Wafer-scale microwave dielectric loss extraction using a split-post superconducting cavity

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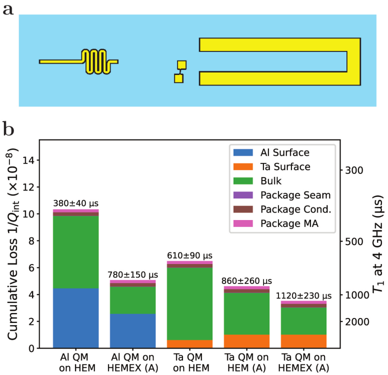
Introduction

- Superconducting qubits are approaching their bulk substrate loss limits[1]



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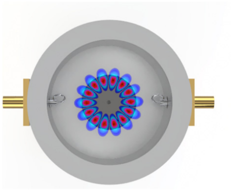
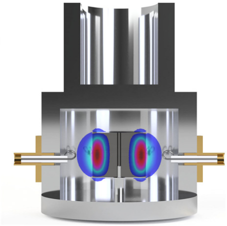
[2] Bourhill et al., Phys. Rev. Appl. **11**, 044044 (2019).
[3] Krupka et al., IEEE Transactions on Microwave Theory and Techniques **47**, 752 (1999).
[4] Read et al., Phys. Rev. Appl. **19**, 034064 (2023).
[5] Checchin et al., Phys. Rev. Appl. **18**, 034013 (2022).

Introduction

- Superconducting qubits are approaching their bulk substrate loss limits[1]
- Superconducting cavities are increasingly becoming the system of choice to extract bulk losses[2]





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Introduction

- Superconducting qubits are approaching their bulk substrate loss limits[1]
- Superconducting cavities are increasingly becoming the system of choice to extract bulk losses[2]
- All experiments up to this point have extracted bulk losses from proxies: boules[3], pieces of wafers[4], rods[5], etc.

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[2] Bourhill et al., Phys. Rev. Appl. **11**, 044044 (2019).
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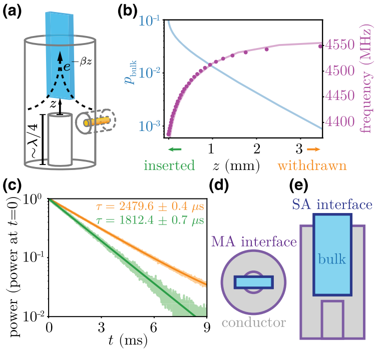
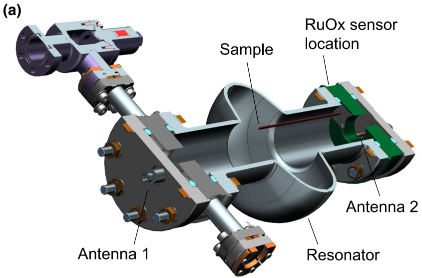
Introduction





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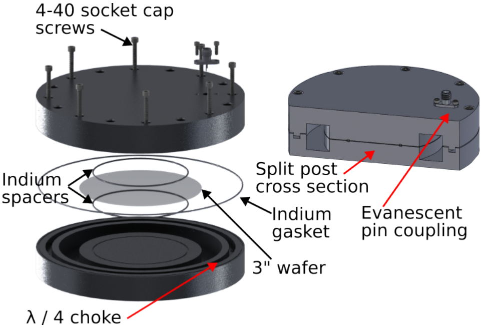
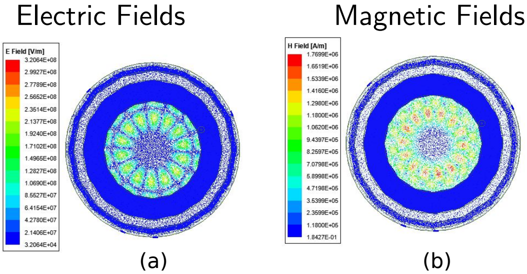
Split Post Cavity Design

- Design goals: high wafer participation, ease of assembly, low bare cavity loss



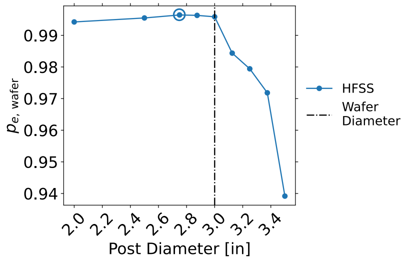
Split Post Cavity Design

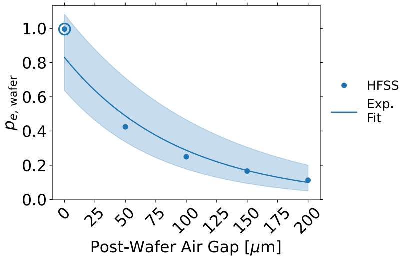
- Design goals: high wafer participation, ease of assembly, low bare cavity loss
- High order quasi-TM mode as the measurement mode with frequency 5.210 GHz



Split Post Cavity Design

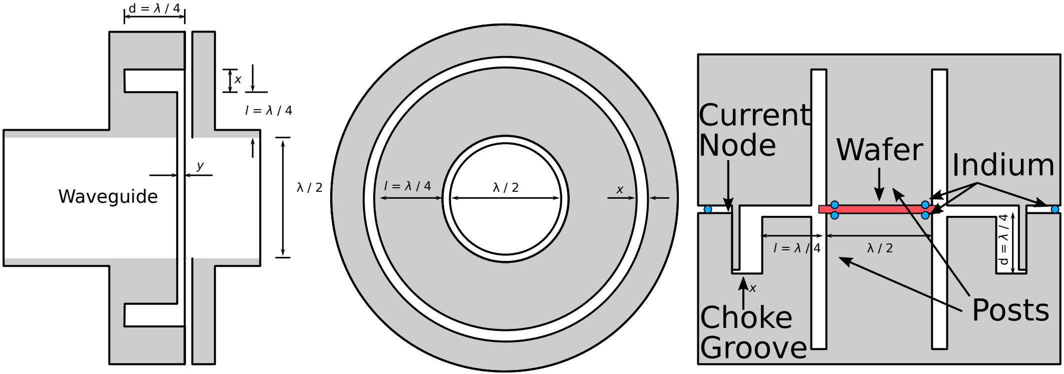
- Design goals: high wafer participation, ease of assembly, low bare cavity loss
- High order quasi-TM mode as the measurement mode with frequency 5.210 GHz
- Posts must contact the wafer to maximize participation; post diameter just less than wafer diameter





Seam Loss Mitigation

- Minimize current at H-plane seam with $\lambda/4$ choke[6,7]



(a) (b) (c)

[6] G. L. Ragan. *Microwave Transmission Line Circuits*. 1948.

[7] T. Brecht, PhD Thesis, (2017).

Loss Extraction Approach

- Measure the loss of the bare cavity, extract loss contributions from seam and walls using multiple cavity resonances

$$Q_{\mathrm{walls}}^{-1} = \frac{R_s}{X_s} \frac{\lambda_L \int_S |\mathbf{H}|^2 \, \mathrm{d}^2\mathbf{x}}{\int_V |\mathbf{H}|^2 \, \mathrm{d}^3\mathbf{x}} = \frac{R_s}{X_s} p_{\mathrm{cond}}$$

$$Q_{\mathrm{seam}}^{-1} = G_{\mathrm{seam}}^{-1} L \frac{\int_{\gamma_{\mathrm{seam}}} |\mathbf{J} \times \mathbf{l}|^2 \, \mathrm{d}l}{\omega \mu_0 \int_V |\mathbf{H}|^2 \, \mathrm{d}^3\mathbf{x}} = \frac{y_{\mathrm{seam}}}{g_{\mathrm{seam}}}$$

[8] J. Gao, PhD Thesis, (2008).

[9] Woods et al., Phys. Rev. Applied **12**, 014012 (2019).

Loss Extraction Approach

- Measure the loss of the bare cavity, extract loss contributions from seam and walls using multiple cavity resonances
- Dielectric contribution to the loss from the wafer

$$Q_{\mathrm{wafer}}^{-1} = \delta_{\mathrm{wafer}} = F\delta_{TLS}^{0} \frac{\tanh(\hbar\omega/2k_B T)}{\left(1 + \frac{\langle n \rangle}{n_c}\right)^{\beta}}$$

$$F = p_{\mathrm{wafer}} = \frac{\frac{1}{2}\epsilon_{\mathrm{wafer}} \int_{V_{\mathrm{wafer}}} |\mathbf{E}|^2 \, \mathrm{d}^3\mathbf{x}}{\frac{1}{2}\epsilon \int_{V_{\mathrm{all}}} |\mathbf{E}|^2 \, \mathrm{d}^3\mathbf{x}}$$

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Loss Extraction Approach

- Measure the loss of the bare cavity, extract loss contributions from seam and walls using multiple cavity resonances
- Dielectric contribution to the loss from the wafer
- Measure the loaded cavity, extract wafer loss[8]

$$Q^{-1}_{\text{bare,tot}} = Q^{-1}_{\text{walls}} + Q^{-1}_{\text{seam}}$$
$$Q^{-1}_{\text{loaded,tot}} = Q^{-1}_{\text{bare,tot}} + Q^{-1}_{\text{wafer}}$$

[8] J. Gao, PhD Thesis, (2008).

[9] Woods et al., Phys. Rev. Applied **12**, 014012 (2019).

Loss Extraction Approach

- Measure the loss of the bare cavity, extract loss contributions from seam and walls using multiple cavity resonances
- Dielectric contribution to the loss from the wafer
- Measure the loaded cavity, extract wafer loss[8]
- $p_{\mathrm{wafer}} = 0.996$, $(\delta^0_{\mathrm{TLS,\,Si}} \sim 5 \times 10^{-7})$[9], we want $Q^{-1}_{\mathrm{bare,tot}} < Q^{-1}_{\mathrm{wafer}}/2$

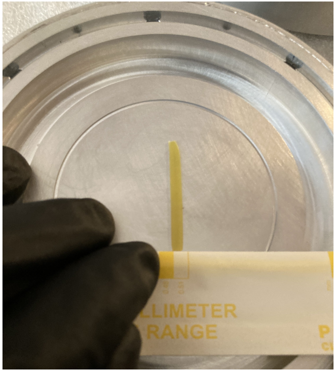
$$Q^{-1}_{\mathrm{loaded,tot}} < \frac{1}{2} Q^{-1}_{\mathrm{wafer}} \lesssim 2.5 \times 10^{-7}$$

[8] J. Gao, PhD Thesis, (2008).

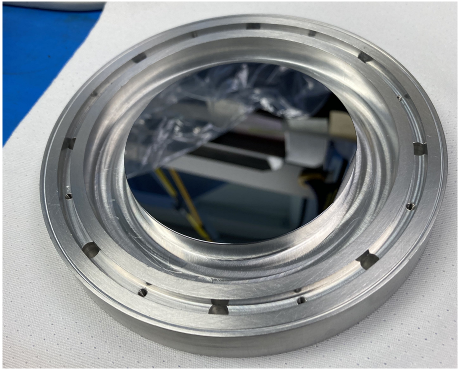
[9] Woods et al., Phys. Rev. Applied **12**, 014012 (2019).

Experiment Preparation

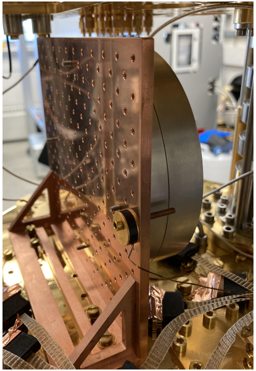
- Post separation measurement with (a) plastigauge post gap measurement, (b) wafer mounting, (c) cavity mount and RuOx temperature sensor



(a)



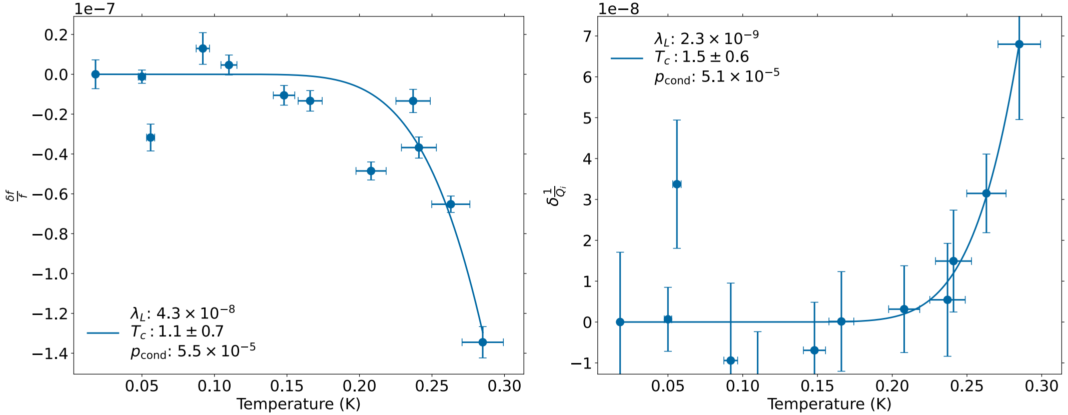
(b)



(c)

Temperature Dependent Measurements

- Extract the London Penetration Depth $\lambda_L = 43\,\mathrm{nm}$ from Mattis Bardeen fits



(a) (b)

Preliminary Measurements

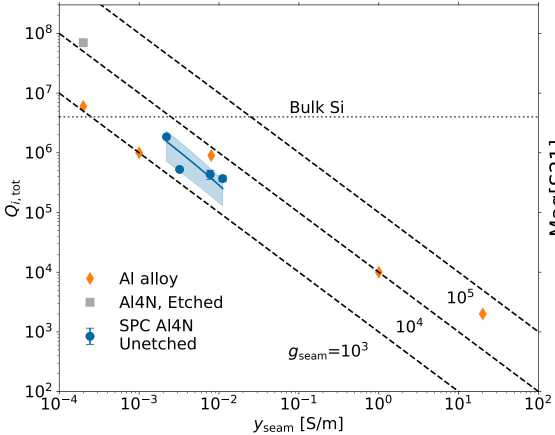
- Bare, unetched cavity losses of four resonances fit with a linear model

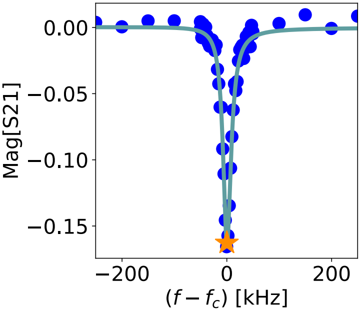
$$\frac{Q^{-1}_{\text{bare, tot}}}{y_{\text{seam}}} = \frac{1}{g_{\text{seam}}} + R_s \frac{p_{\text{cond}}}{X_s y_{\text{seam}}},\ y = ax + b,\ a = R_s,\ b = g^{-1}_{\text{seam}}$$

Table: Unetched cavity estimated wall and seam losses. Between post resonances in orange.

Mode Frequency [GHz]	p_{cond}	y_{seam}	Q^{-1}_{walls}	Q^{-1}_{seam}	$Q^{-1}_{\text{bare, tot}}$
4.657	9.78×10^{-6}	7.75×10^{-3}	1.9×10^{-7}	2.4×10^{-6}	$(2.3 \pm 0.4) \times 10^{-6}$
5.2101	1.15×10^{-5}	1.11×10^{-2}	2.0×10^{-7}	3.4×10^{-6}	$(2.7 \pm 0.3) \times 10^{-6}$
6.551	1.33×10^{-5}	3.21×10^{-3}	1.5×10^{-7}	9.8×10^{-7}	$(1.90 \pm 0.02) \times 10^{-6}$
7.875	1.25×10^{-5}	2.2×10^{-3}	1.5×10^{-7}	6.7×10^{-7}	$(5.4 \pm 0.2) \times 10^{-7}$

Unetched Cavity Results

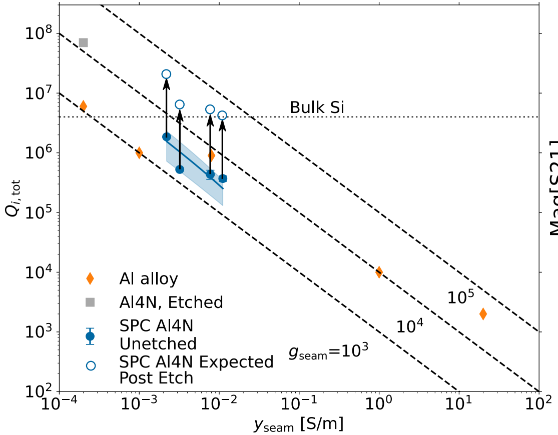


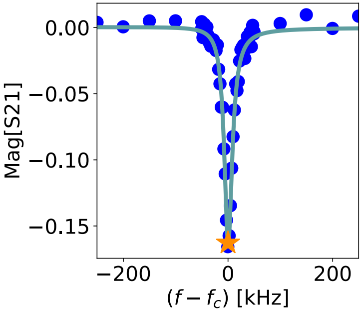


$g_{\mathrm{seam}} = 3 \times 10^3\,\mathrm{S/m}$, $R_s = 60\,\mu\Omega$, Al alloy (6061) and Al4N, Etched data from[10]

[10] T. Brecht, PhD Thesis, (2017).

Expected Etched Cavity Losses





$g_{\mathrm{seam}} = 3 \times 10^3\,\mathrm{S/m}$, $R_s = 60\,\mu\Omega$, Al alloy (6061) and Al4N, Etched data from[11]

[11] T. Brecht, PhD Thesis, (2017).

Next Steps

- Measure the etched bare cavity, extract updated g_{seam}, R_s
- Measure the loaded cavity with a silicon wafer and extract its bulk loss
- Measure multiple wafers from different boules, manufacturers, pre-fabrication processing
- Improve $\lambda/4$ choke to reduce seam loss to allow measurements of low loss sapphire wafers

Acknowledgements

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References

[1] Suhas Ganjam et al. "Surpassing millisecond coherence times in on-chip superconducting quantum memories by optimizing materials, processes, and circuit design". In: *arXiv e-prints*, arXiv:2308.15539 (Aug. 2023), arXiv:2308.15539. DOI: 10.48550/arXiv.2308.15539. arXiv: 2308.15539 [quant-ph].

[2] J. Bourhill et al. "Low-Temperature Properties of Whispering-Gallery Modes in Isotopically Pure Silicon-28". In: *Phys. Rev. Appl.* 11 (4 Apr. 2019), 044044. DOI: 10.1103/PhysRevApplied.11.044044.

[3] J. Krupka et al. "Use of whispering-gallery modes for complex permittivity determinations of ultra-low-loss dielectric materials". In: *IEEE Transactions on Microwave Theory and Techniques* 47.6 (1999), 752. DOI: 10.1109/22.769347.

[4] Alexander P. Read et al. "Precision Measurement of the Microwave Dielectric Loss of Sapphire in the Quantum Regime with Parts-per-Billion Sensitivity". In: *Phys. Rev. Appl.* 19 (3 Mar. 2023), 034064. DOI: 10.1103/PhysRevApplied.19.034064.

[5] M. Checchin et al. "Measurement of the Low-Temperature Loss Tangent of High-Resistivity Silicon Using a High-Q Superconducting Resonator". In: *Phys. Rev. Appl.* 18 (3 Sept. 2022), 034013. DOI: 10.1103/PhysRevApplied.18.034013.

[6] G. L. Ragan. *Microwave Transmission Line Circuits*. Vol. 9. MIT Radiation Laboratory. McGraw Hill, New York, 1948.

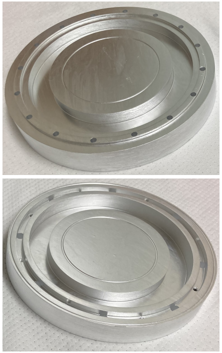
[7] T. Brecht. "Micromachined Quantum Circuits". PhD thesis. Yale University, 2017.

[8] J. Gao. "The Physics of Superconducting Microwave Resonators". PhD thesis. California Institute of Technology, 2008.

[9] W. Woods et al. "Determining Interface Dielectric Losses in Superconducting Coplanar-Waveguide Resonators". In: *Phys. Rev. Applied* 12 (1 July 2019), 014012. DOI: 10.1103/PhysRevApplied.12.014012.

Transene A Etch

(a)



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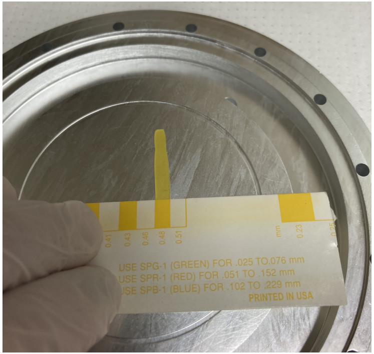

(c)

External Coupling Quality Factor Simulations