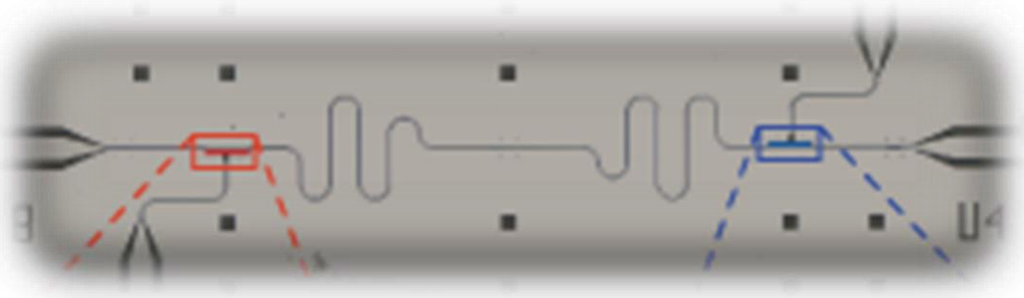
Superconducting Cavities for Modular Quantum Information Processing



CEC-ICMC

July 24, 2019

Luke Burkhart, Yale University

Chan U Lei, Lev Krayzman, Teresa Brecht,

Robert Schoelkopf (PI)

Yale University

Yale Quantum Institute

Leveraging modularity and integration

- Modularity for complex quantum machines

- Superconducting cavities as quantum circuitry

- What makes a good (or bad) cavity?

- Looking forward: high-Q cavities and integrated quantum circuits

A very incomplete TODO for quantum information

Long-term goals:
- Quantum computers which can do everything (universal QC)
  - Algorithms for cryptography, search, optimization, classification (c. 1990-present)
- Continental/global scale quantum networks
  - Quantum internet for secure communication

# of qubits required:

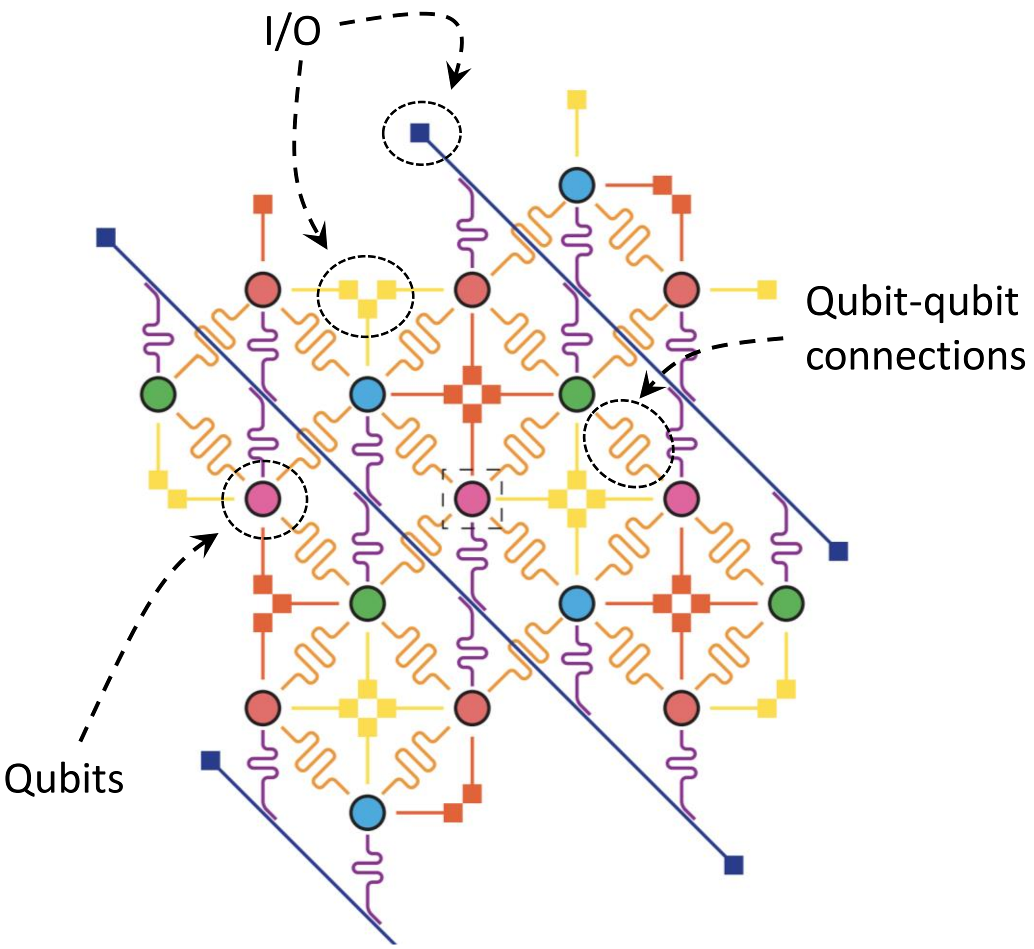
$\sim 10^5 - 10^6$

Fewer if quality is higher

Near-term goals:
- Quantum computers which can do *anything at all*
- Quantum simulation – chemistry and solid-state physics
- Small-scale quantum networks
  - Quantum *intra*net

~10 – 100

Monolithic approach to complexity



Advantages:

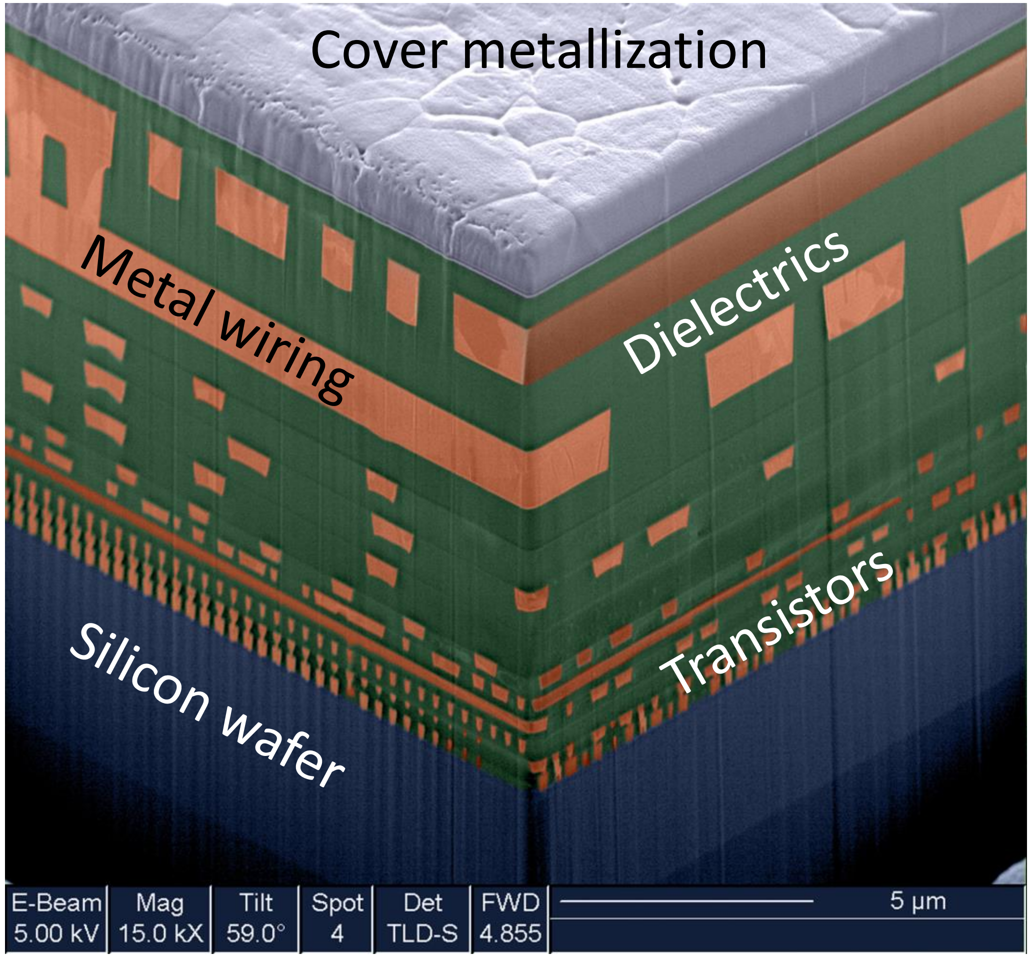
- Integrated circuits on single chip or stack of chips
- Dense, connected grid for multi-qubit operations

Challenges:

- 100% of the complexity in one place

"Scalable Quantum Circuit and Control for a Superconducting Surface Code," R. Versluis et al., Phys Rev Applied, 2017 (Delft)

Monolithic approach to complexity



Cross-section, IBM 90 nm microprocessor ca. 2005
>6 materials, >13 layers

Advantages:

- Integrated circuits on single chip or stack of chips
- Dense, connected grid for multi-qubit operations

Challenges:

- 100% of the complexity in one place
- Requires industrial-scale design and fabrication
- **And** all metals superconducting, with pristine dielectrics

Modular approach to complexity

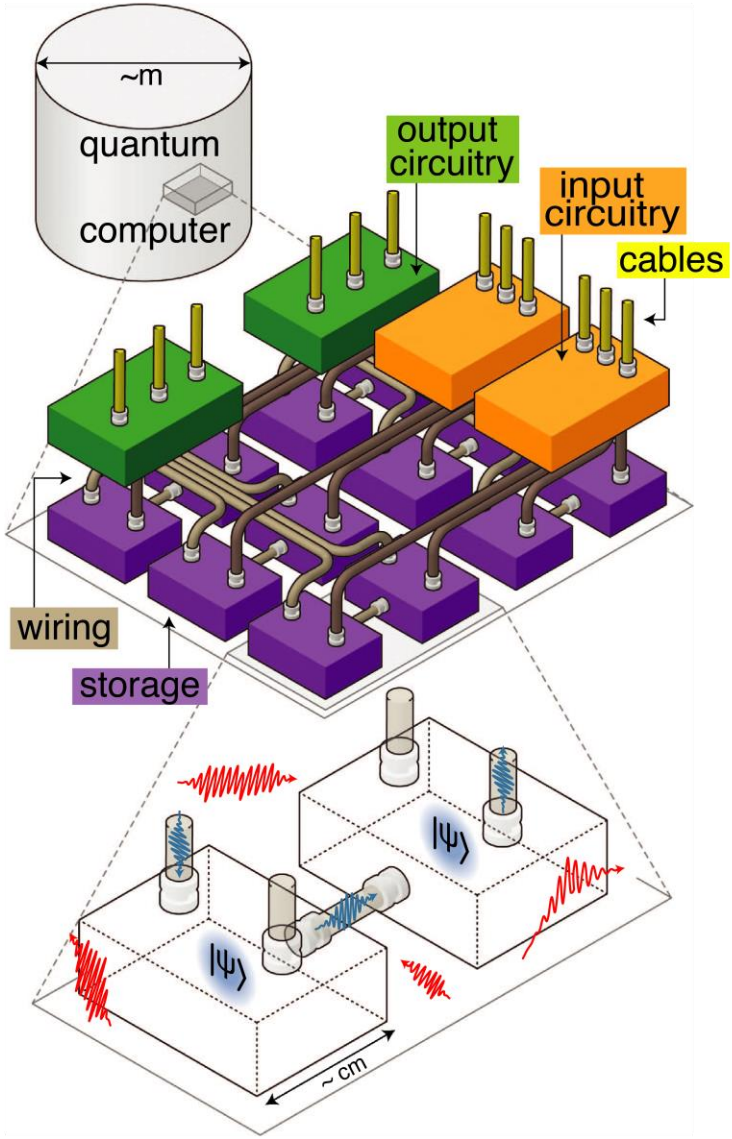
IBM Summit supercomputer @ Oak Ridge NL

Break the computer into testable, replaceable, reconfigurable chunks – the most complex thing you can make **well**

Separate external functions (communication, networking) from computation

Keeping the modules simple means academic labs can share in the innovation

Modular approach to complexity



T. Brecht al., Nature Quantum Info (2016)

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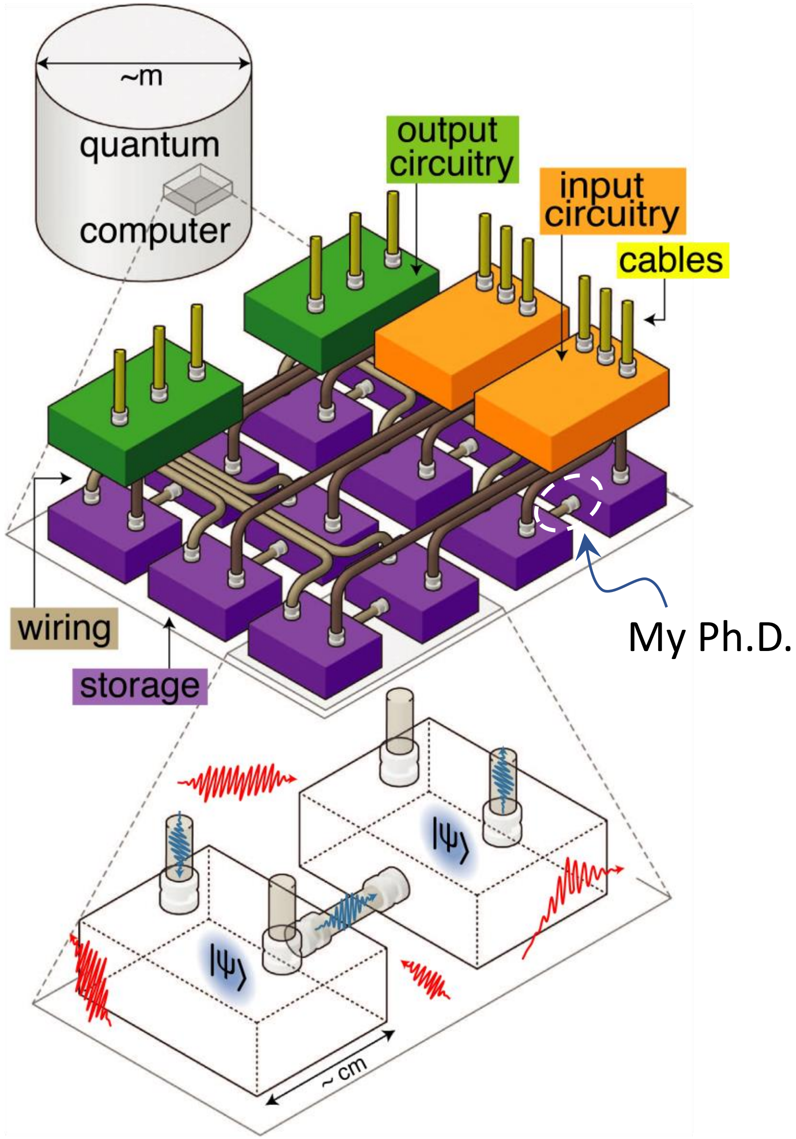
Modular approach to complexity



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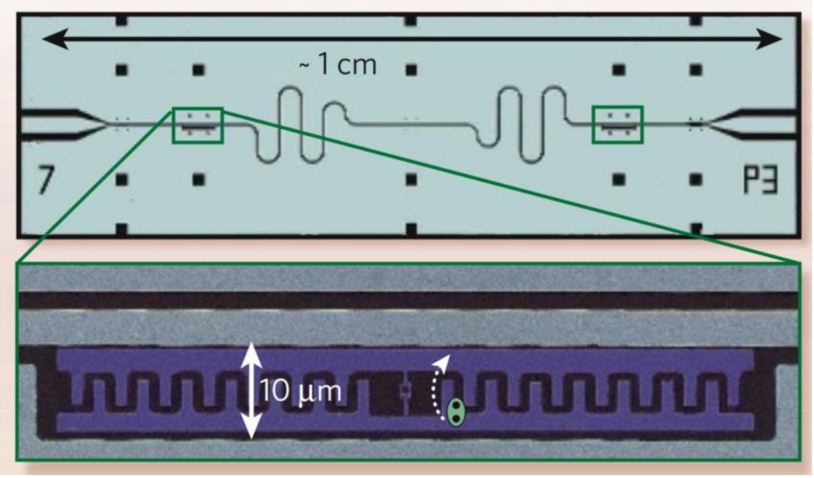
(Some) challenges in designing a module

ca. 2007, Yale



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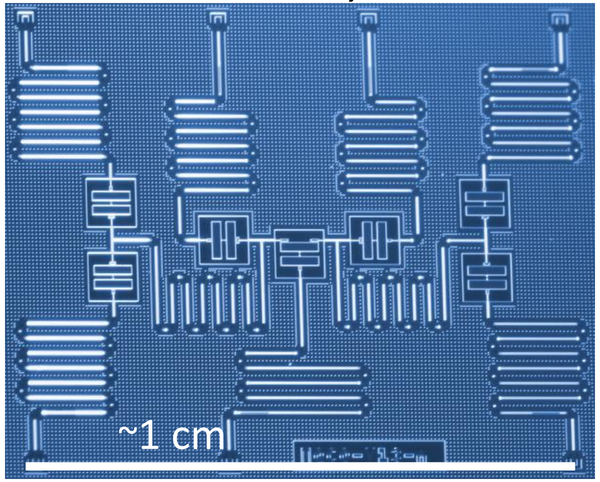

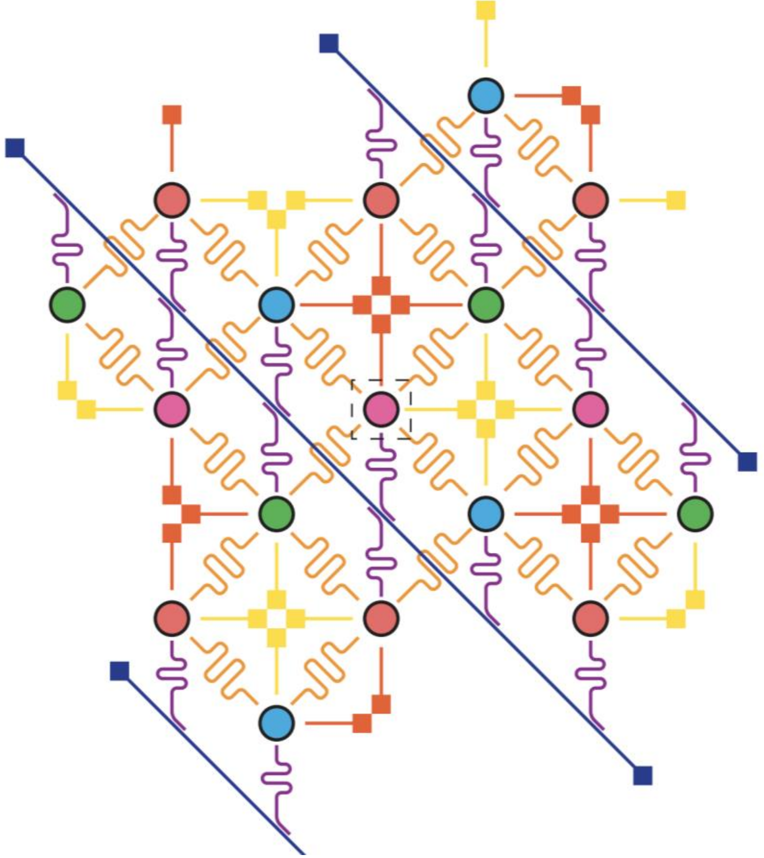

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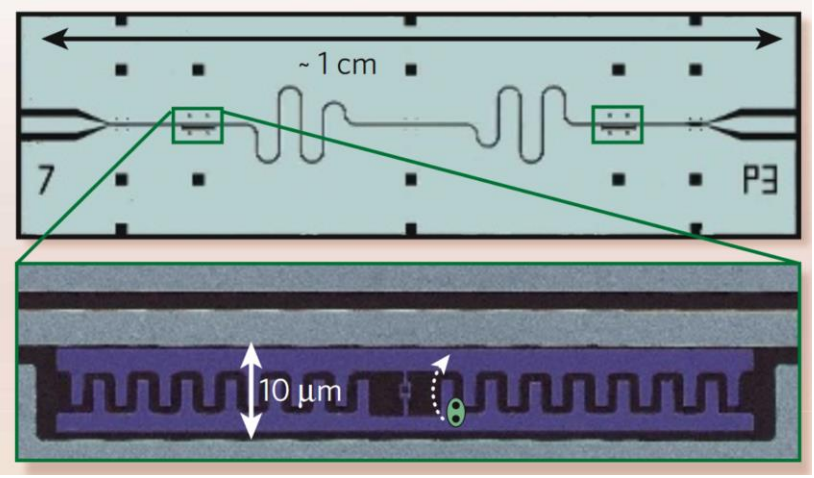

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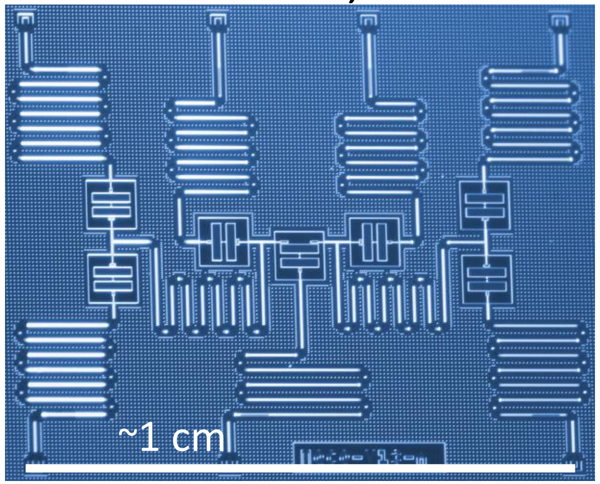

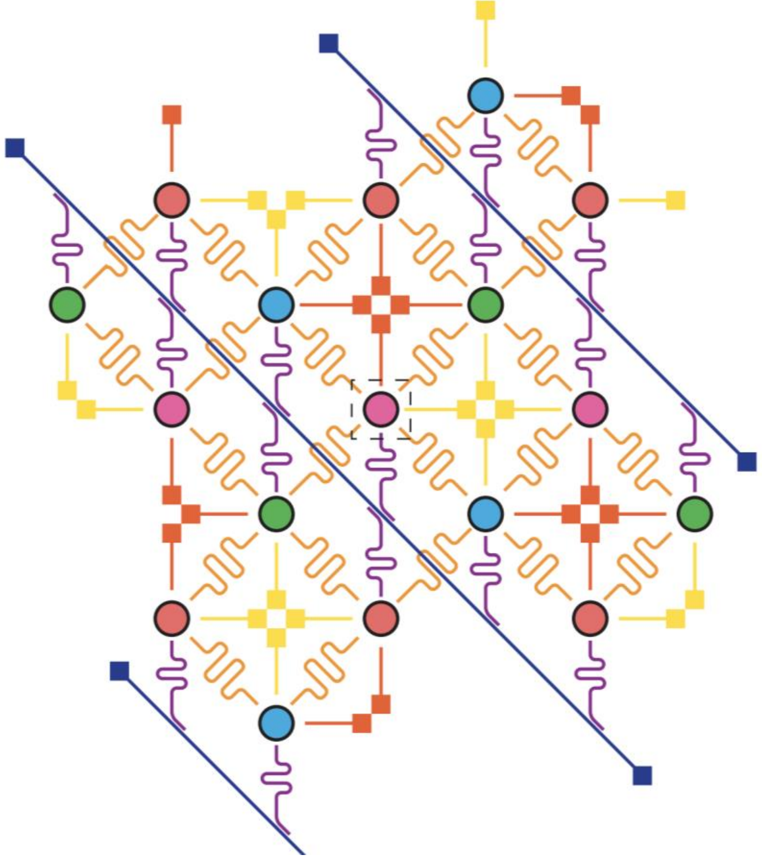

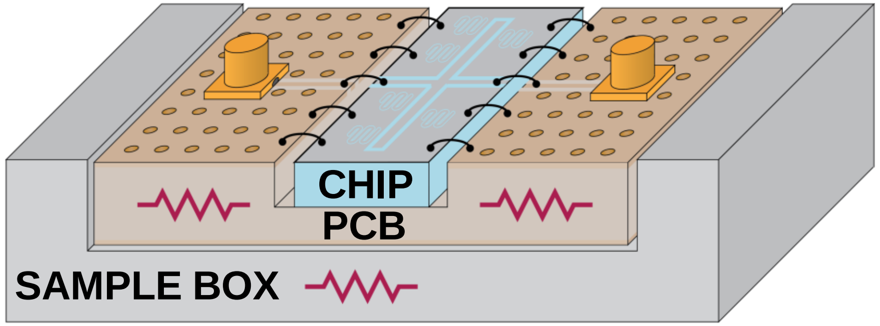

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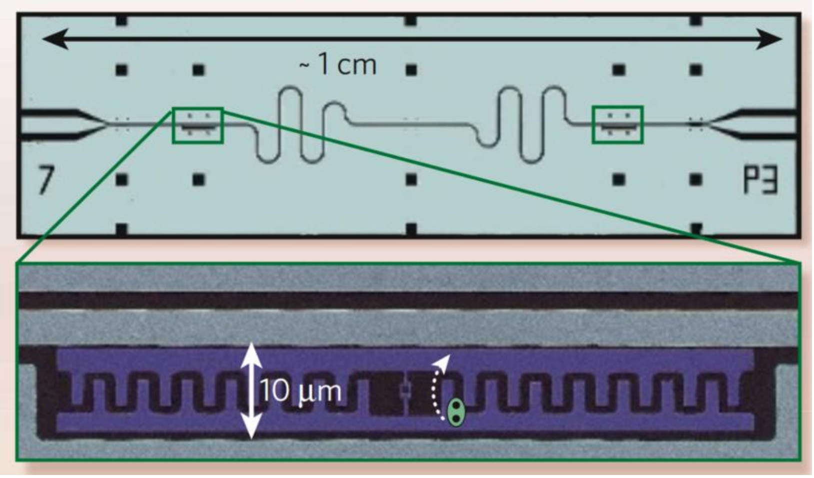

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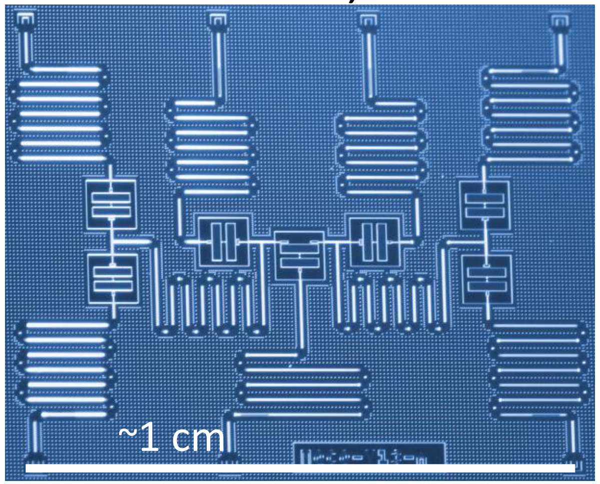

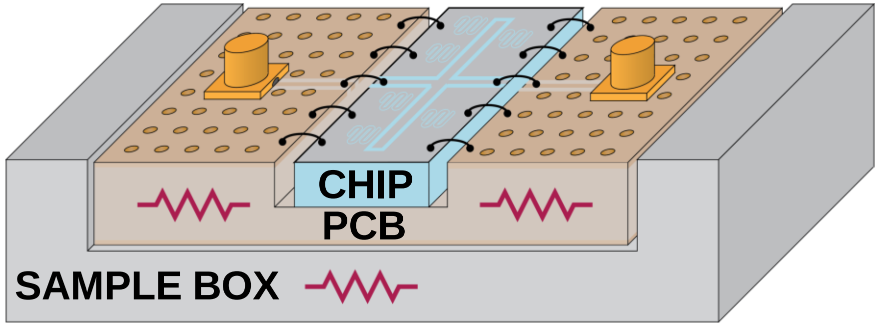

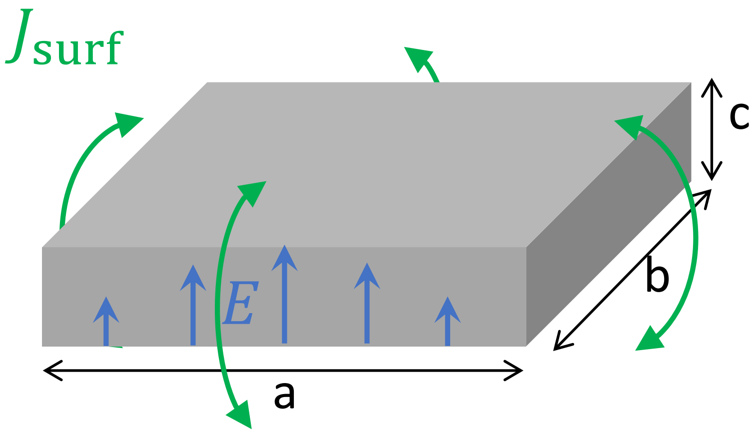

Lowest frequency mode:

$$\omega_{110} = \frac{1}{\sqrt{\epsilon\mu}}\sqrt{\left(\frac{\pi}{a}\right)^2 + \left(\frac{\pi}{b}\right)^2}$$

~10 GHz for 2x2 cm chip, or lower w/ dielectric

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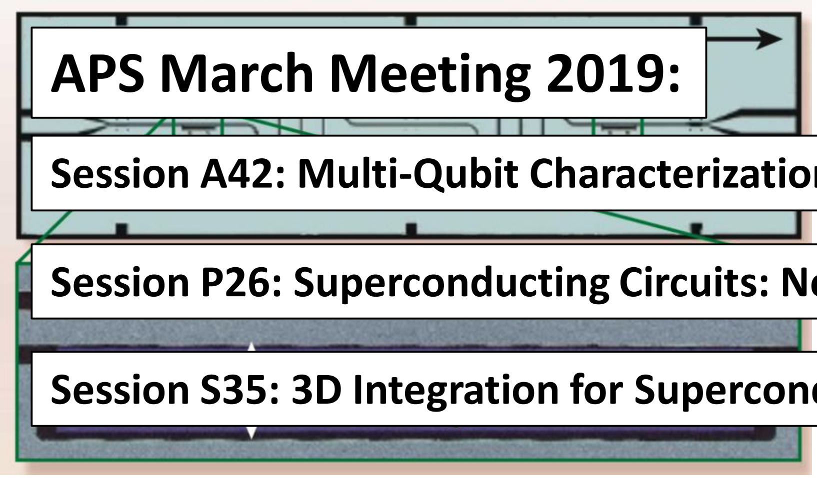

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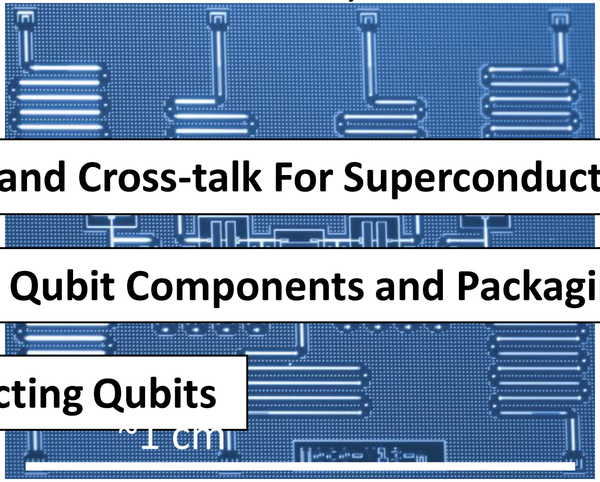
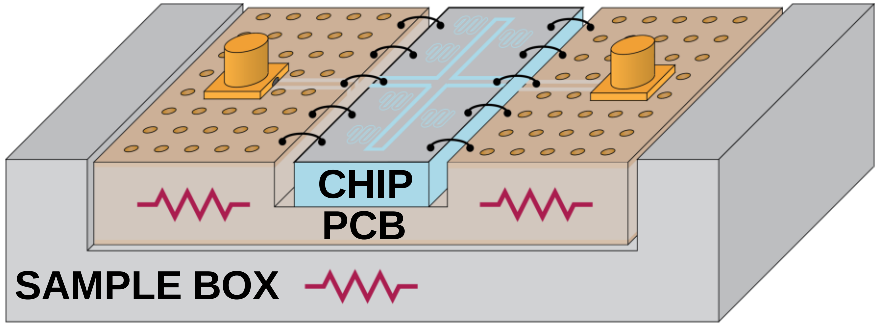


APS March Meeting 2019:

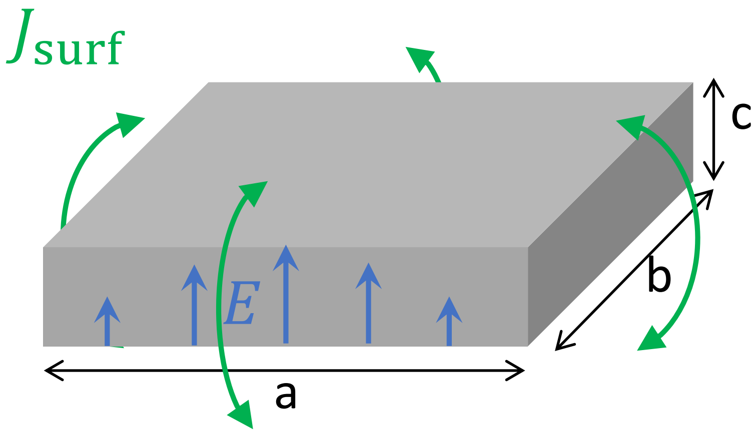
Session A42: Multi-Qubit Characterizations and Cross-talk For Superconducting Qubits

Session P26: Superconducting Circuits: New Qubit Components and Packaging

Session S35: 3D Integration for Superconducting Qubits



Crossovers, thru-Si vias, PCBs…
All of which need to preserve the quality of the qubits!



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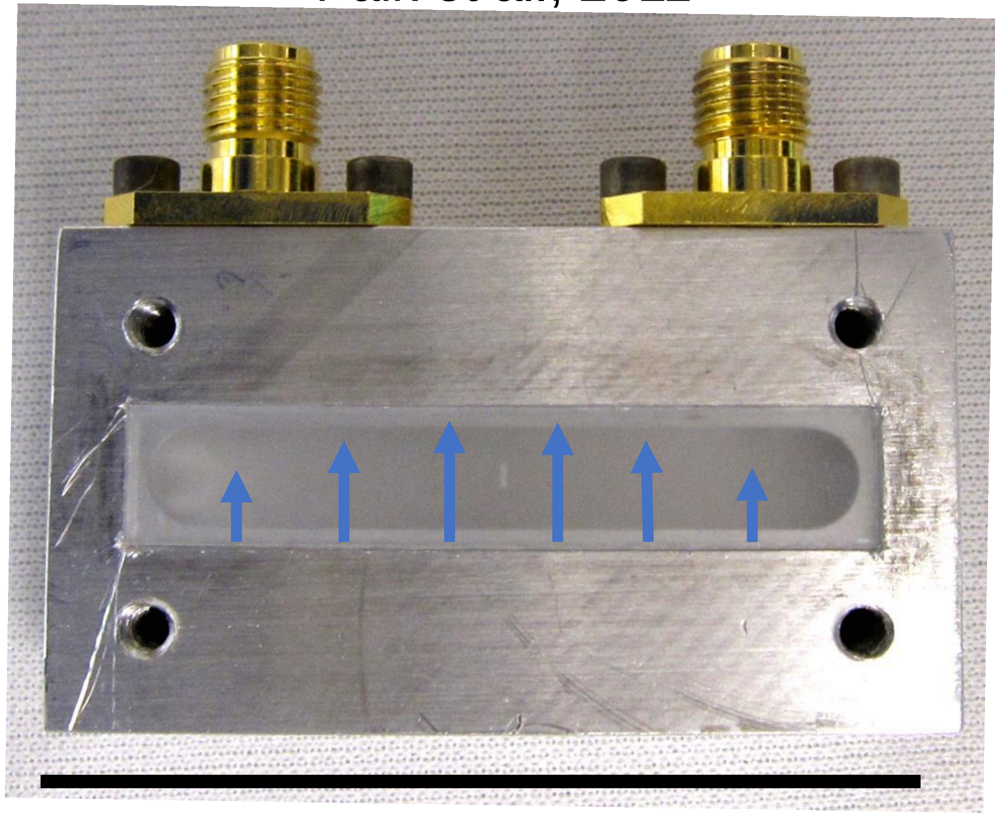
Why fight against the enclosure?

Alternative approach: using the box as a resource

Paik et al., 2011



5 cm

Aluminum waveguide cavity

V ~ 1 cm^3

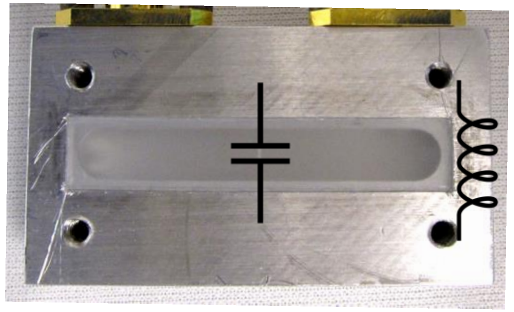
Q ~ 60,000,000*

$$Q = \omega_0 \tau$$

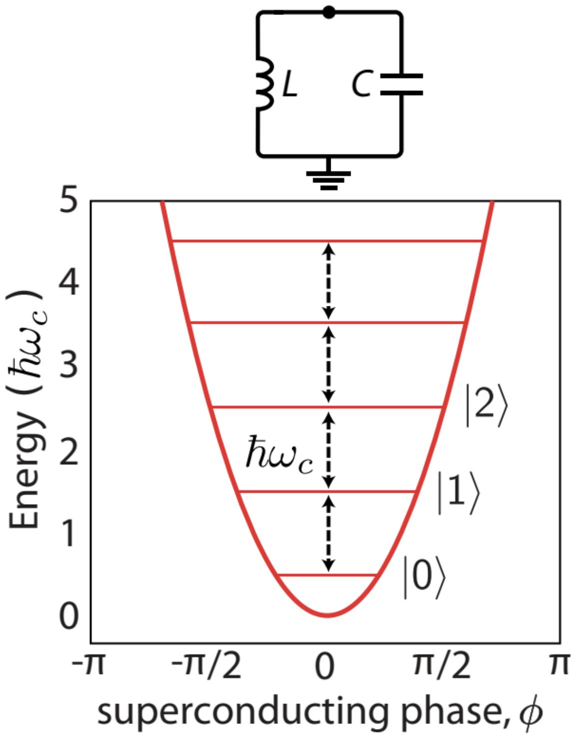
~10x longer lived than typical transmon qubits and on-chip resonators

*99.99% pure Al w/ chemical etching

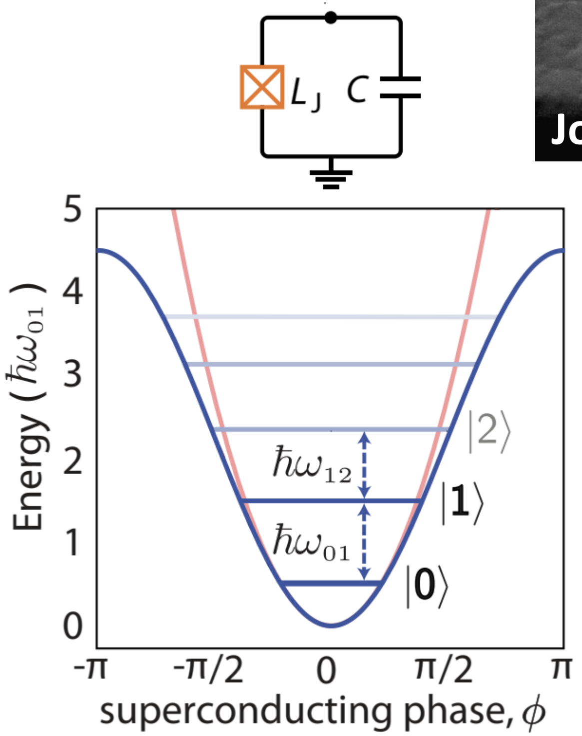
Why cavities make interesting elements

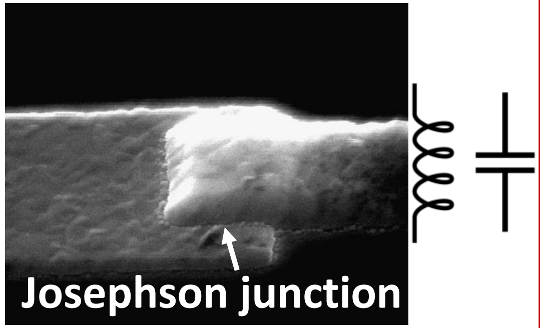


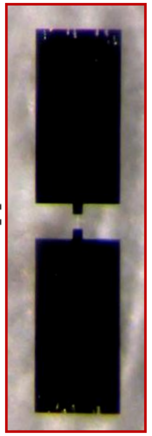
Cavity resonator:
(harmonic)



Transmon:
(anharmonic)







Figures: "Superconducting Qubits: Current State of Play," M. Kjaergaard et al., 2019

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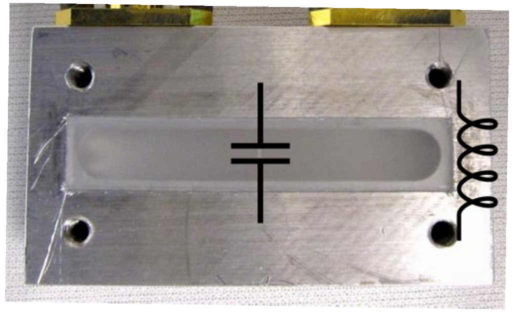

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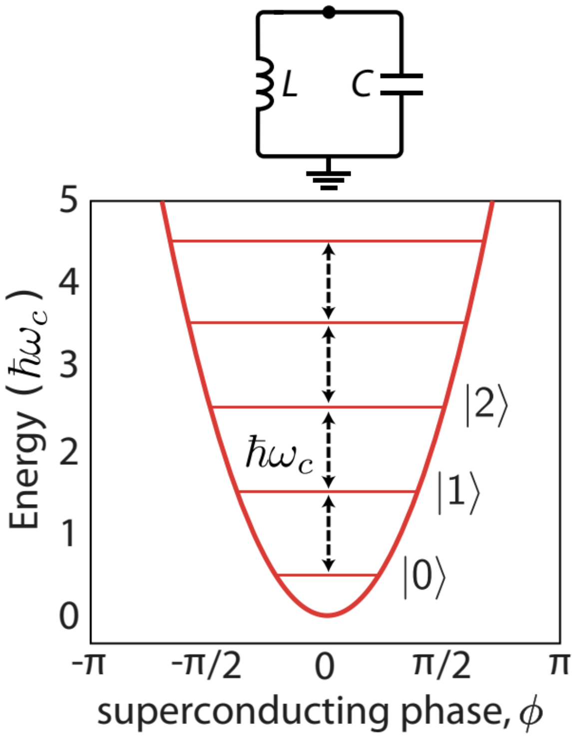

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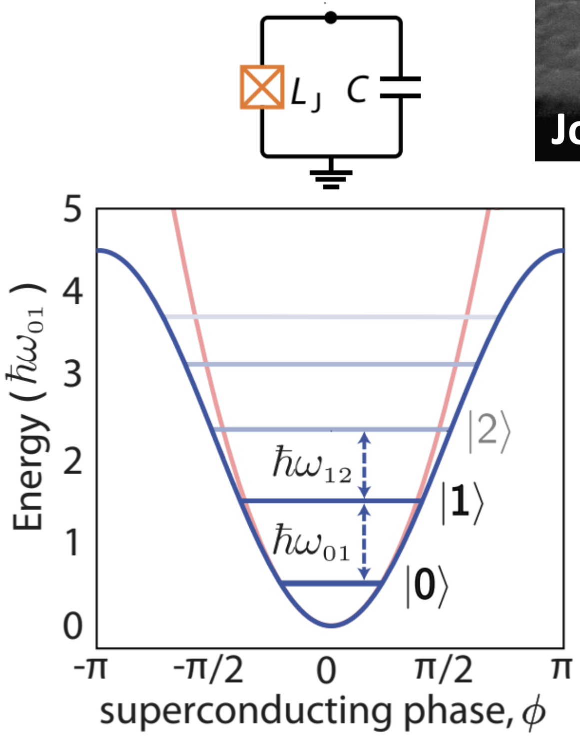
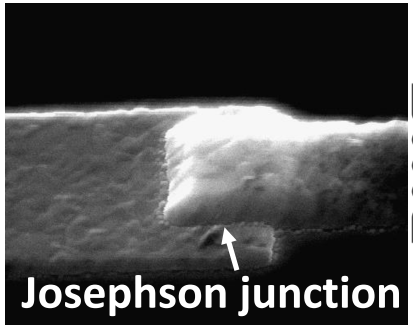
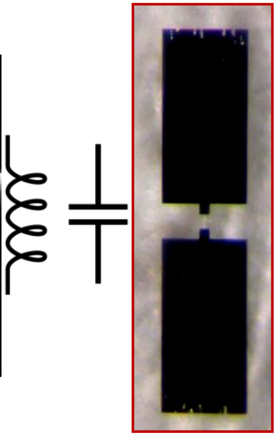






Larger information carrying capacity

Operations are more complex and slower (~1 us)

Simple, robust control (~10 ns)

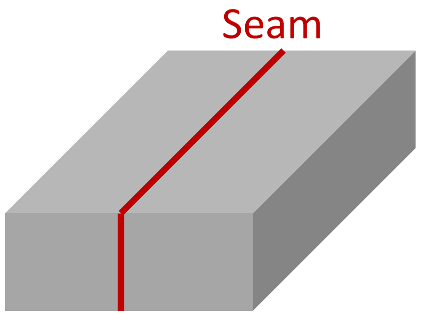
Multiple modes required to correct errors

Requirements for Quantum Error Correction (QEC):	1 mode (+1 ancilla)*	At least 5 modes

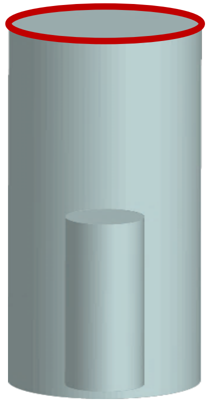
*QEC Demonstration:
N. Ofek et al., Nature, 2016
Multi-mode cavity memories:
Schuster group, U Chicago

Figures: “Superconducting Qubits: Current State of Play,” M. Kjaergaard et al., 2019

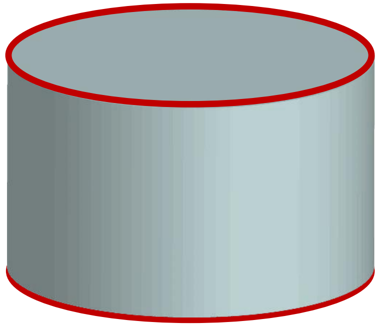
Some 3D cavity realizations



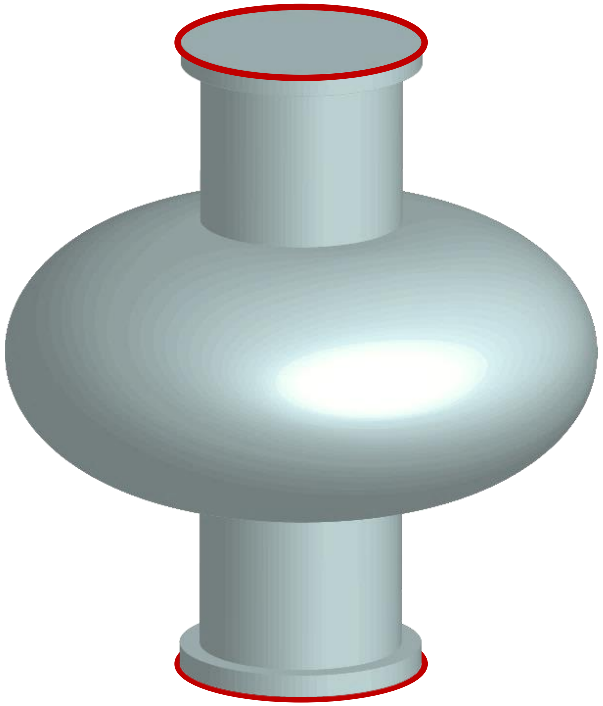
Al rectangular
$Q = 60 \times 10^6$
$\tau = 1\ \mathrm{ms}$



Al stub
$Q = 70 \times 10^6$
$\tau = 3\ \mathrm{ms}$



Al cylindrical
$Q = 740 \times 10^6$
$\tau = 10\ \mathrm{ms}$



Nb TESLA*

	heat treated
$Q = 1 \times 10^9$	$Q = 17 \times 10^9$
$\tau = 30\ \mathrm{ms}$	$\tau = 2\ \mathrm{s}$

Reagor *et al*. Appl. Phys. Lett. **102**, 192604 (2013)
T. Brecht *et al*. Appl. Phys. Lett. **107**, 192603 (2015)
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∗A. Romanenko *et al*. arXiv: 1810.03703 (Fermilab)

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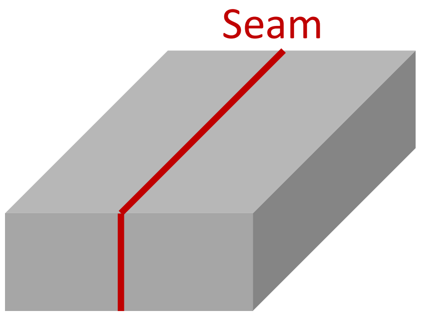

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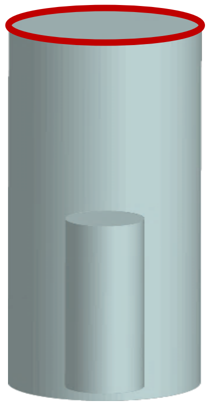

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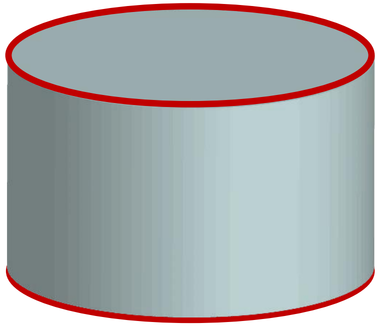

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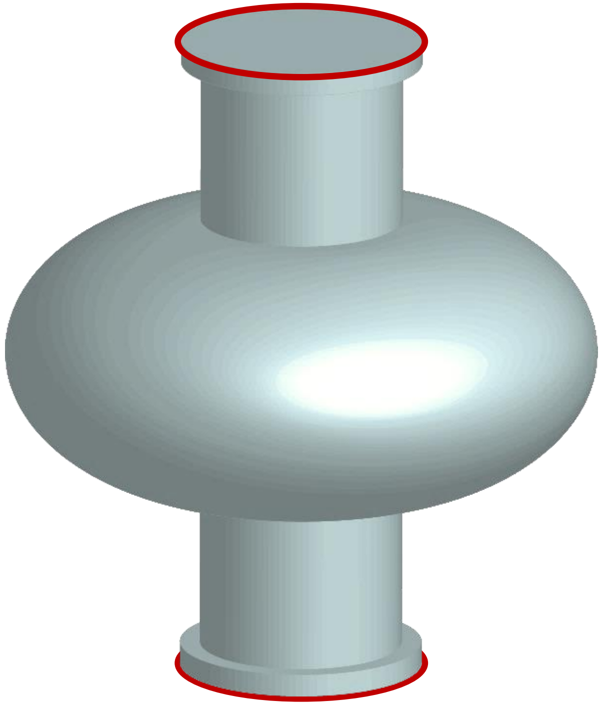

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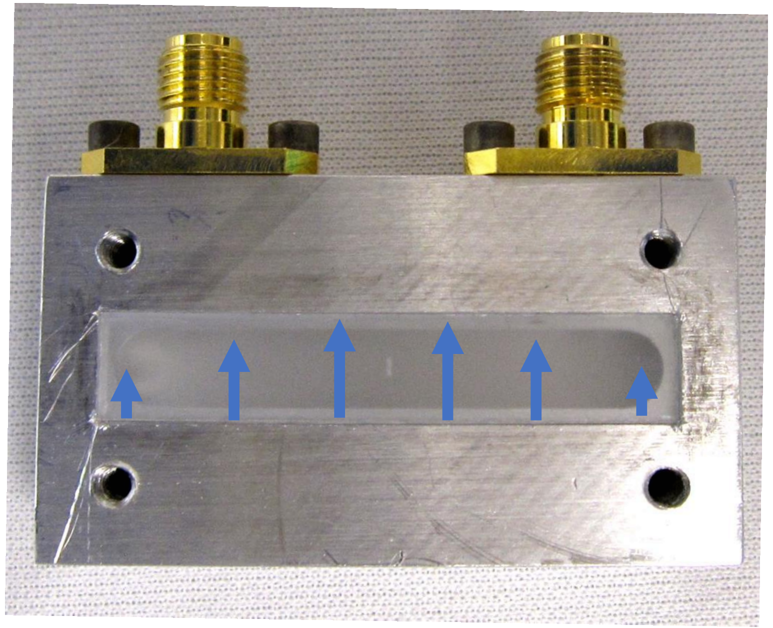
The experts look ahead

Electronics, Volume 38, Number 8, April 19, 1965

Cramming more components onto integrated circuits



With unit cost falling as the number of components per circuit rises, by 1975 economics may dictate squeezing as many as 65,000 components on a single silicon chip

By Gordon E. Moore

Director, Research and Development Laboratories, Fairchild Semiconductor division of Fairchild Camera and Instrument Corp.

Electronics, Volume 38, Number 8, April 19, 1965

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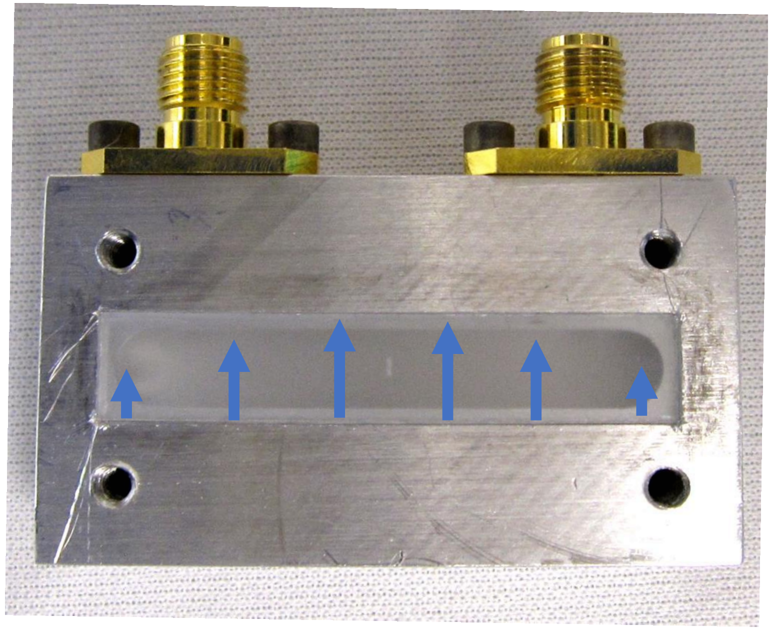

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Linear circuitry

Integration will not change linear systems as radically as digital systems. Still, a considerable degree of integration will be achieved with linear circuits. The lack of large-value capacitors and inductors is the greatest fundamental limitations to integrated electronics in the linear area.

By their very nature, such elements require the storage of energy in a volume. For high Q it is necessary that the volume be large. The incompatibility of large volume and integrated electronics is obvious from the terms themselves.

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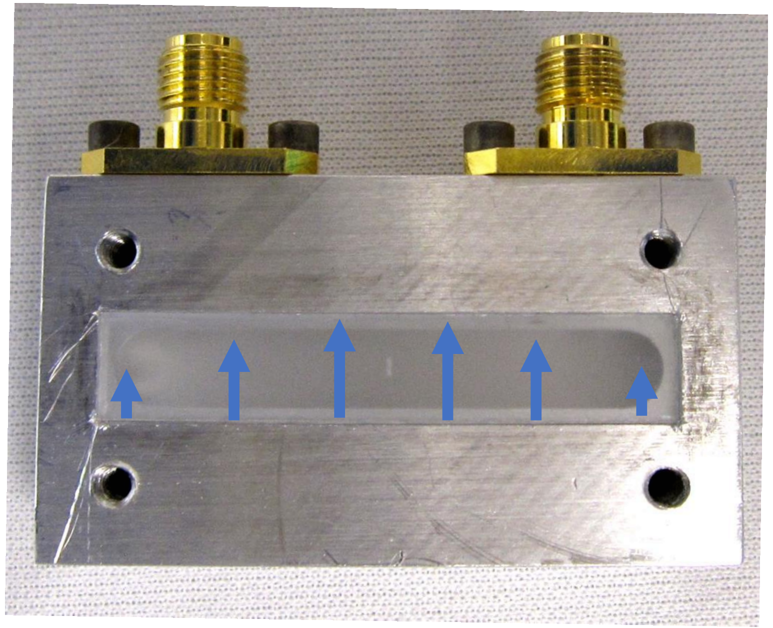
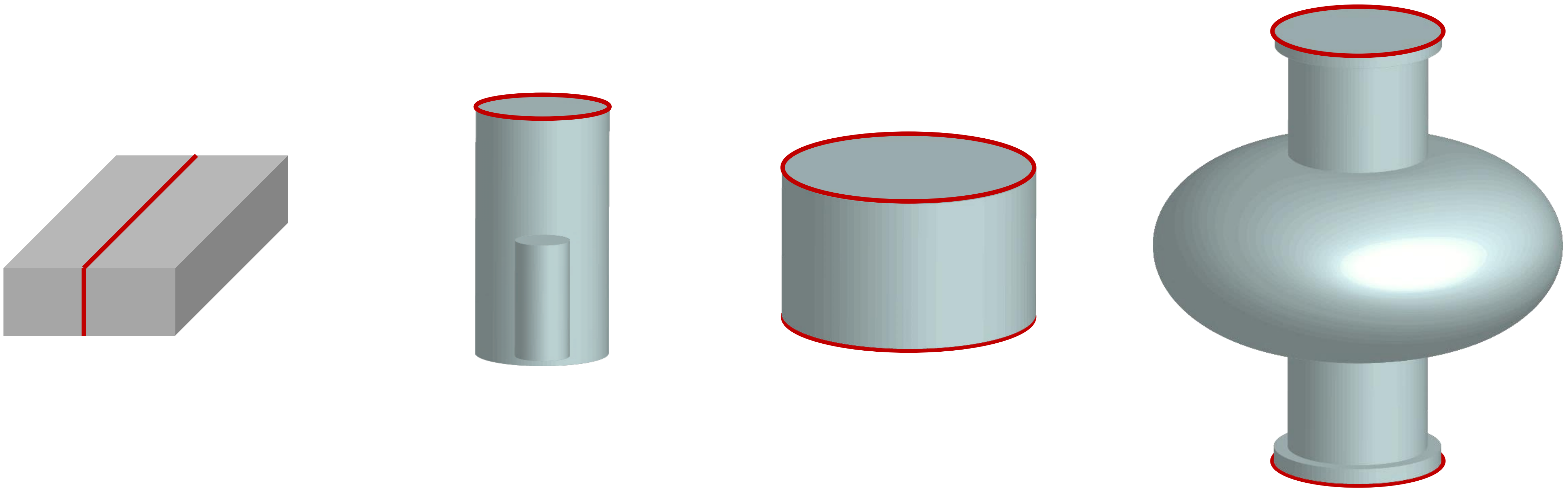


Miniaturization is **not** the name of the game
Instead, a careful understanding of what imperfections matter

What can go wrong in an empty box?



$$\frac{1}{Q_{\text{int}}} = \frac{P_{\text{diss}}}{\omega U_{\text{tot}}} = \sum_i \frac{P_{\text{diss},i}}{\omega U_{\text{tot}}} = \sum_i \frac{p_i}{q_i}$$

geometry → p_i

material → q_i

$$p_i = \frac{\text{energy stored in element } i}{\text{total energy}}$$

For systematic studies, see for example:
C. Wang et al., Appl. Phys. Lett. (2015)
W. Woods et al., Phys. Rev. Applied (2019)

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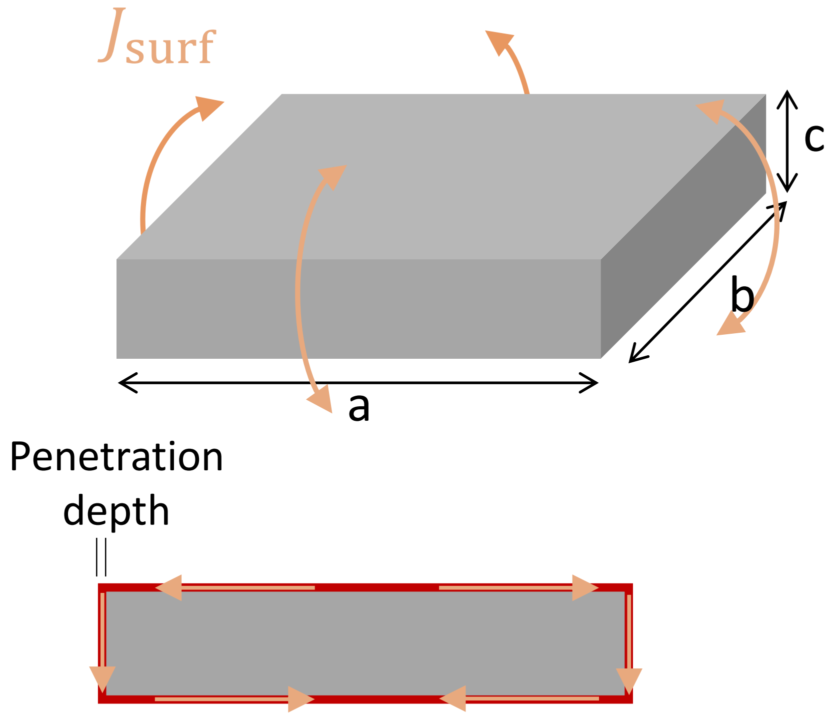

Conductor loss: magnetic losses in w/in penetration depth (quasiparticles, vortices, magnetic impurities,…)

$$\frac{1}{Q_{\rm cond}} = \frac{R_{\rm sq}}{\mathcal{G}} = \frac{p_{\rm cond}}{q_{\rm cond}}$$

$p_{\rm cond}$ ← Kinetic inductance fraction

$q_{\rm cond}$ ← (Surface resistance)$^{-1}$

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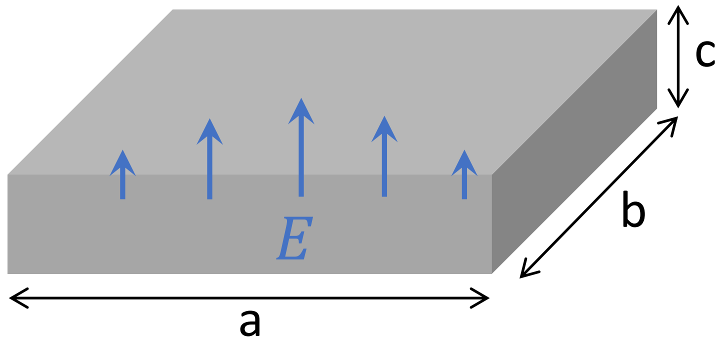

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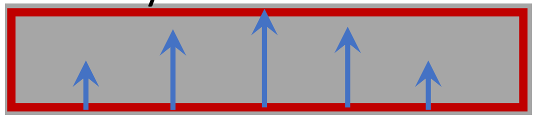

Dielectric loss: electrical losses in thin surface dielectric (lossy oxides, contaminants)

$$\frac{1}{Q_{\mathrm{surf}}} = \frac{p_{\mathrm{surf}}}{q_{\mathrm{surf}}}$$

← Electric energy near surface (p_{surf})

← (Loss tangent)$^{-1}$ (q_{surf})

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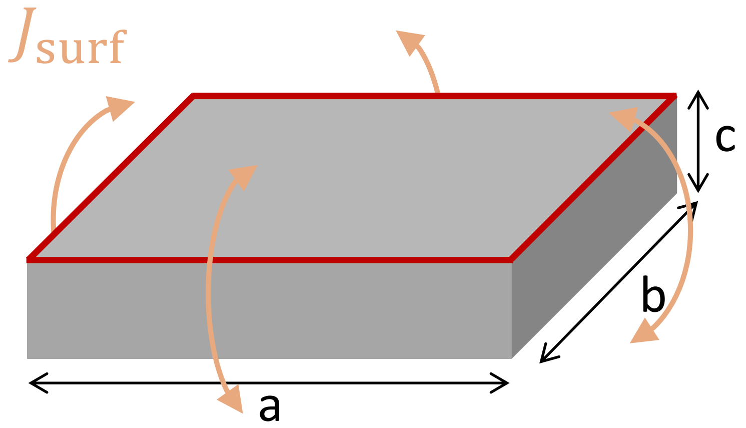

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p_{surf} ← Electric energy near surface

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Seam loss: resistance at joint between two halves of cavity (unbroken oxides, contaminants)

$$\frac{1}{Q_{\mathrm{seam}}} = \frac{y_{\mathrm{seam}}}{g_{\mathrm{seam}}}$$

y_{seam} ← Current across seam

g_{seam} ← Seam conductance

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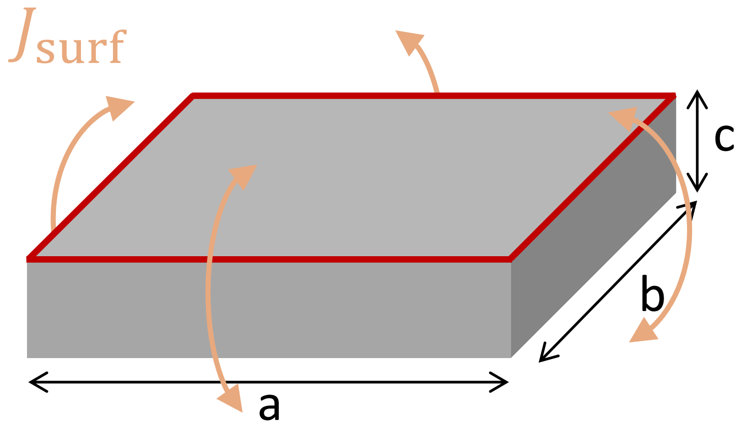
W. Woods et al., Phys. Rev. Applied (2019)

What can go wrong in an empty box?



Conductor loss: magnetic losses in w/in penetration depth (quasiparticles, vortices, magnetic impurities,…)

$$\frac{1}{Q_{\mathrm{cond}}} = \frac{R_{\mathrm{sq}}}{\mathcal{G}} = \frac{p_{\mathrm{cond}}}{q_{\mathrm{cond}}}$$

p_{cond} ← Kinetic inductance fraction

q_{cond} ← (Surface resistance)$^{-1}$

Dielectric loss: electrical losses in thin surface dielectric (lossy oxides, contaminants)

$$\frac{1}{Q_{\mathrm{surf}}} = \frac{p_{\mathrm{surf}}}{q_{\mathrm{surf}}}$$

p_{surf} ← Electric energy near surface

q_{surf} ← (Loss tangent)$^{-1}$

Seam loss: resistance at joint between two halves of cavity (unbroken oxides, contaminants)

$$\frac{1}{Q_{\mathrm{seam}}} = \frac{y_{\mathrm{seam}}}{g_{\mathrm{seam}}}$$

y_{seam} ← Current across seam

g_{seam} ← Seam conductance

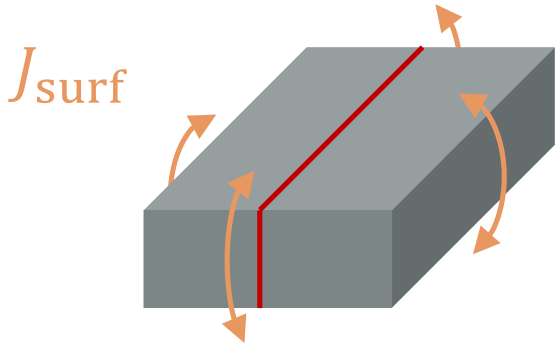
$$\frac{1}{Q_{\mathrm{int}}} = \frac{p_{\mathrm{cond}}}{q_{\mathrm{cond}}} + \frac{p_{\mathrm{surf}}}{q_{\mathrm{surf}}} + \frac{y_{\mathrm{seam}}}{g_{\mathrm{seam}}} + \cdots$$

Typically, all participations drop with increasing volume

For systematic studies, see for example:
C. Wang et al., Appl. Phys. Lett. (2015)
W. Woods et al., Phys. Rev. Applied (2019)

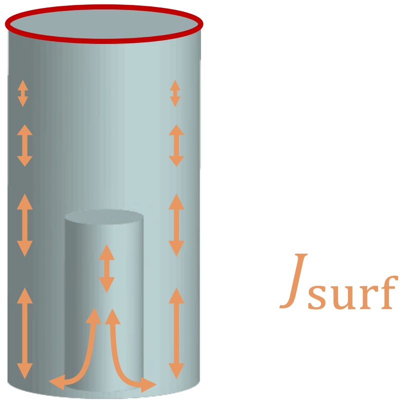
Avoiding seam loss through clever design

Design zero current across lossy seam (by symmetry)



Al rectangular
$\mathrm{Q} = 77 \times 10^6$
$\tau = 1\ \mathrm{ms}$

Design exponentially small current across lossy seam



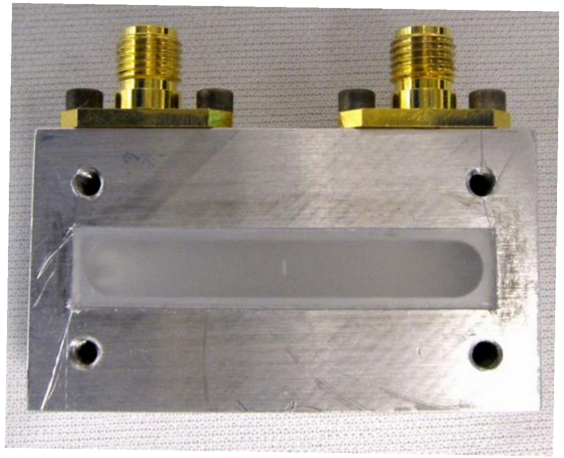
Al stub
$\mathrm{Q} = 70 \times 10^6$
$\tau = 3\ \mathrm{ms}$

What about a use case where this is impossible?

Moving forward: complex circuits with 3D cavities?

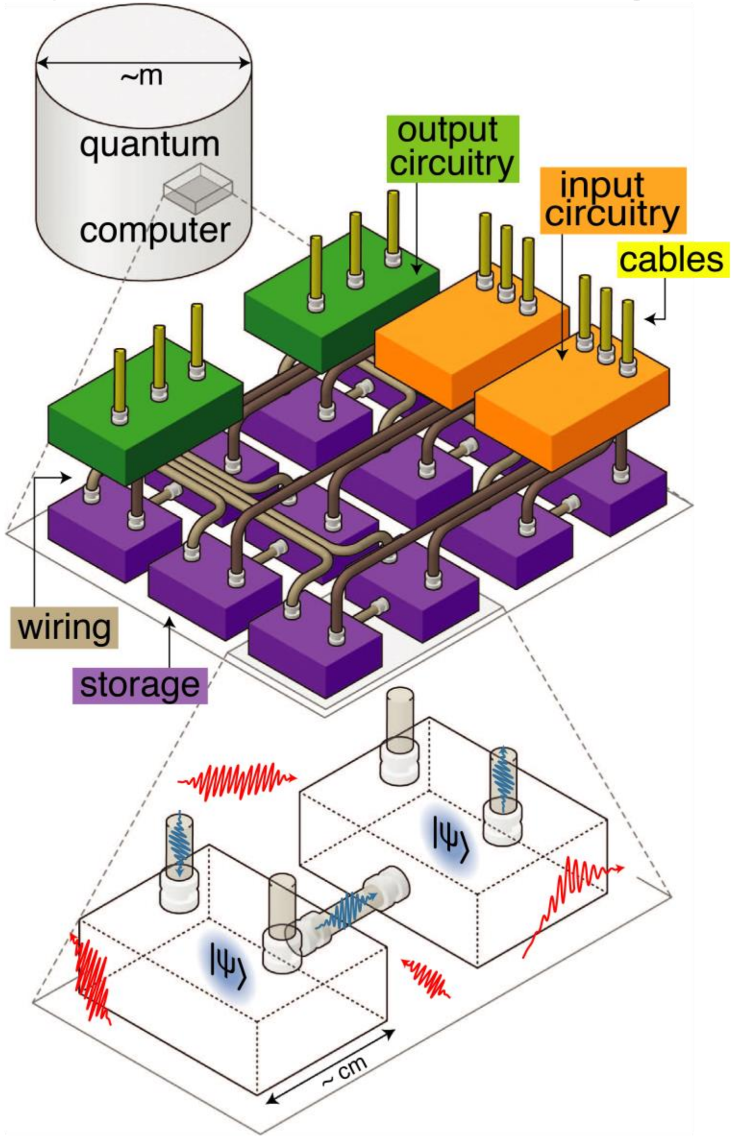
Bulk machining is a "necessary evil"

- Huge (10x) variability in surface quality
- Far less precision compared to lithography
- Milling machines have a particular set of design constraints
- **Difficult to integrate with certain useful circuitry**

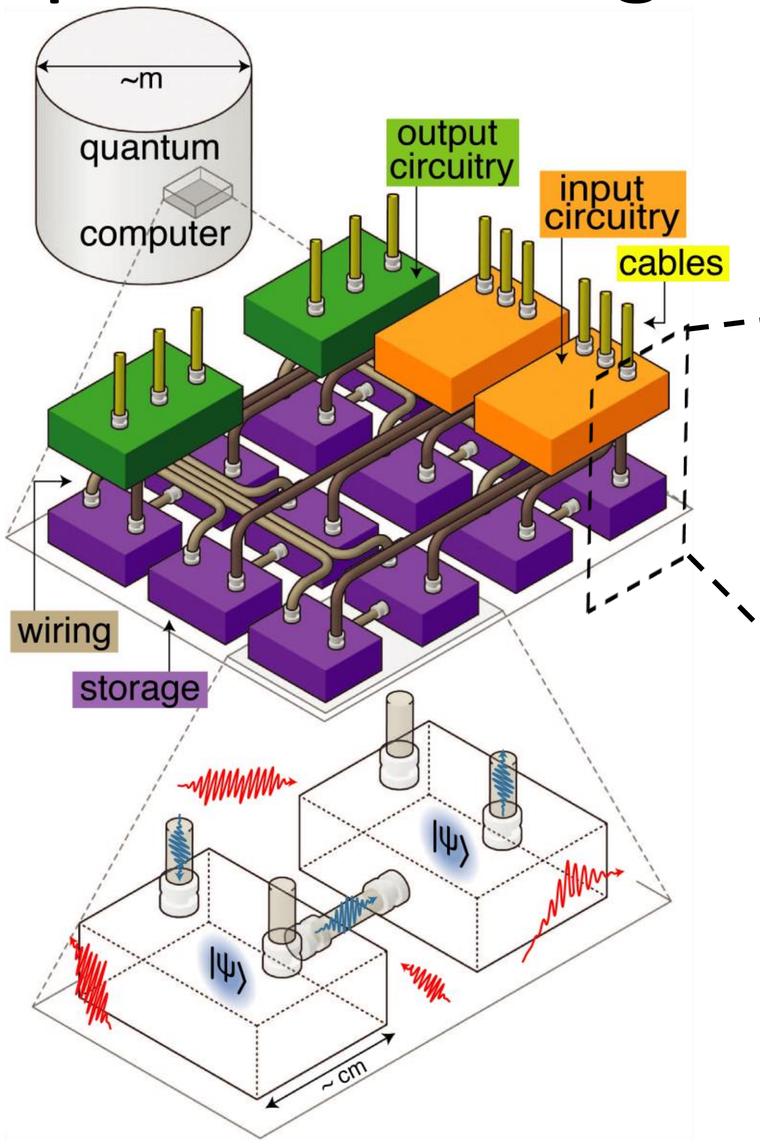


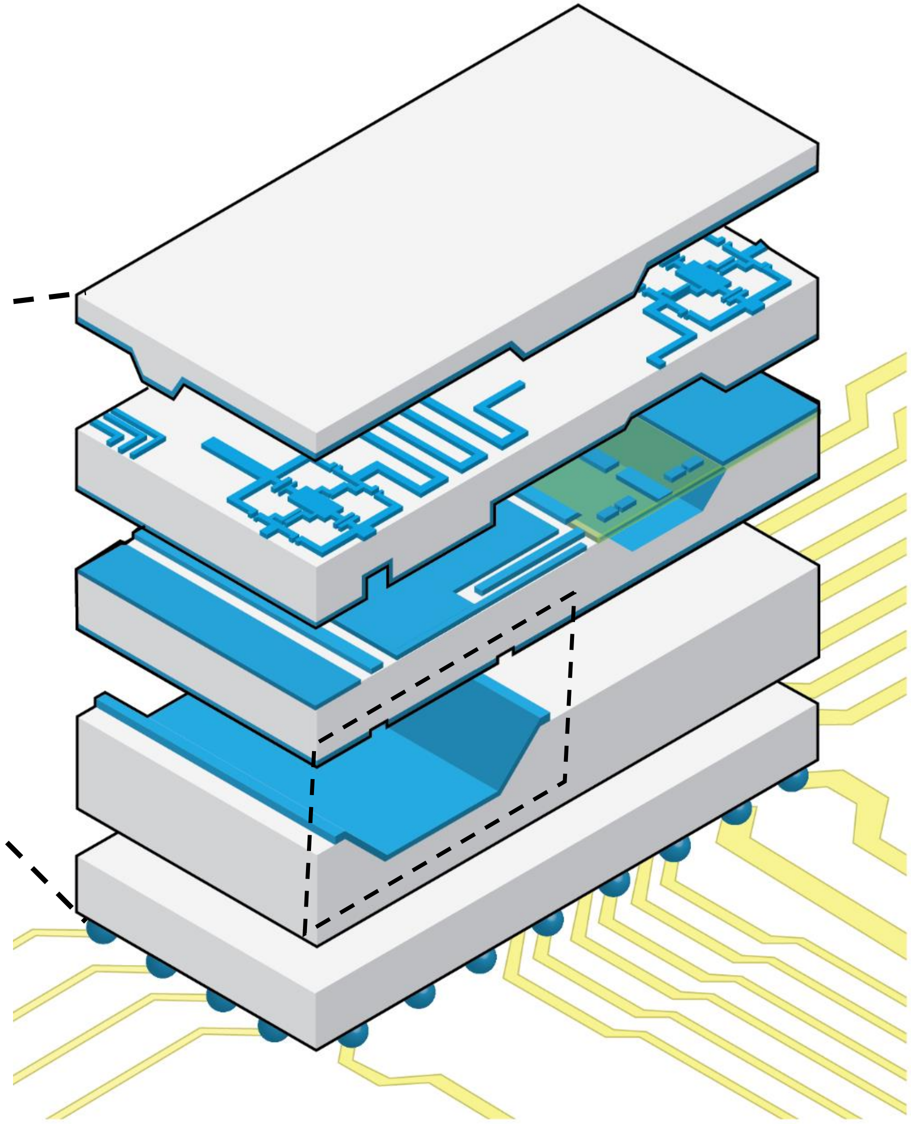
Can we make a cavity lithographically with the same (or higher) quality?

Prospects for integration within a module



Prospects for integration within a module





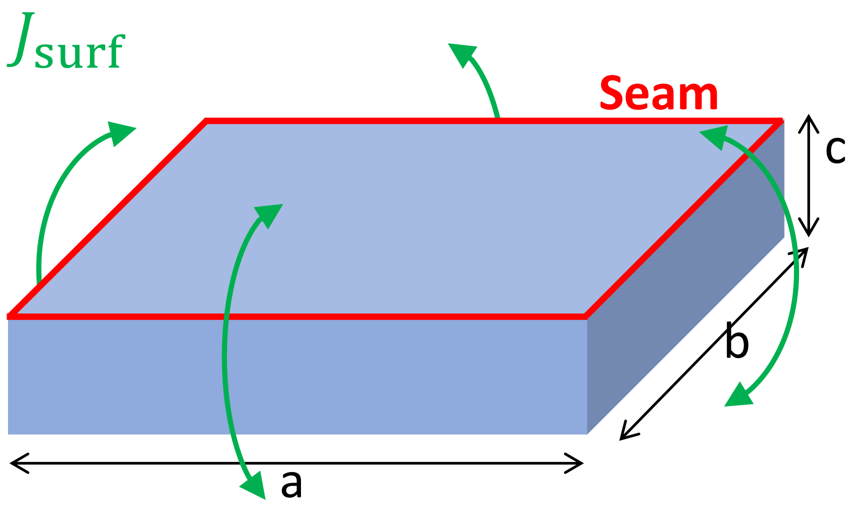
I/O

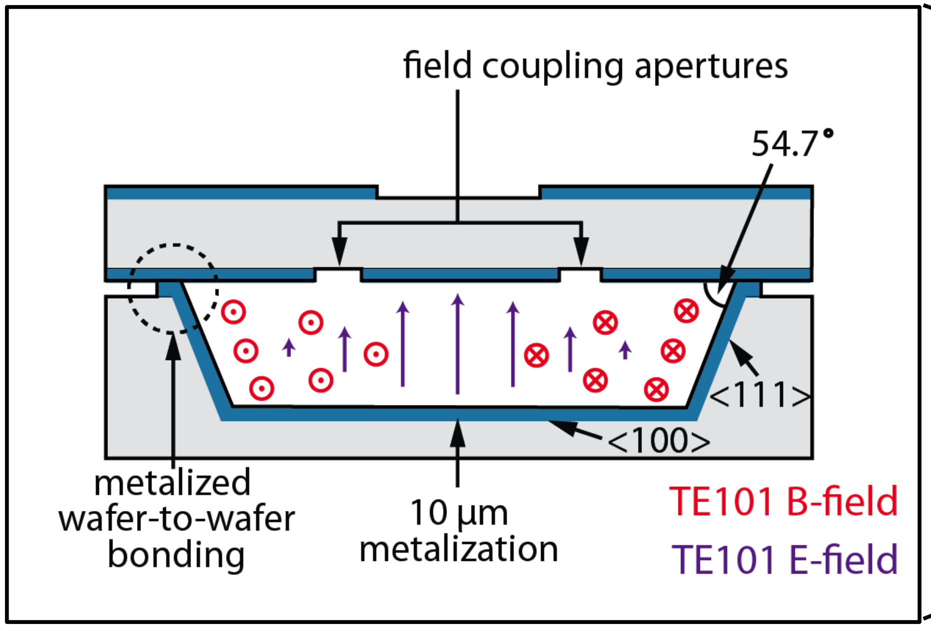
Connectivity

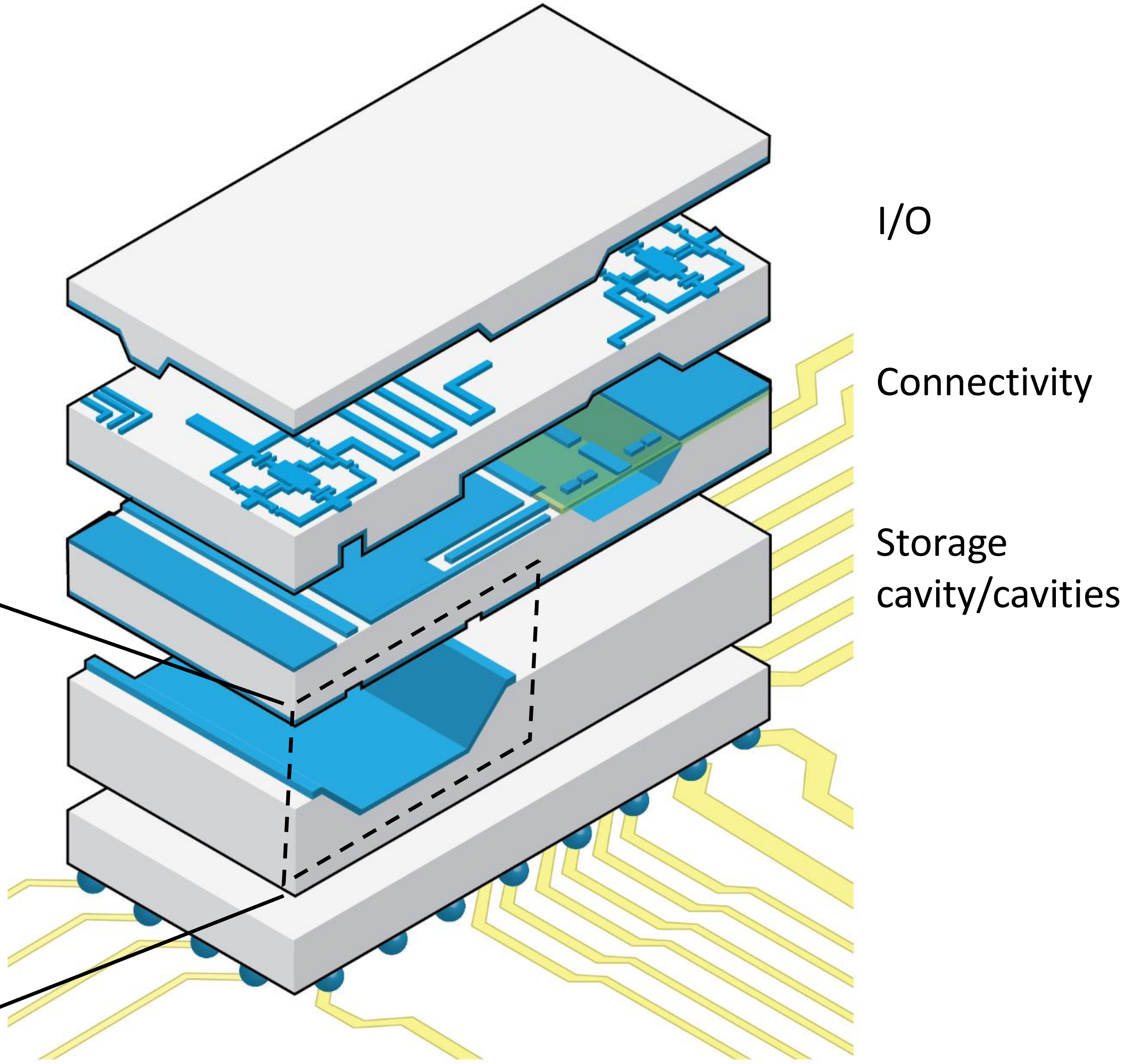
Storage
cavity/cavities

T. Brecht *et al*., Nature Quantum Info, 2016
D. Rosenberg *et al*., Nature Quantum Info, 2017

Prospects for integration within a module

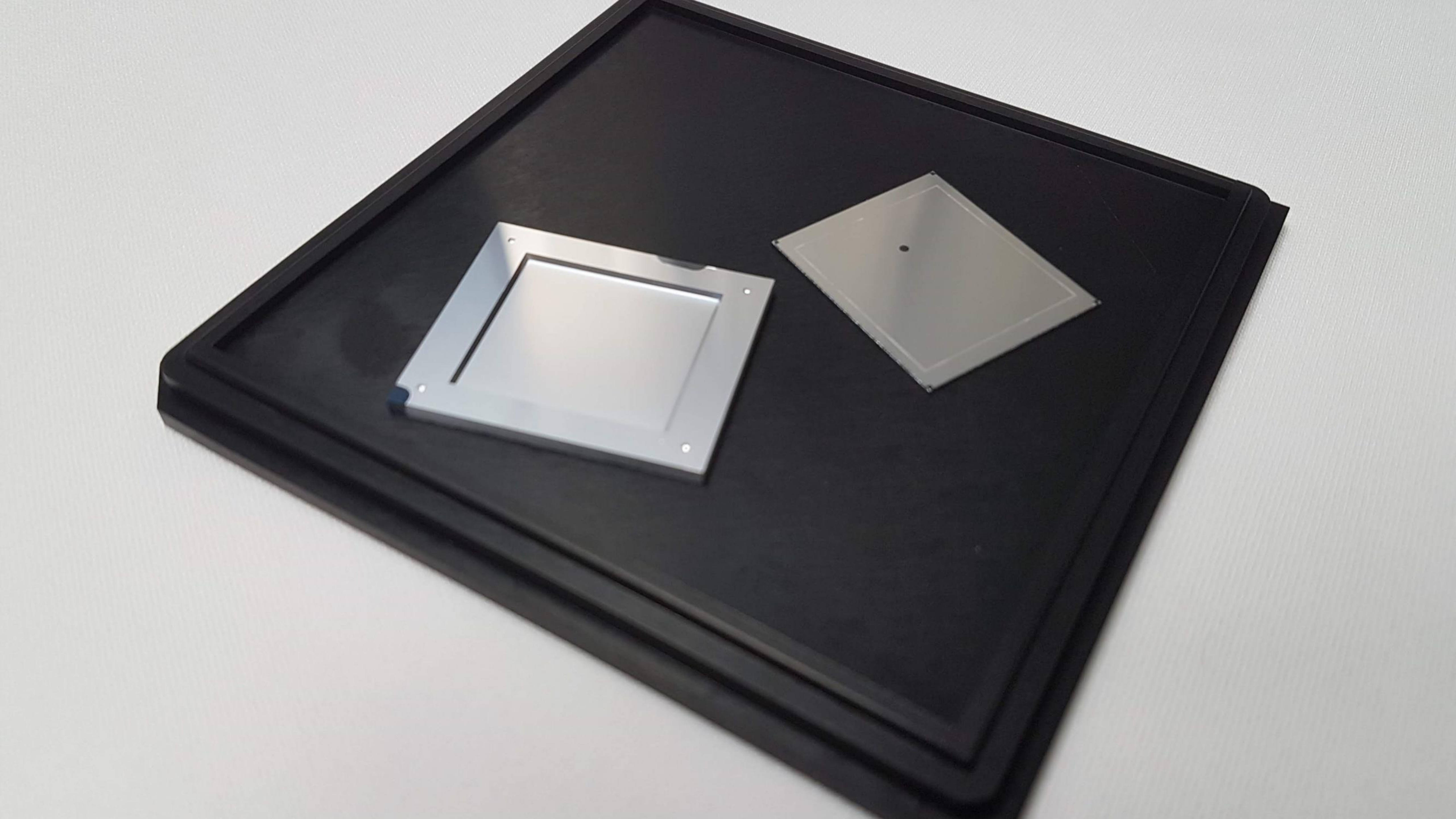


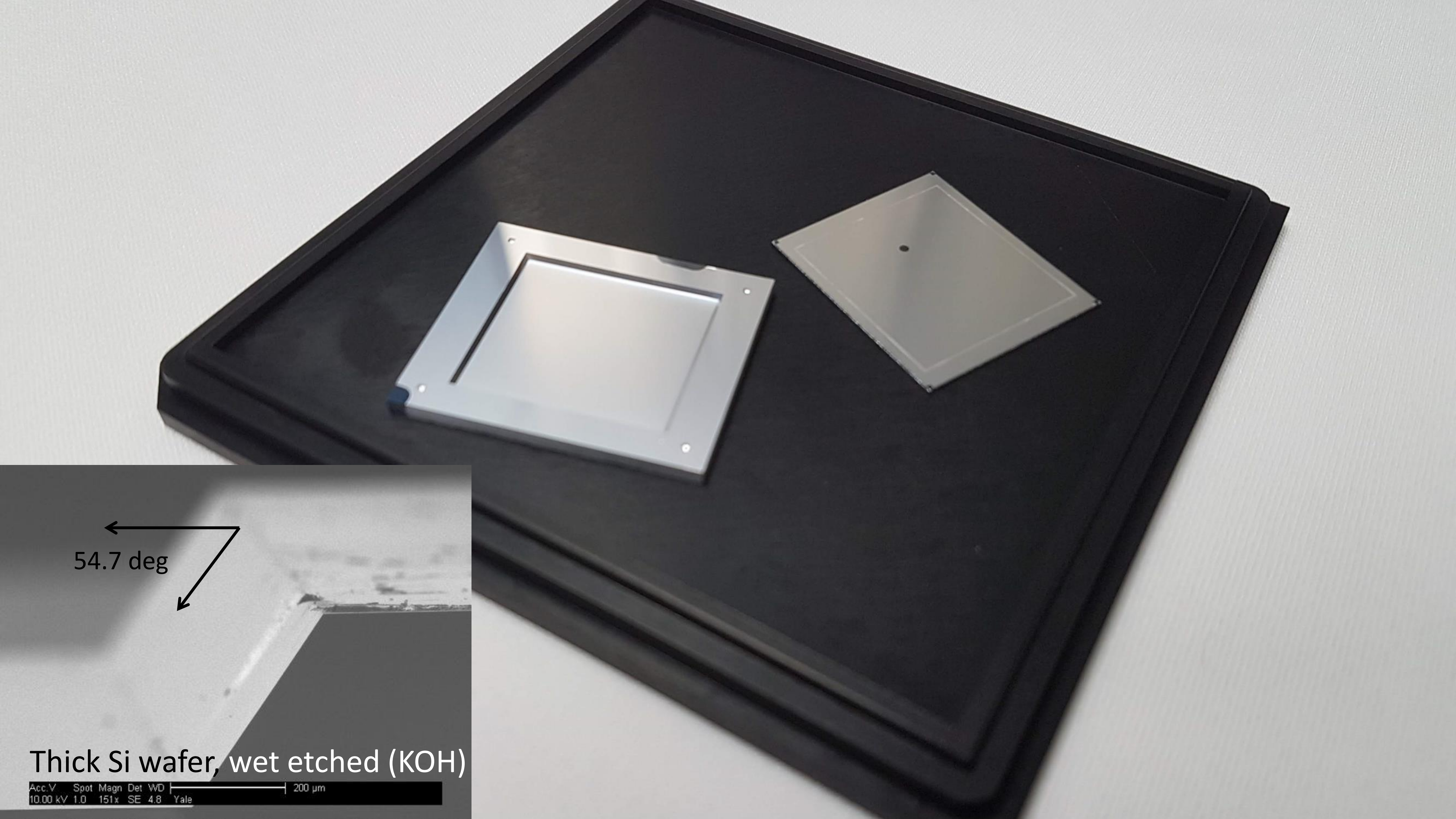


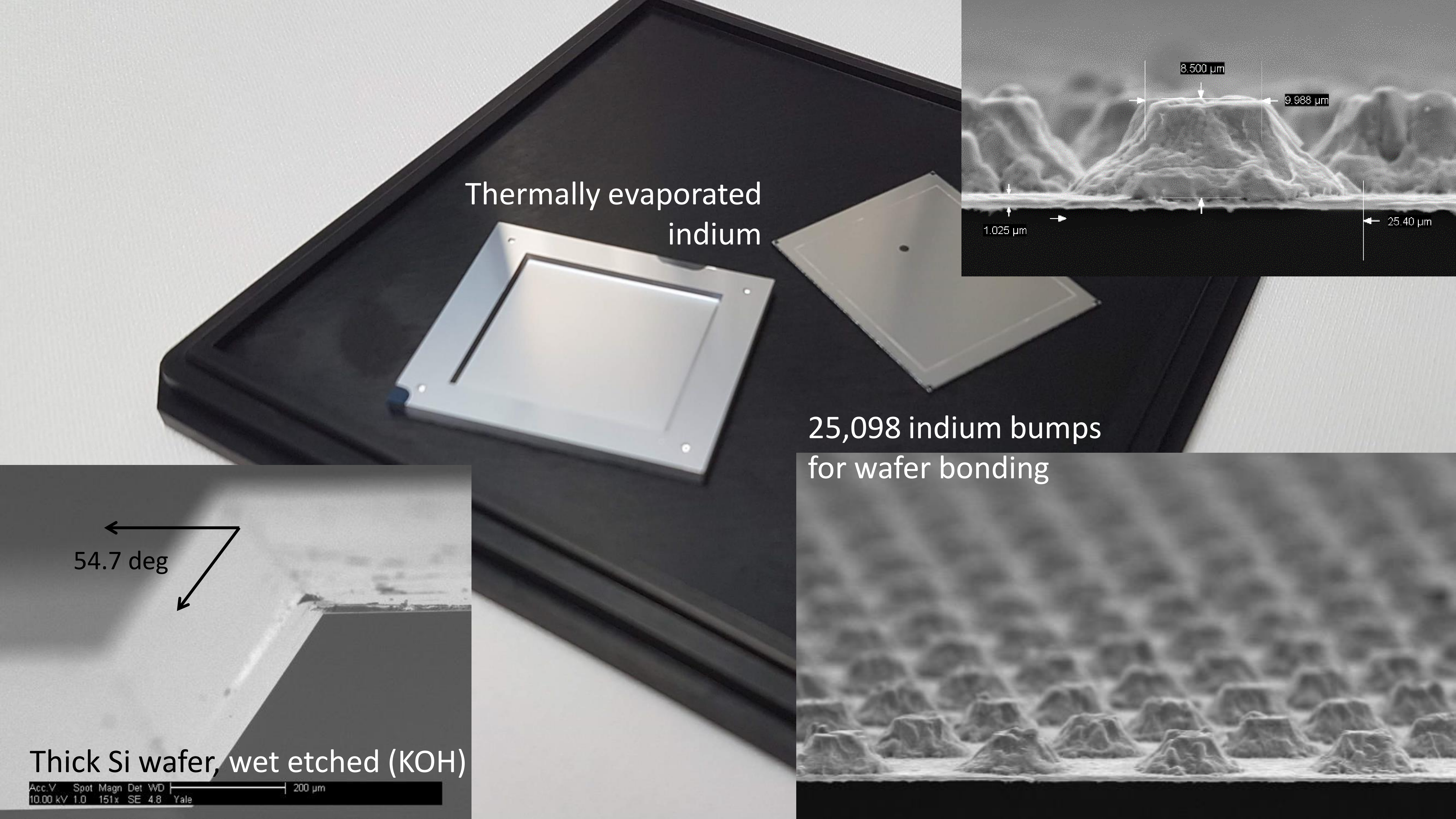


T. Brecht *et al.*, Nature Quantum Info, 2016

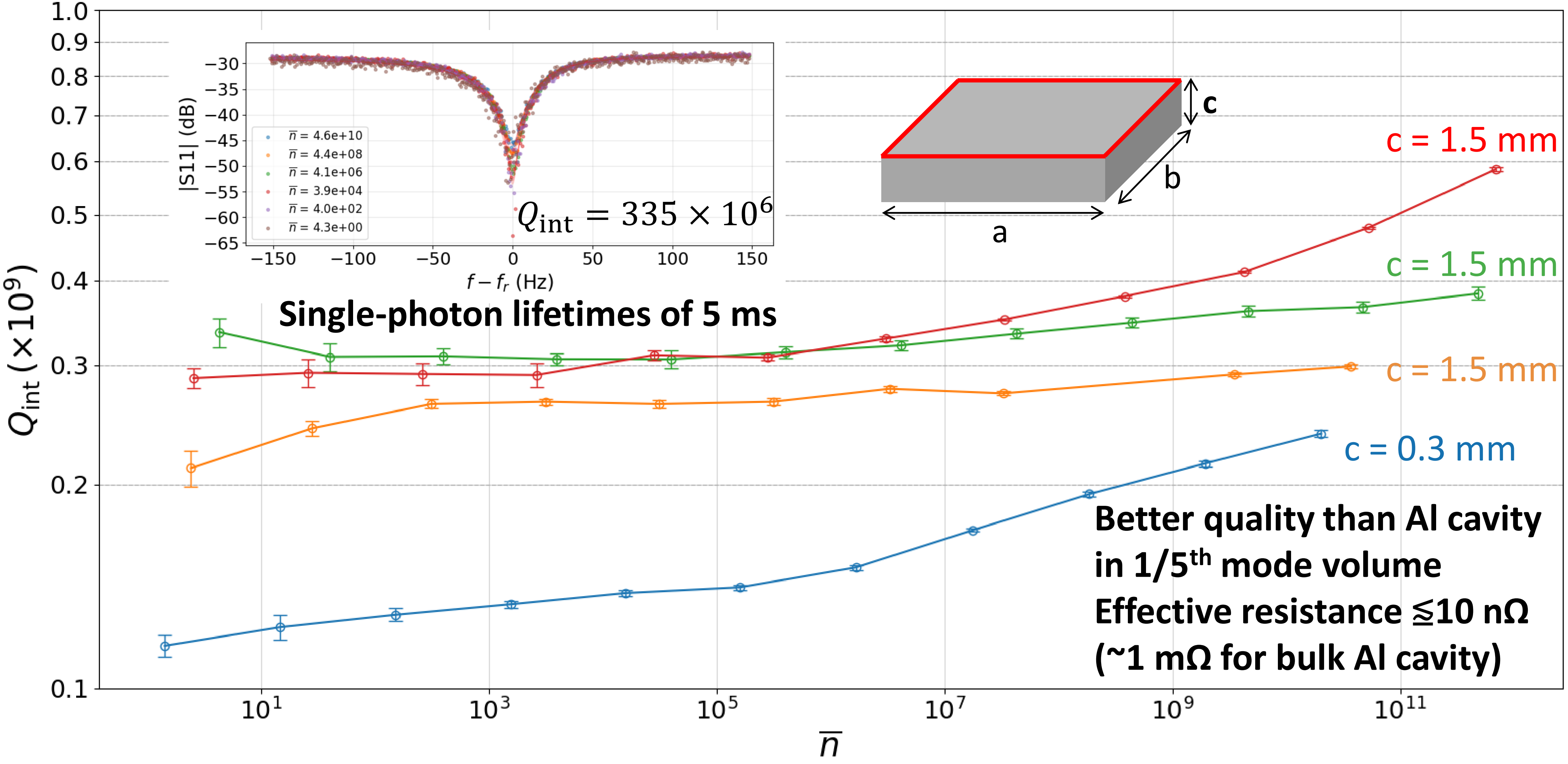
D. Rosenberg *et al.*, Nature Quantum Info, 2017




54.7 deg
Thick Si wafer, wet etched (KOH)
Acc.V Spot Magn Det WD 200 µm
10.00 kV 1.0 151x SE 4.8 Yale


Thermally evaporated indium
8.500 µm
9.988 µm
1.025 µm
25.40 µm
25,098 indium bumps for wafer bonding
54.7 deg
Thick Si wafer, wet etched (KOH)
Acc.V Spot Magn Det WD 200 µm
10.00 kV 1.0 151x SE 4.8 Yale

A (very) high-Q cavity in a wafer



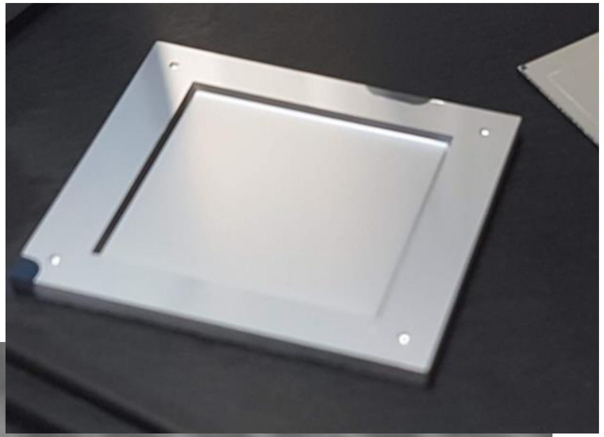
Outlook: high-Q cavities in integrated quantum circuits

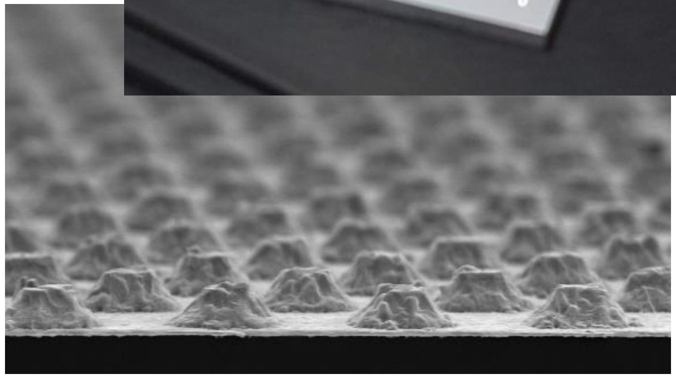
As technology develops, complexity within modules can increase, and connecting modules gets us to the next level of scale

Cavities make excellent circuit elements for modular quantum computers

3D integration of microwave circuits in a very novel regime

- nano-ohm RF resistance
- extremely low-loss dielectrics
- thin and rare contaminants





Thank you!

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Rob Schoelkopf (PI)

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