Bulk Loss Measurements of III-V Semiconductor Materials in a Microwave Cavity at Single Photon Powers and Millikelvin Temperatures

Nick Materise[1], William Strictland[2], John Pitten[3,4], Sheng-Xiang Lin[3,4], David Pappas[5], Anthony McFadden[4], Haozhi Wang[7], Javad Shabani[2], Eliot Kapit[1], and Corey Rae H. McRae[3,4,6]

[1]Colorado School of Mines, Department of Physics, Golden, CO 80401, USA

[2]Center for Quantum Phenomena, Department of Physics, New York University

[3]Department of Physics, University of Colorado, Boulder, CO 80309, USA

[4]National Institute of Standards and Technology, Boulder, CO 80305, USA

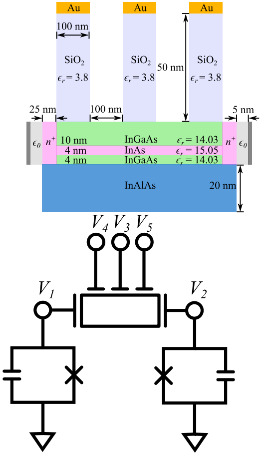
[5]Rigetti Computing, Berkeley, CA 94710, USA

[6]Boulder Cryogenic Quantum Testbed, University of Colorado, Boulder, CO 80309, USA

[7]Laboratory for Physical Sciences, University of Maryland, College Park, MD 20740, USA

Introduction & Motivation

- Motivation: voltage-tunable couplers and gatemons



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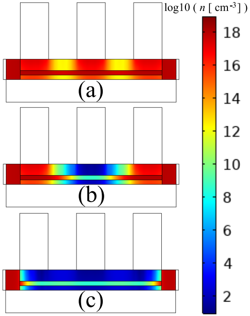

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	t_j [nm]	p_j	δ_j
InGaAs	10	2.08E-5	?
InAs	4.0	3.18E-5	?
InGaAs	4.0	2.86E-5	?
InAlAs	20	5.64E-4	?
InP	3.5E+3	2.92E-2	?
Al_2O_3[3]	50	9.04E-1	5.00E-3
Total	-	-	5.00E-3

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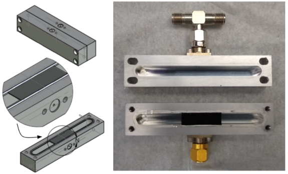

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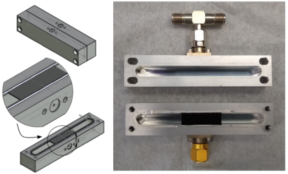

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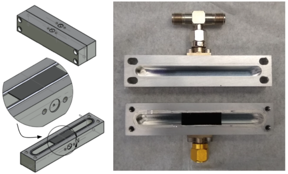

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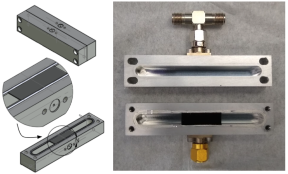

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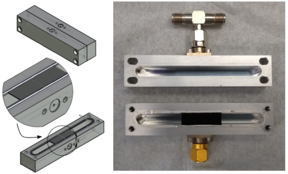

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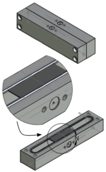

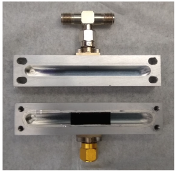

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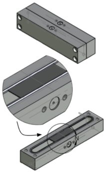

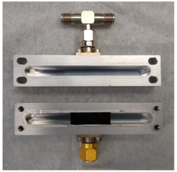

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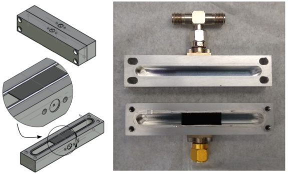

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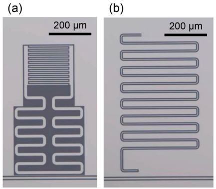

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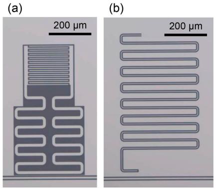

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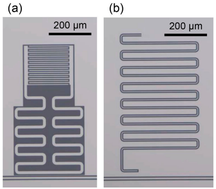

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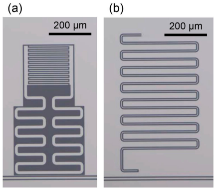

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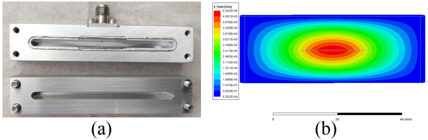

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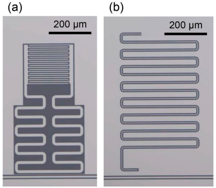

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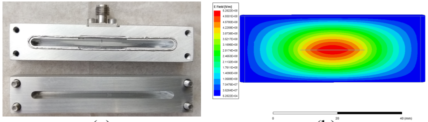

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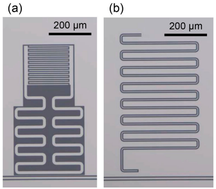

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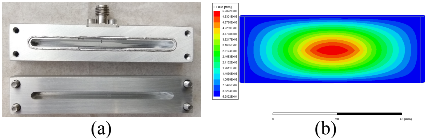

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- Can study bulk and surface roughness losses directly

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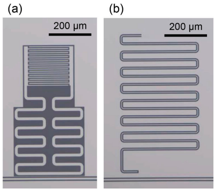
Design and measure bare cavity with f_c ~7 GHz



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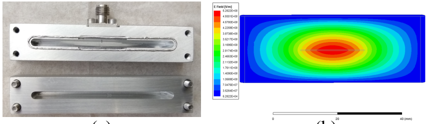

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p_{surf}	5.8e-05	2e-05
p_{bulk}	0.97	0.36
$p_{\mathrm{surf,norm}}$	4.3e-05	1.5e-05
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Table: Participation ratios

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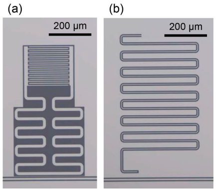

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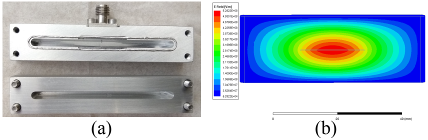

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- Total loss, TLS loss from [3,7]

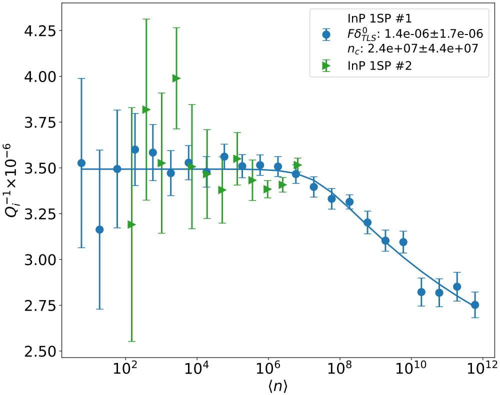
$$Q_i^{-1} = \tan\delta \simeq \delta, \delta \ll 1 \quad (1)$$

$$\delta_{\mathrm{tot}} = \delta_{\mathrm{TLS}} + \delta_{\mathrm{other}} \quad (2)$$

$$\delta_{\mathrm{TLS}} = F\delta^0_{\mathrm{TLS}} \frac{\tanh\left(\frac{\hbar\omega_0}{2k_B T}\right)}{\left(1 + \frac{\langle n \rangle}{n_c}\right)^{\beta}} \quad (3)$$

- Repeated 1SP InP measurements agree for $\langle n \rangle < n_c$

Repeated 1SP InP Cavity Measurements



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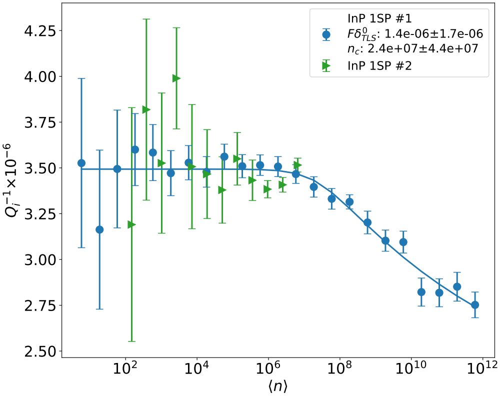

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Mattis-Bardeen Theory

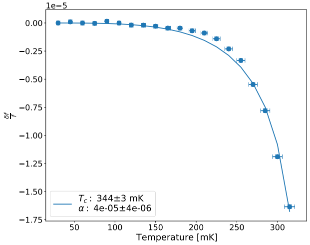
- Fractional frequency shift from Mattis-Bardeen theory, two fluid model[8,9]

$$\frac{\delta f}{f} = \frac{f - f(T_{min})}{f} = \frac{\alpha}{2}\left(1 - \frac{1}{\sqrt{1 - (T/T_c)^4}}\right) \quad (4)$$

- Kinetic inductance fraction is related to the magnetic participation ratio by[10]

$$\alpha = \lambda_L p_m = \lambda_L \frac{\int_S |\mathbf{H}|^2 dS}{\int_V |\mathbf{H}|^2 dV} \quad (5)$$

Planar Al CPW Resonator on InP (NYU)

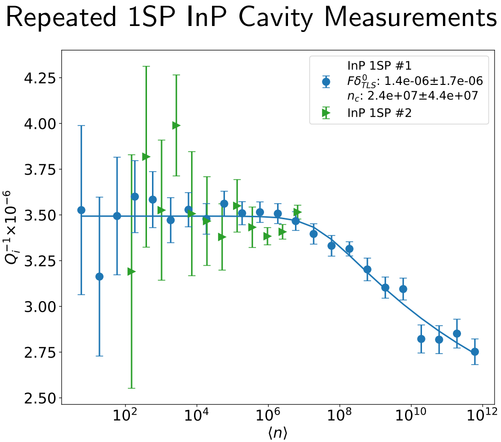


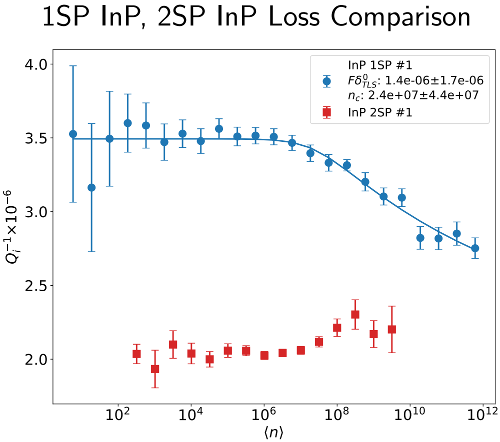
[8] Holland et al., Applied Physics Letters **111**, 202602 (2017).

[9] Turneaure, Halbritter, and Schwettman, Journal of Superconductivity **4**, 341 (1991).

[10] Reagor et al., Applied Physics Letters **102**, 192604 (2013).

Measure samples with / without etching (1SP, 2SP InP)





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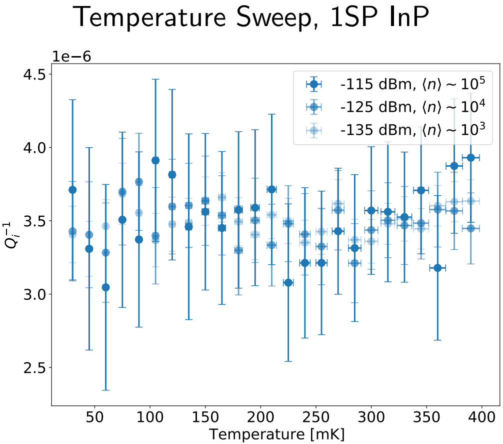
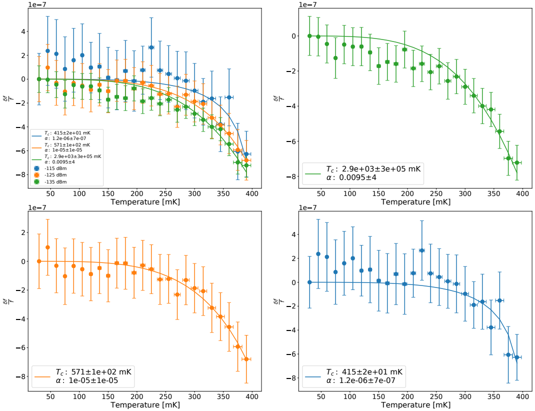


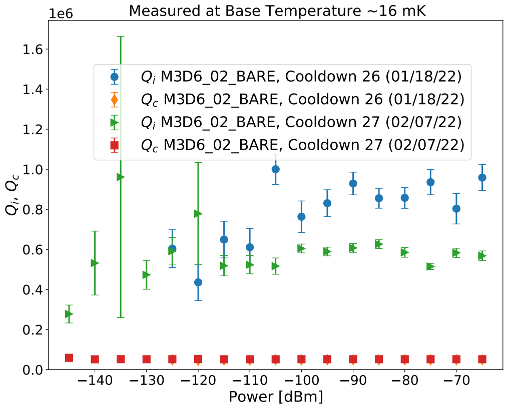
Measure samples with / without etching (1SP, 2SP InP)

Frequency Shifts, 1SP InP: Mattis-Bardeen Fit



Measure samples with / without etching (1SP, 2SP InP)

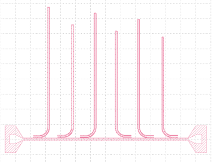
Power Sweep, Bare Cavity (9.2 GHz): Overcoupled.



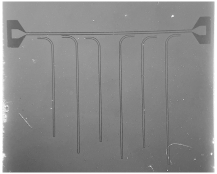
Compare with CPW Al on InP measurements

Image of Sample Package

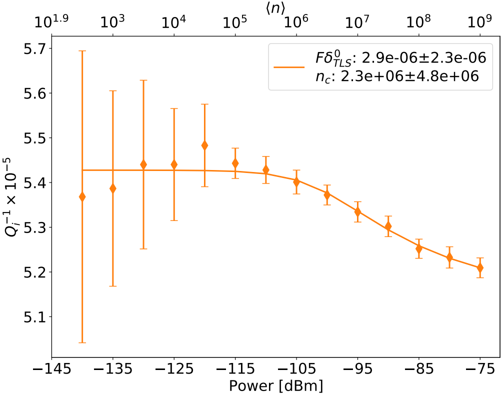
Six Resonator GDS



Optical Image



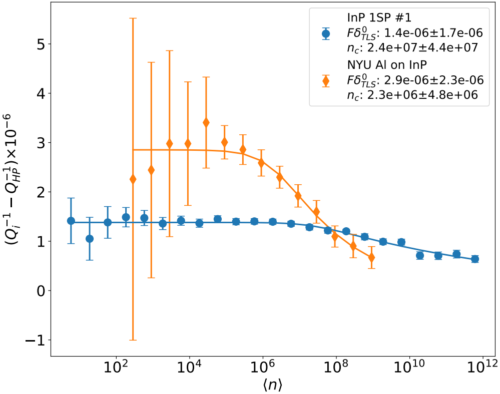
Loss vs. Power – Not TLS Dominated



Compare with CPW Al on InP measurements

- Subtract Q_{HP}^{-1} offsets to compare power dependence
- Comparable $F\delta^0_{\mathrm{TLS}}$, in CPW and cavity measurements
- 10x larger n_c in cavity relative to CPW ⇒ need more photons *in the cavity* to saturate TLS
- Different power dependence – surface roughness vs. interface losses

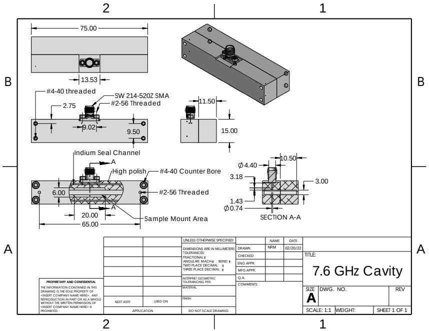
Comparison of 1SP InP & CPW Al on InP



Next Steps

- Improve Q_i/Q_c match in the bare cavity measurements[11]

New Cavity Design, Lower Frequency



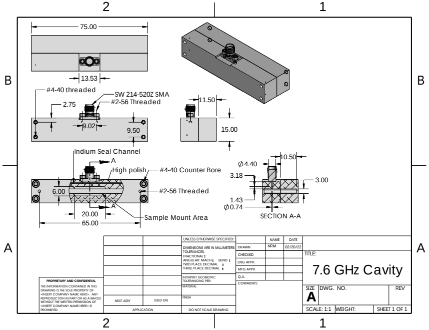
[7] Scigliuzzo et al., New Journal of Physics **22**, 053027 (2020).

[11] M. Reagor, PhD Thesis, (2015).

Next Steps

- Improve Q_i/Q_c match in the bare cavity measurements[11]
- Measure the new cavity with a lower resonance frequency – bare, with SiO_x, with 1SP InP, with 2SP InP, and remaining III-V's in NYU stack

New Cavity Design, Lower Frequency



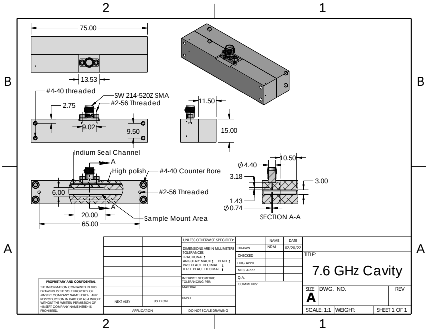
[7] Scigliuzzo et al., New Journal of Physics **22**, 053027 (2020).

[11] M. Reagor, PhD Thesis, (2015).

Next Steps

- Improve Q_i/Q_c match in the bare cavity measurements[11]
- Measure the new cavity with a lower resonance frequency – bare, with SiO_x, with 1SP InP, with 2SP InP, and remaining III-V's in NYU stack
- Develop a basic theory for piezoelectric loss and compare with dominant δ_{other}[7]

New Cavity Design, Lower Frequency



[7] Scigliuzzo et al., New Journal of Physics **22**, 053027 (2020).

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Acknowledgements

- We acknowledge funding from the Graduate Fellowship for STEM Diversity, NSF grant PHY-1653820, ARO grant No. W911NF-18-1-0125 and W911NF-18-1-0115, and Google.
- We would like to thank Hakan Ayaz, Joel Howard, Paul Niyonkuru, David Rodríguez Pérez, Zhijie Tang, and Paul Varosy for helpful discussions

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