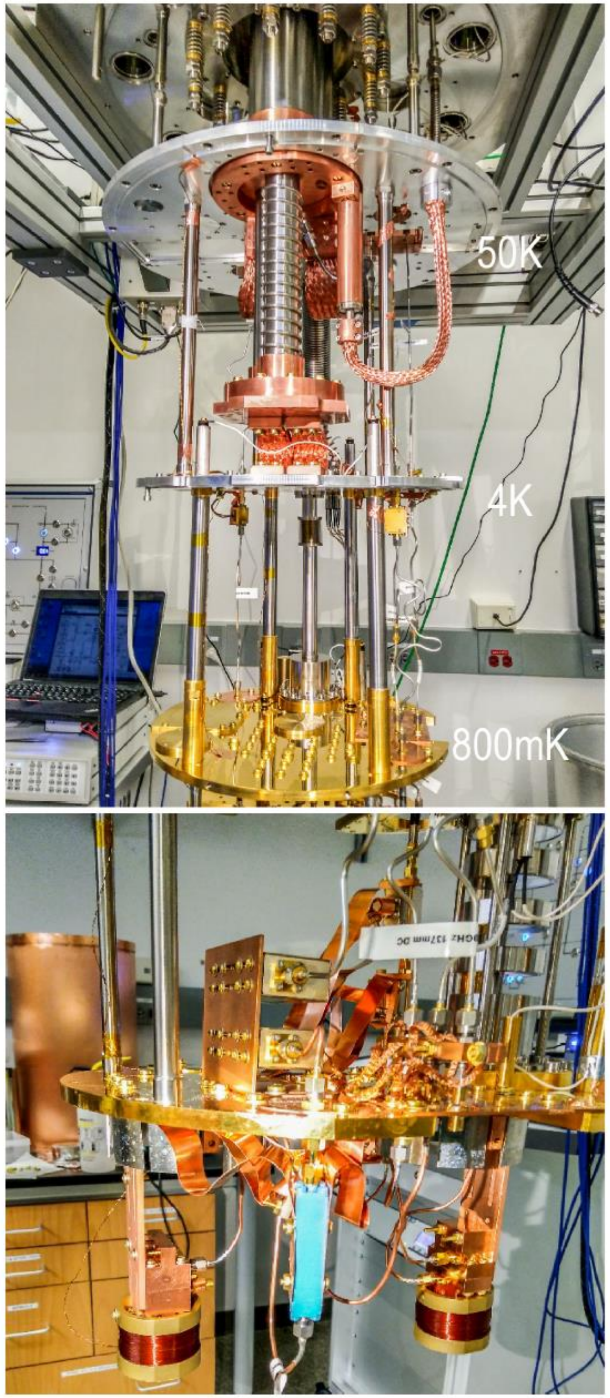
Example of Josephson Junction and Array Fabrication

Shadow evaporation



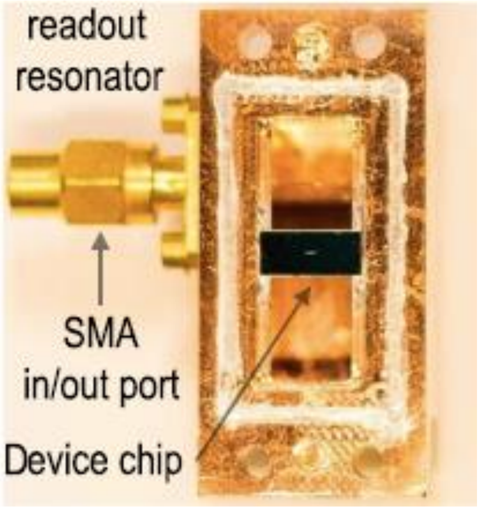

600nm
5 um
500 nm


Output
Input
50K
3K
HEMT
amplifier
20dB
attenuator
Eccosorb CR110
low-pass filter
Eccosorb CR110
low-pass filter
800mK
12GHz
low-pass filter
100mK
20dB
attenuator
12GHz
low-pass filter
20mK
20dB
attenuator
4-8GHz
isolators
SC coil
Cryoperm
shield
DUT

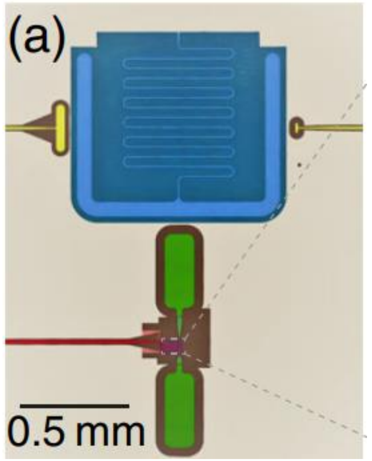

50K
4K
800mK

How to readout fluxonium superconducting qubits?

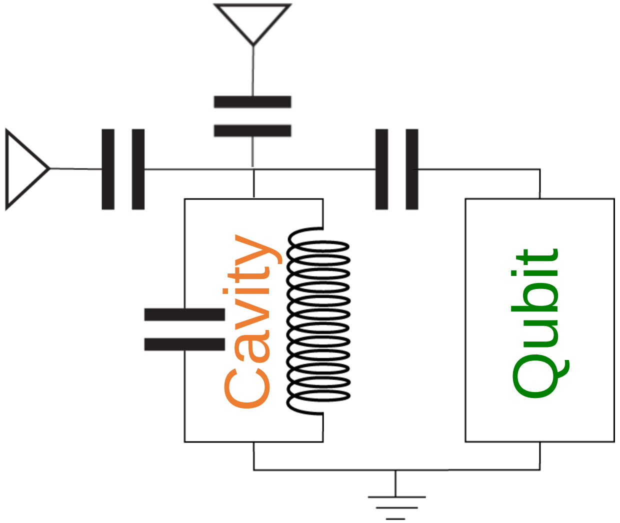
Element for protection and readout: cavity

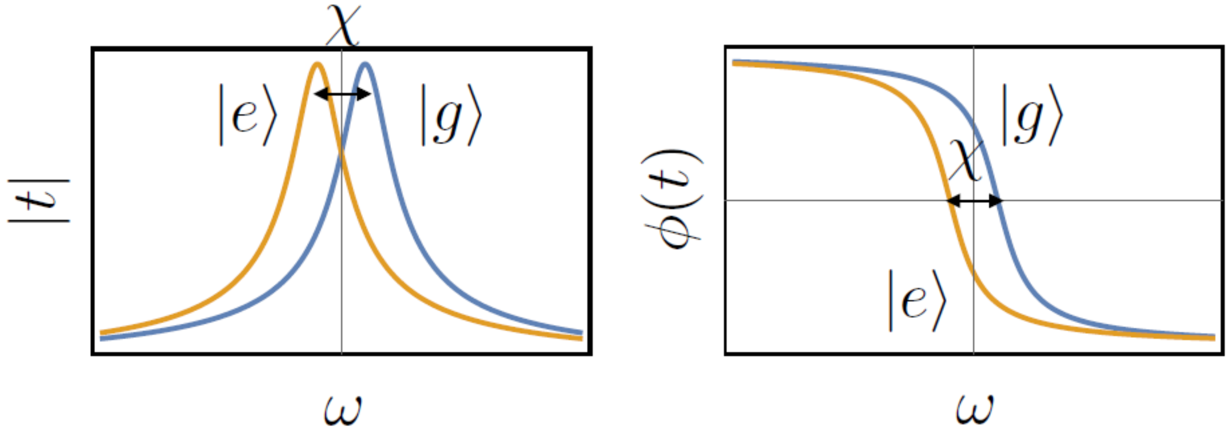


Nguyen, **Lin**, et al.
Phys. Rev. X. 9, 041041(2019)



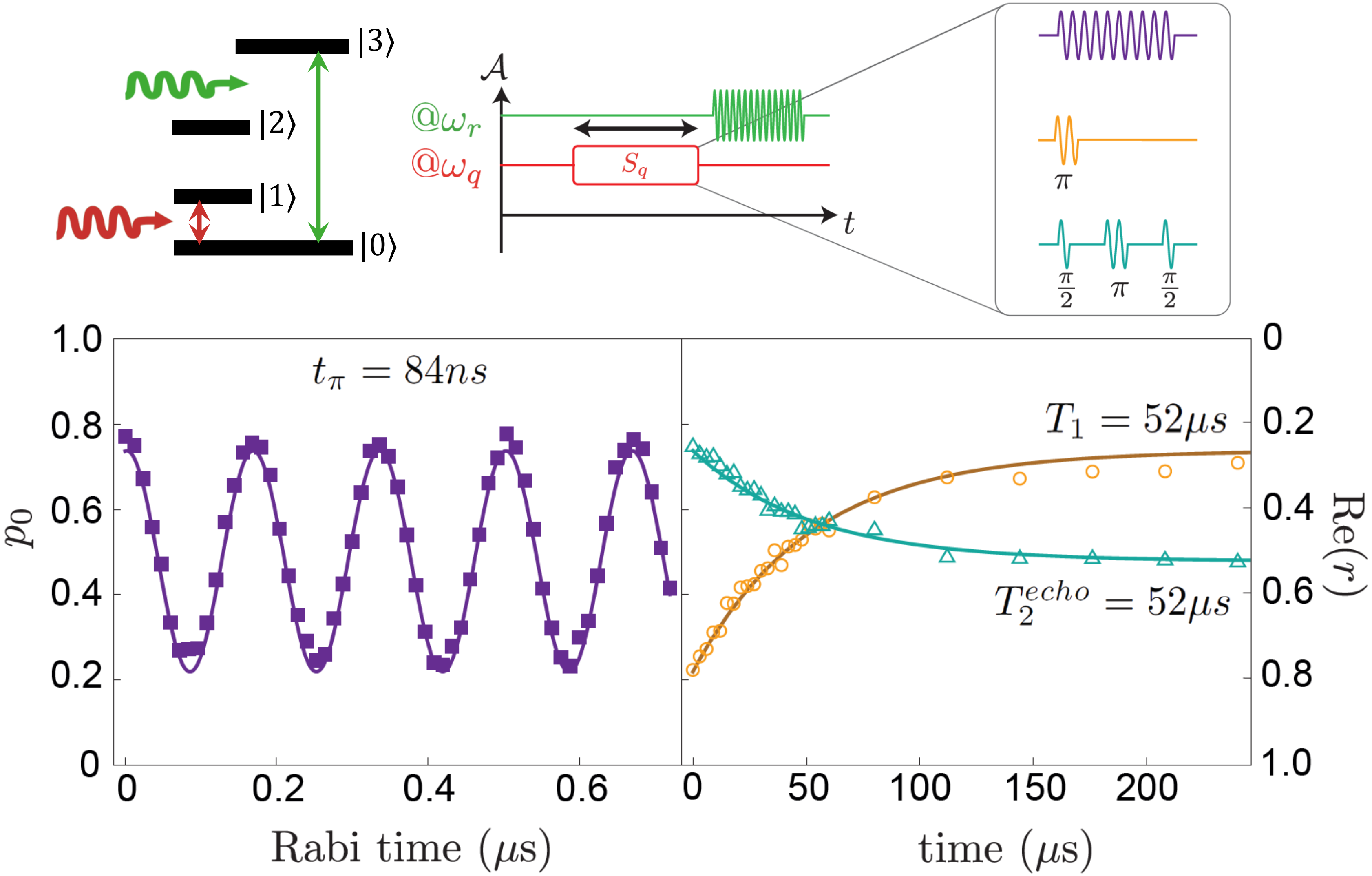
Zhang, et al.
Phys. Rev. X. 11, 011010(2021)

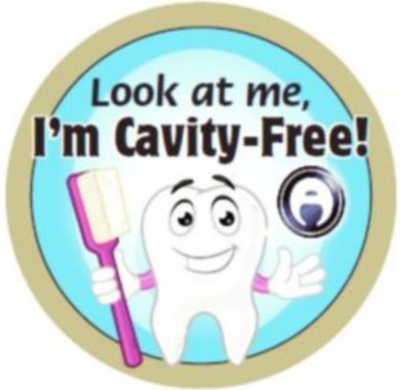




- Cavity acts as protection from environment
- Cavity mode coupling to qubits works as a readout by detecting shift of qubit's frequency

Alternative Readout: Electronic Shelving Readout

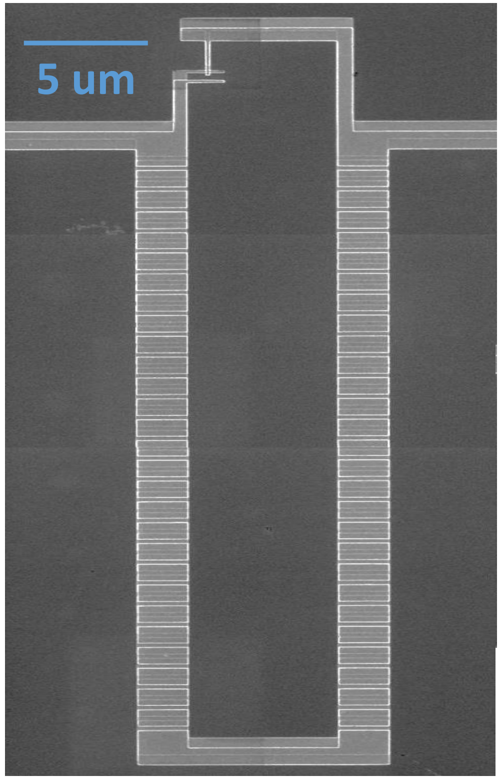




Cottet, Xiong, Nguyen, **Lin**, and Manucharyan Nature Comm. 12, 63883 (2021)

How long is fluxonium superconducting qubits’ coherence time?

Reproducible Long T2 of fluxonium superconducting qubit



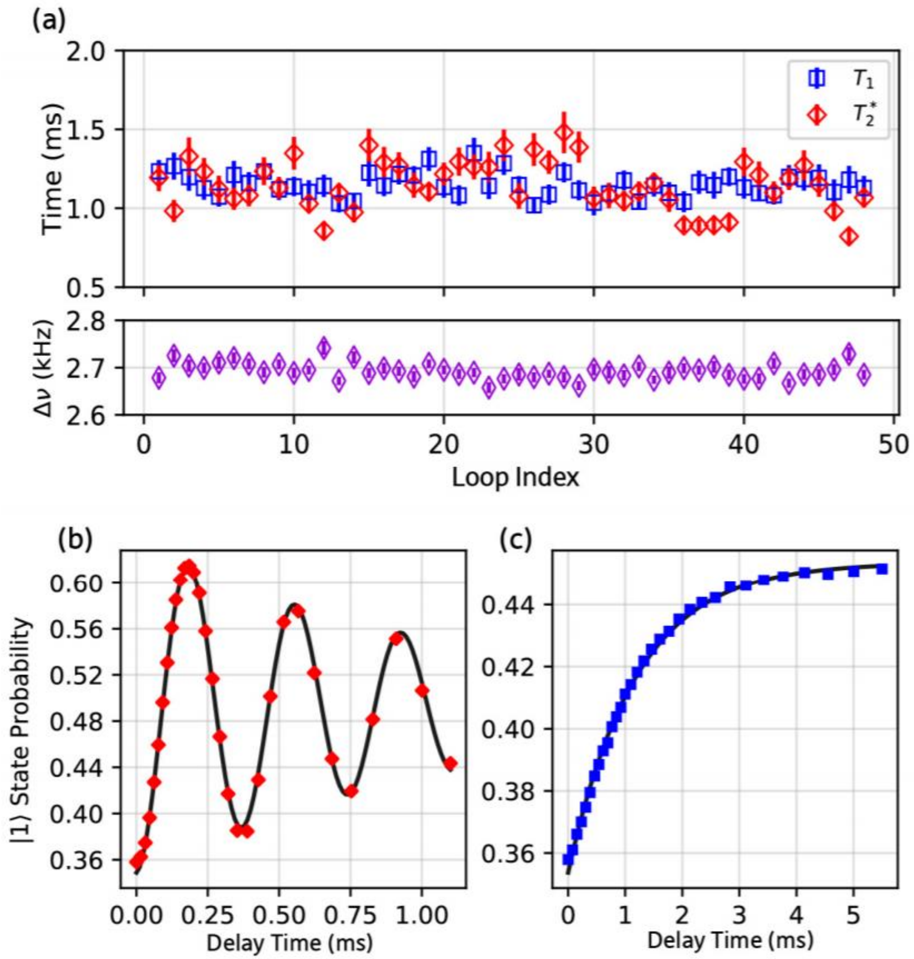
Qubit	E_J	E_C	E_L	N	T_1	T_2	$\omega_{01}/2\pi$
	GHz	GHz	GHz	-	μs	μs	GHz
A	3	0.84	1	100	110	160	0.78
B	4.86	0.84	1.14	136	250	150	0.32
C	2.2*	0.55	0.72	102	260	350	0.48
D	2.2	0.83	0.52	196	70	90	0.56
E	1.6	0.86	0.5	100	108	140	0.83
F	3.4	0.8	0.41	348	270	165	0.17
G	1.65	1.14	0.19	400	110	140	0.55
H	4.43	1	0.79	100	230	235	0.32

Nquyen, **Lin** et al., PRX 9, 041041(2019)

IBM Q 20 Tokyo: average T1= 78.34μs,T2=50.62μs

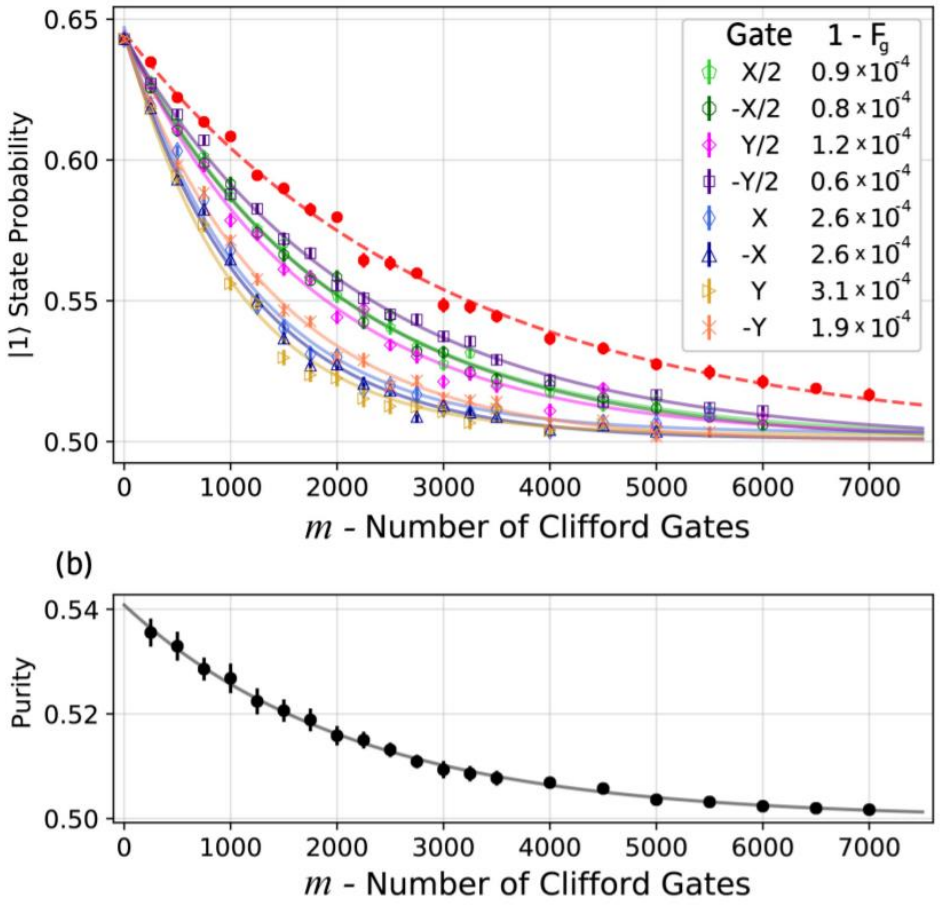
https://www.research.ibm.com/ibm-q/technology/devices/

World Record T2 of superconducting qubit



$$\bar{T}_2^* = 1.16 \pm 0.05 \text{ ms.}$$

$$\bar{T}_1 = 1.20 \pm 0.03 \text{ ms.}$$



Average single qubit gate fidelity 99.991%

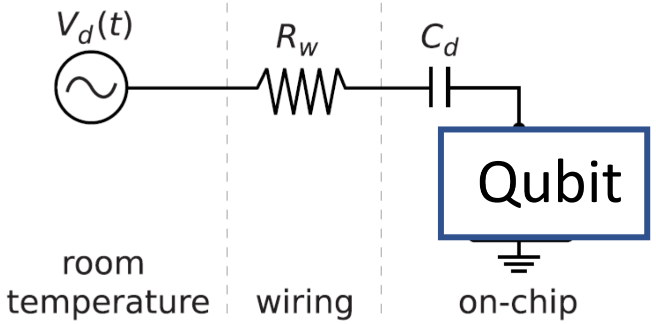
arXiv:2103.08578 (2021) by Manucharyan’s group

How to apply quantum gates with fluxonium?

Control of Superconducting Qubit

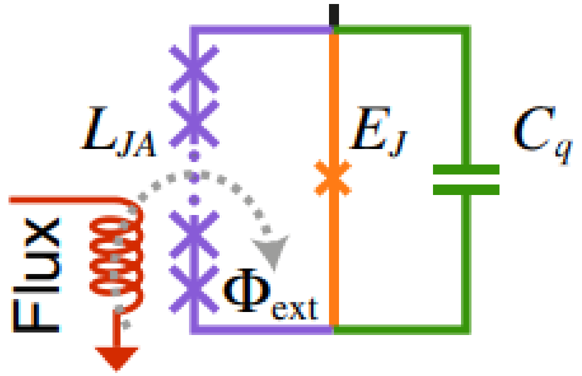
Operate fluxonium superconducting qubits' states:

- Electrical coupling
- Magnetic coupling



$$\tilde{H}_d = -\frac{\Omega}{2} V_0 s(t)(I\sigma_x + Q\sigma_y)$$

Appl. Phys. Rev. **6**, 021318 (2019)



$$R_z(\theta) = e^{-i\sigma_z\theta/2},$$

$$R_{xz}(\theta) = e^{-i(\theta\sigma_x + \lambda|\theta|\sigma_z)/2}.$$

Phys. Rev. X **11**, 011010 (2021)

Two-qubit gates of fluxonium qubits

- Microwave Driven Induced C-Phase gate

Theory: Phys. Rev. A 98, 030301(R) (2018)

Exp: PRX 11, 021026 (2021), PRResearch 4, 023040(2022)(F=0.992)

- Cross Resonance CNOT gate

Theory:arXiv:2202.04583 (2022)

Exp: arXiv. 2204.11829(2022) (F=0.9949)

- Magnetic flux tuded iSWAP gate

Theory: PRL 129, 010502 (2022)

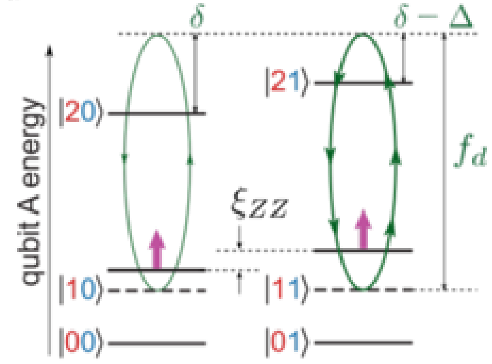
Exp: PRL 129, 010502 (2022)(F=0.9972)

- Tunable Coupler:

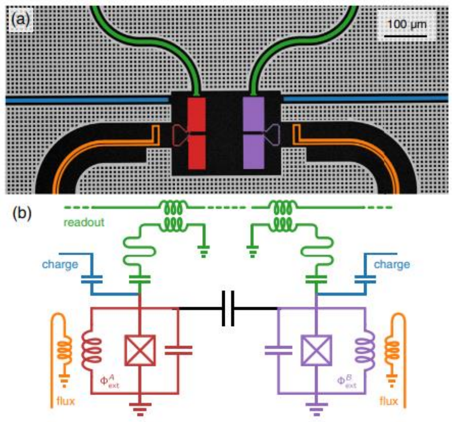
Theory: arXiv 2203.16302(2022), arXiv 2207.03971(2022)

Exp: Not reported yet

- New mechanism?



PRResearch 4, 023040(2022)



PRL 129, 010502 (2022)

Scaling up with Fluxonium Qubits

PRX QUANTUM **3**, 037001 (2022)

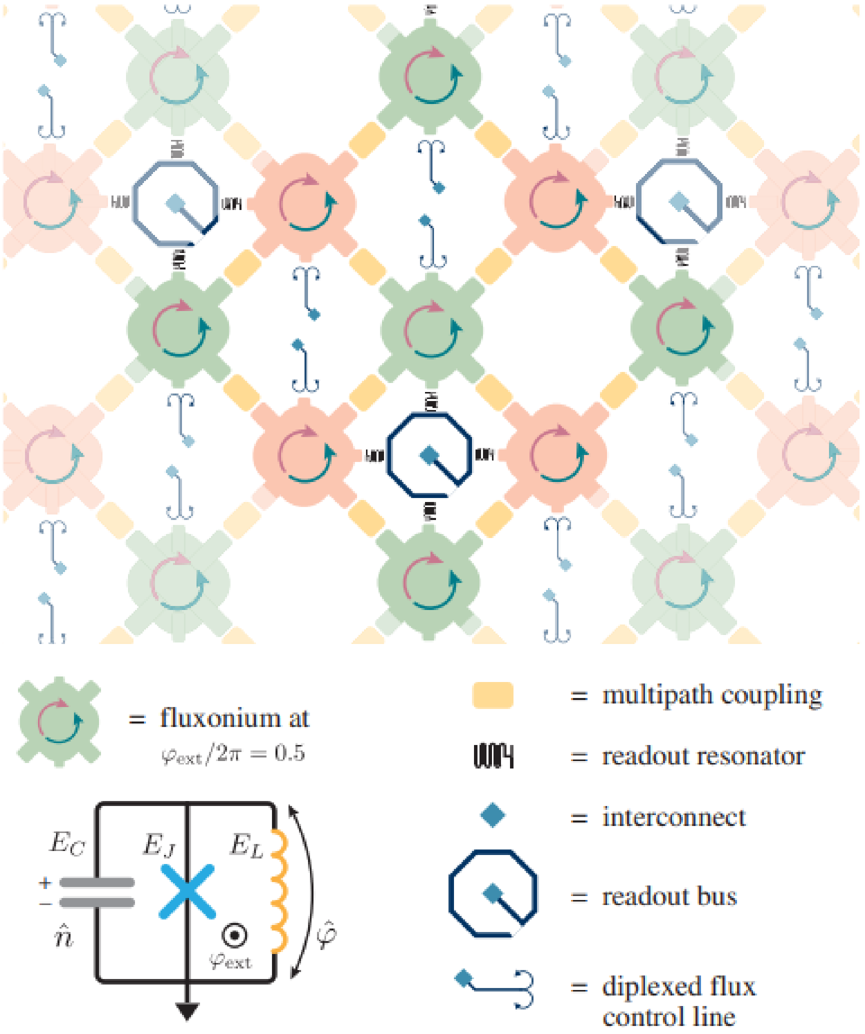
Roadmap

Blueprint for a High-Performance Fluxonium Quantum Processor

Long B. Nguyen,[1,2,*] Gerwin Koolstra,[1,2] Yosep Kim,[1,2,‡] Alexis Morvan,[1,2,§] Trevor Chistolini,[2] Shraddha Singh,[3,4] Konstantin N. Nesterov,[5] Christian Jünger,[1,2] Larry Chen,[2] Zahra Pedramrazi,[1,2] Bradley K. Mitchell,[1,2] John Mark Kreikebaum,[2,6] Shruti Puri,[3,4] David I. Santiago,[1,2] and Irfan Siddiqi[1,2,6,†]

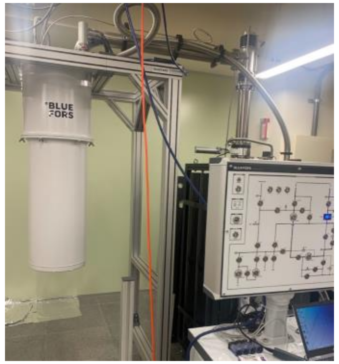
TABLE IV. Expected average Pauli errors in the processor for different average relaxation times T_1.

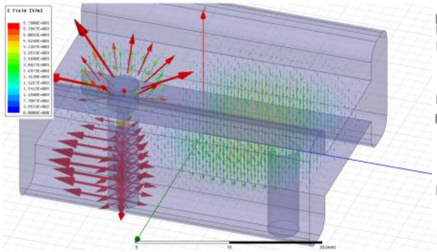
Operation	Error ε		
	300 μs	700 μs	1 ms
2Q CZ	5.3×10^{-4}	2.3×10^{-4}	1.6×10^{-4}
1Q H	1.1×10^{-5}	4.7×10^{-6}	3.3×10^{-6}
Readout	10^{-2}	10^{-2}	10^{-2}
Reset	10^{-2}	10^{-2}	10^{-2}
Idle (2Q)	2.2×10^{-4}	9.5×10^{-5}	6.6×10^{-5}
Idle (1Q)	1.1×10^{-5}	4.7×10^{-6}	3.3×10^{-6}
Idle (R)	2.2×10^{-4}	9.5×10^{-5}	6.6×10^{-5}



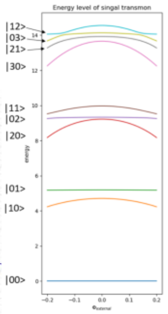
Fluxonium superconducting qubits in Taiwan?

Efforts of developing fluxonium qubits in NTHU





HFSS



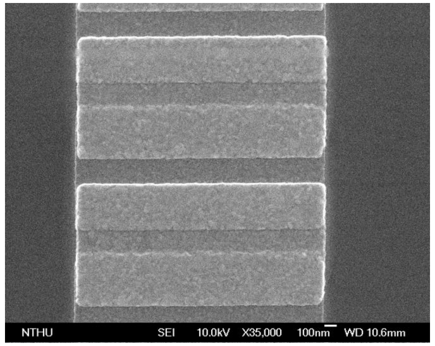
QuTip

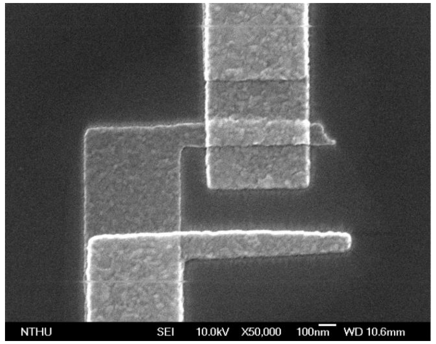
Design

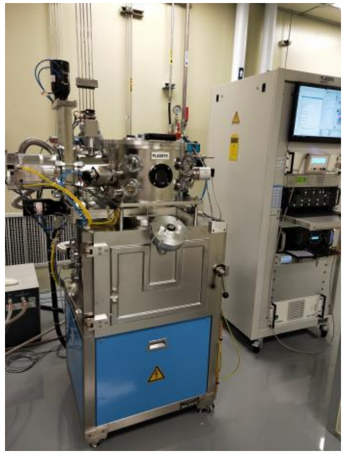
Measurement

Material Growth

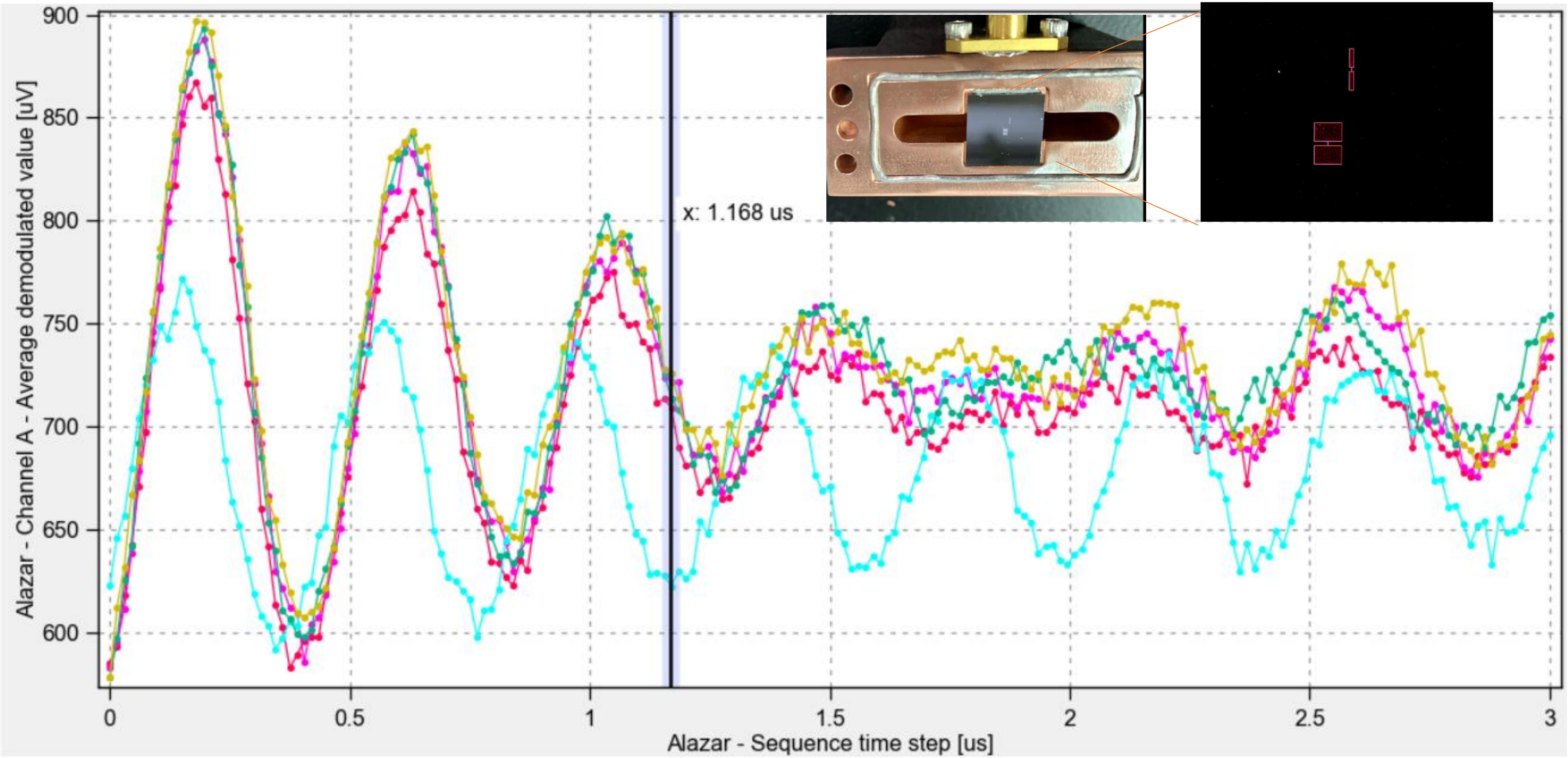
Fabrication





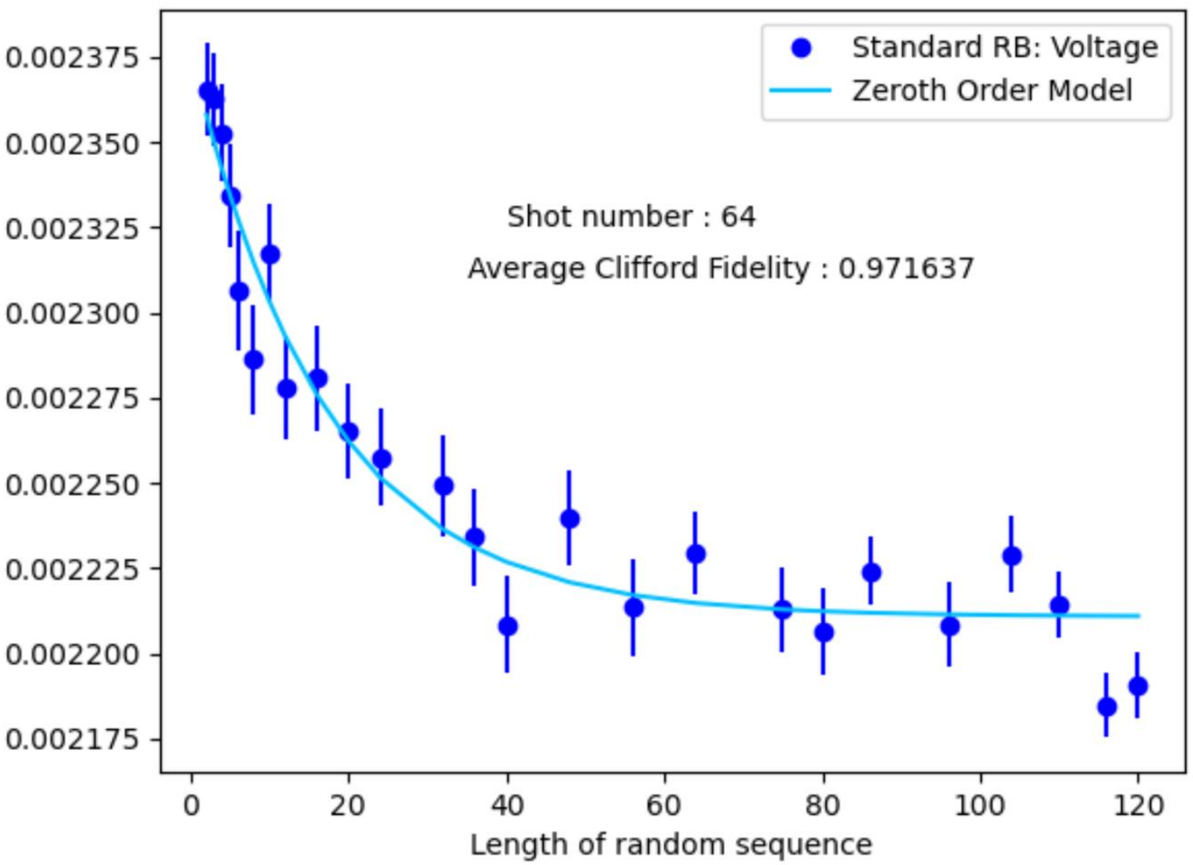


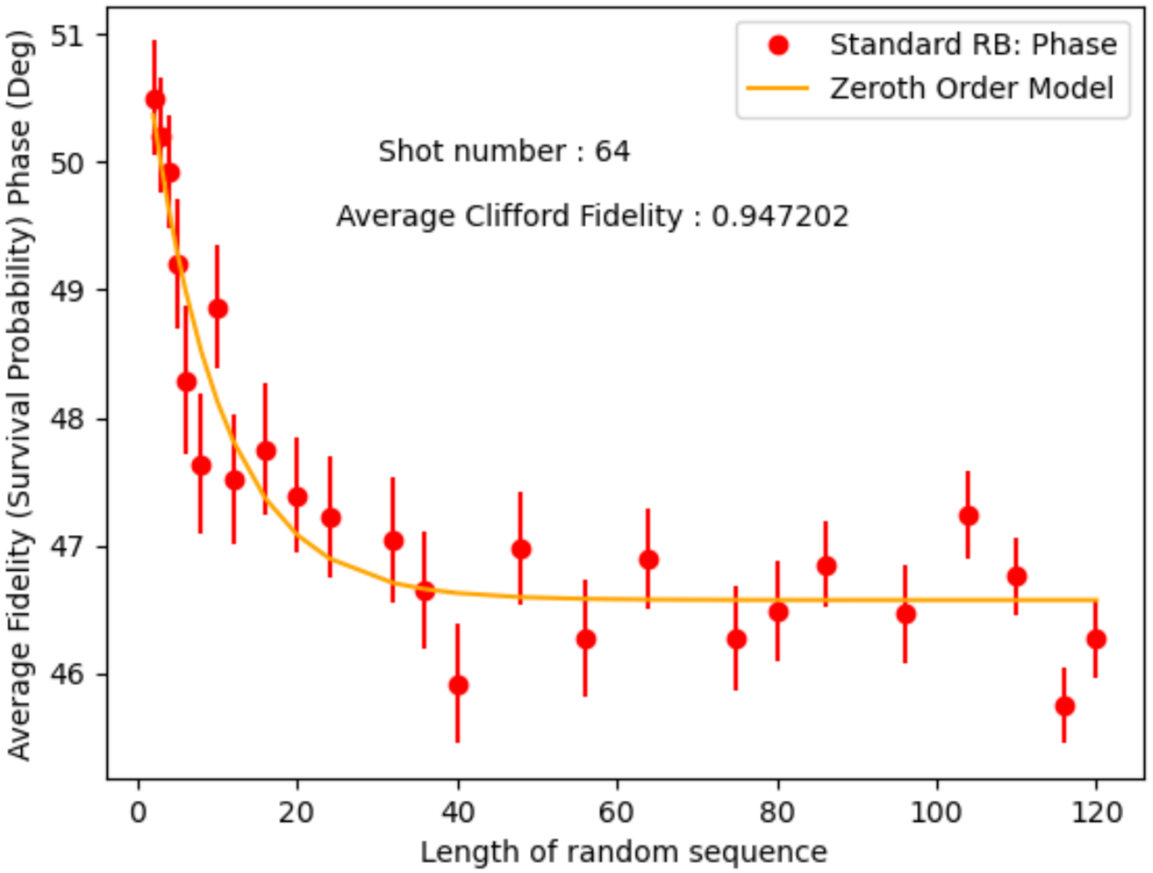
Realization of Two-qubits Gate with 3D Transmon qubit



Different phase accumulation rate in Ramsey fringe of Q2 depending on state of Q1=> MAP Gate!

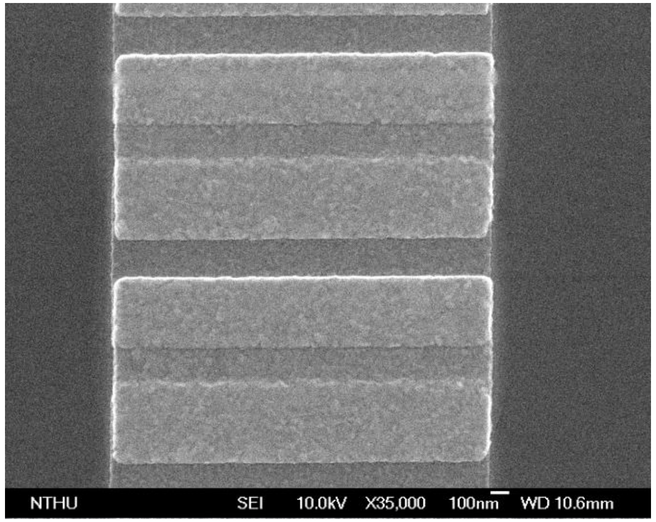
Gate Fidelity Characterization Tool: Randomized Benchmarking

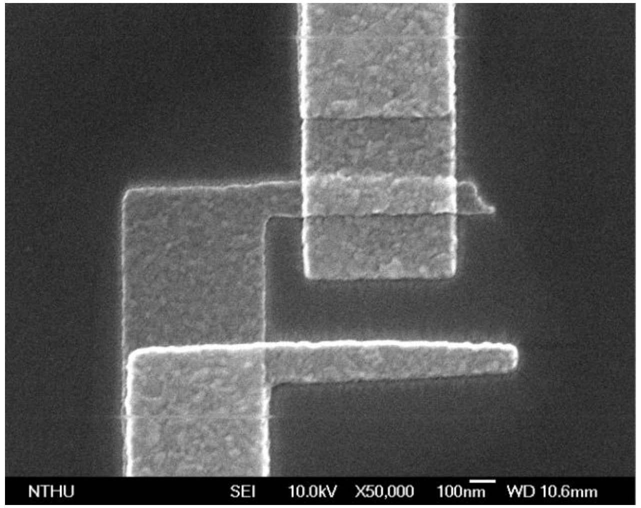


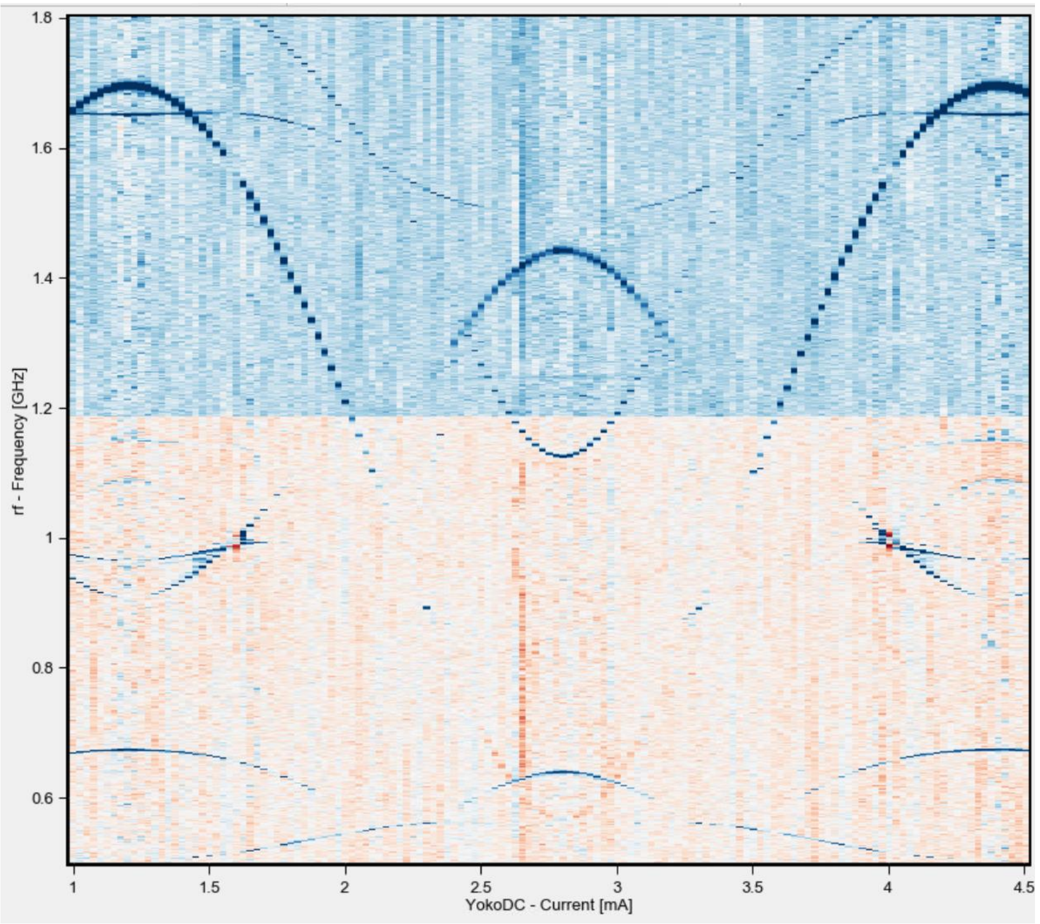


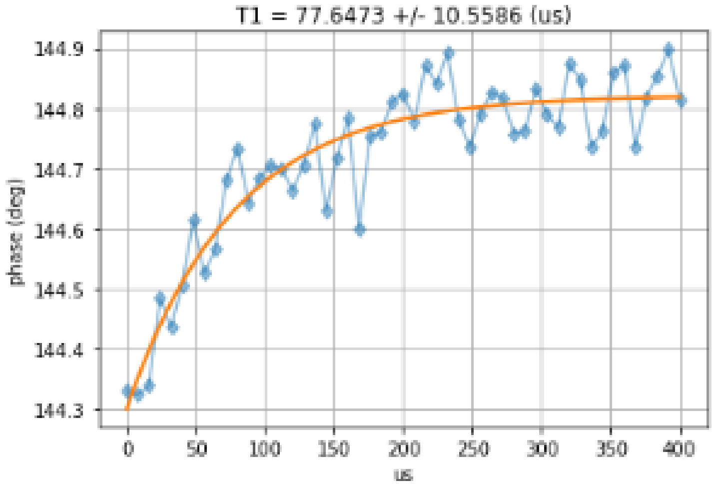
We are able to use Randomized Benchmarking to characterize gate for 3D transmon and fluxonium.

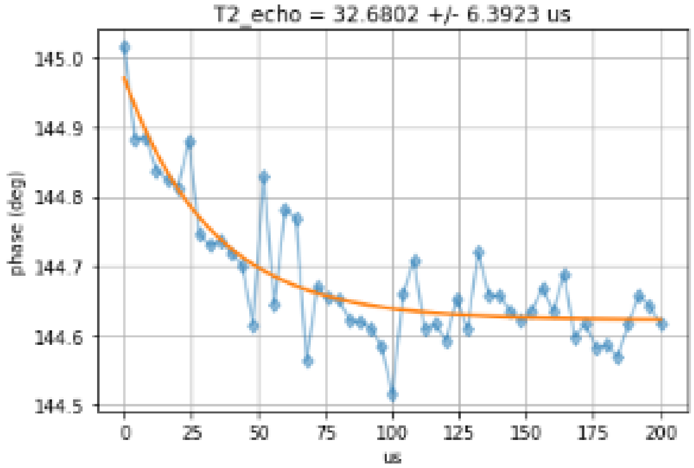
Single Fluxonium qubit in NTHU











Not Yet optimized T1=77μs, T2=32μs.

Thanks to teams in UMD and NTHU

Team UMD

Team NTHU

Summary

- By inserting an large inductor, fluxonium superconducting qubits has variable transition frequency, large anharmonicity and rich spectrum compare to transmon qubits
- Above 1ms coherence time has been observed in fluxonium qubit.
- Various interaction mechanisms can be used for quantum gates
- We have ability to design, fabricate, and measure fluxonium qubits in Taiwan now.