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Losses in superconducting circuits fabricated on thin silicon membranes for hybrid quantum systems integration

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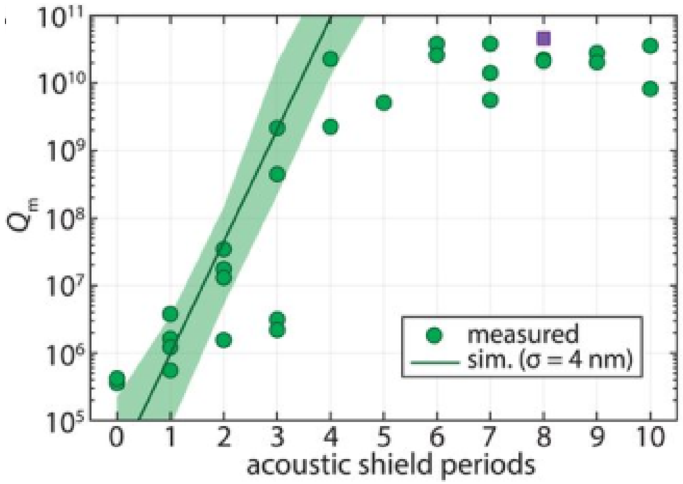
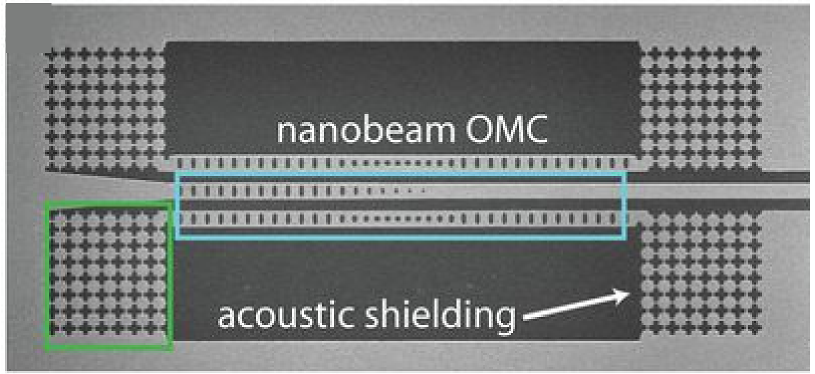
Hybrid systems enhancing quantum computing

Phononic crystal resonators could form a memory for superconducting qubit

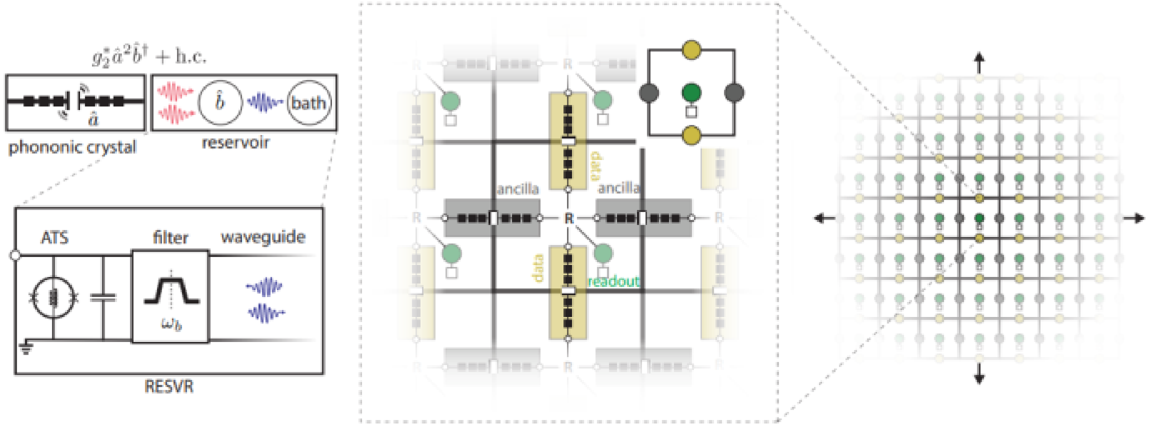
- second-scale long lifetimes compared to 100 µs lifetimes for transmon qubits





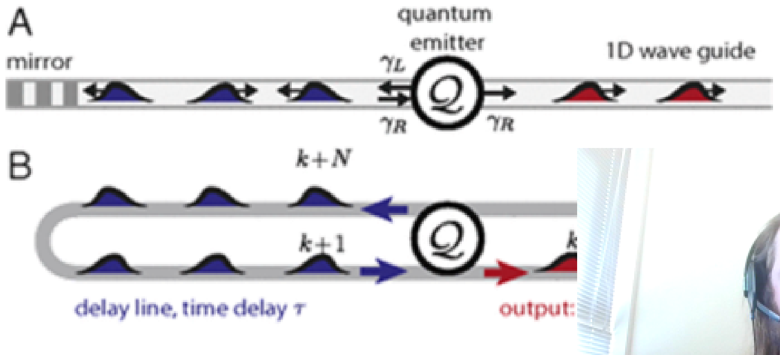
Science **370**, 6518, 840 (2020)

A quantum processor build from phononic crystal resonators



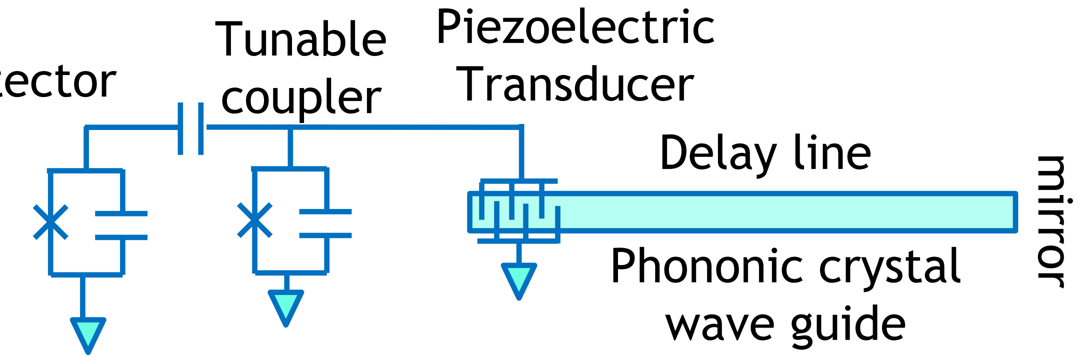
arxiv:2012.04108

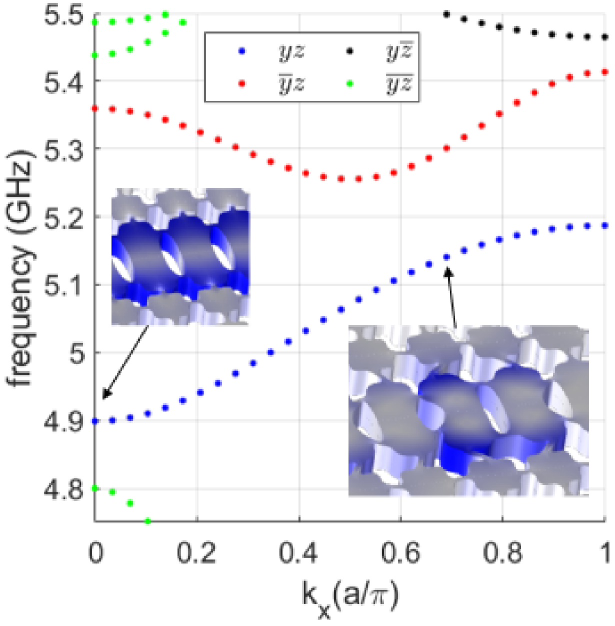
Potential universal computing with entangled phonons



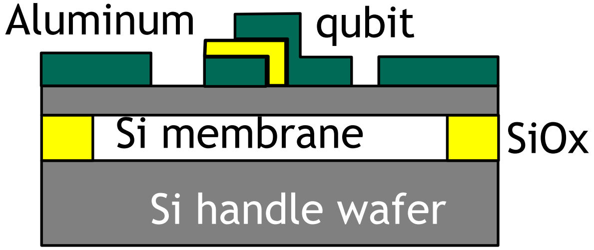
PNAS **14** 43 (2017)

Phononic quantum state generator





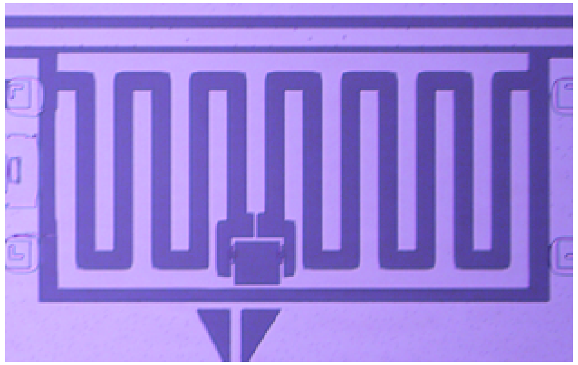
npj Quantum Information
8, 19 (2022)



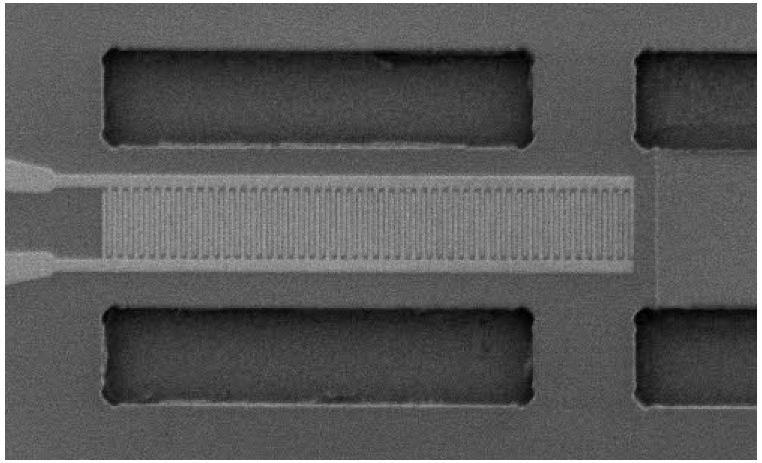
Sandia fabricated components

Piezoelectric Transducer

Qubit on solid Si substrate



180 µm

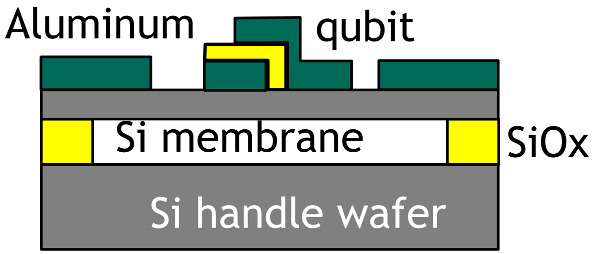


100 µm

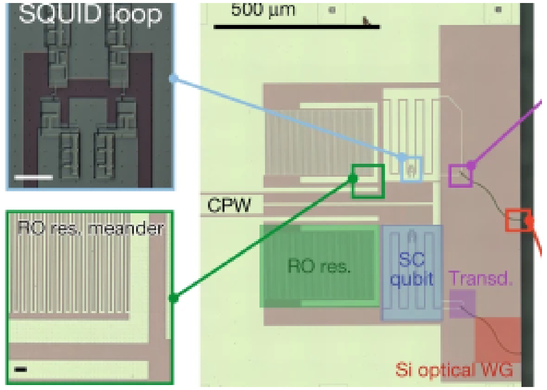
Phononic crystal wave guide

Contributions to microwave loss in devices on silicon membranes are not fully understood

Examples of qubit on Si membrane's have much shorter lifetimes than on solid Si or sapphire substrates.

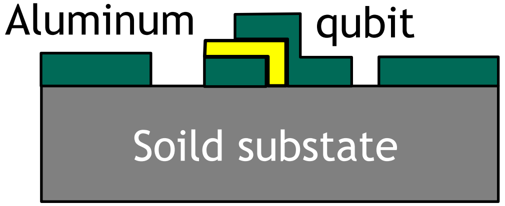


$T_{1,q}$
$= 522 \pm 9$ ns
$Q_q = 16{,}400$



Nature **588**, 599–603 (2020)

Extensive body of work looking at contributions to losses in qubits on bulk Si substrates

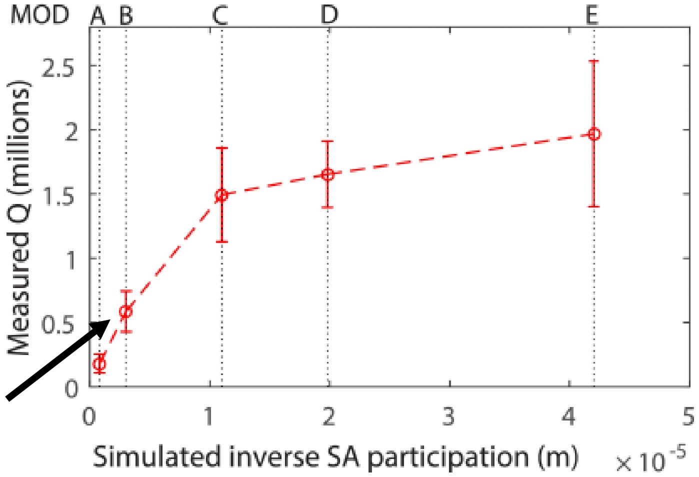


Loss mechanisms

- Dielectric material loss
- Defects and two-level-systems at surface and interfaces

State of the art $T_{1,q}$ = 20 to 100's µs

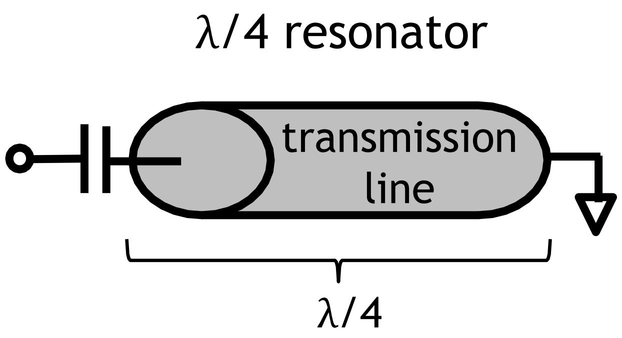
surface loss dominates

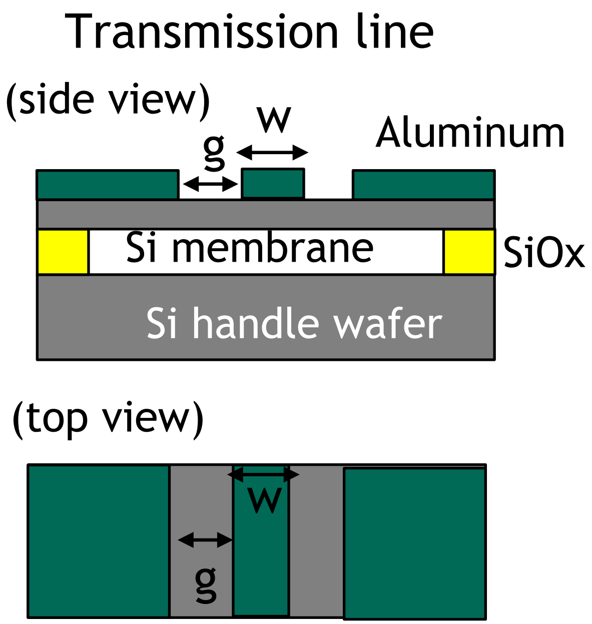


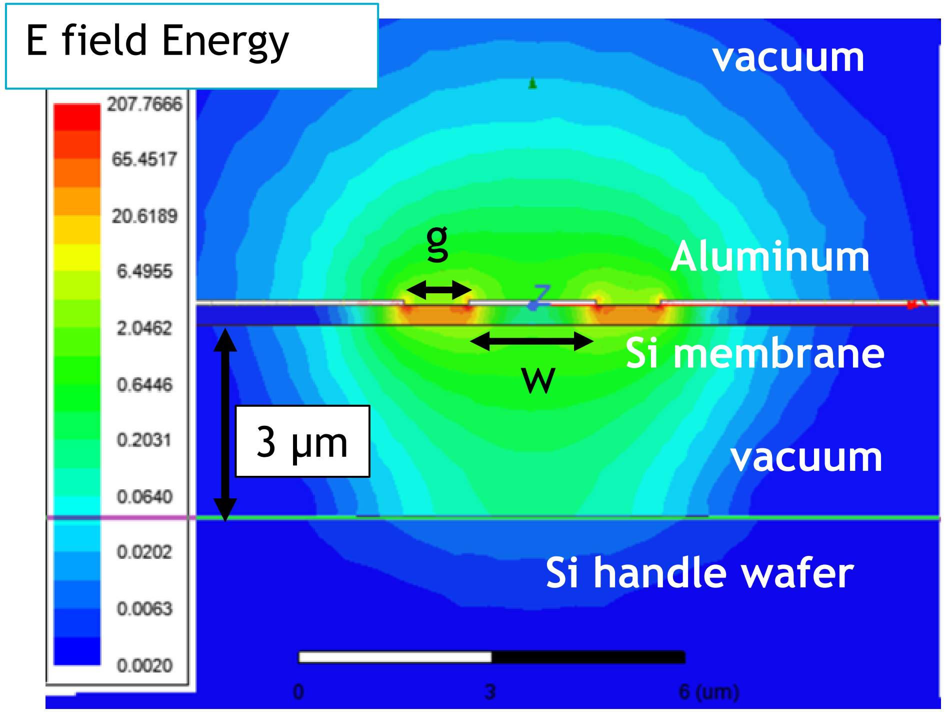
J. M. Gambetta *et al.*, *IEEE Transactions on Applied Superconductivity*,27, 1,. 1-5, Jan. 2017

Differentiating contributions to microwave loss in resonators on Si membranes

To differentiate surface loss from bulk loss, we fabricate resonators with varying designs







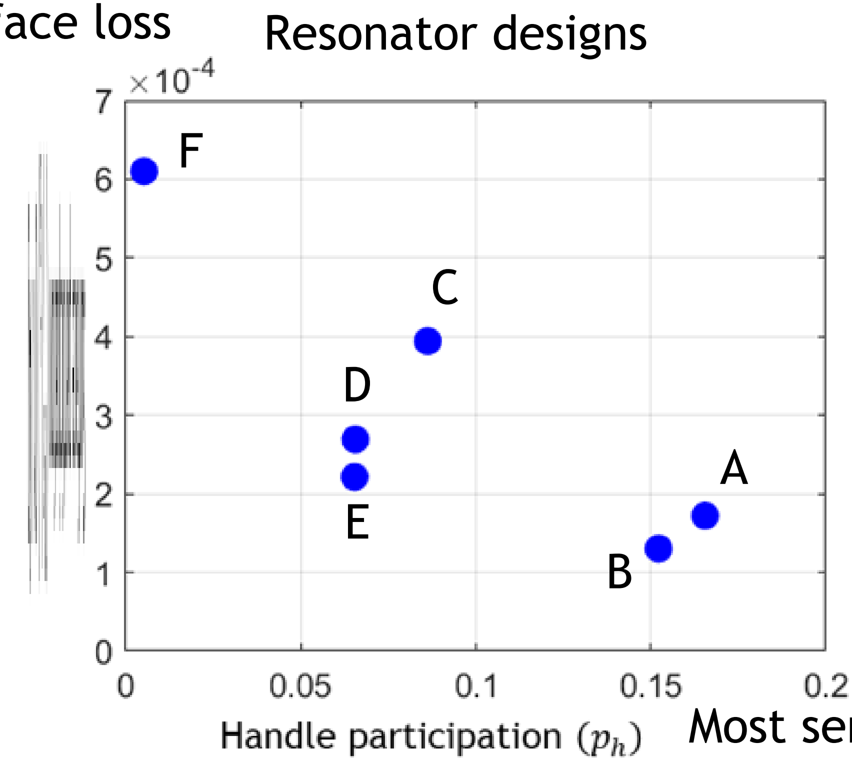
ANSYS HFSS

Handle participation $p_h = \dfrac{\int_{\text{handle}} \boldsymbol{E} \cdot \boldsymbol{E}\, \epsilon_h dV}{U_{tot}}$ goes **up** with feature size (g, w)

Surface participation $p_s/t_s = \dfrac{\int_s \boldsymbol{E} \cdot \boldsymbol{E}\, \epsilon_i dS}{U_{tot}}$ goes **down** with feature size (g, w)

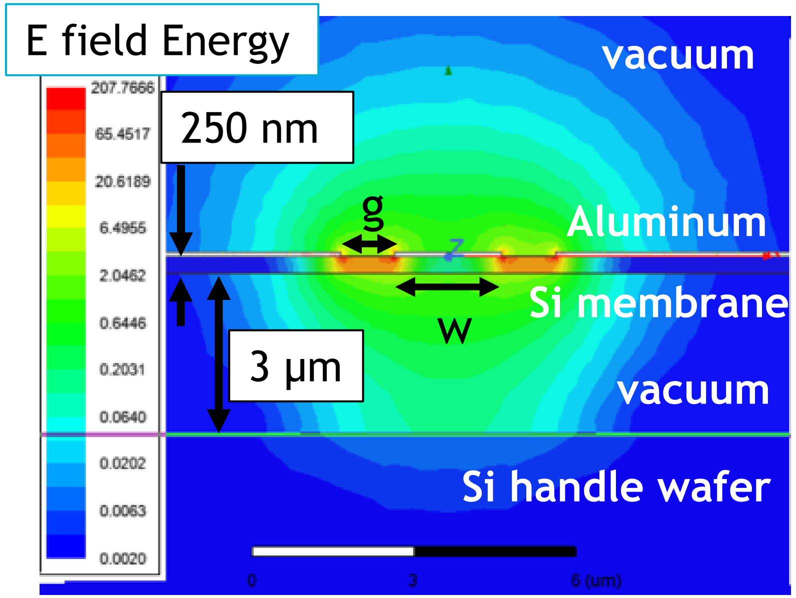
Devices to study contributions to microwave loss on Si membranes

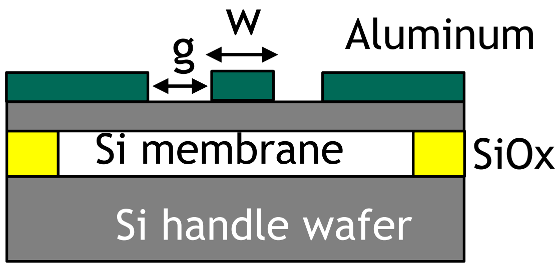
Most sensitive to surface loss



Most sensitive to handle wafer loss

ANSYS HFSS calculation

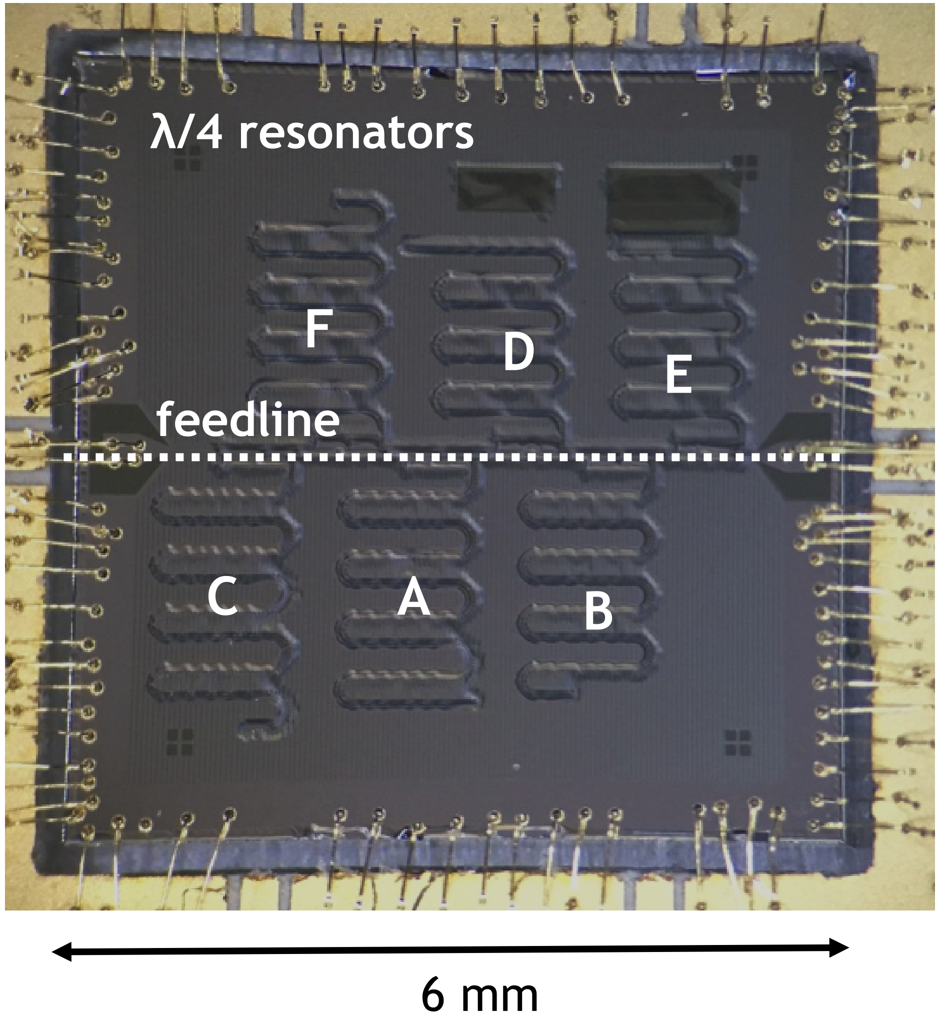


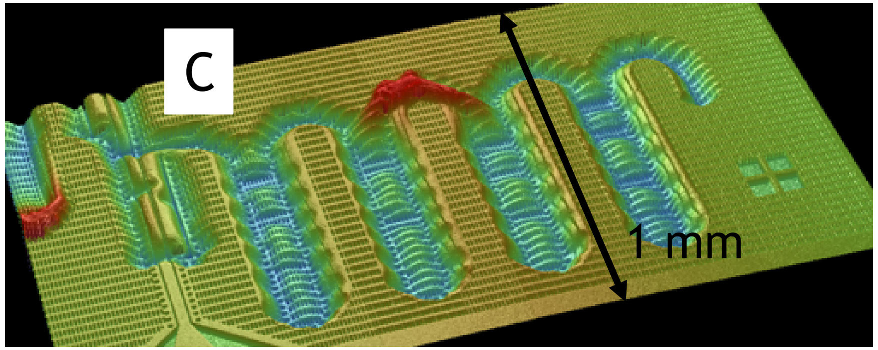


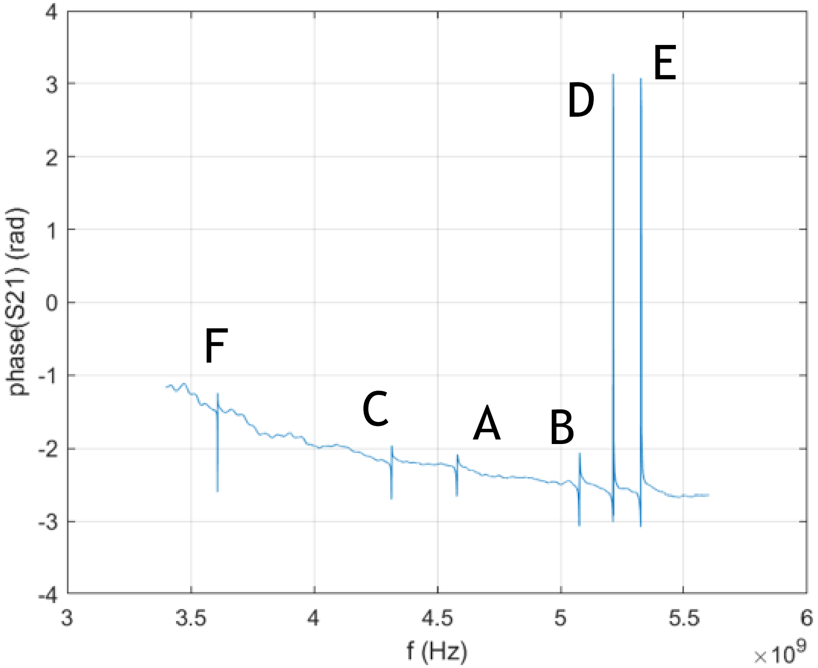
Resonator Design	g (μm)	w (μm)	Surface energy participation (1/Å)	Handle energy participation
A	2	32	1.721×10^{-4}	0.1655
B	3	19.5	1.303×10^{-4}	0.1522
C	1	24	3.941×10^{-4}	0.0862
D	2	9	2.692×10^{-4}	0.0655
E	3	6	2.214×10^{-4}	0.0653
F	1	2	6.101×10^{-4}	0.0051

Fabricate devices on Si membranes

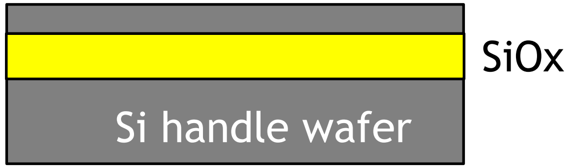
Fabricate on in-stock Si on insulator (SOI) wafers with lossy handle



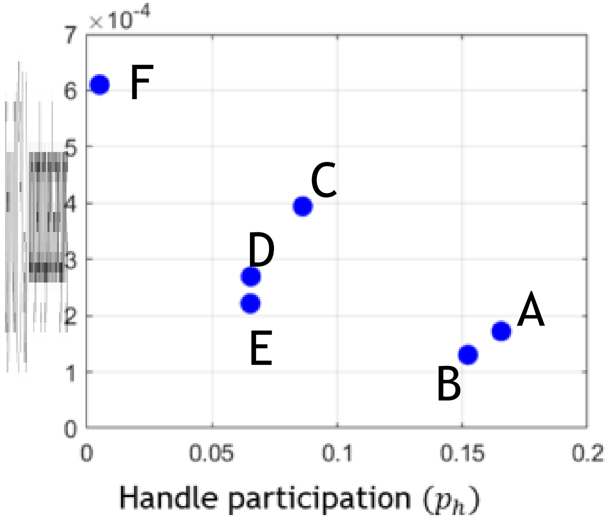




Si membrane: high resistivity
> 5000 $\Omega \cdot$ cm

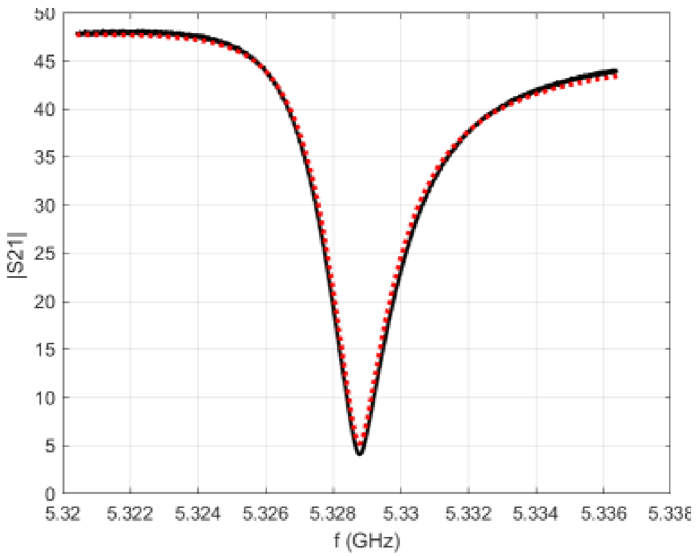


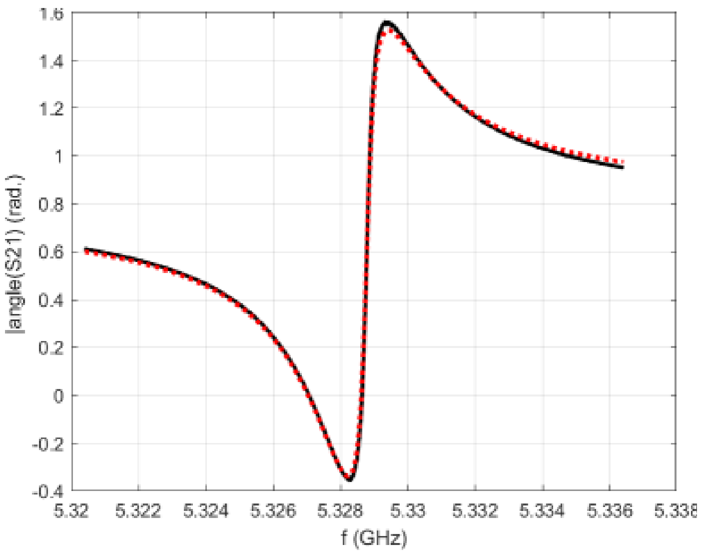
Si Handle wafer:
moderate resistivity (lossy)
14 to 22 $\Omega \cdot$ cm

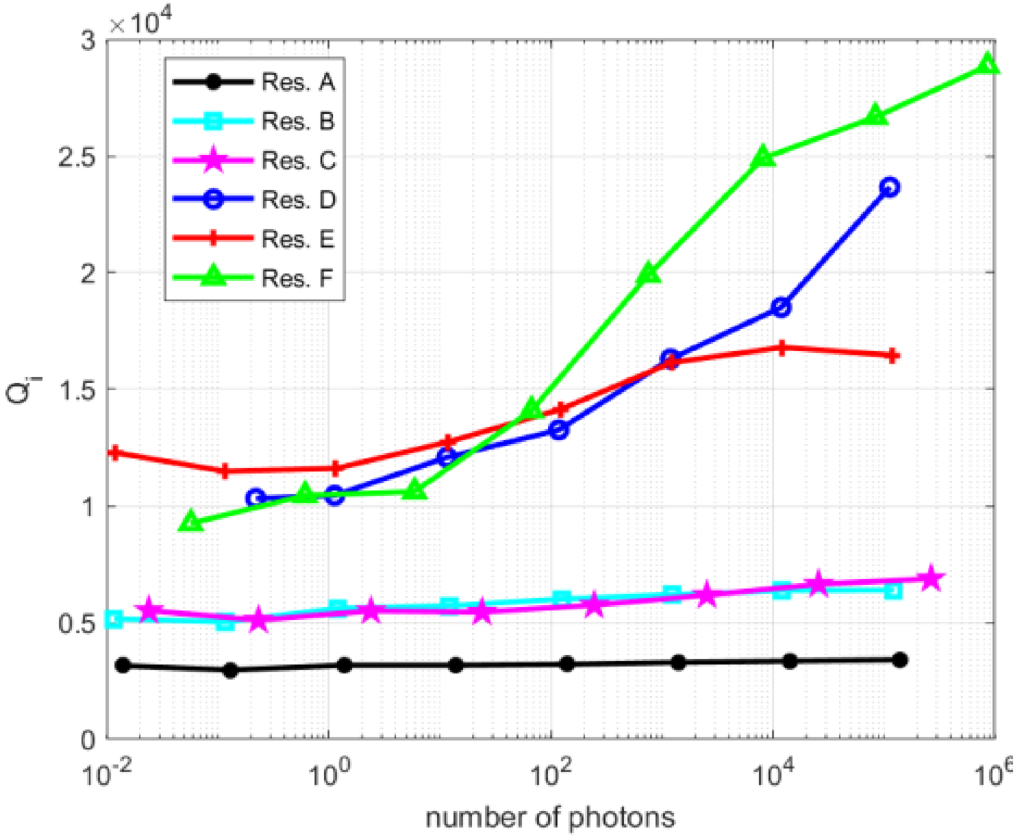


Expect to be most sensitive to handle wafer loss

Extract internal loss with transmission measurements







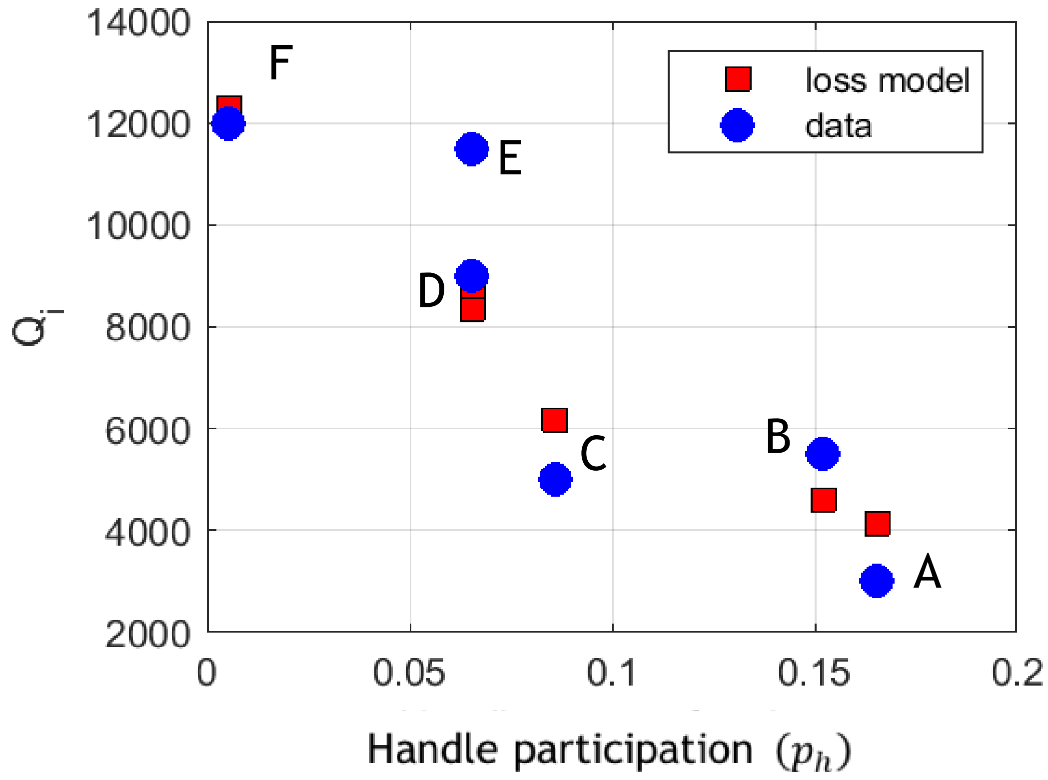
$$= 13436$$

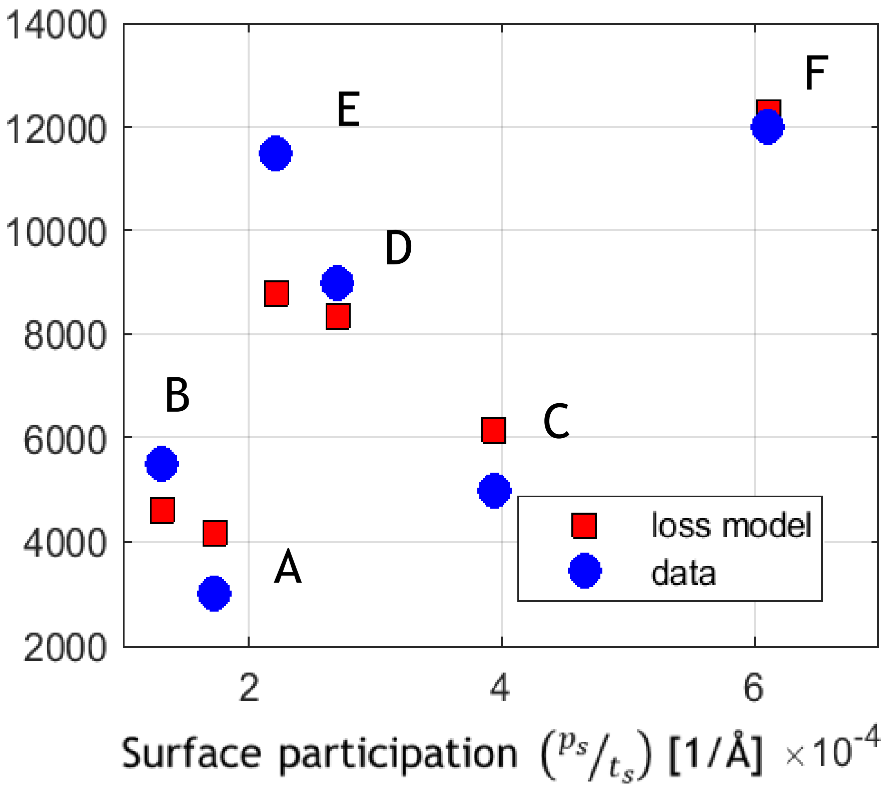
$$\omega_0/_{2\pi} = 5.3294\ \text{GHz}$$

$$= 1751$$

$$S_{21} = A_0 e^{-i(\omega\tau+\phi)}\left(1 - \frac{Q_i - 2iQ_eQ_i\frac{\delta\omega}{\omega_0}}{(Q_e+Q_i) + 2iQ_eQ_i\frac{\omega-\omega_0}{\omega_0}}\right)$$

Results and loss model





loss model $$\frac{1}{Q_i} = \tan(\delta_h)\, p_h + \eta_s \frac{p_s}{t_s}$$

Bulk loss in handle

loss tangent $_h = 0.0013$

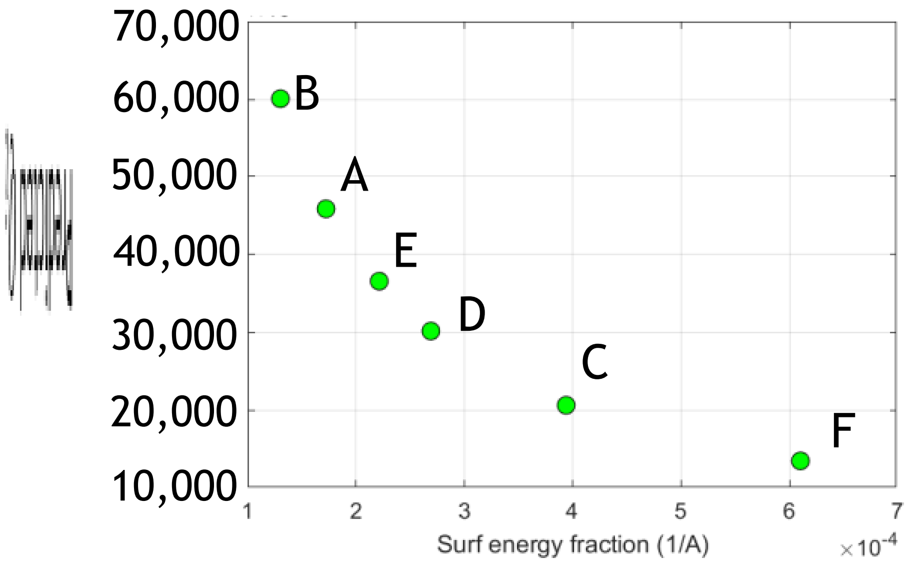
Surface loss

$= 0.122$ Å

Handle dominate loss as expected for 14 to 22 $\Omega \cdot \mathrm{cm}$ handle wafer

Conclusions

- Demonstrated a method to determine contribution of loss in superconducting devices on Si membranes
- Applied this method to devices on a lossy Si handle wafer
- Will apply to high resistivity (low loss) handle wafers when they arrive (supply chain issues!)



- Will fabricate qubits on low loss handle wafers and then integrate with phonon crystal waveguides

Questions: contact me <wkindel@sandia.gov>
Interested in being a postdoc: contact me or Matt Eichenfield <meichen@sandia.gov>