Quantum Computing and Electron Beam Lithography

Bethany Niedzielski Huffman

5/28/24

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

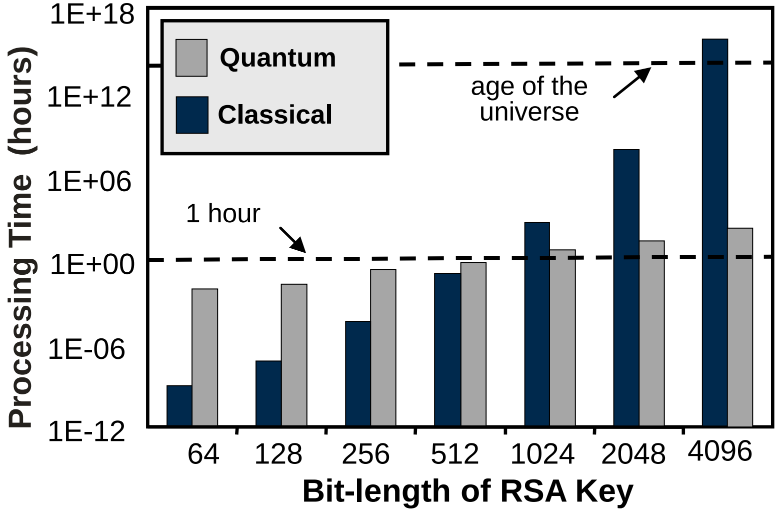
How is a Quantum Computer Different?

	Classical Computer	Quantum Computer
Logic element	"Bit" : classical bit (transistor, spin in magnetic memory, …)	"Qubit" : quantum bit (any coherent two-level system)

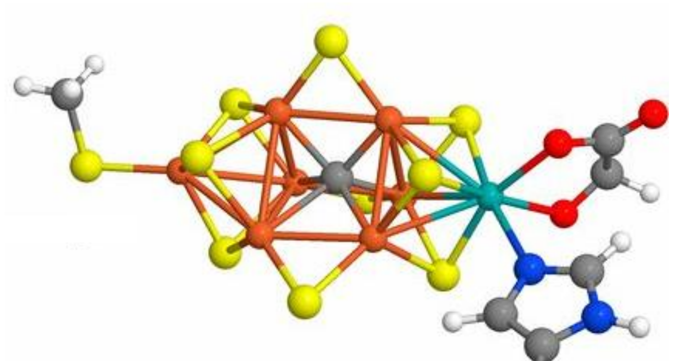
Why all the attention?

Quantum computers may revolutionize high-performance computing.

Shor's Algorithm for Prime Factorization:
RSA Key Decryption

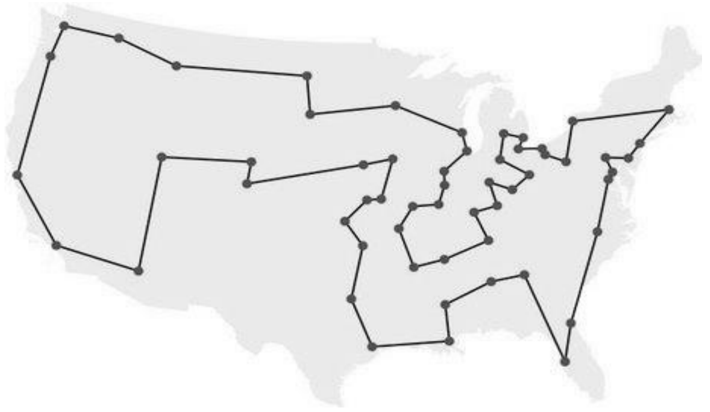


Quantum Chemistry Calculations:
Nitrogen Fixation



Reiher et al., *PNAS* (2017)

Efficient Optimization:
Traveling Salesman



Or they could be completely useless.

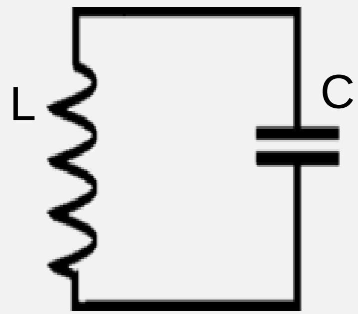
Building Superconducting Qubits

Need: A quantum system with two energy levels
- **(0 and 1 states)**

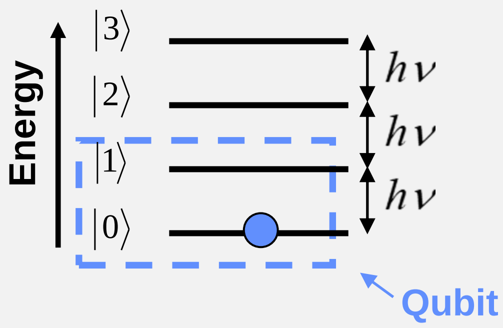
Choose: Superconducting LC Circuit
- **Macroscopic quantum system**

Qubit Components

- **Capacitors**
- **Inductors**
- **Signal Carrying Lines**



L: inductor
C: capacitor



Building Superconducting Qubits

Need: A quantum system with two energy levels

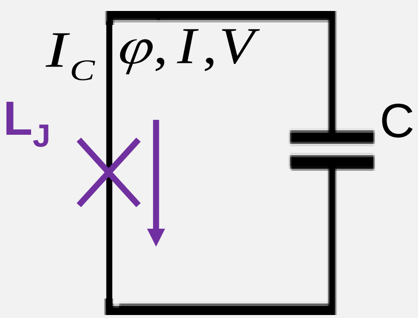
- **(0 and 1 states)**

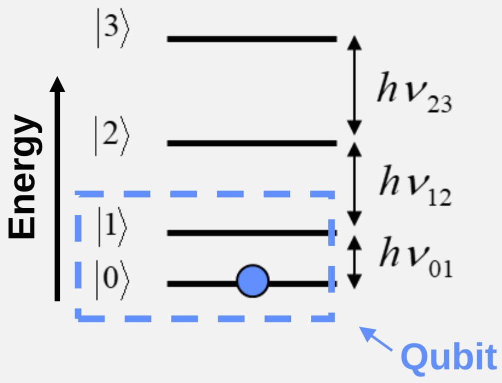
Choose: Superconducting LC Circuit

- **Macroscopic quantum system**

Qubit Components

- **Capacitors**
- **Inductors**
- **Signal Carrying Lines**
- **Non-linear Inductor (Josephson Junction)**





Building Superconducting Qubits

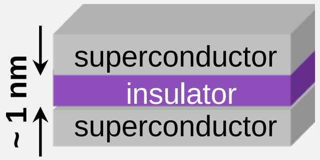
Need: A quantum system with two energy levels
- **(0 and 1 states)**

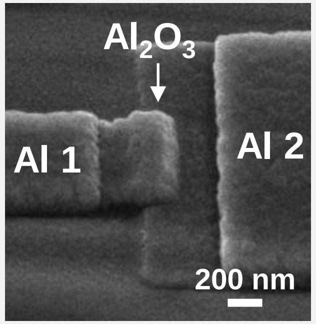
Choose: Superconducting LC Circuit
- **Macroscopic quantum system**

Qubit Components

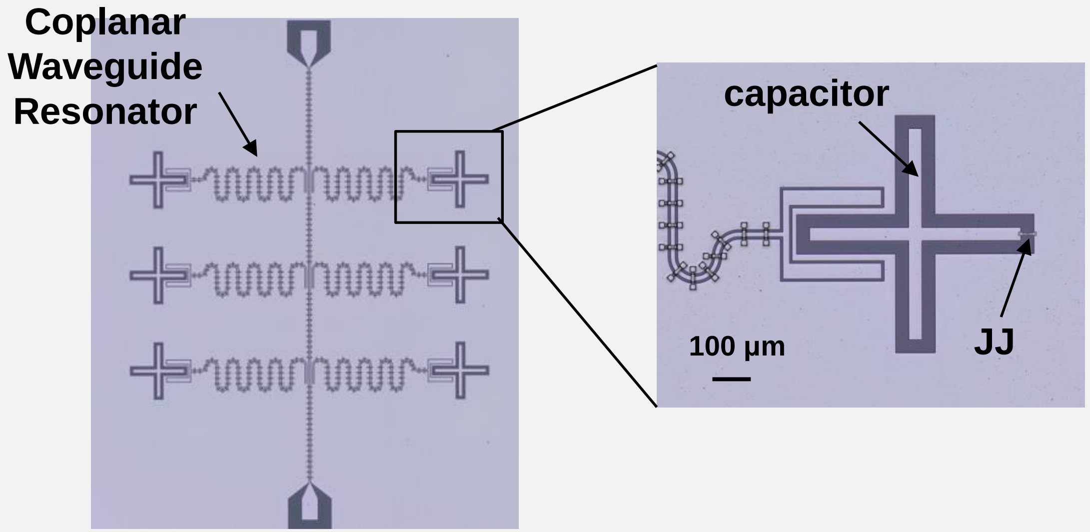
- **Capacitors**
- **Inductors**
- **Signal Carrying Lines**
- **Non-linear Inductor (Josephson Junction)**

Josephson Junction (JJ)





Qubit Control and Readout



- **Control:** **Send microwave pulses at qubit frequency to change qubit state**
- **Read out:** **Measure the resonator frequency which shifts depending on the qubit state**

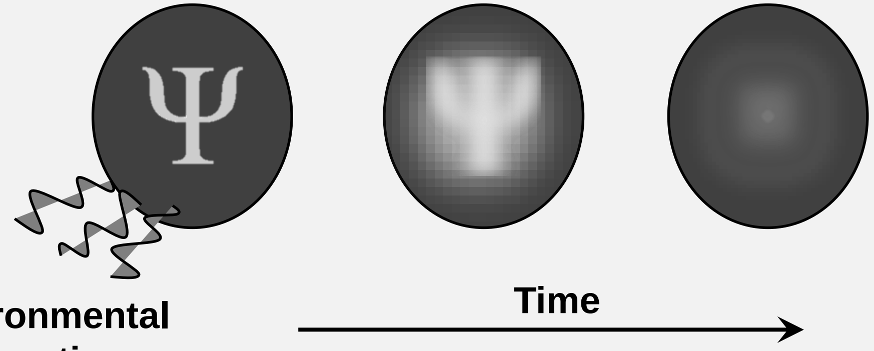
Superconducting Qubit Performance

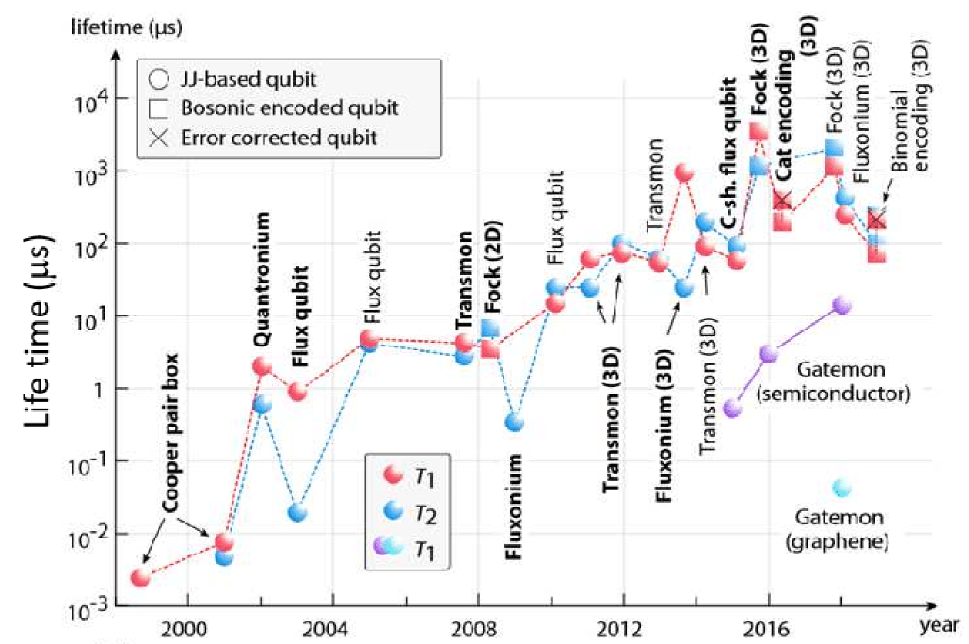
Benefits of Superconducting Qubits

- Compatible with Si-based fabrication techniques
  - Al, Nb, Ta, TiN materials typically used
- Full control over device parameters
- Can manipulate and read out with off-the-shelf electronics

Want Longer Qubit Lifetime

Coherence time: Qubit lifetime





“coherence” time $\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$

dephasing: noise “on” ω_{01}

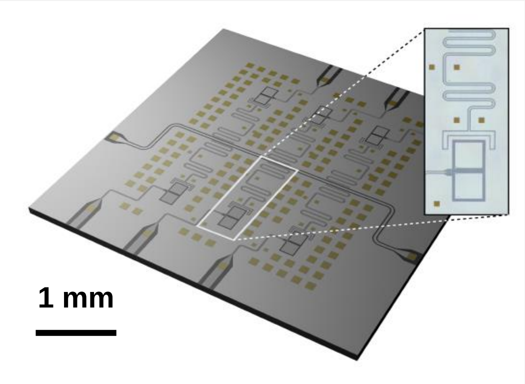
energy relaxation: environment “at” ω_{01}

quality factor $Q = 2\pi\omega_q T_1$

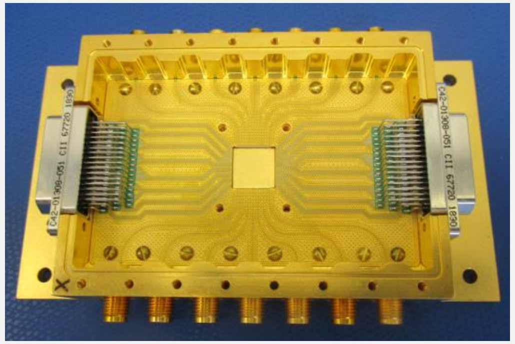
Kjaergaard et al, Annual Review of Condensed Matter Physics 2020 11:1, 369-395

Building a Superconducting Quantum Computer

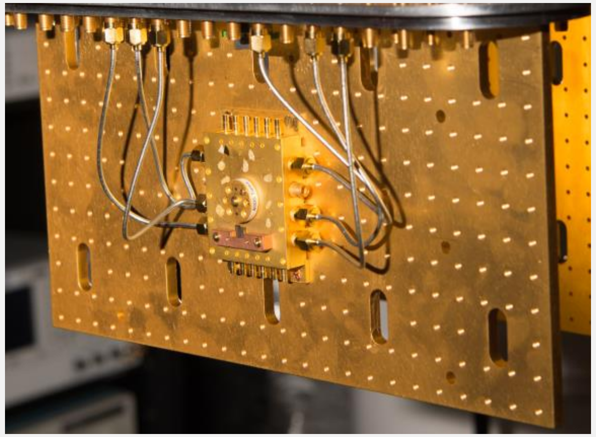
Qubit Chip



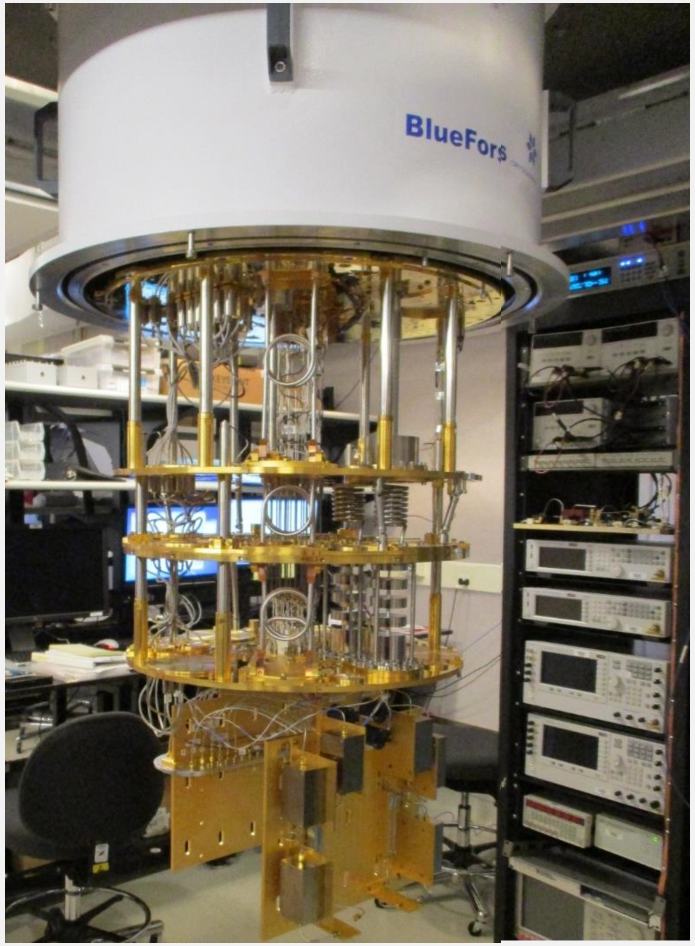
Packaged Qubit Chip



Package Mounted in Dilution Refrigeration



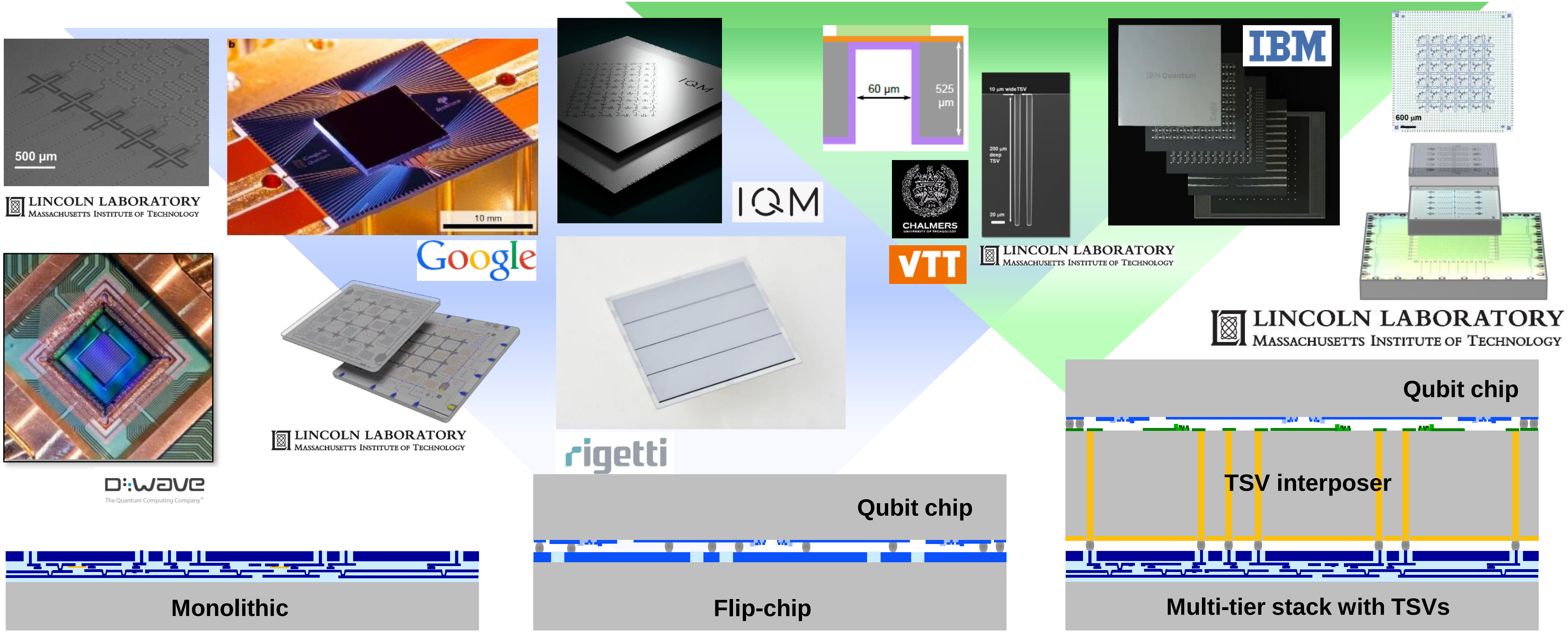
Dilution Refrigerator and Control Electronics



- **Packages shield qubits and provide access to control wiring**
- **Mount and measure qubits at mK temperatures**
- **Dilution refrigerators and control electronics can now be purchased commercially**

Superconducting Qubit Community

Overall Goal: Fault-tolerant quantum processor for universal gate-based operation



Rosenberg, *et al.*, *npj QI* (2017)
Gold, *et al.*, *npj QI* (2021)

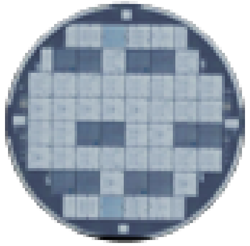
Dickel *et al.*, *PhysRev B* (2018)
Foxen *et al.*, *QS&T* (2017)

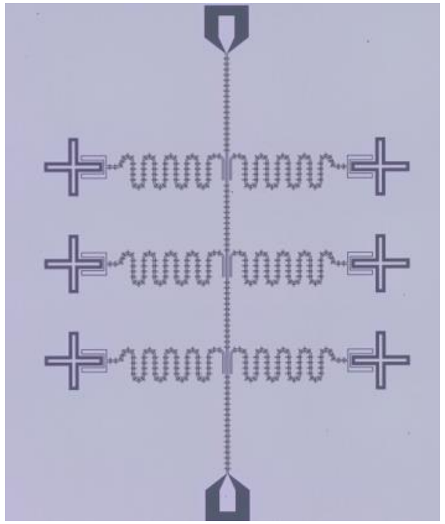
Grigoras *et al.*, arXiv:2201.10425 (2022)
Yost*, Schwartz*, Mallek*, *et al.*, *npj QI* (2020)

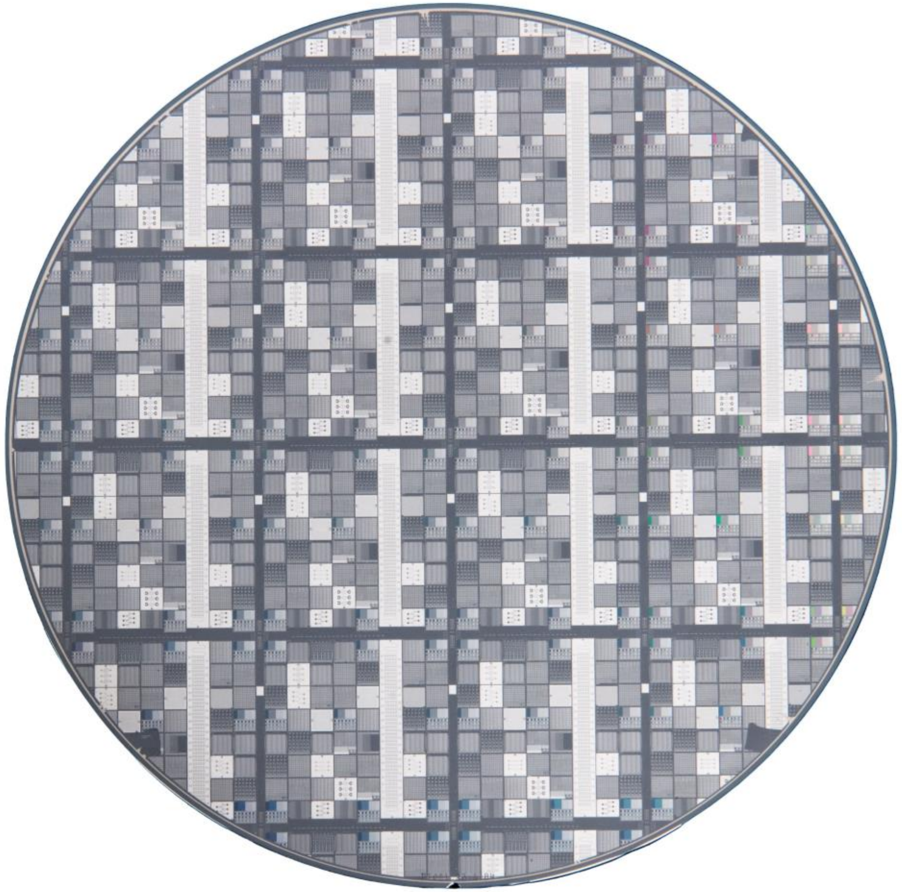
E-beam Lithography

Circuit elements fabricated using E-beam lithography

- **Almost always: Josephson Junctions**
- **Group dependent: Everything else**
  - **Feedlines**
  - **Coplanar waveguide Resonators**
  - **Capacitors**







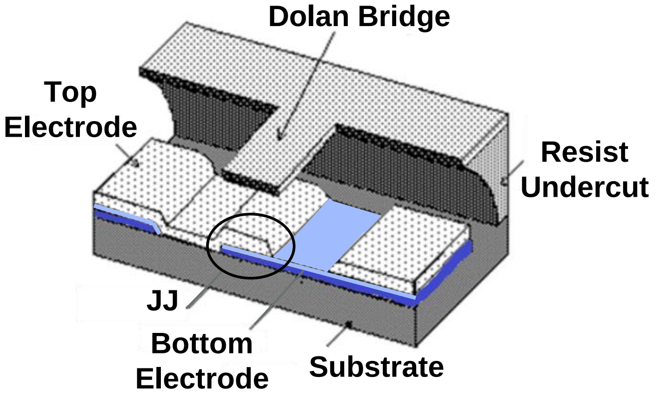
Junction process flavors:

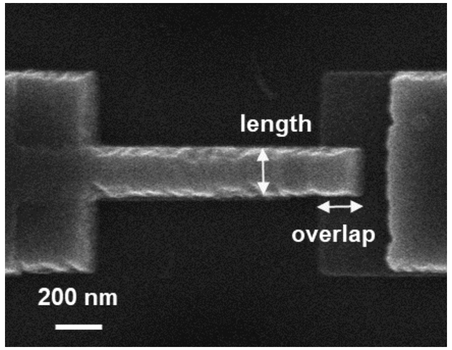
- **Dolan bridge**
- **Manhattan**
- **Two-step Lithography**

Dolan Process

Process Requirements

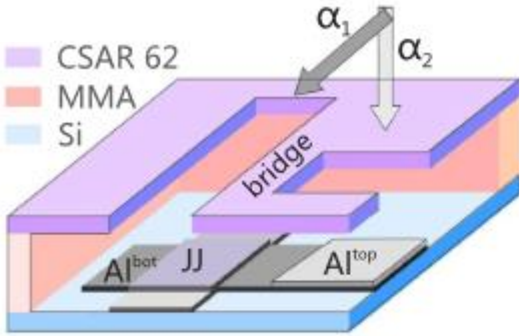
- Resist stack: e-beam bilayer (commonly MMA/PMMA, CSAR, ZEP)
- Moderate undercut needed
- Metal deposition needs tilt stage (+/- wafer tilt)

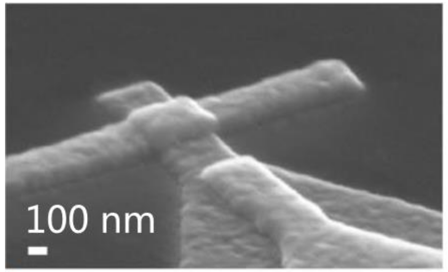




Pros/Cons

- Full JJ formed under vacuum
- Relatively compact design
- Suspended bridge limits design space
- Resist stack height dictates JJ overlap
  - But can be compensated by angle
- T-variant loses some tile-ability
  - But removes size dependence on resist height



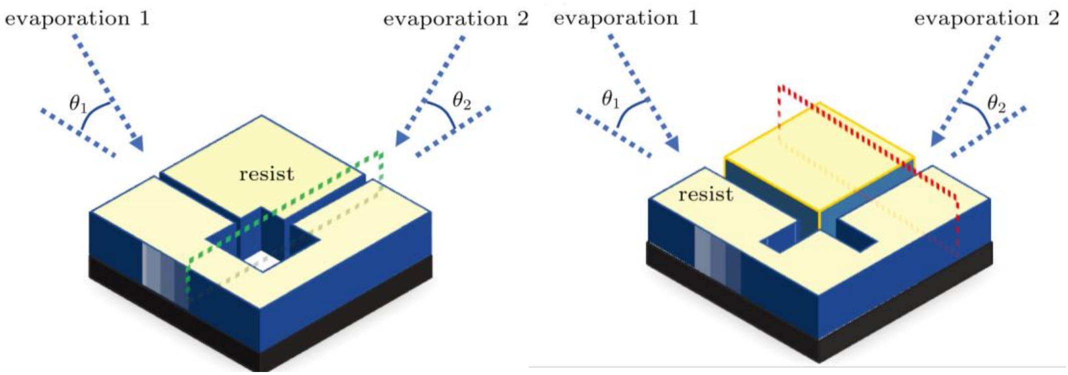


Anastasiya A Pishchimova *et al*, Scientific Reports. 13. 10.1038/s41598-023-34051-9 2023

Manhattan Bridgeless Process

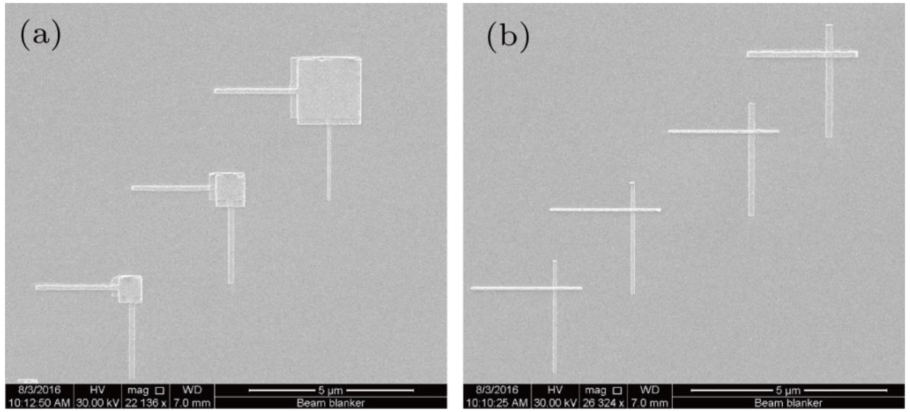
Process Requirements

- Resist stack: e-beam bilayer (commonly MMA/PMMA, CSAR, ZEP)
- Undercut for lift-off only
- Metal deposition needs tilt and rotation stage



Pros/Cons

- Full JJ formed under vacuum
- Easier fabrication process with no bridge
- JJ CDs are set by ebeam (resist height independent)
  - Until crossover from X to □ layout
- Larger areas accessible with □ layout
- Some extra metal needed to connect to leads
- Not easily tiled in series



Zhang Ke *et al*, *Chinese Physics B*, 2017, 26(7): 078501 (2017)

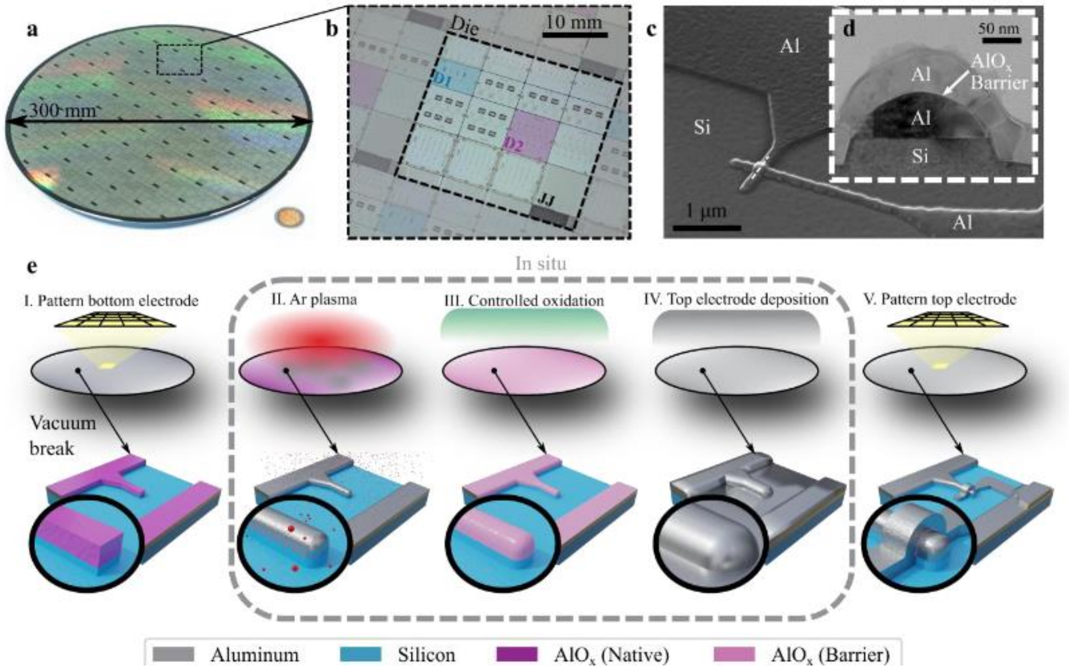
Two-Step Lithography Process

Process Requirements

- Resist stack: PMMA for bottom electrode (BE), MAN for top electrode
- Subtractive etching landing on BE

Pros/Cons

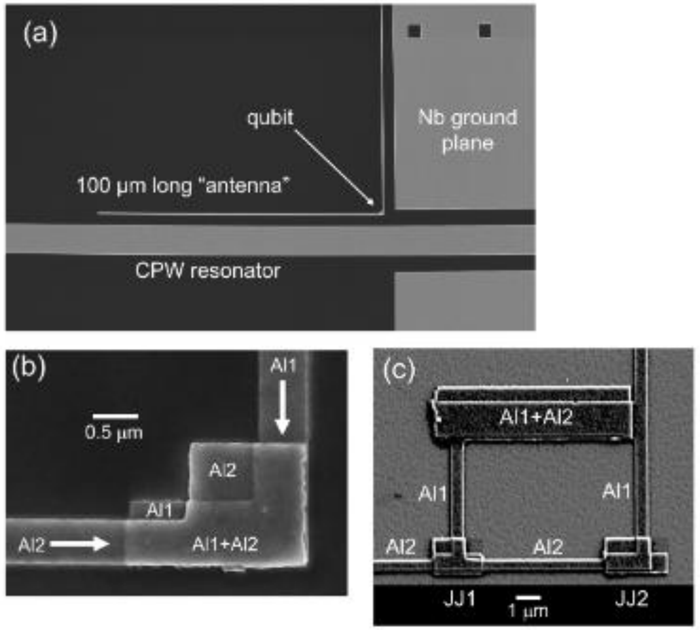
- Manufacturable fabrication with no bridge or angled deposition
- JJ CDs are set by ebeam (resist height independent)
- Larger areas accessible
- Mill-in-the-middle required
- Extra processing steps
- Some extra metal needed to connect to leads



Jacques Van Damme *et al*, 0.48550/arXiv.2403.01312. (2024)

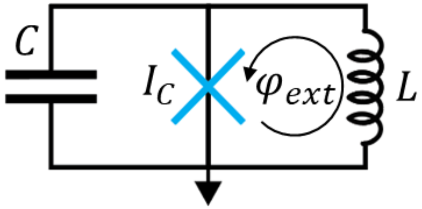
Compound Elements

- **Merged Element Transmon**
  - **Combination JJ and shunt-capacitor for smaller footprint device**
  - **Concentrates E+M energy inside the JJ, reducing relative participation at other interfaces**



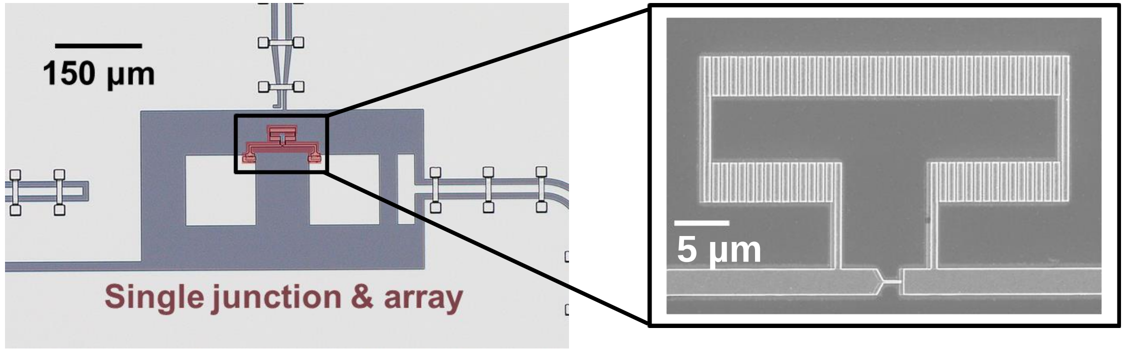
H.J. Mamin *et al*, Phys. Rev. Applied 16, 024023 (2021)

- **Fluxonium**
  - **Qubit circuit that uses an inductor, typically made from a series chain of JJs**



V. E. Manucharyan *et al*, Science 326, 113 (2009).

  - **Reduced sensitivity to dielectric loss and protection against quasiparticles at the small JJ lead to very high performance!**



E-beam Considerations

SEBL Parameters

- Beam current
- Spot size
- Beam step size
- Field sizes
- Dosing
- PEC

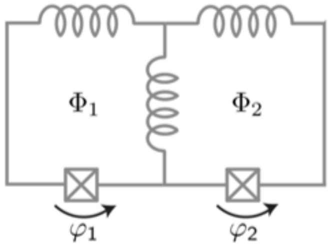
Device Parameters

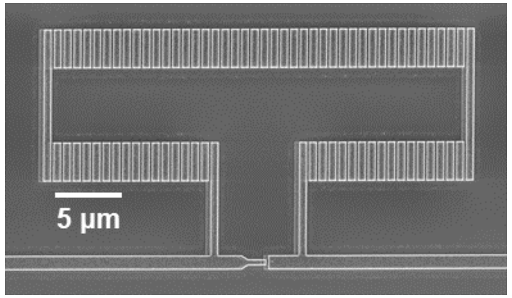
- Feature size precision
- Feature size range
- Write speed
- Uniformity
- Line edge roughness
- Undercut requirements
- Ease of lift-off

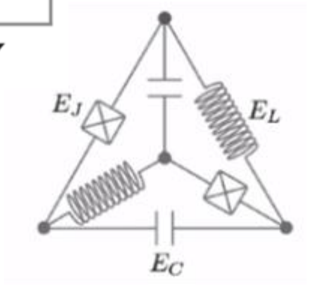
Fundamental understanding and implementation of e-beam write parameters is critical to the fabrication of high quality superconducting qubit chips

Superconducting Qubit Development

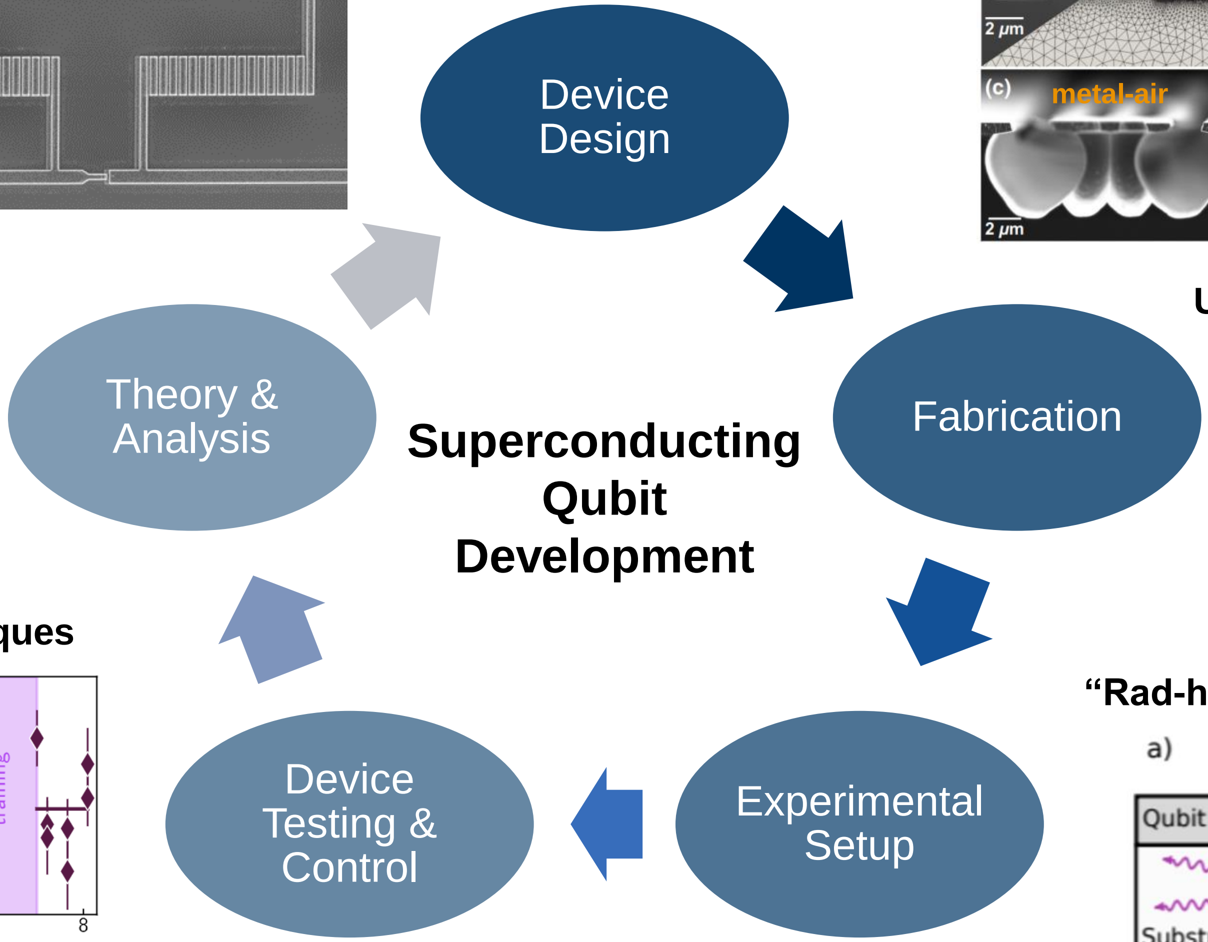
Intrinsic noise protection

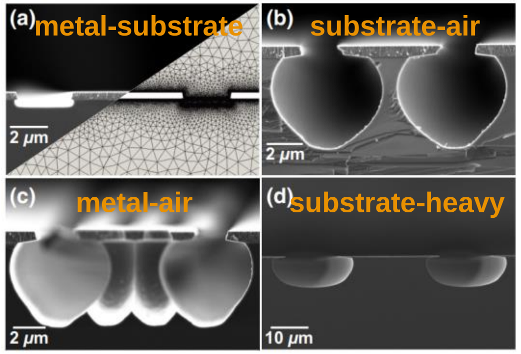




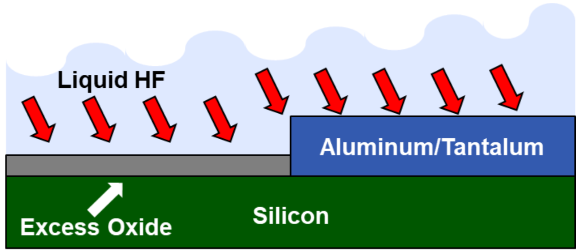


Improving qubit design

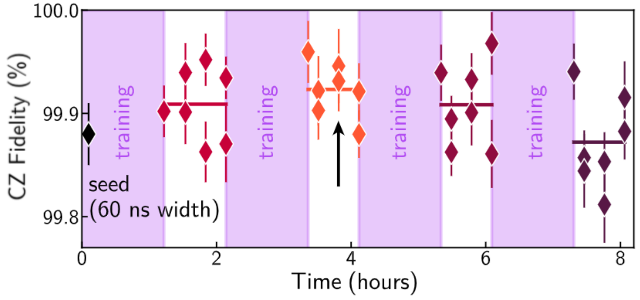




Understanding materials losses



Advanced control techniques



“Rad-hard” superconducting qubits

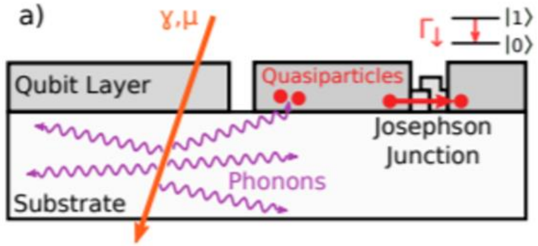
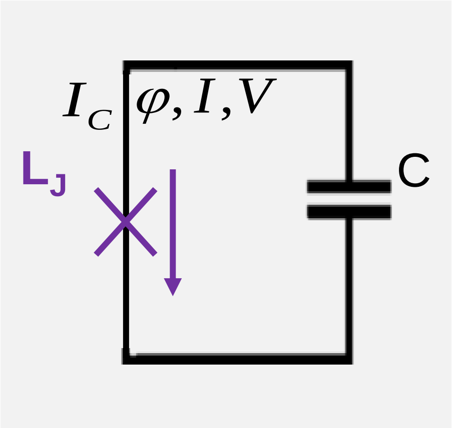
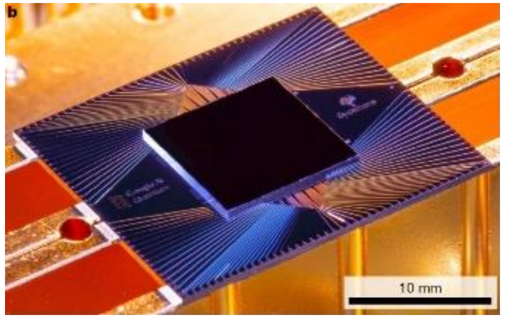


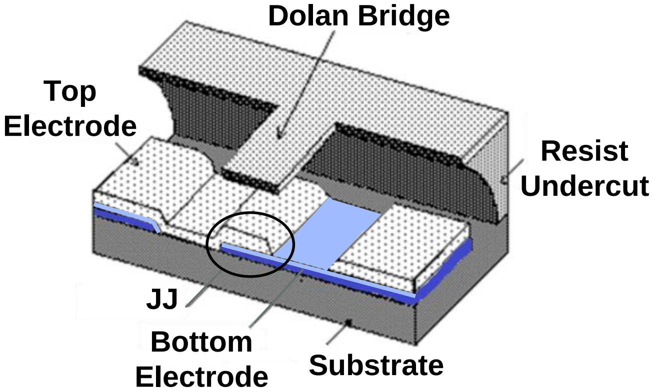
Fig. from McEwen et al., *Nat. Phys.* (2022)

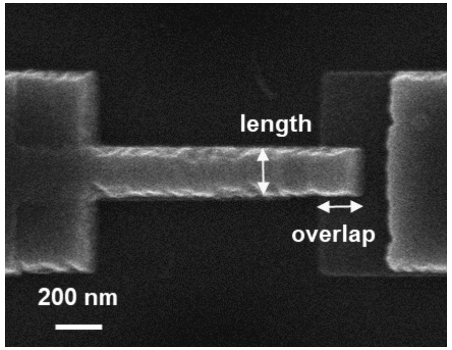
Summary

- Quantum computers will do calculations in a new way to solve SOME kinds of hard problems
- We can make qubits from superconducting circuits
- E-beam lithography is highly used to pattern most sensitive circuit element, the Josephson junction
- Ongoing research to further improve device performance









LINCOLN LABORATORY
Massachusetts Institute of Technology

Our team!

Quantum Information and Integrated Nanosystems Group, MIT-LL

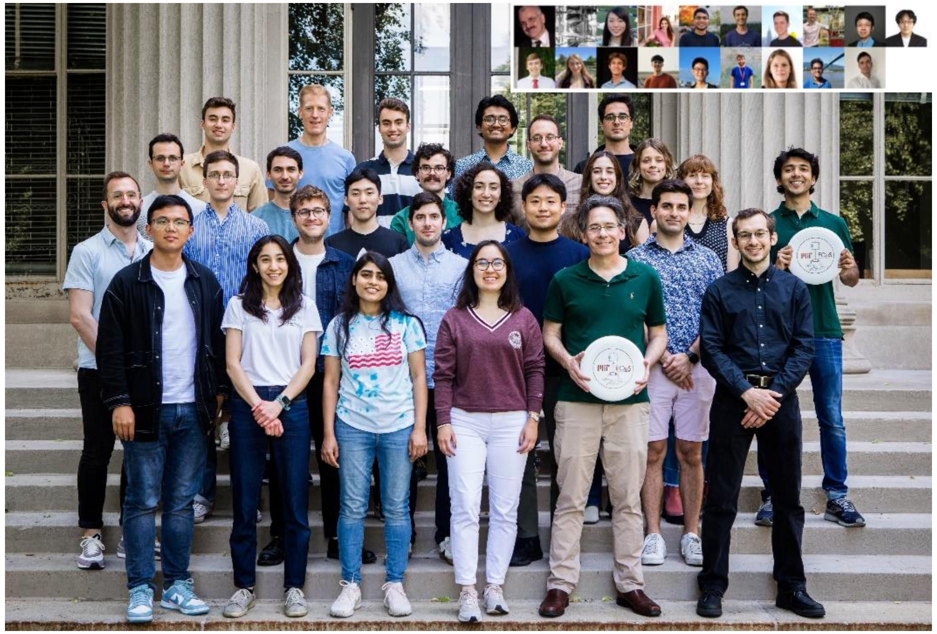
Superconducting Qubits Team:

Group Leaders: Mollie Schwartz, Jonilyn Yoder

Team Leads: Rabindra Das, Michael Gingras, Thomas Hazard, Cyrus Hirjibehedin, Bethany Niedzielski Huffman, Kyle Serniak, Katrina Sliwa, Steven Weber, Donna-Ruth Yost

Team: Mike Augeri, Kate Azar, Peter Baldo, Jeffrey Birenbaum, John Blue, Vlad Bolkhovsky, Luke Burkhart, Tristan Brown, Gregory Calusine, Glenn Carl, Felipe Contipelli, John Cummings, David Danza, Dan Davis, Renée DePencier Piñero, Steven Disseler, Justin Elenewski, Bryce Fisher, Jeffrey Gertler, Evan Golden, Kevin Grossklaus, Karen Harmon, Mike Hellstrom, Gerry Holland, Jennifer Hritz, Lenny Johnson, Andrew J. Kerman, David Kim, Jeff Knecht, Arthur Kurlej, Justin Mallek, Duncan Miller, Jovi Miloshi, Maddie Morocco, Peter Murphy, Rylee Newman, Kevin Obenland, Christopher O'Connell, Mallika Randeria, Ravi Rastogi, Benjamin Rempfer, Lila Rodgers, Robert Rood, Ali Sabbah, Gabriel Samach, Meghan Schuldt, Arjan Sevi, Marcus Sherwin, Hannah Stickler, Chris Thoummaraj, Kunal Tiwari, David Volfson, Terry Weir

MIT Engineering Quantum Systems (EQuS)



William D. Oliver, Simon Gustavsson, Terry Orlando, Jeff Grover, Joel Wang, Kyle Serniak, Chihiro Watanabe, Margaret McCroby

Postdocs: Réouven Assouly, Aranya Goswami, Patrick Harrington, Max Hays, Jorge Marques, Daniel Rodan-Legrain, Doug Pinckney, Ilan Rosen, Helin Zhang

PhD students: Aziza Almanakly, Junyoung An, Lamia Ateshian, William Banner, Cora Barrett, Shoumik Chowdhury, Gabriel Cutter, Andy Ding, Shantanu Jha, Harry Kang, Junghyun Kim, Chris McNally, Miguel Moreira, Sarah Muschinske, David Pahl, Lukas Pahl, David Rower, Chia-Chin Tsai, Hong-Yu Tsao, Beatriz Yankelevich, Sameia Zaman

Undergraduates: Catherine Tang

Visiting Members: Fabrizio Berritta, Frederike Brockmeyer, Melvin Mathews, Pablo Mercader

IARPA DARPA LPS