Superconducting Coplanar Waveguide Resonators as a Diagnostic Tool for Quantum Circuits

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Boulder, CO

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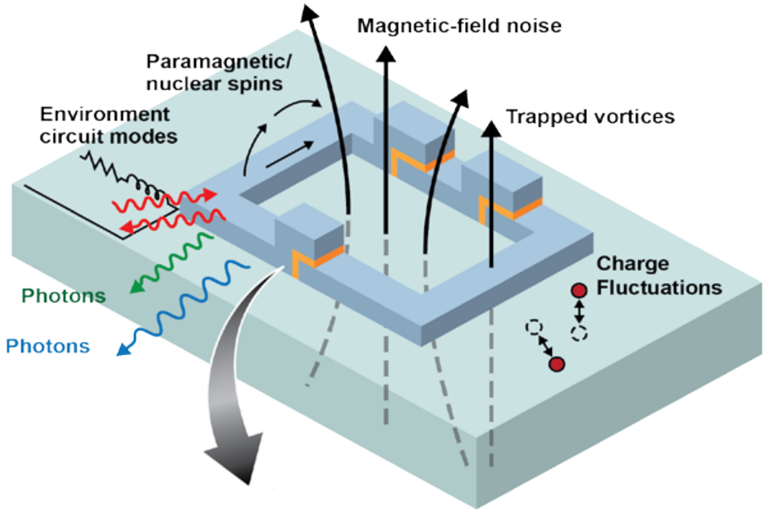
Noise and Loss in Superconducting Quantum Circuits

Sources of Noise and Loss

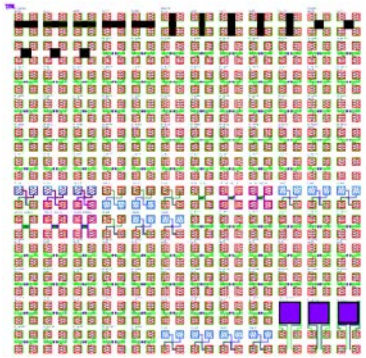


Oliver and Welander, MRS Bulletin 38, 816 (2013)

Wanted: Diagnostic tools for studying sources of noise and loss

Analogous to…

CAD of JJ Test Array



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RT Electrical Testing

Challenge	**Requirement**
Fab, measurement time + resources	Need surrogate device/probe
Device-to-device variability	Statistical measurement and analysis
Low T, vacuum, “quiet” EM environment	Realistic operating conditions
Competing signals/behavior	Model or mitigate other mechanisms

Goal: Use statistical device testing of superconducting CPW resonators to perform quantitative analysis of TLS losses at interfaces

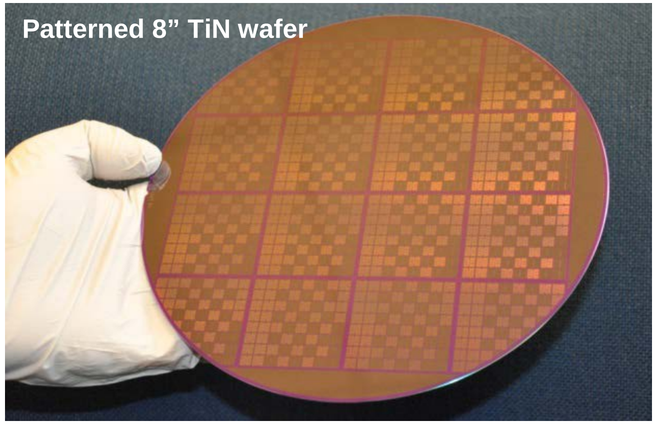
Outline

- A/B Testing
- Characterizing 3D integration
- Surface Loss Extraction (SLE)
- Sources of device-to-device variability

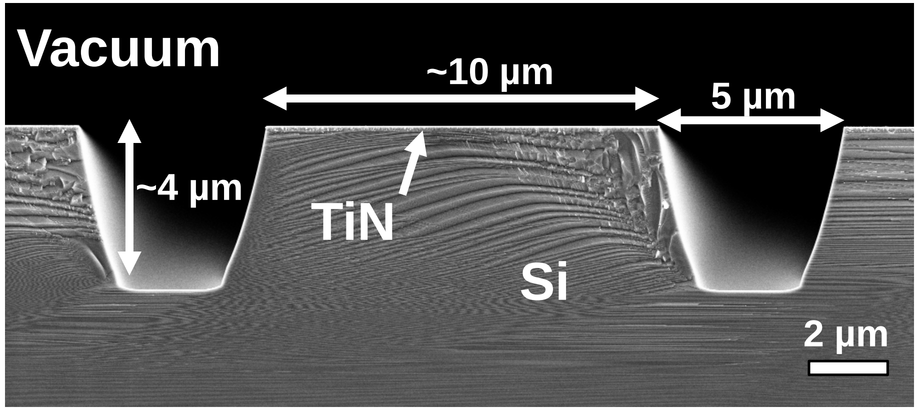
High-throughput Fabrication and Testing

- **Fabrication**
  - 8-inch toolset
  - In-house process characterization and analysis
- **Measurement**
  - Automated device characterization and statistical analysis
  - 2 banks x 6 chips x 5 resonators → 60 per DR cooldown
- **Best process: mean Q_i ~2.2 million**

Established, highly reproducible high-Q TiN process & high-throughput statistical device characterization



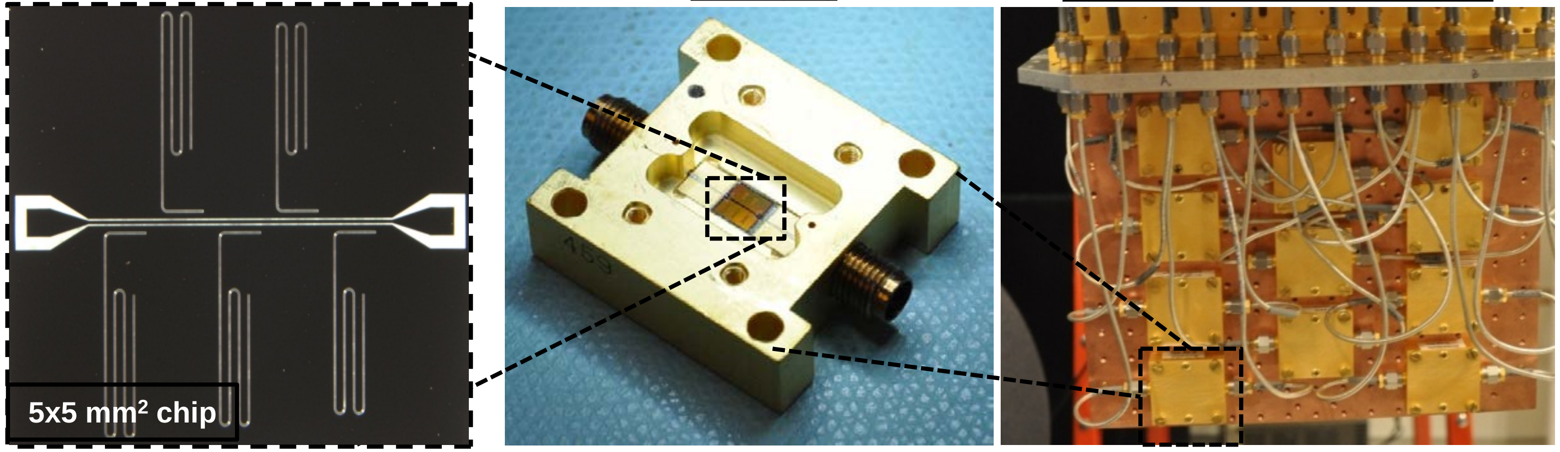
Trenched CPW Cross-section



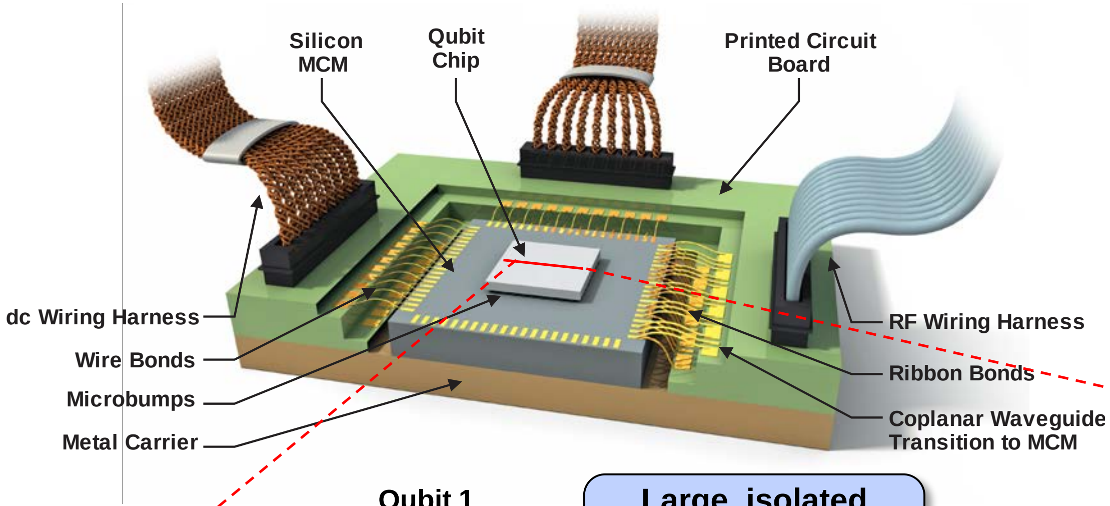
Frequency-multiplexed λ/4 resonators

Packaging

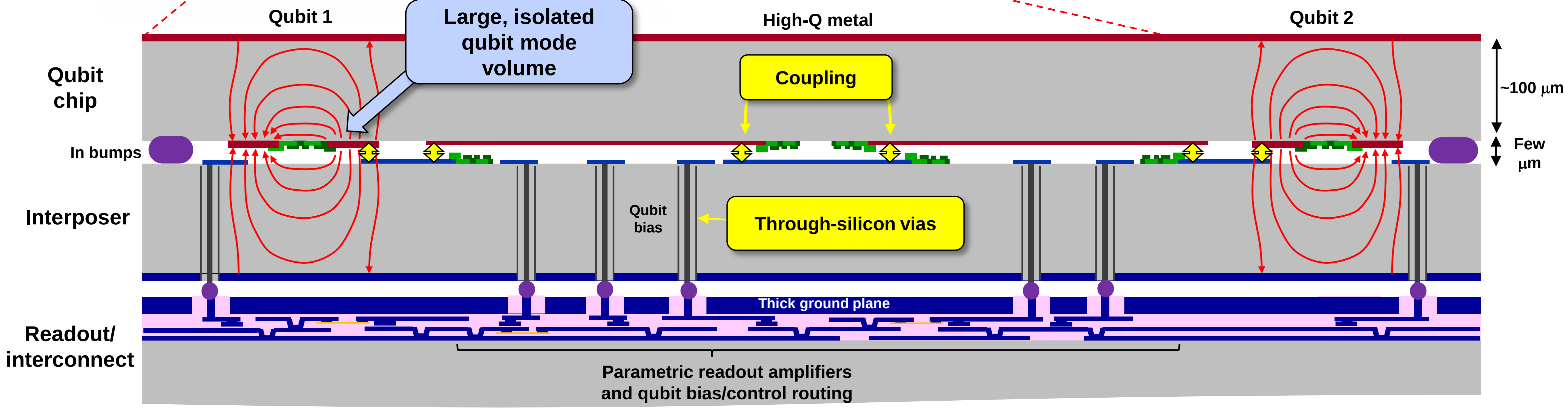
High-throughput measurement



Can we use resonators to qualify new chip fab/materials,…?



Three-tier stack for quantum annealing enables high connectivity while maintaining qubit coherence



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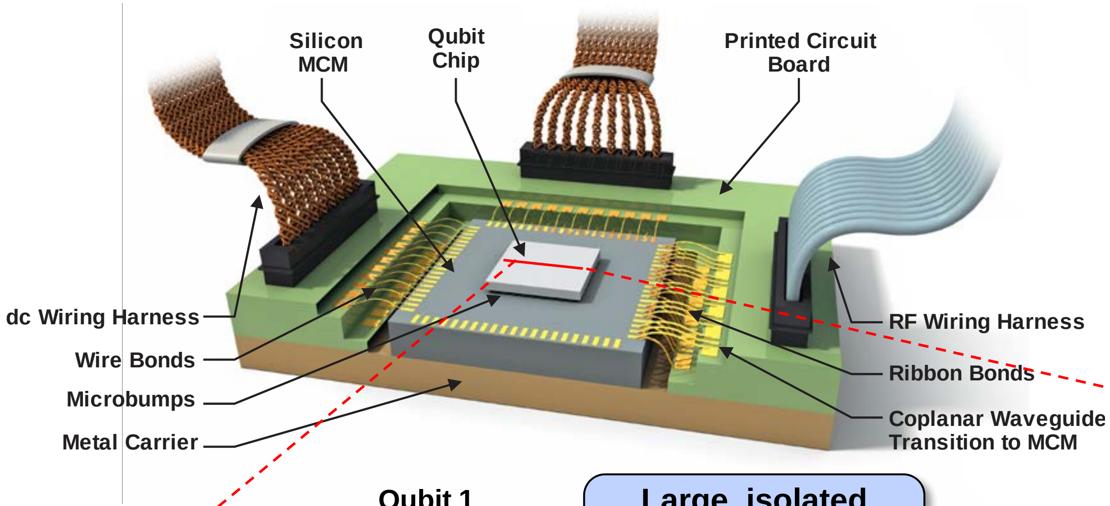

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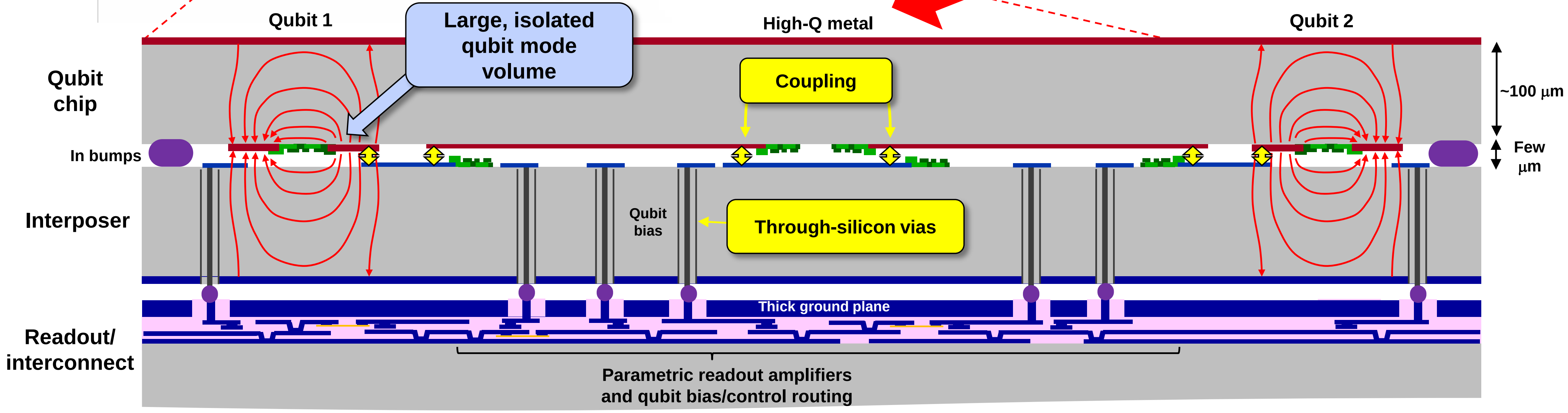

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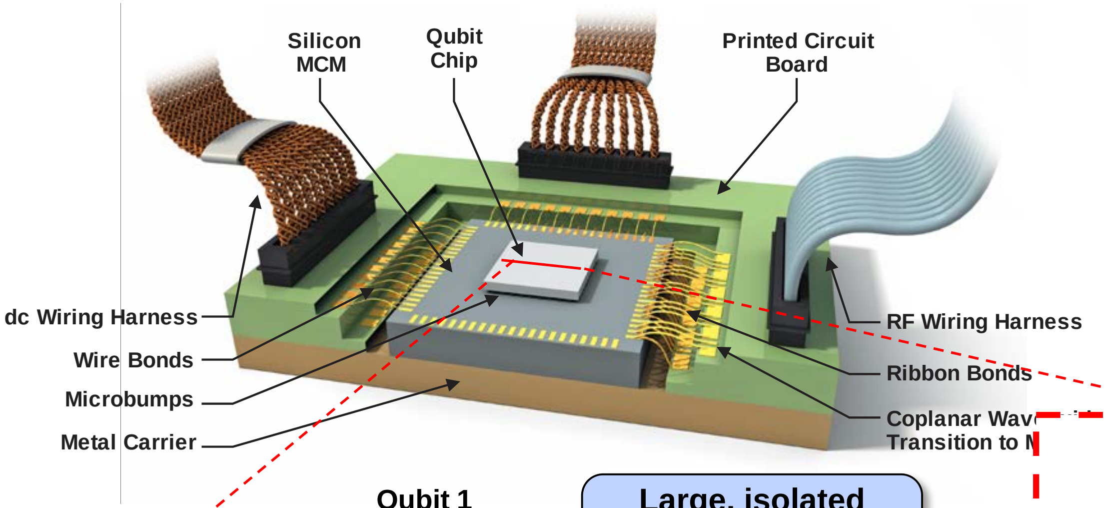

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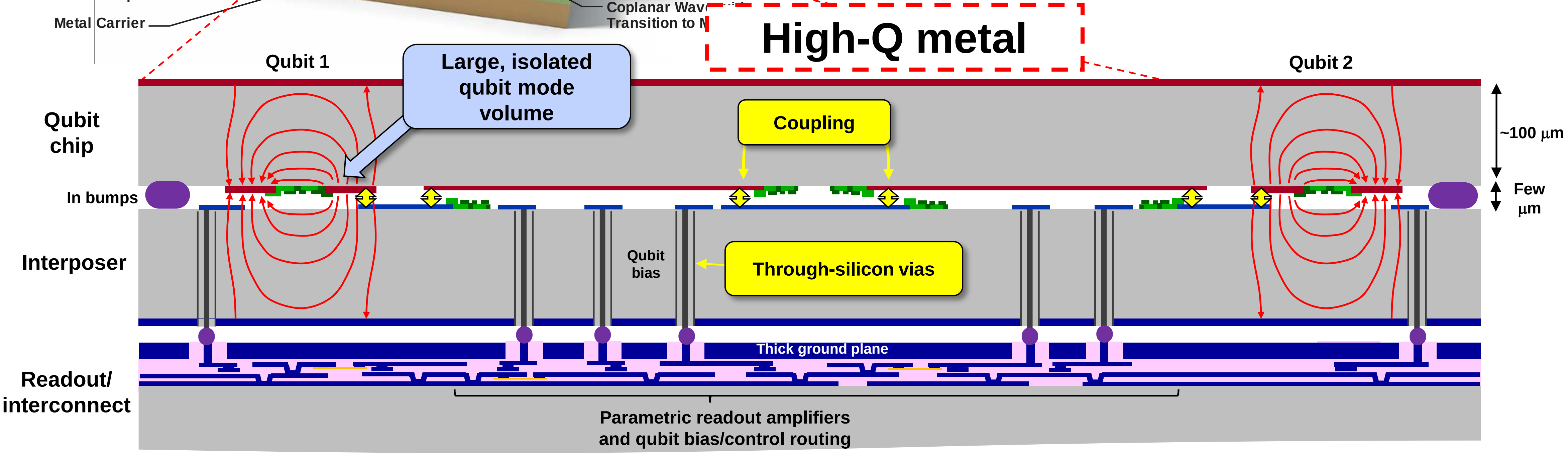

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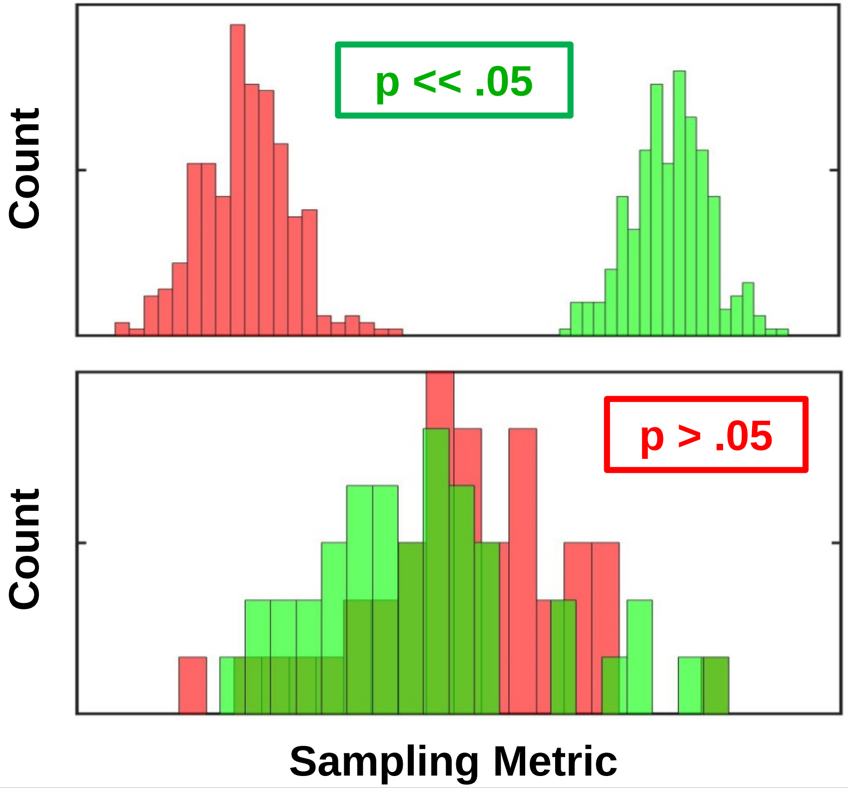
A/B Testing, or "The Canary in the Coal Mine"

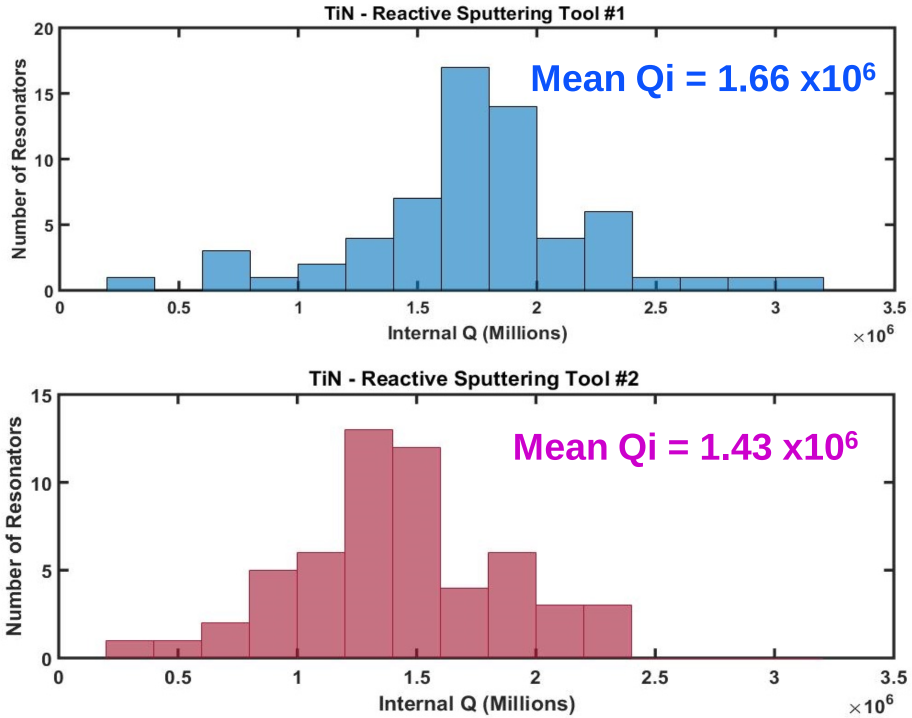
How do we decide if two sampling distributions are different?

<u>Statistical hypothesis testing: Welch's t-test</u>
p-value: the statistical probability that the measured sample originate from the <u>same</u> parent distribution

Standard threshold for significance: p=.05



<u>Example: Sputtered TiN films</u>



TiN Sputtering Tool #1 ~ 50 resonators	TiN Sputtering Tool #2 ~ 50 resonators
Mean Qi = 1.66 x10^6	Mean Qi = 1.43 x10^6
$p < .0057$ → statistically significant	

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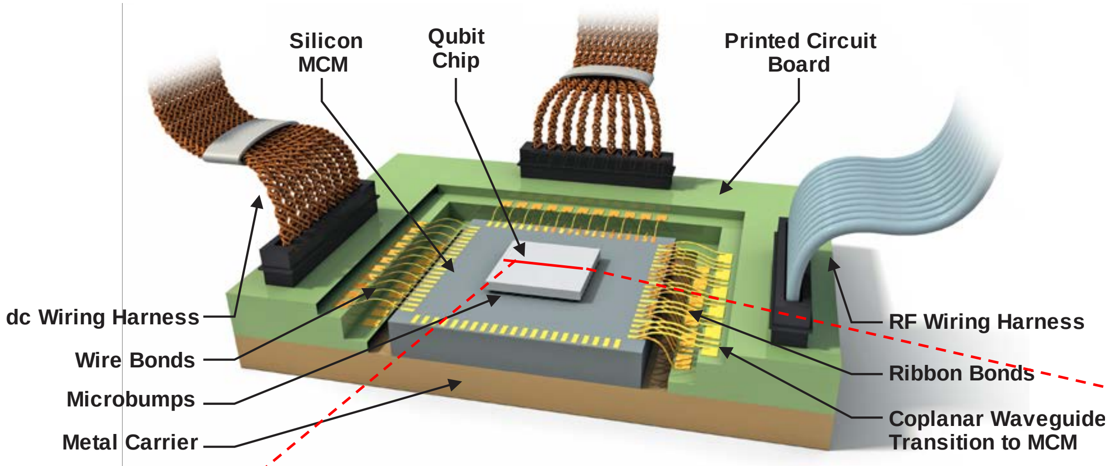
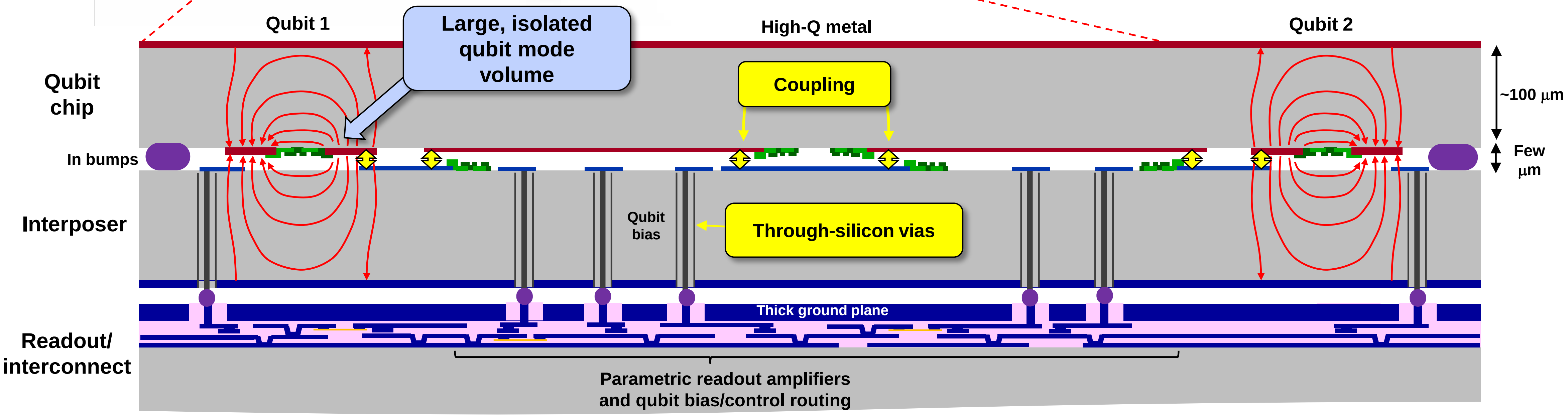
Can we use resonators to qualify new chip fab/materials,…?



Three-tier stack for quantum annealing enables high connectivity while maintaining qubit coherence



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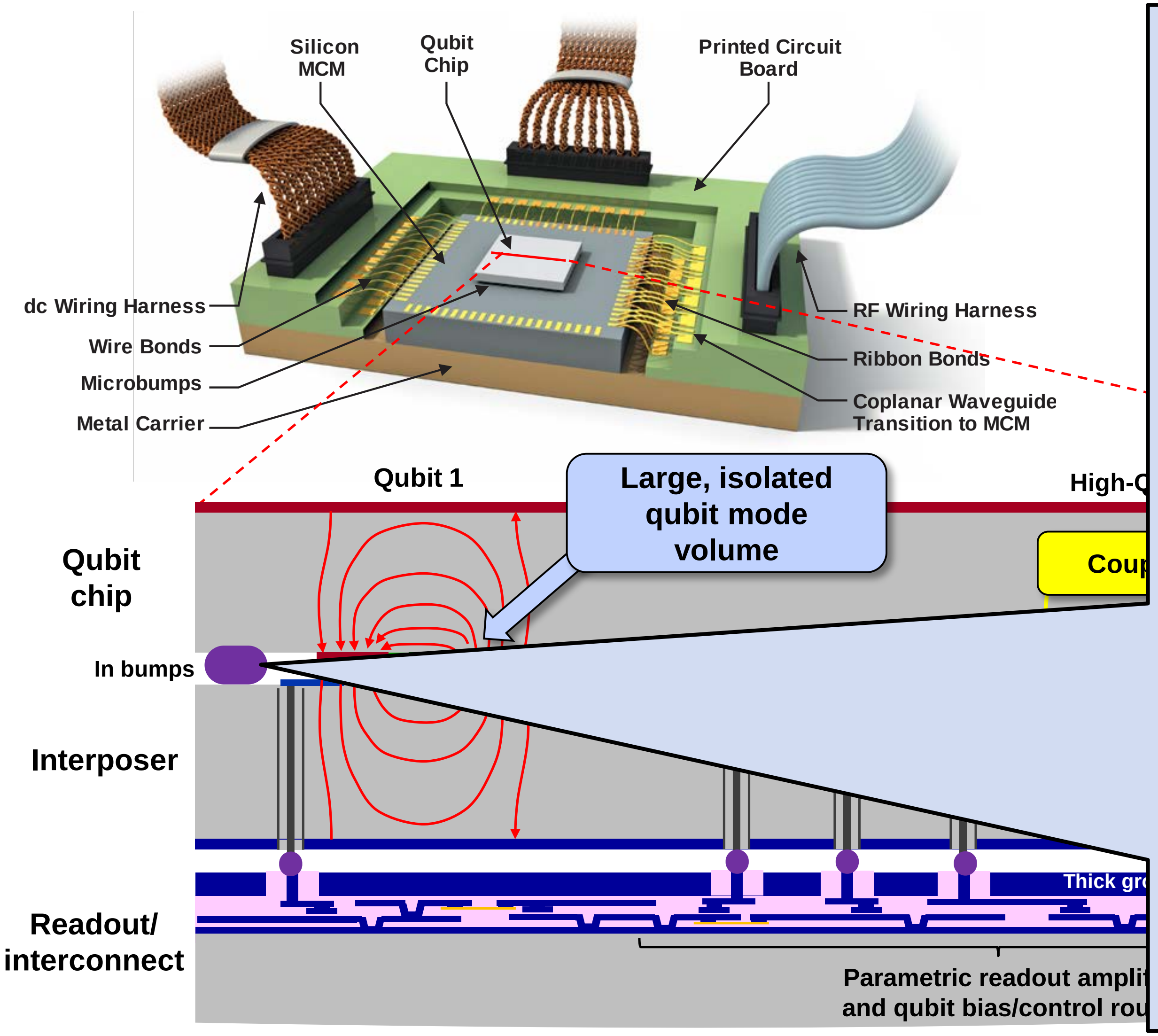
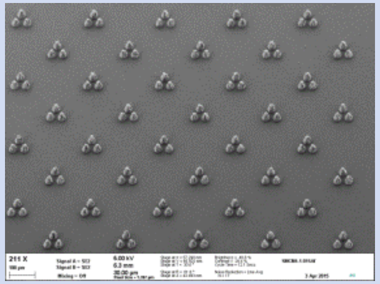
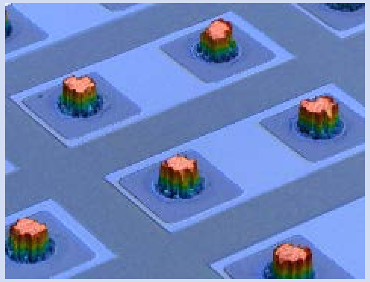


Indium bumps connect chips and provide mechanical support

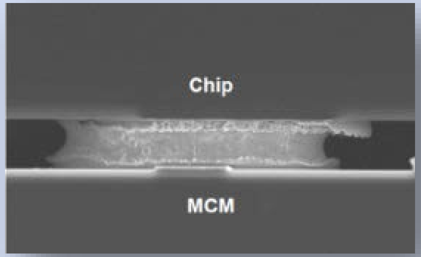
Fabricated In bumps



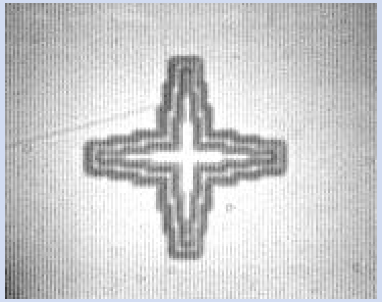
Confocal image of indium bumps on TiPtAu



Cross-section of bump-bonded chips



IR image of bump-bonded chips



Alignment ~1 μm

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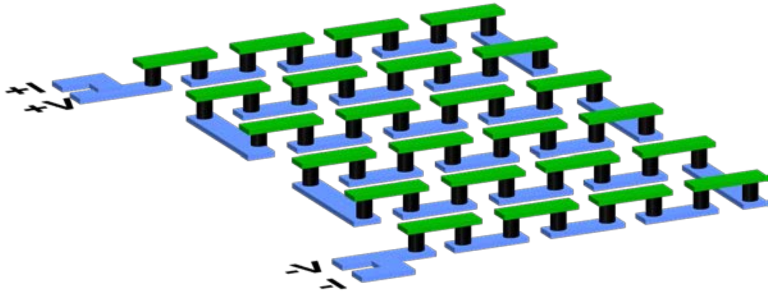
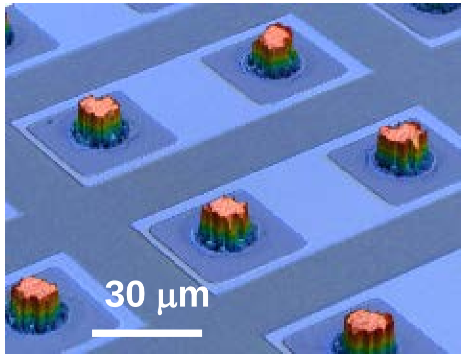
Electrical Properties of Bump Path

Schematic of test structure for DC resistance

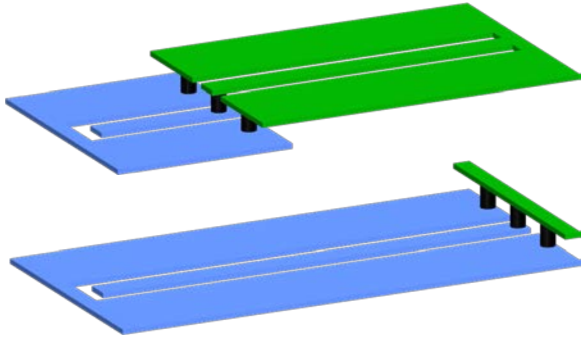


Confocal image of indium bumps on underbump metallization

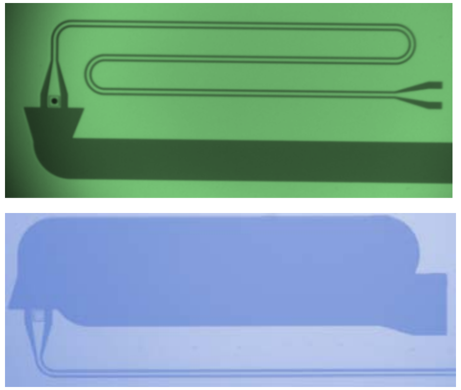


- **2,704 indium bumps in series**
- **Base metal Al**
- **TiPtAu underbump metal**

Schematic of quarter wave resonators with bump interconnects



Fabricated resonator with bump interconnects



- **Bump-interrupted resonators with ~50-100k internal Q**
- **Effective microwave loss of 100's of μohm**

Rosenberg et al, npjQI (2017)

Can we use resonators to qualify new chip fab/materials,…?

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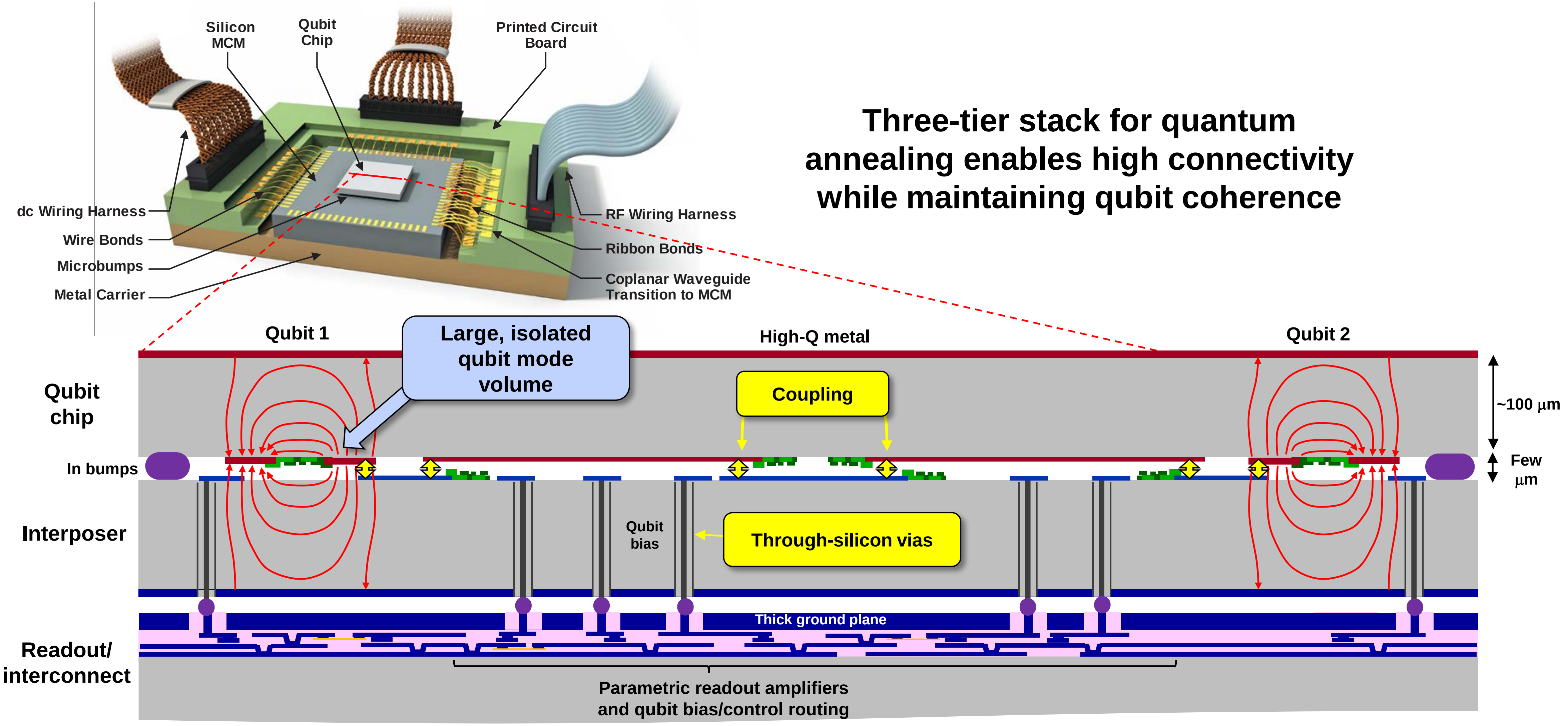

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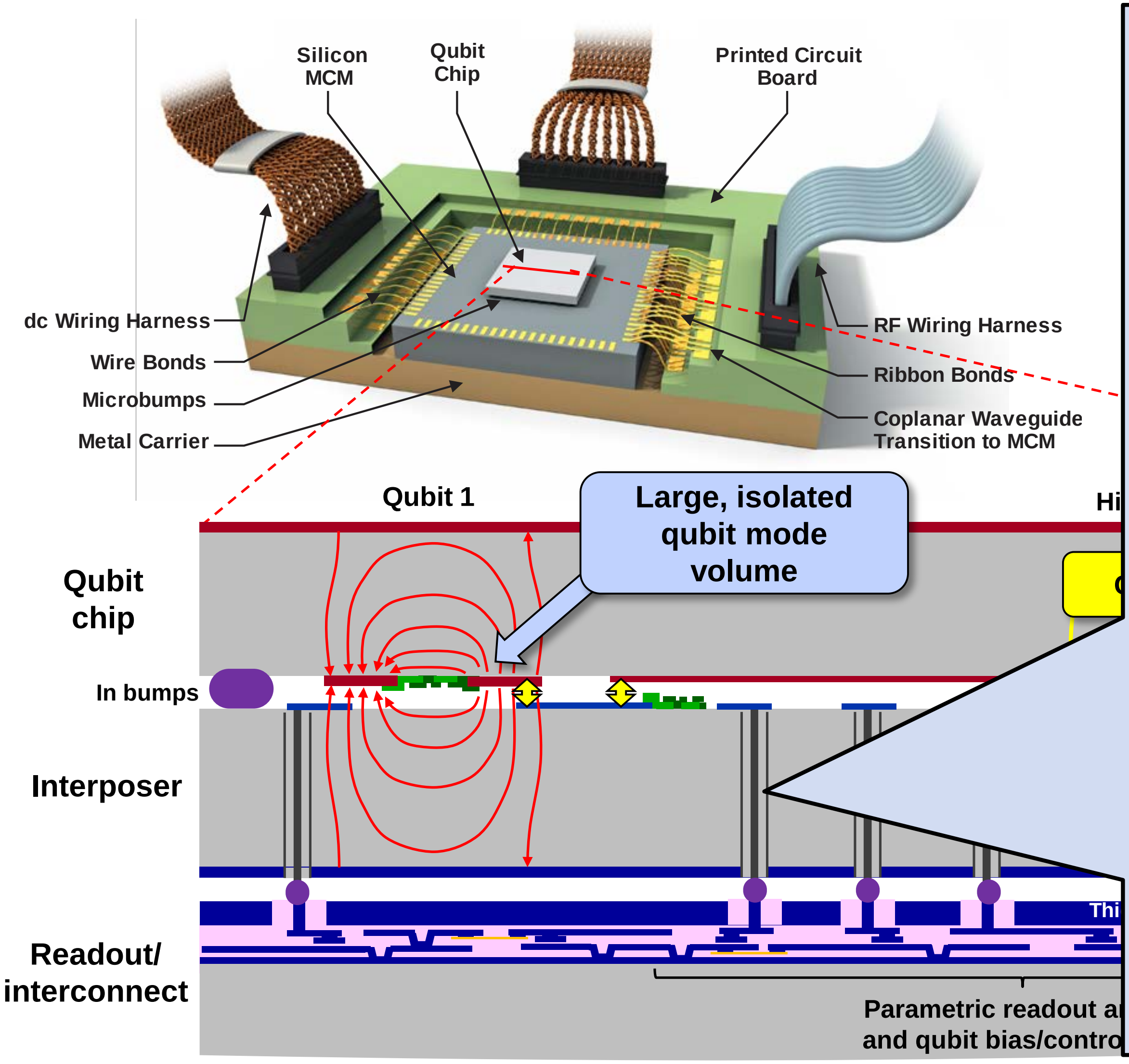
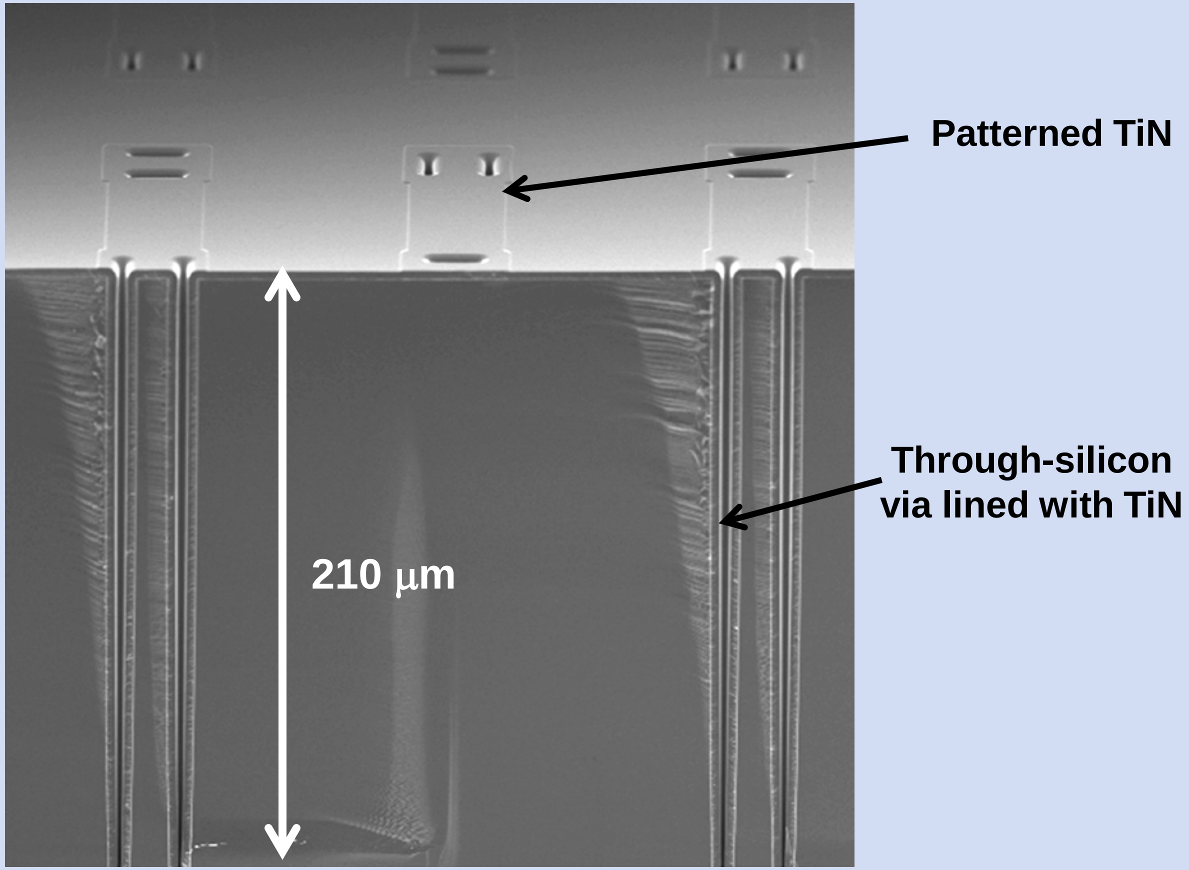


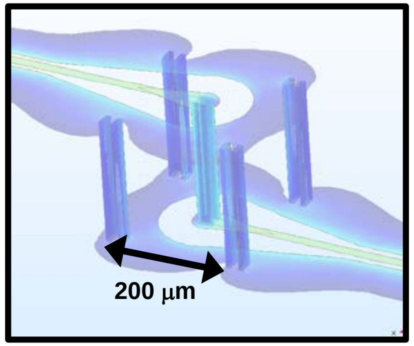
Interposer separates qubit from readout/interconnect layer

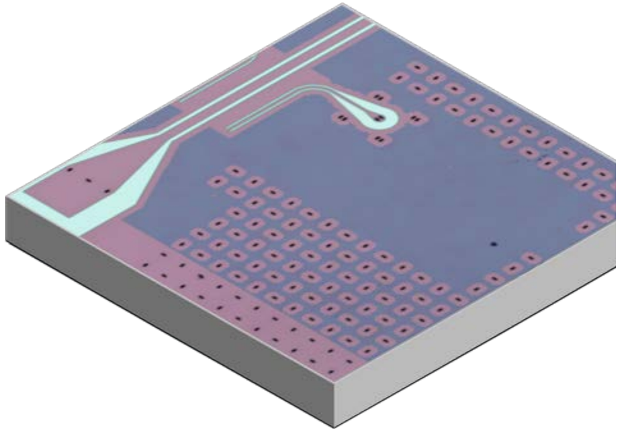


Superconducting through-silicon vias provide connectivity between top and bottom layers

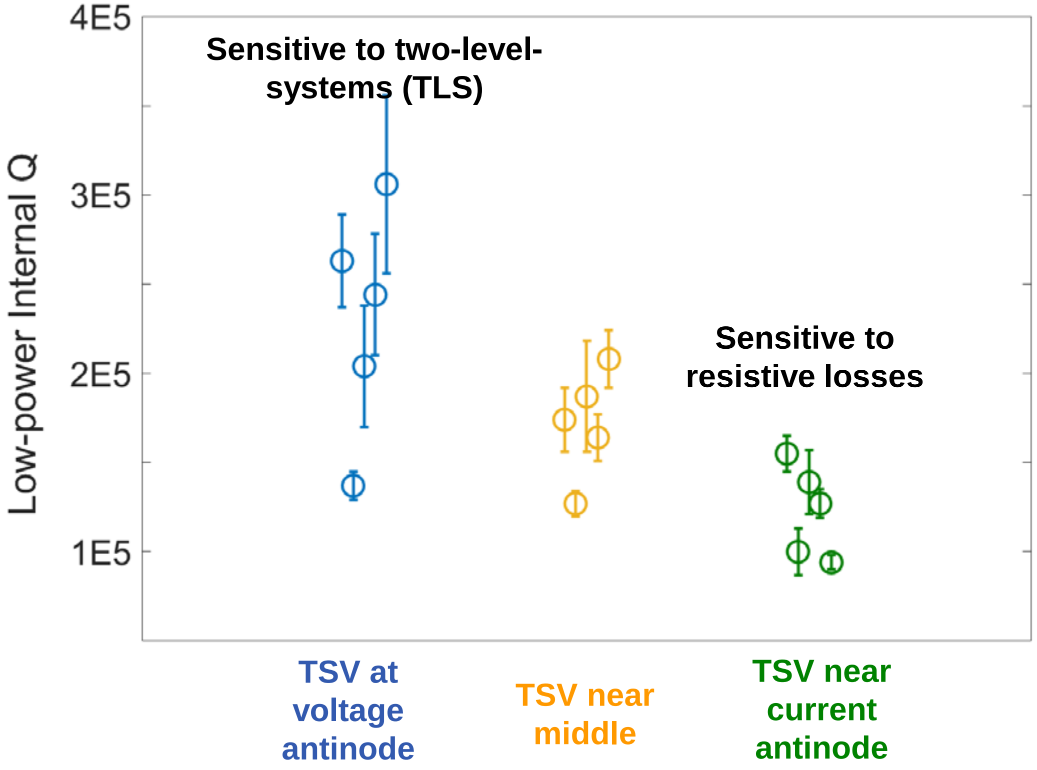
Resonators with TSV interconnects

Simulation of TSV transition





Dependence of internal Q on position of TSV transition



Resonator measurements indicate high-bandwidth, low-loss TSV transitions

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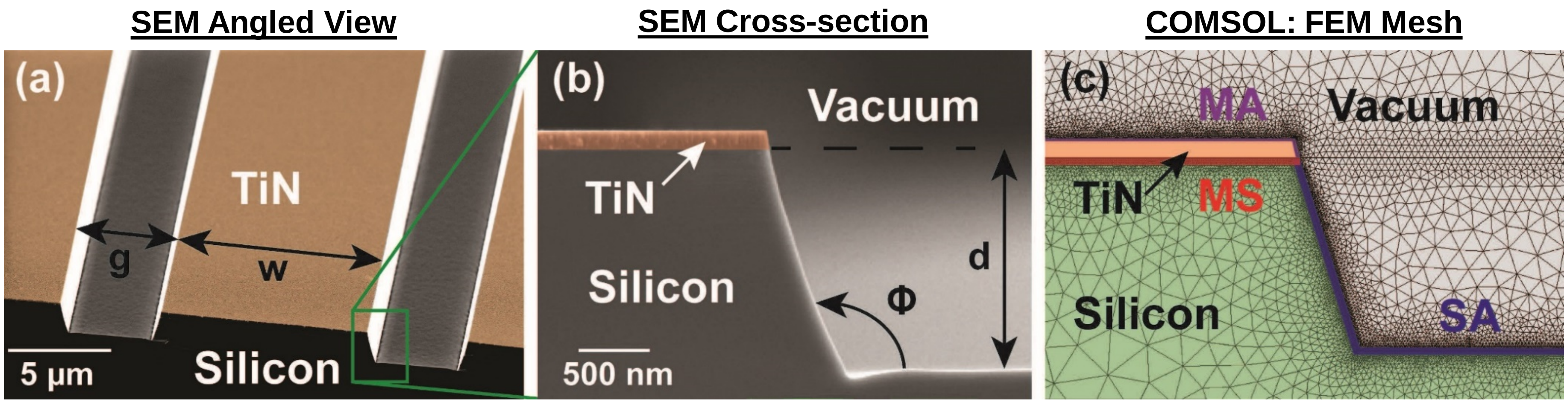
Surface Participation Model



TLS-containing interfaces:

- MS: metal-to-silicon
- SA: substrate-to-air
- MA: metal-to-air/vacuum
- Si: silicon substrate

$$\frac{1}{Q_{TLS}} = \sum_i p_i \tan\delta_i \;\Rightarrow\; \frac{1}{Q} = \sum_i P_i x_i$$

Q_{TLS}: TLS-limited quality factor; p_i: participation region *i*; $\tan\delta_i$: loss tangent region *i*; P_i: scaled participation; x_i: scaled loss tangent (*loss factor*)

Matrix Representation

$$\begin{bmatrix} \frac{1}{Q_1} \\ \frac{1}{Q_2} \\ \frac{1}{Q_3} \\ \vdots \end{bmatrix} = \begin{bmatrix} P_{MS_1} & P_{SA_1} & P_{MA_1} & P_{Si_1} \\ P_{MS_2} & P_{SA_2} & P_{MA_2} & P_{Si_2} \\ P_{MS_3} & P_{SA_3} & P_{MA_3} & P_{Si_3} \\ \vdots & \vdots & \vdots & \vdots \end{bmatrix} \begin{bmatrix} x_{MS} \\ x_{SA} \\ x_{MA} \\ x_{Si} \end{bmatrix}$$

From EM simulation

Measured

Solve for

Loss-factors (tangents) can be extracted directly from TLS-limited Q_i

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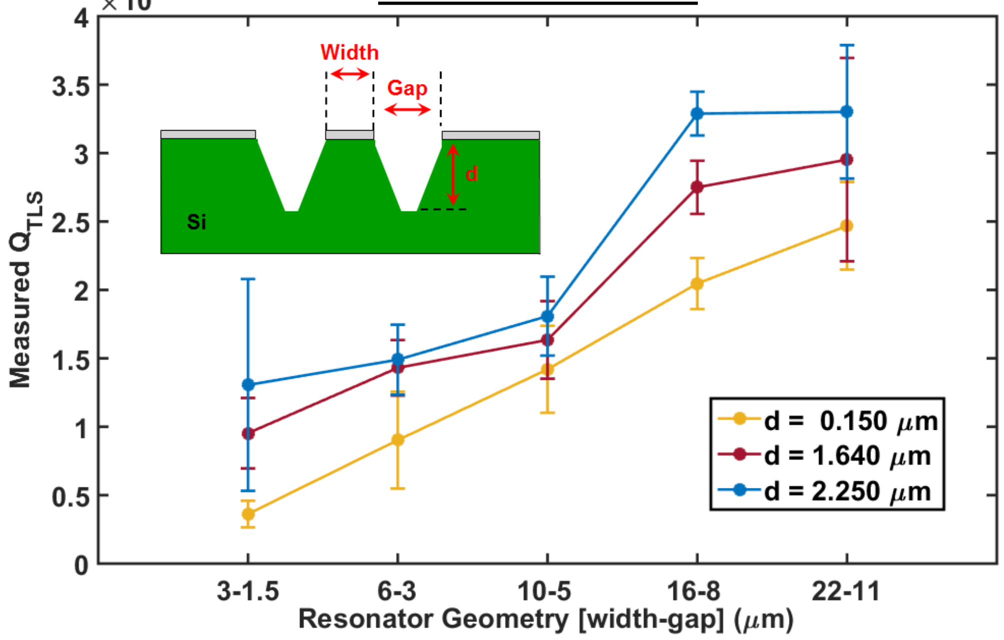
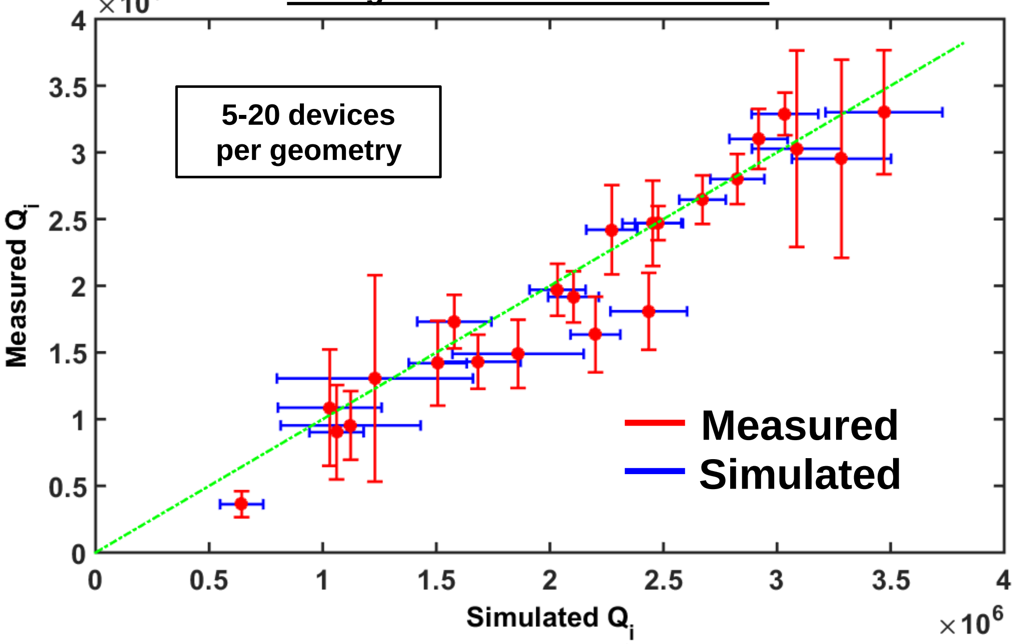
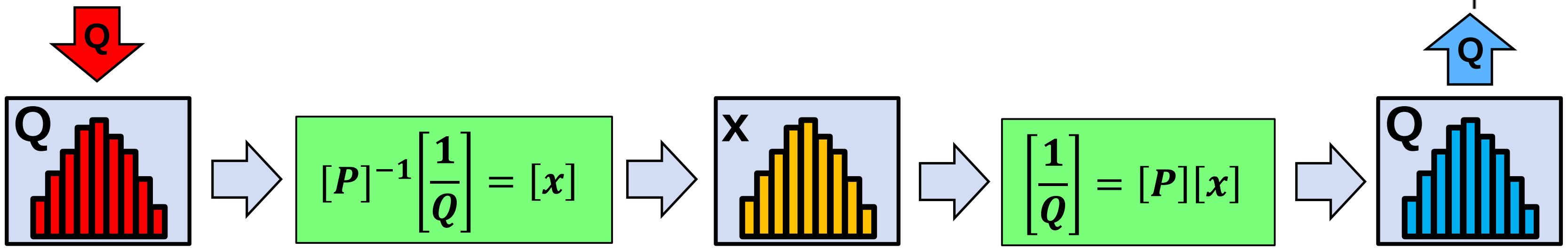
Device Loss Modeling

Measured Device Set



Fitting: Measured vs. Simulated

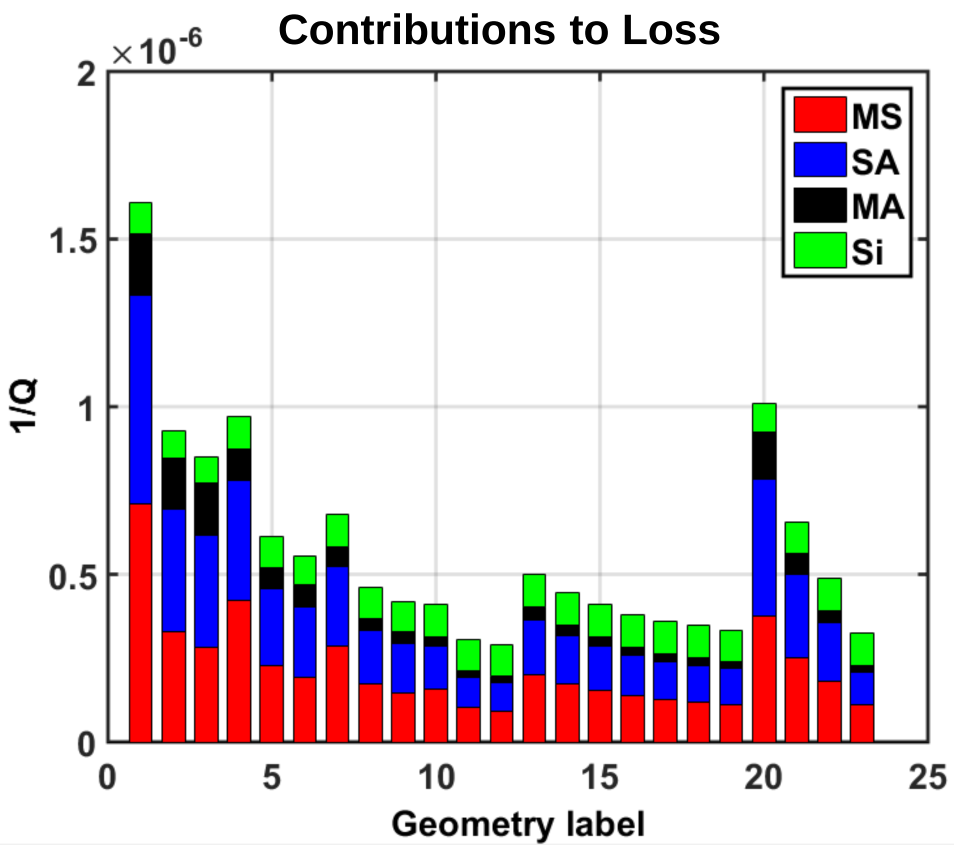


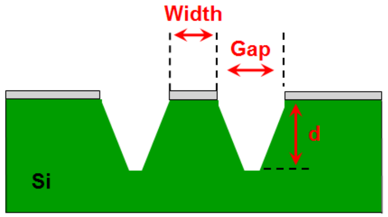


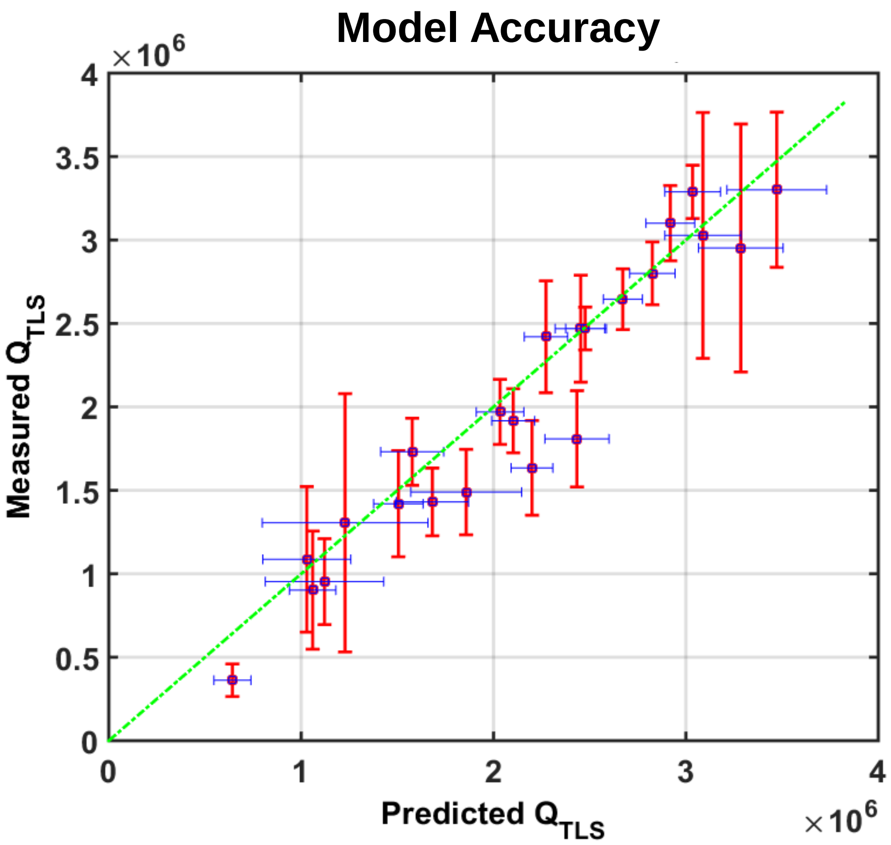
- Monte Carlo analysis estimates uncertainty in extracted losses
- Uncertainty contributions: singularity of participation matric, variation in measured Q, inaccuracy of model assumptions….

G. Calusine, A. Melville, W. Woods, et. al., Appl. Phys. Lett. 112, 062601 (2018)

Limits of Anisotropic Trenching



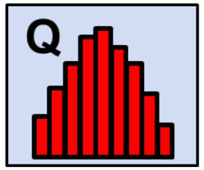




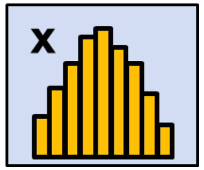
Participation ratios proportional across all geometries, (some) predictive power still possible

G. Calusine, A. Melville, W. Woods, et. al., Appl. Phys. Lett. 112, 062601 (2018)

Improving Matrix Condition Number



$$[P]^{-1}\left[\frac{1}{Q}\right] = [x]$$



Ideal [P]

$$P = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$condition(P) = 1$$

$$\frac{\sigma(X)}{\mu(X)} \approx \frac{\sigma\left(\frac{1}{Q}\right)}{\mu\left(\frac{1}{Q}\right)}$$

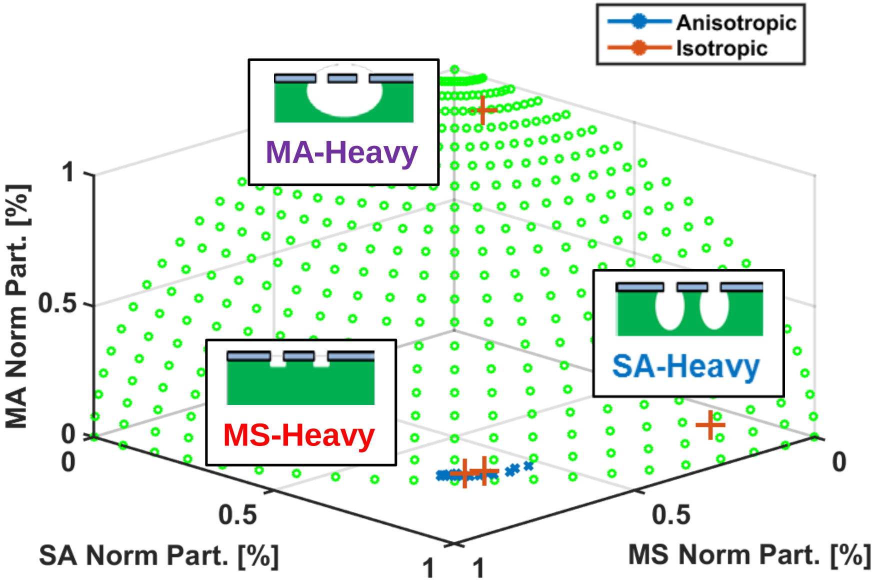
Anisotropic Trenching Example [P]

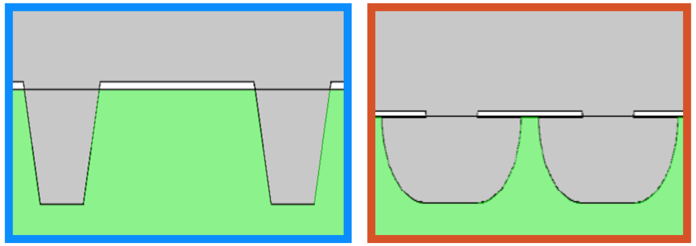
$$P = \left(\frac{1}{100}\right)\begin{bmatrix} 0.1694 & 0.1607 & 0.0048 & 90.8956 \\ 0.3069 & 0.4136 & 0.0272 & 69.8413 \\ 0.2488 & 0.2841 & 0.0109 & 82.7197 \\ 0.1001 & 0.1066 & 0.0029 & 87.6096 \end{bmatrix}$$

$$condition(P) = 61937$$

$$\frac{\sigma(X)}{\mu(X)} \gg \frac{\sigma\left(\frac{1}{Q}\right)}{\mu\left(\frac{1}{Q}\right)}$$

Resonators: normalized (MS,SA,MA) participation vectors:





Anisotropic trenching **Isotropic trenching**

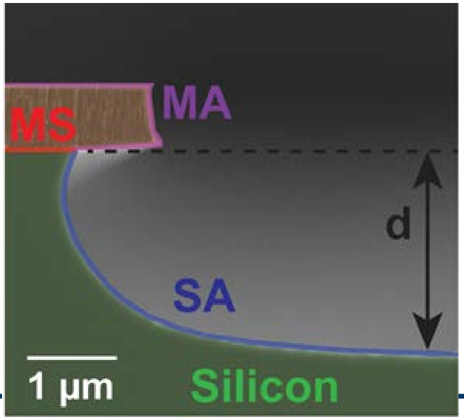
Condition number of [P]: how sensitive is [X] to changes in [1/Q]

Planar, anisotropic trenching → large condition # → large uncertainty

Isotropic trenching → reduced condition # (~30x)

Targeting Dielectric Loss

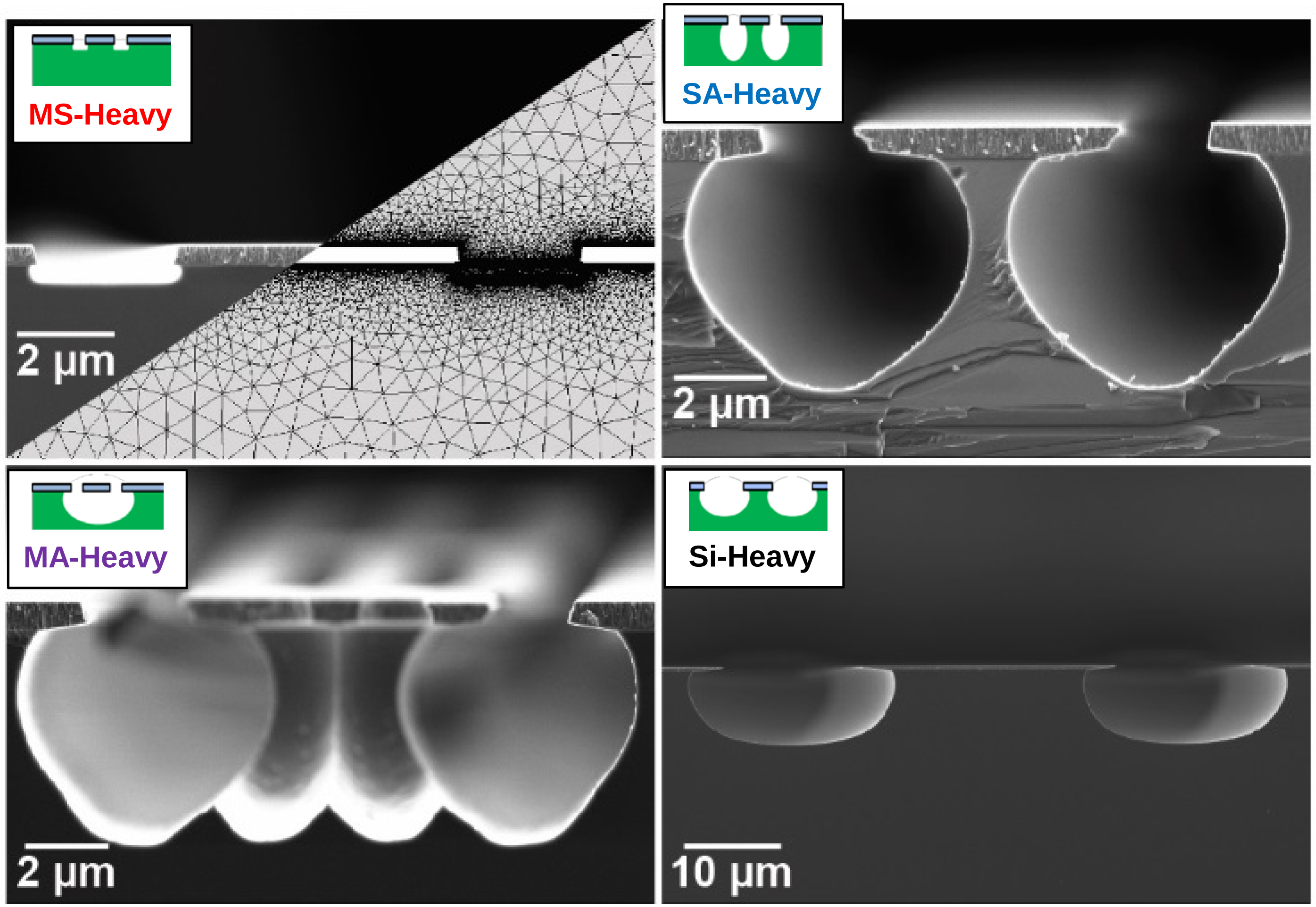
- Isotropic etched resonators
- COMSOL estimated participation vectors
- Four optimal resonators identified
  - Over a range of geometries considered
  - Produced participation matrix with lowest condition number



TLS-containing interfaces:

- MS: metal-to-silicon
- SA: substrate-to-air
- MA: metal-to-air/vacuum
- Si: silicon substrate

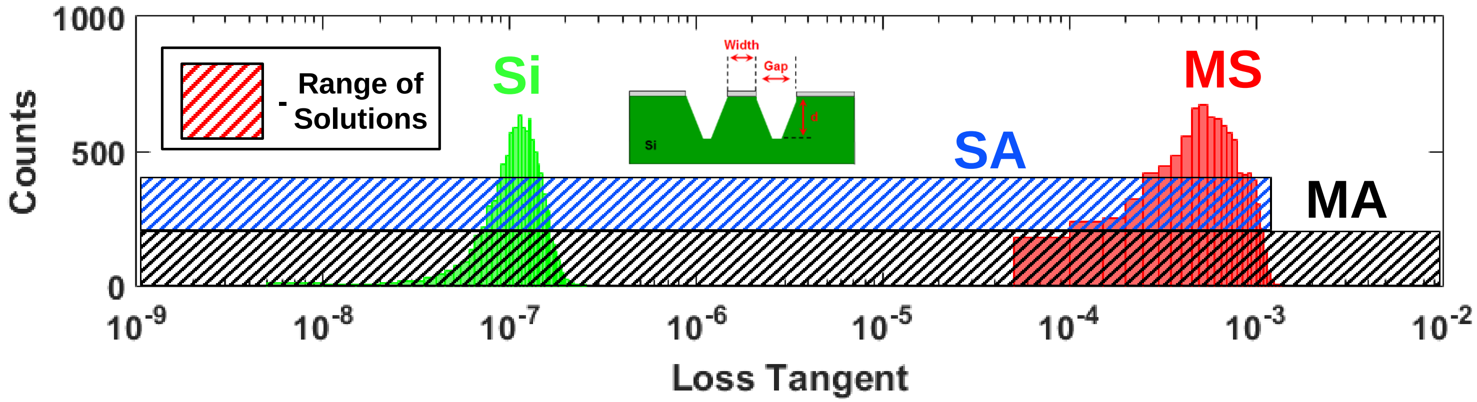
SEM Cross-sections of Optimal 4 Cross-Sections



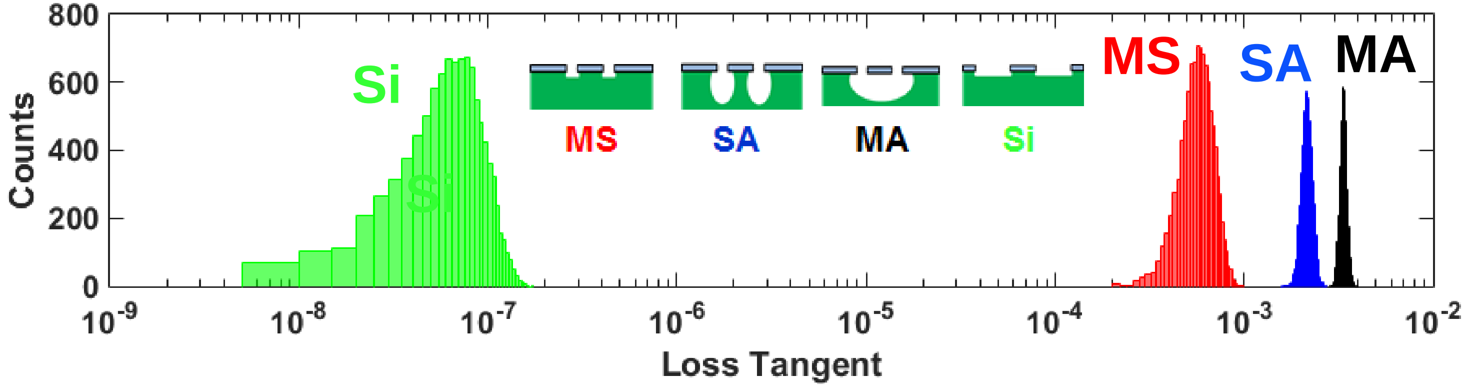
W. Woods, G. Calusine, A. Melville, et.al. (submitted)

Surface Loss Extraction

Anisotropic



Isotropic



tanδ assumes:

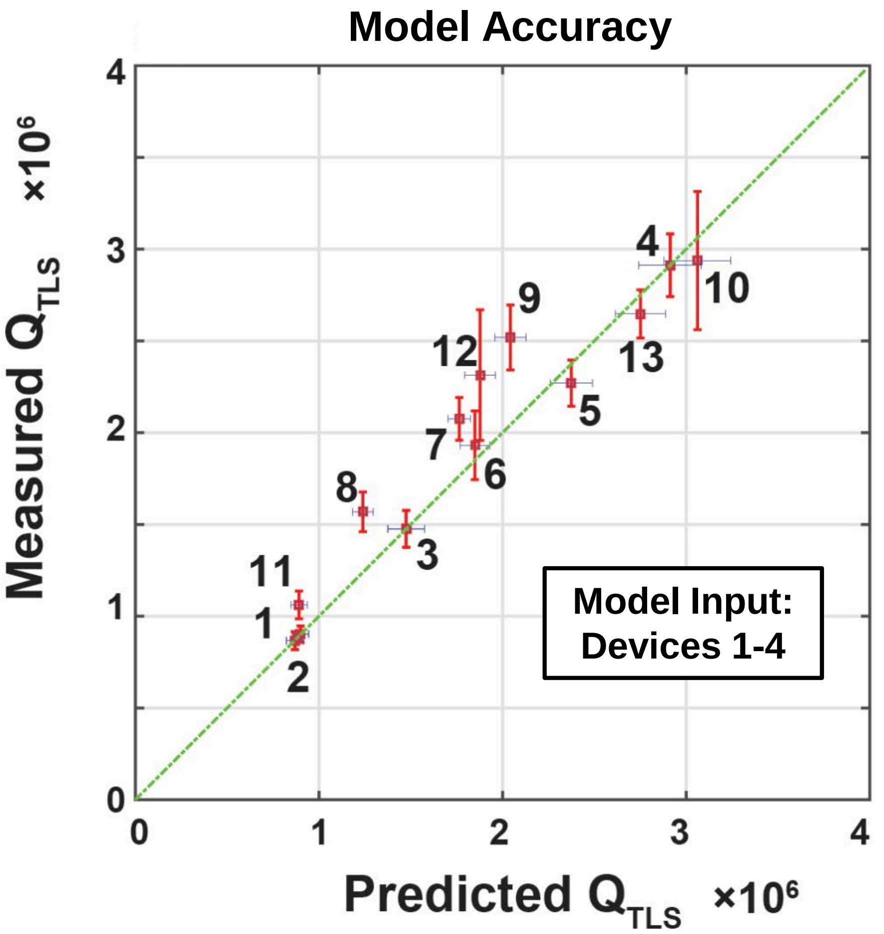
t_{MS} = 2 nm, $\varepsilon_{MS} = 11.35\varepsilon_0$
t_{SA} = 2 nm, $\varepsilon_{SA} = 4\varepsilon_0$
t_{MA} = 2 nm, $\varepsilon_{MA} = 10\varepsilon_0$

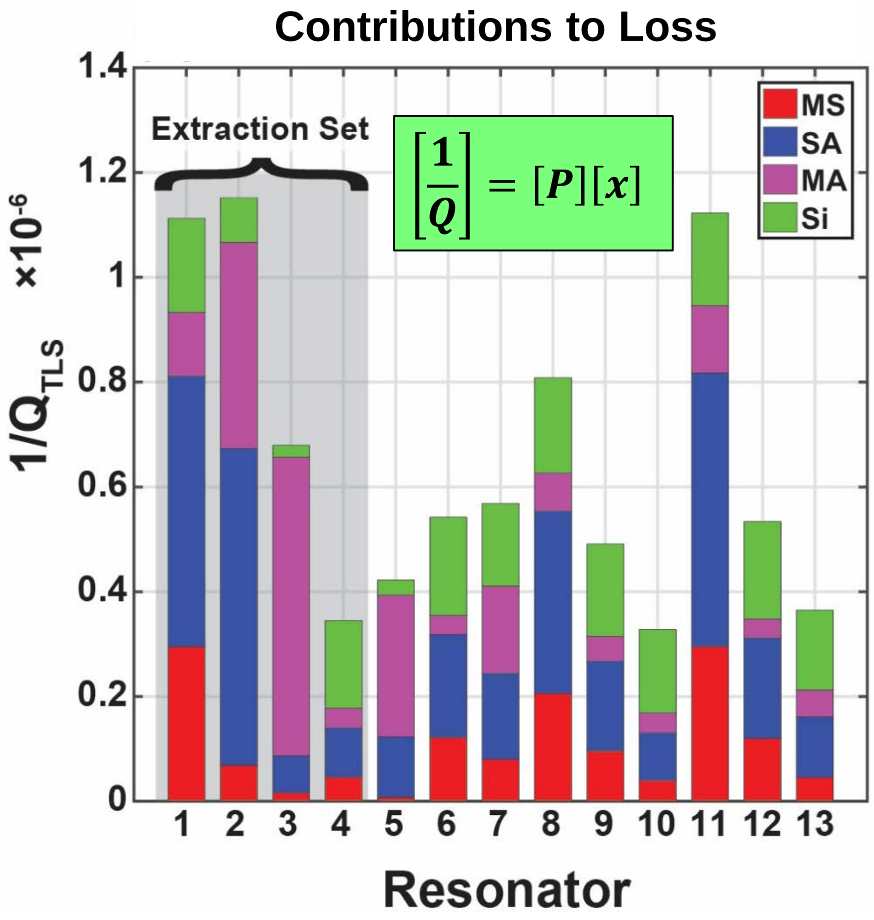
Isotropically trenched geometries: unique estimation of X_{MS}, X_{SA}, $X_{MA,}$, X_{si}

W. Woods, G. Calusine, A. Melville, et.al. (submitted)

Verification and Loss Contributions

- **Model verification:** "Training set" predicts Q_{TLS}'s for range of participations
- Can now determine loss for each interface
- **Question:** What is the 'bad' interface?
- **Answer:** For most 'typical' device (#12), SA is largest contribution

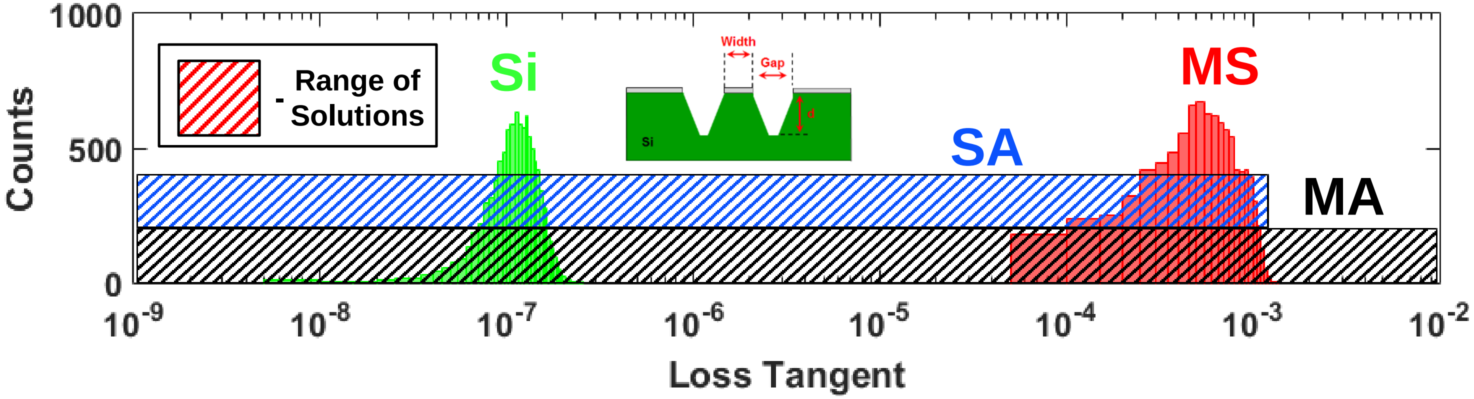




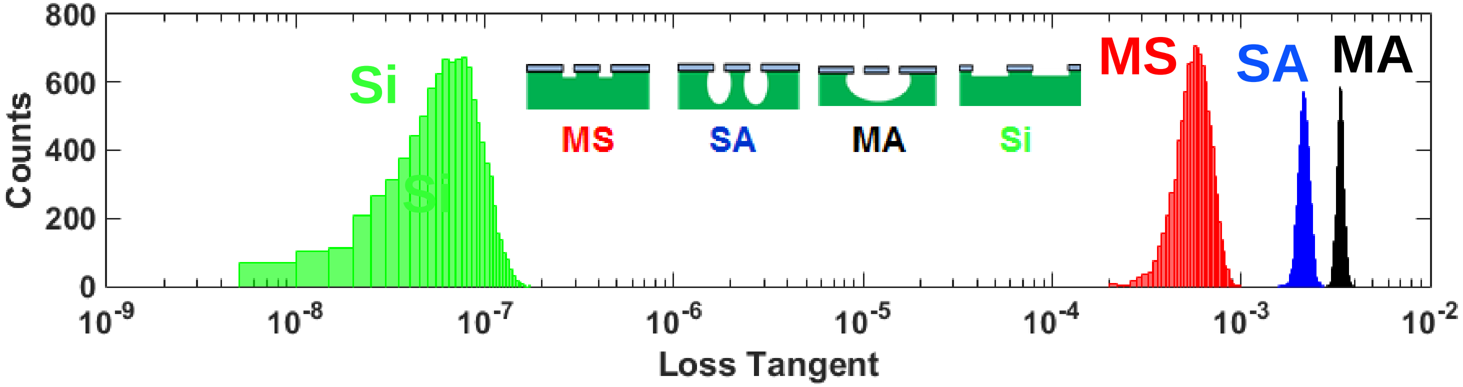
W. Woods, G. Calusine, A. Melville, et.al. (submitted)

Anisotropic vs. Isotropic Trenching

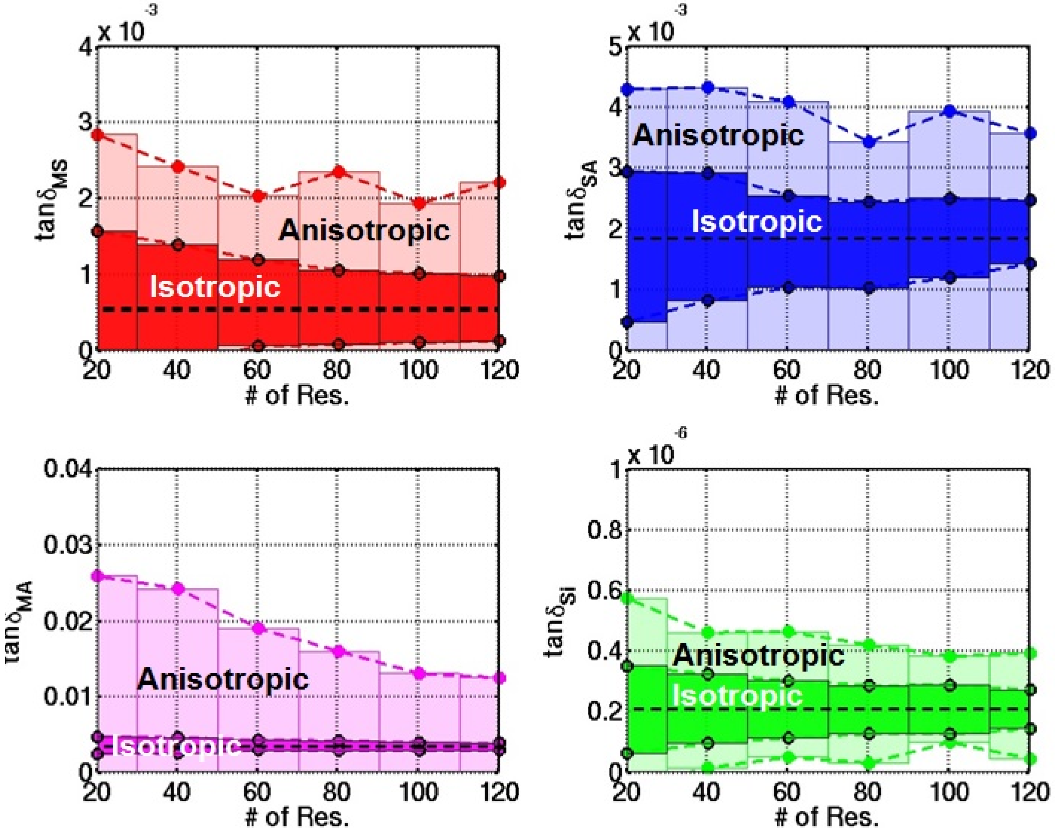
Anisotropic Trenching



Isotropic Trenching



Surface Loss Extraction - Simulated Experiment



Isotropic trench geometry improves accuracy and/or reduces measurement resource requirements

W. Woods, G. Calusine, A. Melville, et.al. (submitted)

Application/Verification: Surface Modification

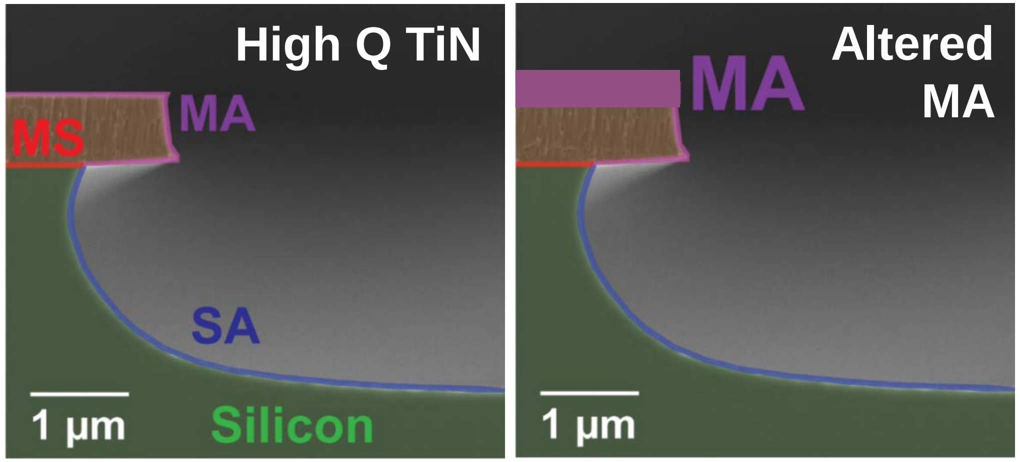
Examples of Deliberate Process Changes

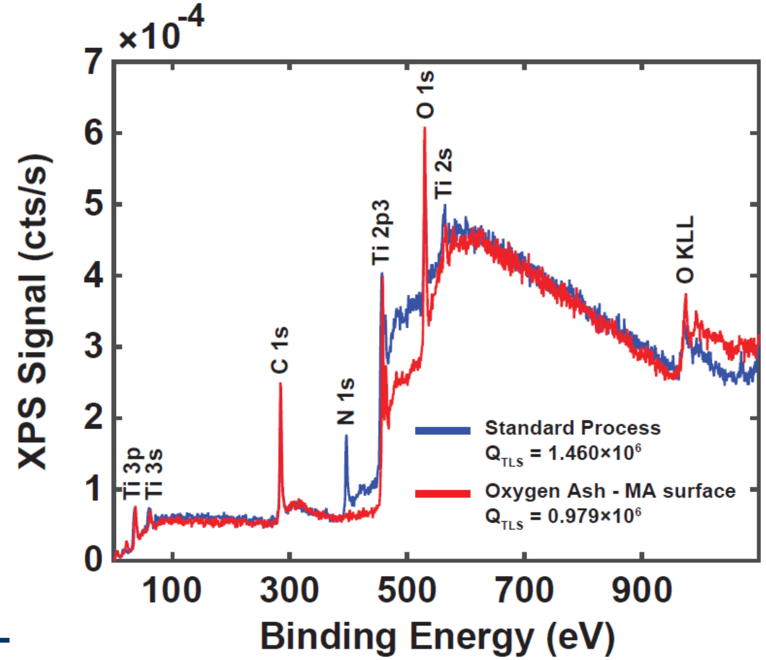
$$\begin{bmatrix} x_{MA} \\ x_{SA} \\ x_{MS} \\ x_{Si} \end{bmatrix}$$

- **Metal-Air: deliberate metal oxidation**
- **Substrate-Air: native oxide removal**
- **Metal-Substrate: native oxide removal**
- **Silicon: lower resistivity boule**

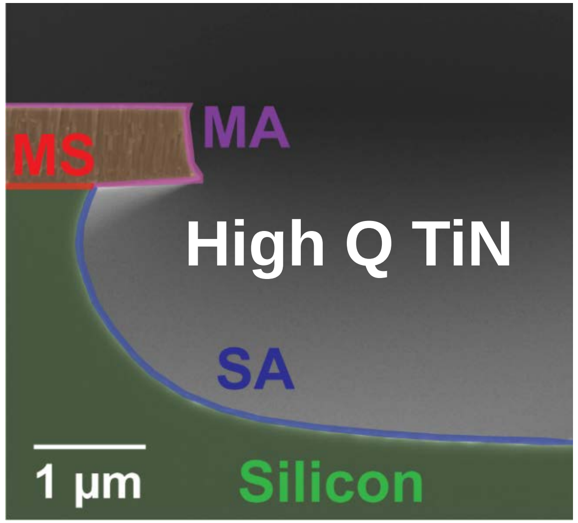
Dielectric Region	High Q TiN (before)	Modified MA TiN (after)
Si	High resistivity	High resistivity
MS	Pre-deposition clean Sputtered TiN	Pre-deposition clean Sputtered TiN
MA	Plasma etch	**Additional O_2-based plasma ash** Plasma etch
MA, SA	Plasma etch Plasma ash/PR strip Wet PR strip	Plasma etch Plasma ash/PR strip Wet PR strip

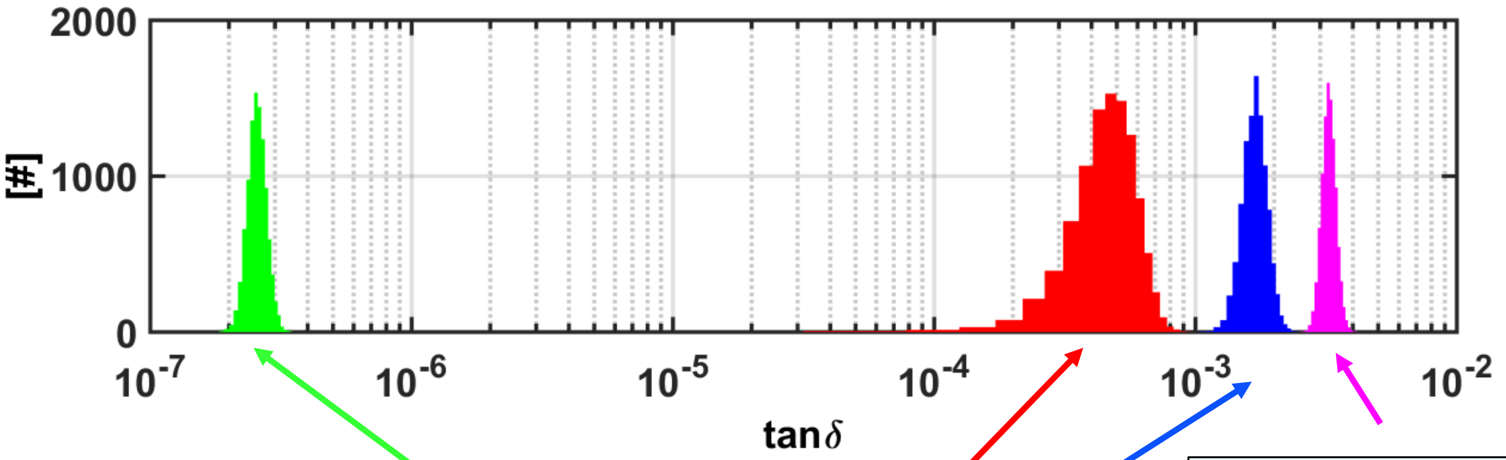
Introduce deliberate fabrication change to ONE region to observe effect on loss factor





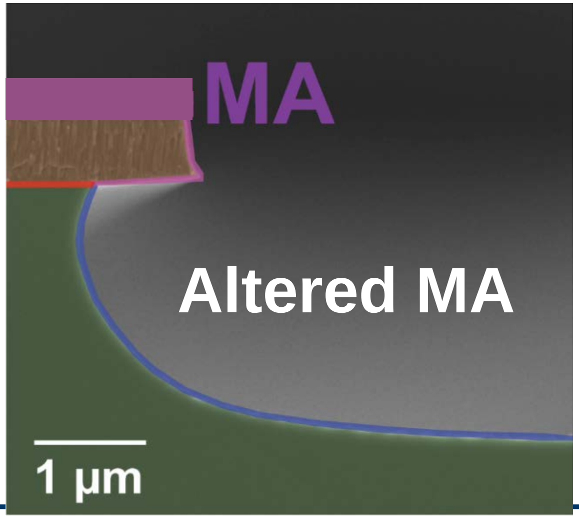
Application/Verification: Surface Modification

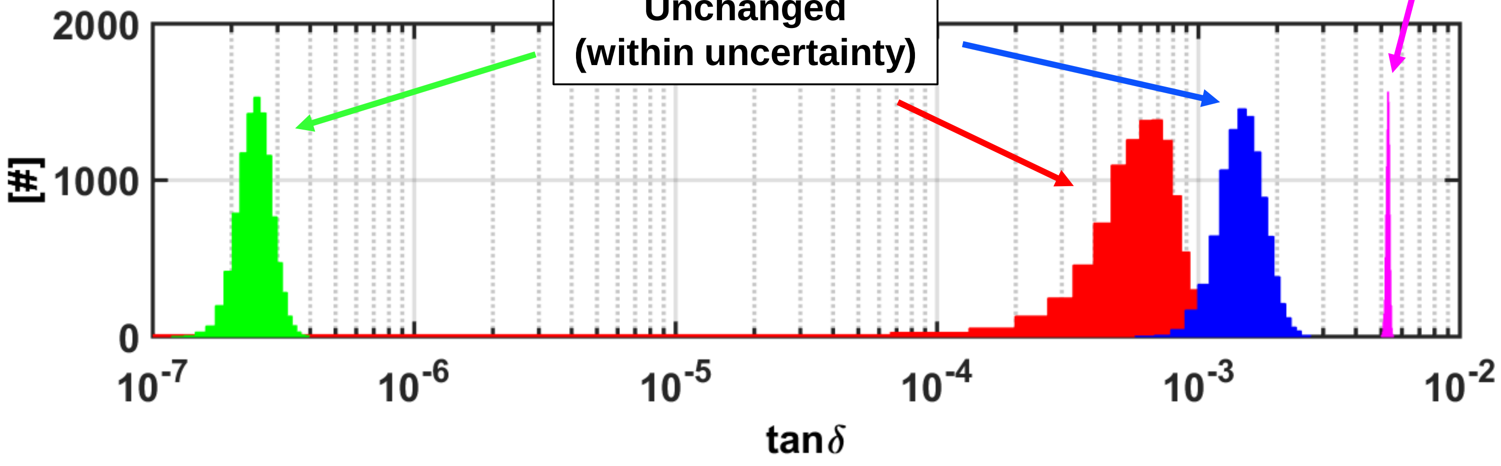




~60% increase in MA

Unchanged
(within uncertainty)





ONLY changed MA → ONLY saw x_{MA} change

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Outline

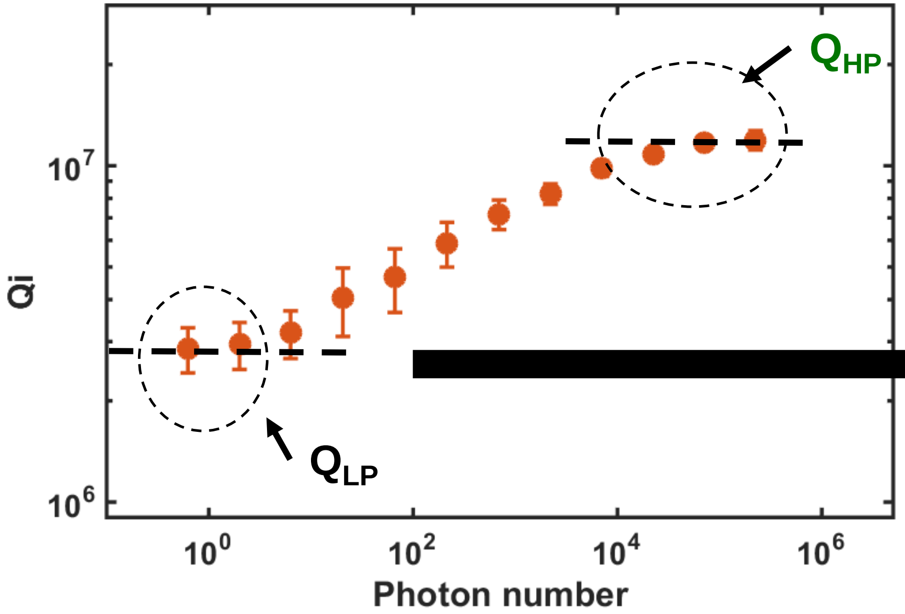
- A/B Testing
- Characterizing 3D integration
- Surface Loss Extraction (SLE)
- Sources of device-to-device variability

Resonator Background Losses

Q_{LP}: Power-Dependent (TLS) & Power-Independent Mechanisms

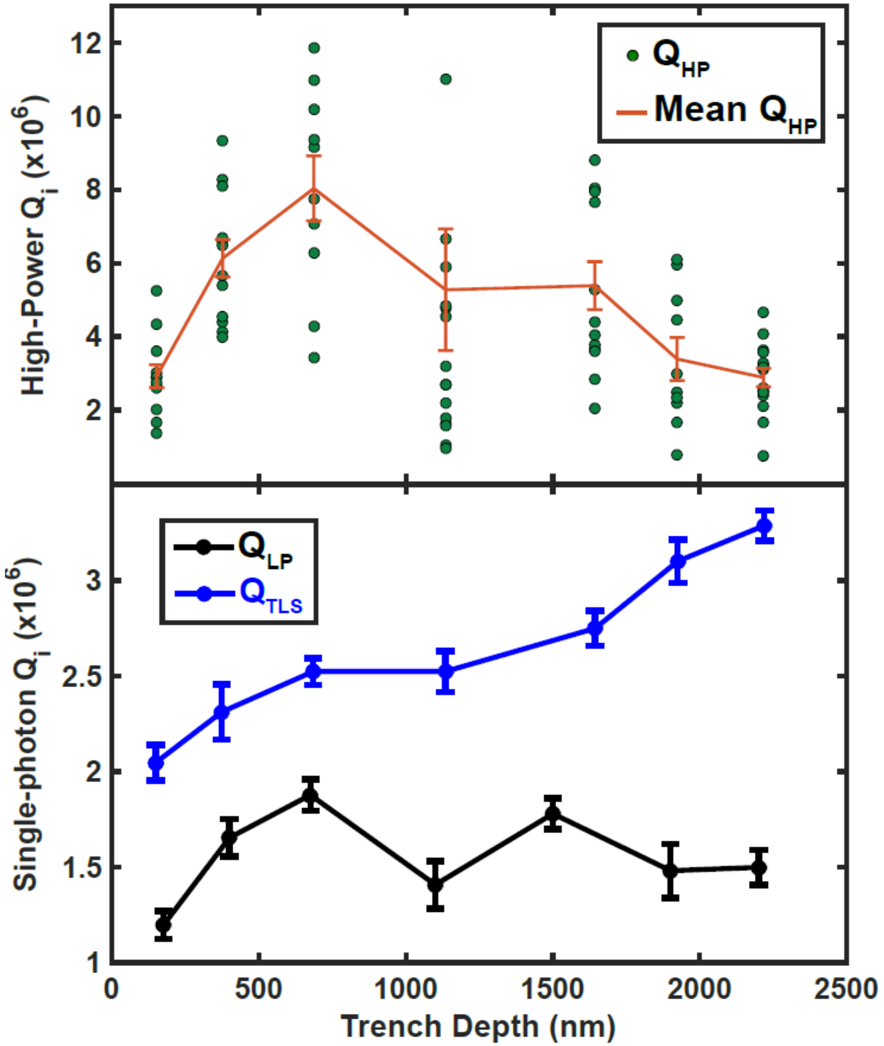
Q_{HP}: Power-Independent Losses e.g., vortices, quasiparticles, radiation/packaging, …

Q vs. Photon Number



$$1/Q_{TLS} = 1/Q_{LP} - 1/Q_{HP}$$

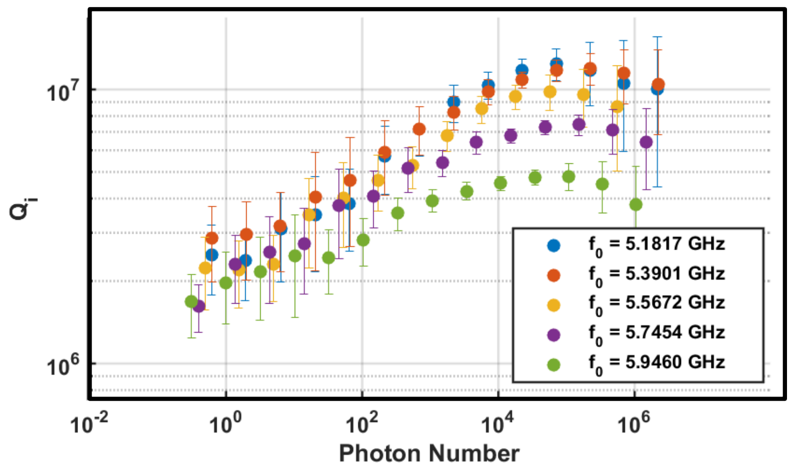
Q vs. Trench Depth

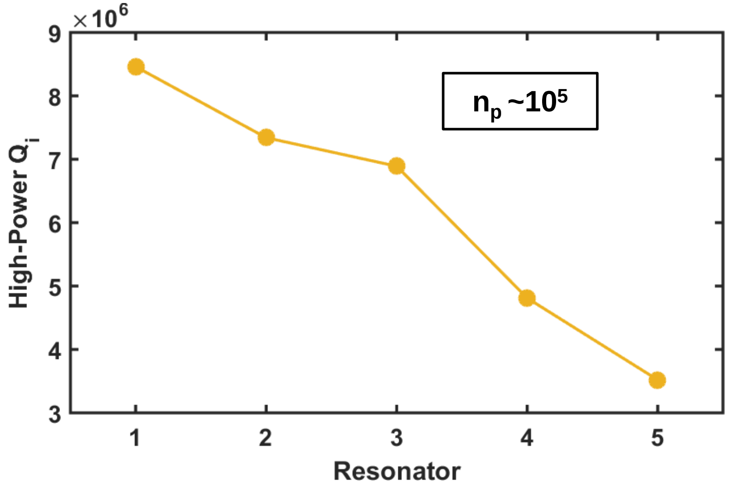


G. Calusine, A. Melville, W. Woods, et. al., Appl. Phys. Lett. 112, 062601 (2018)

Properties of Background Losses

Clue #1: Frequency dependence

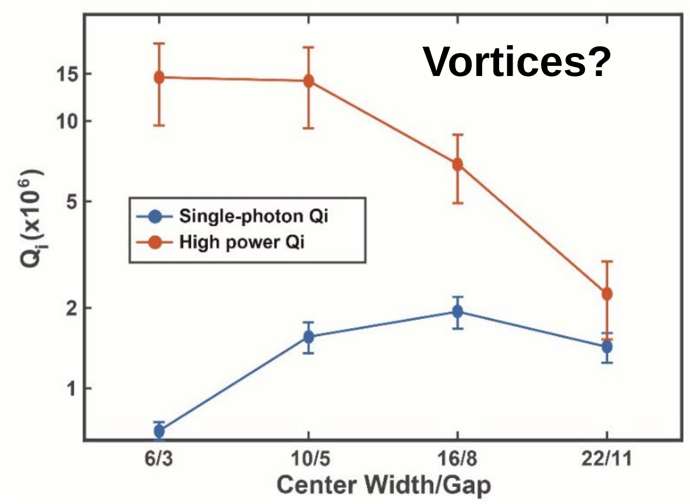




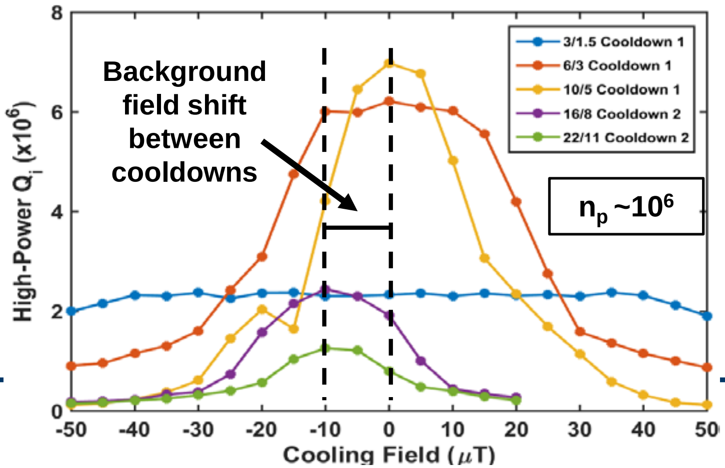
Strong frequency dependence→ package mode?

…none visible in transmission spectrum

Clue #2: Geometric dependence



…too small of a contribution

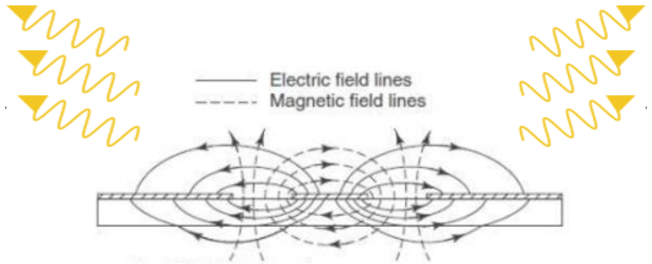


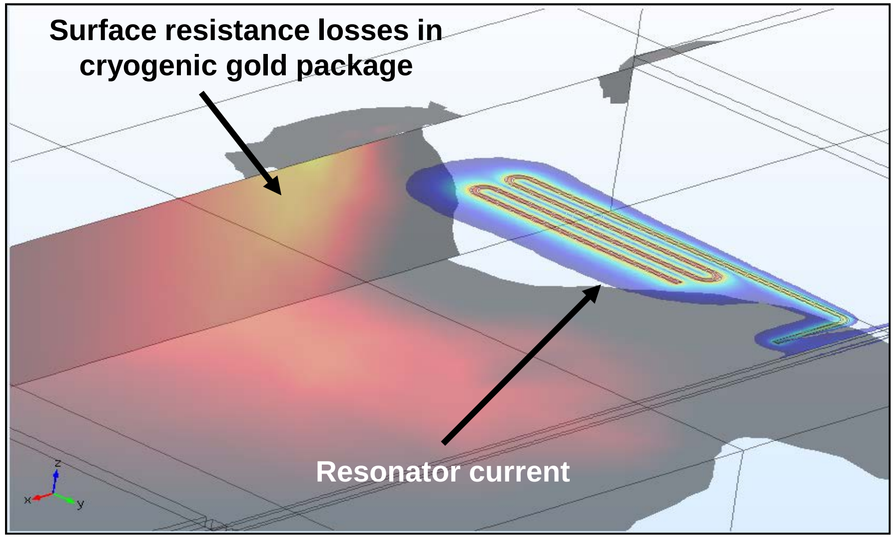
What mechanism explains “background” losses?

$$1/Q_{TLS} = 1/Q_{LP} - 1/Q_{HP}$$

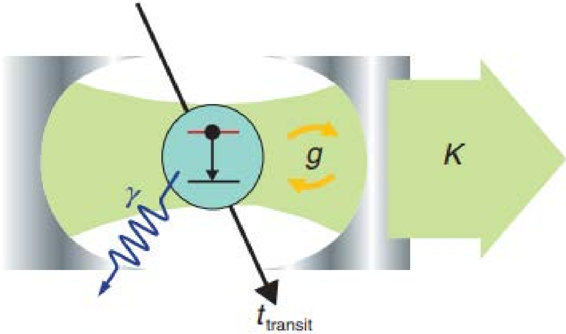
Coupling to Device Packaging

Resistive Metal Losses

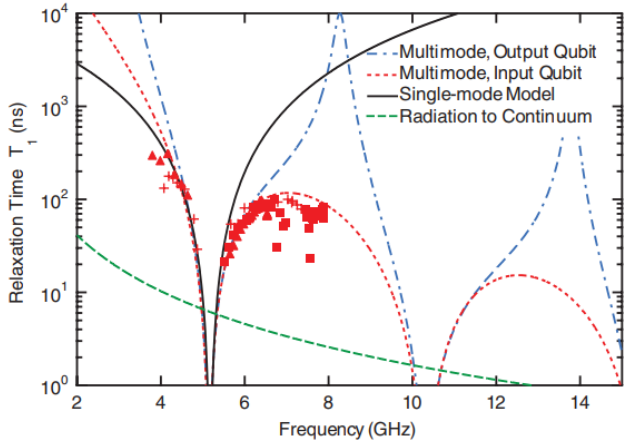




Purcell Decay



$$\hat{H}_{JC} = \frac{1}{2}\hbar\omega\hat{\sigma}_z + \hbar\omega_0\hat{a}^+\hat{a} + \hbar g\,(\hat{\sigma}_+\hat{a} + \hat{\sigma}_-\hat{a}^+)$$



Houck, et al., PRL, 2008

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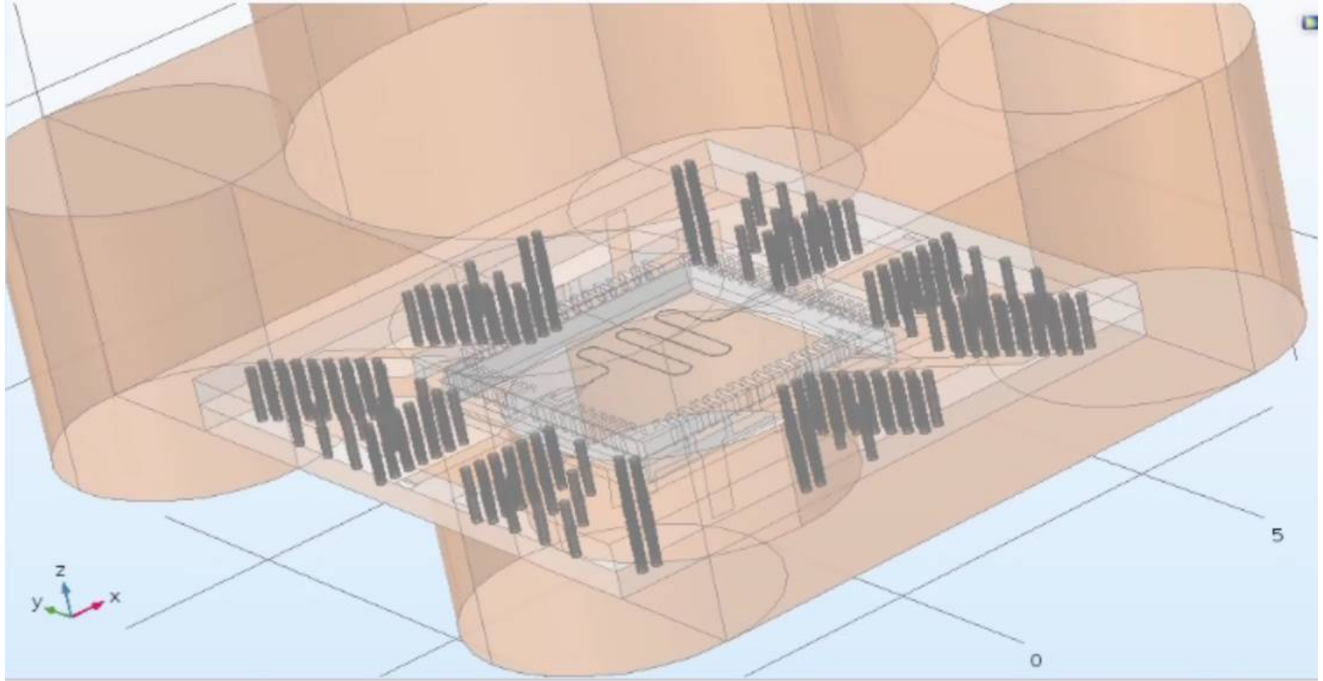
EM Package Modeling

- **Goals: identify…**
  - **Package mode spectrum**
  - **Package mode field profile**
  - **Resistive metallic losses**
  - **Dielectric losses**

- **COMSOL: include <u>"everything"</u>**
  - **Resonators, wirebonds, interposer dielectrics, vias, silicon chip, resistive metals, ….**

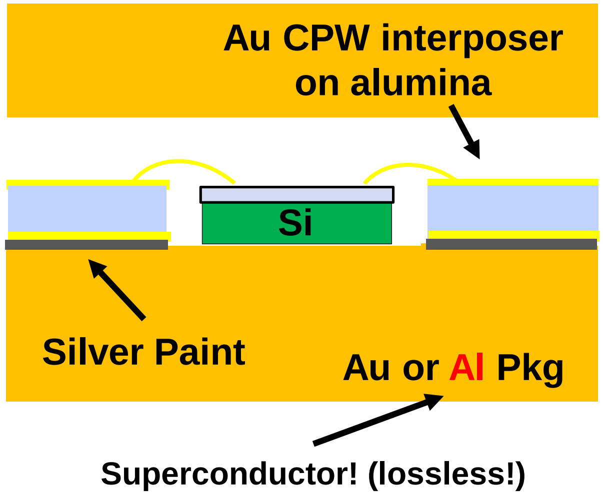
- **Match simulation and measurement**
  - **Broadband transmission spectrum**
  - **Fit narrowband resonator Q_i**

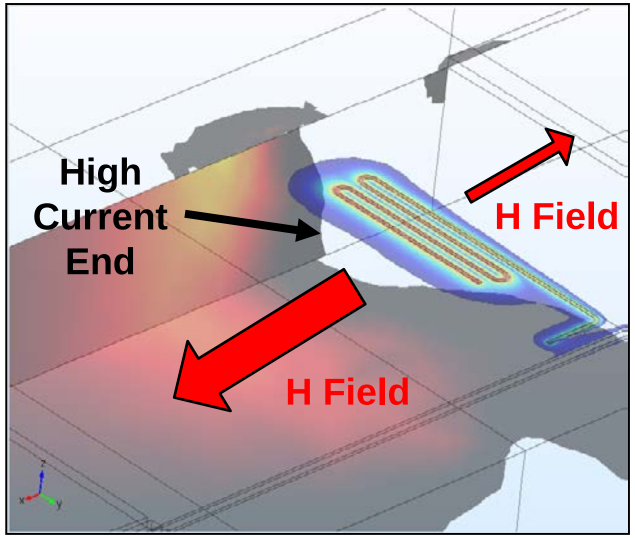
<u>Standard Qubit Package, Interposer, and Chip</u>



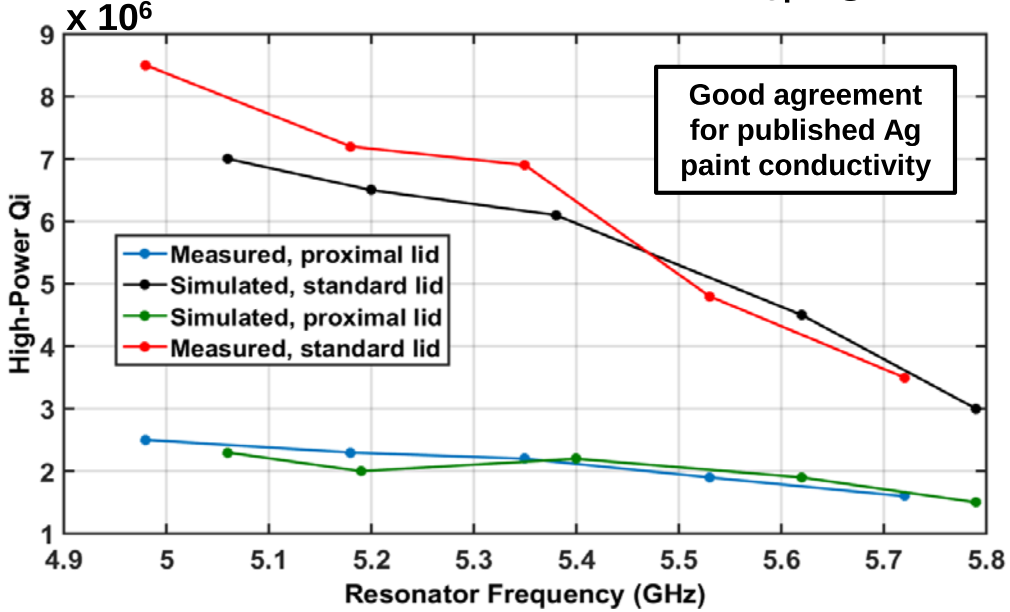
Packaging-induced Losses

Package Cross Section



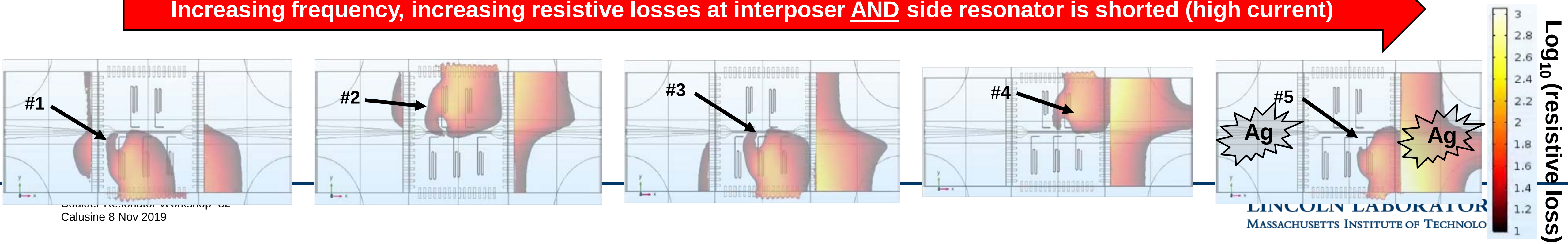


Simulated and Measured Q_i Agree



Culprit: far away (~ 1-5 mm) lossy adhesives

Increasing frequency, increasing resistive losses at interposer AND side resonator is shorted (high current)



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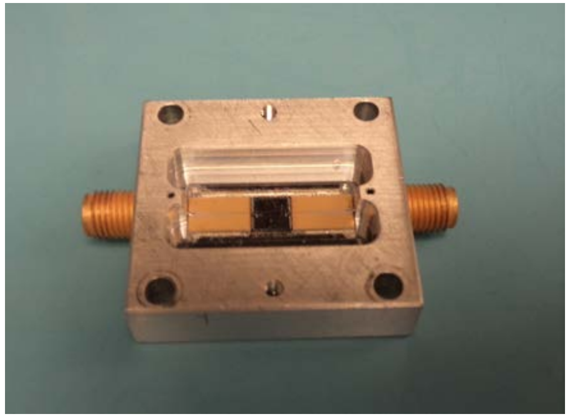
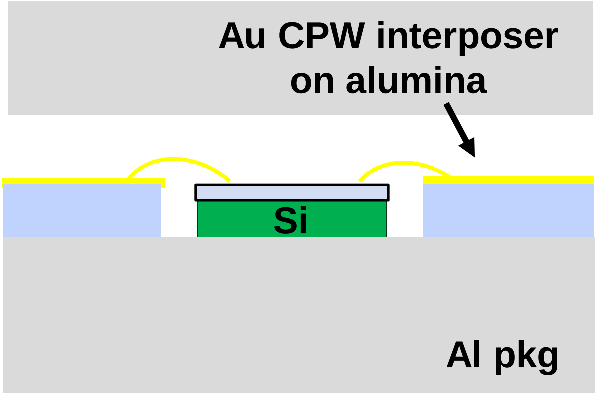
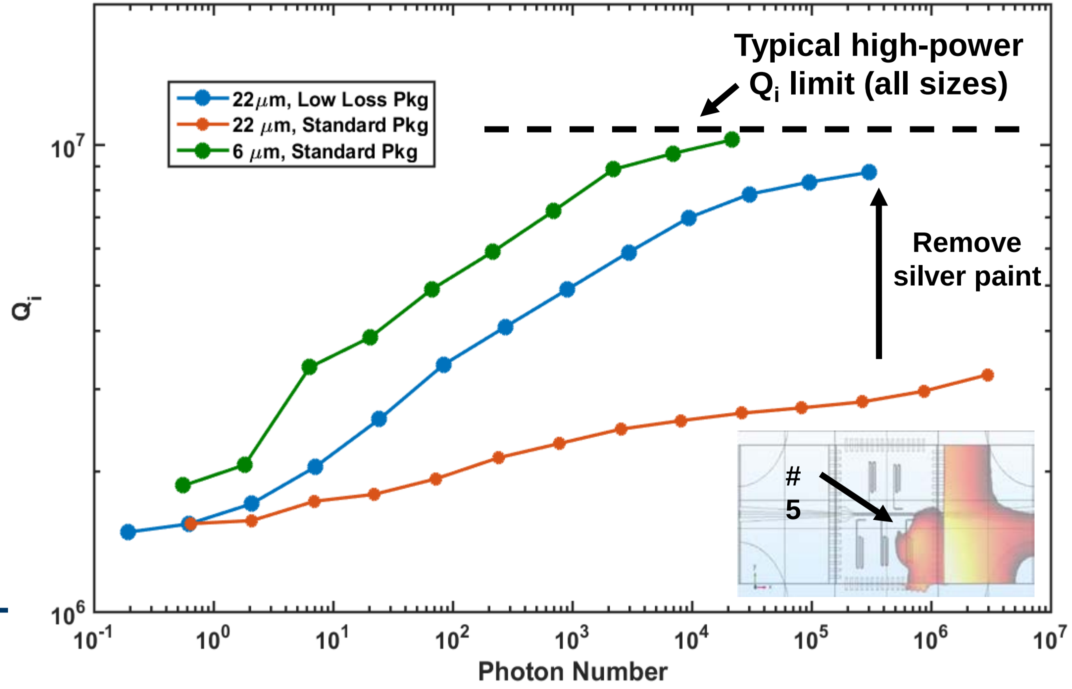
Low-Loss Resonator Packaging

- **Solution**: Remove as much lossy material as possible (no matter how far from chip!)
- **Confirm**: Use wide trace resonators (largest mode volume → most sensitive to package losses)

Al Package







- 22 µm high-power Q_i improved from 1-3M to ~ 10M
- No frequency dependence
- High-power Q_i similar to small mode volume devices
- Outlook: High single photon Q_i, less variation (better SLE!)

Outline

- A/B Testing
- Characterizing 3D integration
- Surface Loss Extraction (SLE)
- Sources of device-to-device variability

So…how useful are resonators?

Pros:

- Easy/Easier to fabrication
- Easy/Easier to measure/automate
- Easy/Easier to simulate (2D, classical)
- Some analytic results exist
- High Q → high sensitivity

Optimist's outlook: Resonators are useful tool for characterizing the properties of the enabling technologies for superconducting quantum circuits.

Cons:

- Not many 'knobs'
- May not address specific questions
- Extra fab steps for qubit caps
- Variability/fluctuations
- Too reductionist/worth the effort?

Pessimist's outlook: Resonators are too blunt and unwieldy of a tool to meaningfully assess the properties of the enabling technologies for superconducting quantum circuits.

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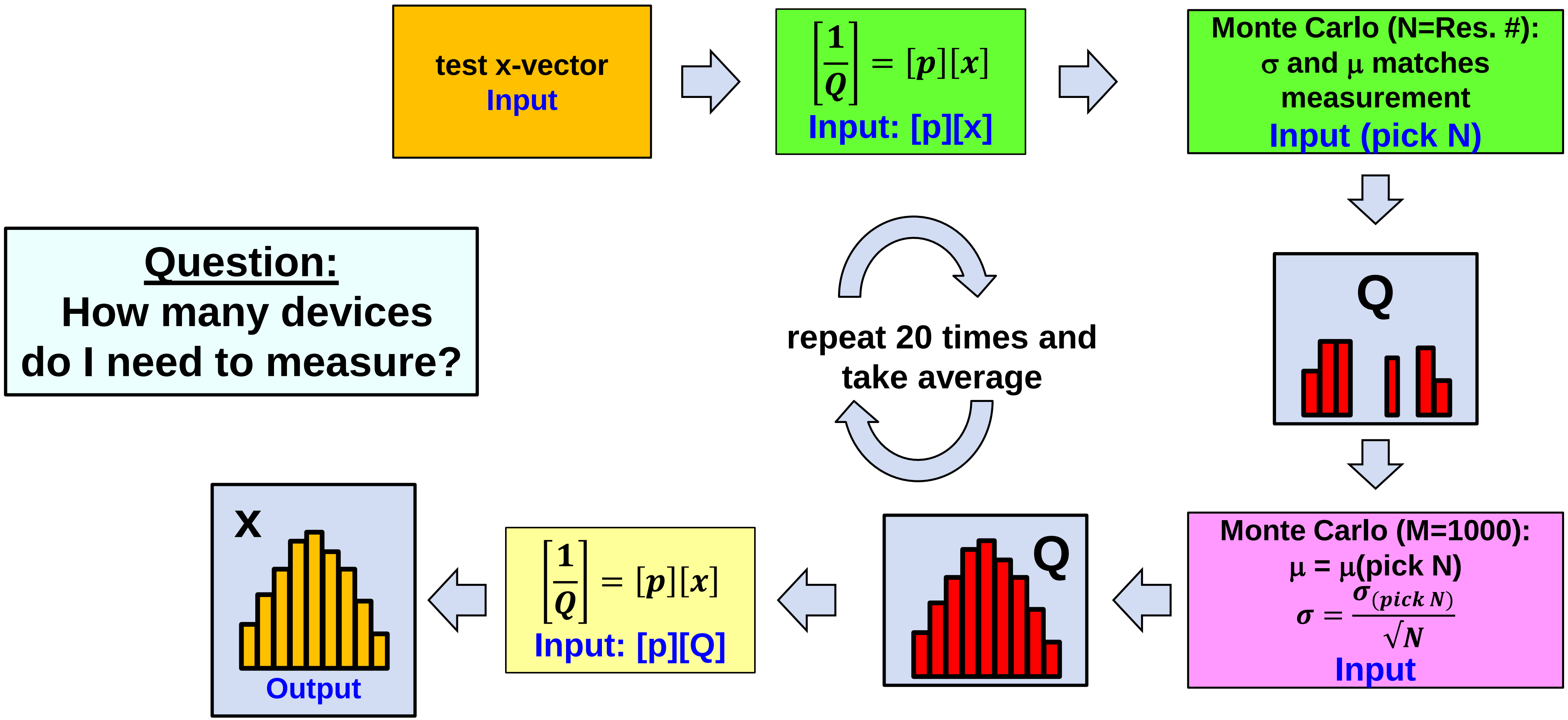
IARPA

QUANTUM ENHANCED OPTIMIZATION

Backup

Estimating Measurement Accuracy



"Simulated Experiment": estimation of extraction accuracy

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W. Woods, G. Calusine, A. Melville, et.al. (in preparation)