High Throughput Loss Measurements of III-V Semiconductor Materials Stack of 2DEG-Based Tunable Couplers.

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

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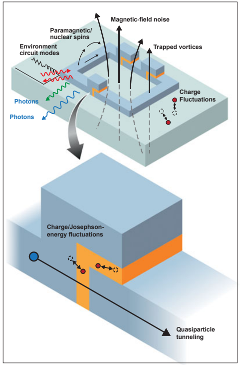
[4]National Institute of Standards and Technology, Boulder, CO 80305, USA

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

November 9, 2022

Introduction

- Most superconducting qubits use Al/AlOx, Nb, Si, sapphire[1]



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[1] Oliver and Welander, MRS Bulletin **38**, 816 (2013).

[2] Siddiqi, Nature Reviews Materials **6**, 875 (2021).

[3] O'Connell Yuan et al., Journal of Vacuum Science & Technology A **39**, 033407 (2021).

[4] Phan et al., arXiv e-prints, arXiv:2206.05746 (2022).

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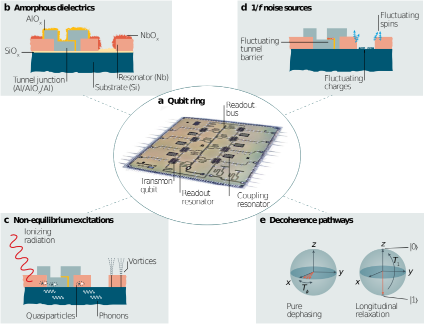
- These materials are well characterized, but fundamental questions remain[2]



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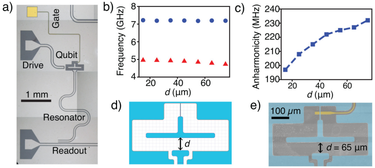

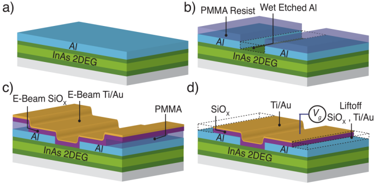

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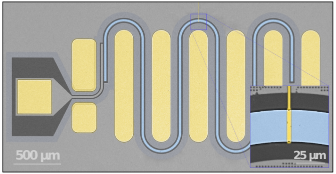
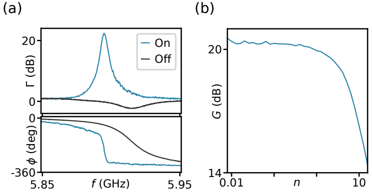
(a)





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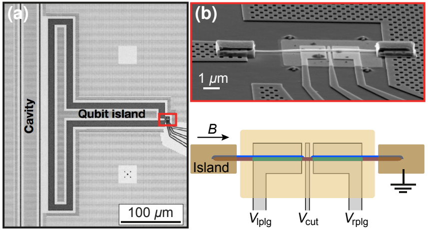

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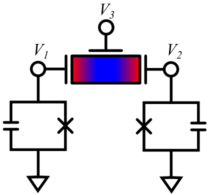
Introduction: Tunable Couplers & III-V Materials

- Tunable coupler designed with voltage-controlled Josephson junctions[6]



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[6] Kapit, Materise, and Shabani, US Patent Appl. No. US17/564,789 .

Introduction: Tunable Couplers & III-V Materials

- Unknown losses of III-V's at $\langle n \rangle \sim 1$, $T \sim$10 mK[7,8,9]

	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)[10]	50	9.04E-1	5.00E-3
Total	-	-	5.00E-3

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[7] Strickland et al., arXiv e-prints, arXiv:2210.02491 (2022).

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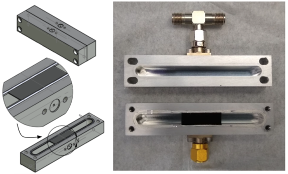

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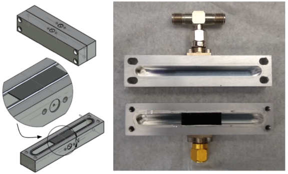

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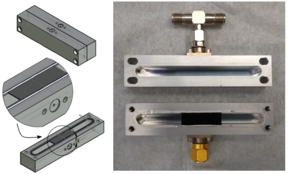

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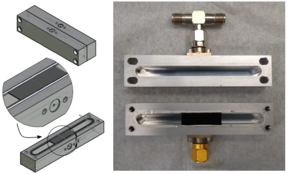

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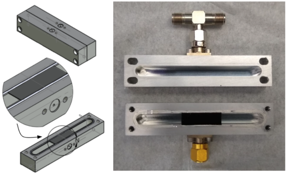

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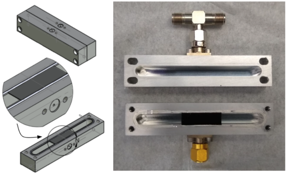

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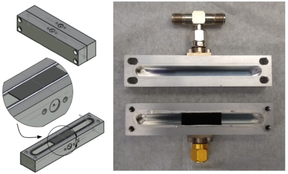
  - Measure samples with / without etching (1SP, 2SP InP)



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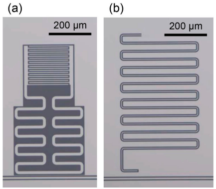
2D vs. 3D Measurement Techniques



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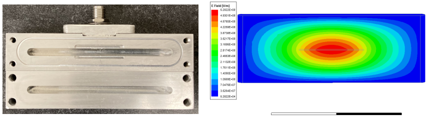
(a) (b)

- Ease of tuning the coupling quality factor, $Q_c \sim Q_i$

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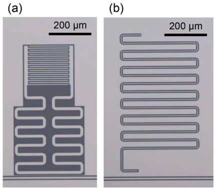

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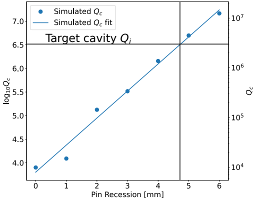

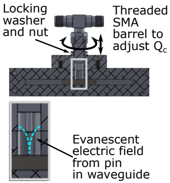

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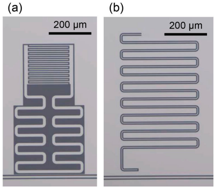
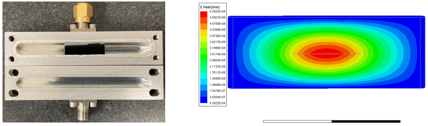


- Q_c fixed by geometry
- Devices sensitive to surfaces and interfaces



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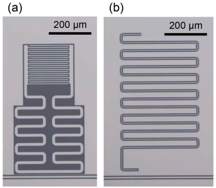
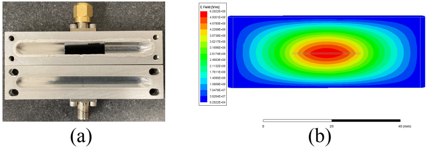


- Q_c fixed by geometry
- Devices sensitive to surfaces and interfaces
- External field bias to stimulate TLS[14]



(a) (b)

- Ease of tuning the coupling quality factor, $Q_c \sim Q_i$
- Sensitive to sample bulk loss rather than surface loss
- Can study bulk and surface roughness losses directly

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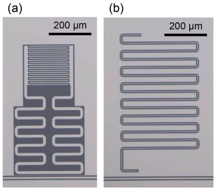

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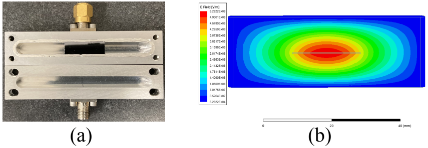

(a) (b)

	Cavity	Substrate (InP)
p_{surf}	5.8e-05	2e-05
p_{bulk}	0.97	0.36
$p_{\mathrm{surf,norm}}$	4.3e-05	1.5e-05
$p_{\mathrm{bulk,norm}}$	0.73	0.27

Table: Participation ratios

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3D Measurement Details

Simulated* Extracted Measured

$$\begin{pmatrix} \widetilde{p}_{\mathrm{cond}}^{\mathrm{bare}} & p_{\mathrm{MA}}^{\mathrm{bare}} & p_{\mathrm{bulk}}^{\mathrm{bare}} \\ \widetilde{p}_{\mathrm{cond}}^{\mathrm{loaded}} & p_{\mathrm{MA}}^{\mathrm{loaded}} & p_{\mathrm{bulk}}^{\mathrm{loaded}} \end{pmatrix} \begin{pmatrix} \widetilde{q}_{\mathrm{cond}}^{-1} \\ q_{\mathrm{MA}}^{-1} \\ q_{\mathrm{sub}}^{-1} \end{pmatrix} = \begin{pmatrix} Q_{\mathrm{bare}}^{-1} \\ Q_{\mathrm{loaded}}^{-1} \end{pmatrix}$$

*With temperature measurements

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$$p_j \equiv \text{participation of } j$$

$$q_k^{-1} \equiv \text{extracted loss of } k$$

$$Q_j^{-1} \equiv \text{measured loss of } j$$

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3D Measurement Details

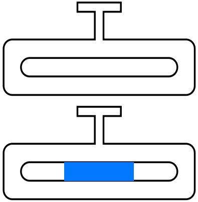
Simulated* **Extracted** **Measured**

$$\begin{pmatrix} \tilde{p}_{\text{cond}}^{\text{bare}} & p_{\text{MA}}^{\text{bare}} & p_{\text{bulk}}^{\text{bare}} \\ \tilde{p}_{\text{cond}}^{\text{loaded}} & p_{\text{MA}}^{\text{loaded}} & p_{\text{bulk}}^{\text{loaded}} \end{pmatrix} \begin{pmatrix} \tilde{q}_{\text{cond}}^{-1} \\ q_{\text{MA}}^{-1} \\ q_{\text{sub}}^{-1} \end{pmatrix} = \begin{pmatrix} Q_{\text{bare}}^{-1} \\ Q_{\text{loaded}}^{-1} \end{pmatrix}$$

$$p_{\text{MA}} = \frac{U_{\text{MA}}}{U_E}, \; p_{\text{bulk}} = \frac{U_{\text{bulk}}}{U_E}, \; \tilde{p}_{\text{cond}} = \omega_0^{-1} \frac{U_{\text{cond}}}{U_E}$$

$$U_E = \frac{1}{2}\epsilon_0 \int_{V_{\text{tot}}} |\vec{E}|^2 dV, \; U_{\text{MA}} = \frac{1}{2} t_{\text{MA}} \frac{\epsilon_0}{\epsilon_{\text{MA}}} \int_{S_{\text{cav}}} |\vec{E}|^2 dS$$

$$U_{\text{bulk}} = \frac{1}{2}\epsilon_0 \epsilon_{\text{sub}} \int_{V_{\text{sub}}} |\vec{E}|^2 dV, \; U_{\text{cond}} = \frac{1}{2}\lambda_L \mu_0 \int_{S_{\text{cav}}} |\vec{B}|^2 dS$$



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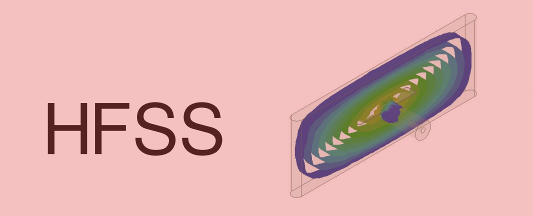
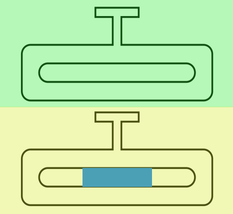
3D Measurement Details

$$\overset{\text{Simulated*}}{\begin{pmatrix} \tilde{p}^{\mathrm{bare}}_{\mathrm{cond}} & p^{\mathrm{bare}}_{\mathrm{MA}} & p^{\mathrm{bare}}_{\mathrm{bulk}} \\ \tilde{p}^{\mathrm{loaded}}_{\mathrm{cond}} & p^{\mathrm{loaded}}_{\mathrm{MA}} & p^{\mathrm{loaded}}_{\mathrm{bulk}} \end{pmatrix}} \overset{\text{Extracted}}{\begin{pmatrix} \tilde{q}^{-1}_{\mathrm{cond}} \\ q^{-1}_{\mathrm{MA}} \\ q^{-1}_{\mathrm{sub}} \end{pmatrix}} = \overset{\text{Measured}}{\begin{pmatrix} Q^{-1}_{\mathrm{bare}} \\ Q^{-1}_{\mathrm{loaded}} \end{pmatrix}}$$





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[15] Read et al., arXiv:2206.14334 [quant-ph] (2022).

TLS Loss Model

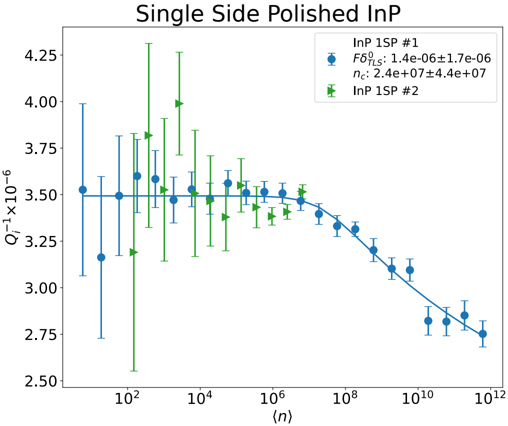
- Total loss, TLS loss from [16,17]

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

$$\delta_{\mathrm{TLS}} + \delta_{\mathrm{hp}} = \delta_{\mathrm{tot}}$$

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

- Input $\{Q_i^{-1}$ vs. $n, \omega_0, T\}$
- Fit $\{\beta, n_c, \delta_{\mathrm{hp}}, F\delta^0_{\mathrm{TLS}}\}$



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[16] McRae et al., Review of Scientific Instruments **91**, 091101 (2020).

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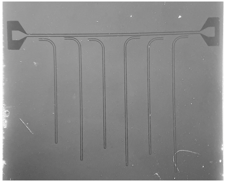
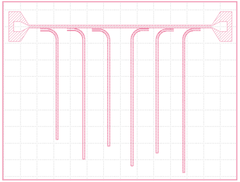
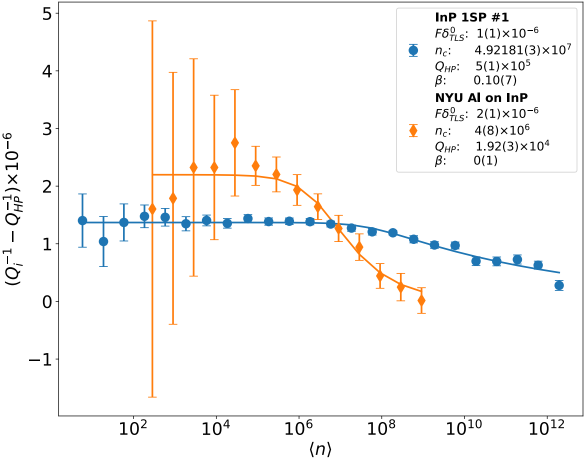
Planar CPW Resonator Comparison Studies

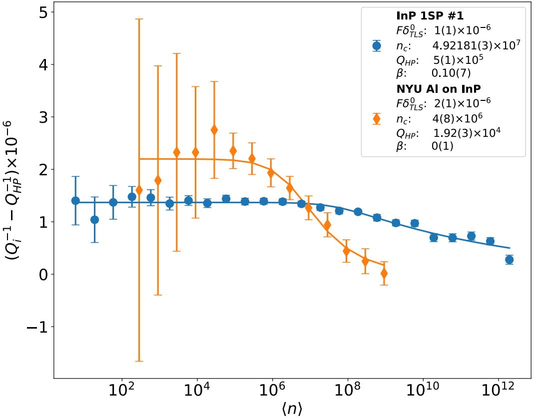




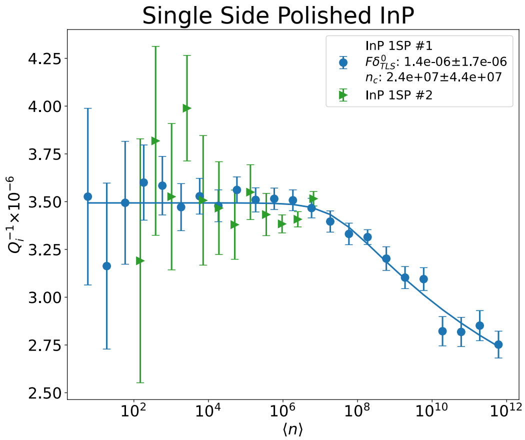


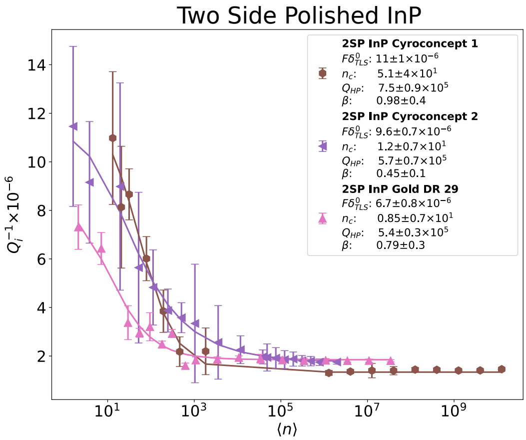
Planar CPW Resonator Comparison Studies

- 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 $\Rightarrow$ need more photons *in the cavity* to saturate TLS
- Different power dependence – surface roughness vs. interface losses



Surface Roughness Loss Comparisons





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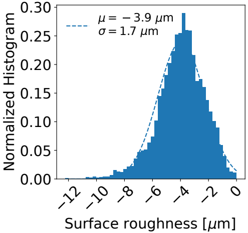
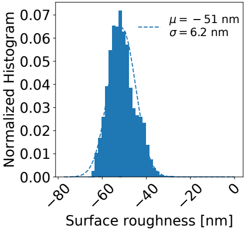
[17] Galliou et al., Scientific Reports **3**, 2132 (2013).

Surface Roughness Loss Comparisons

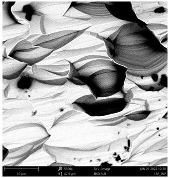
Profilometry (1SP InP)



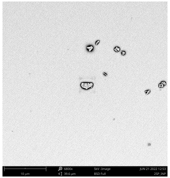
Profilometry (2SP InP)



SEM Image (1SP InP)



SEM Image (2SP InP)



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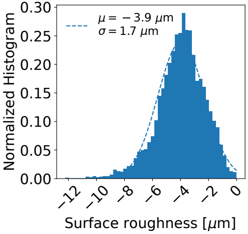
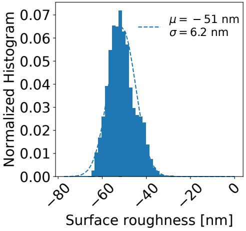
[18] Galliou et al., Scientific Reports **3**, 2132 (2013).

Surface Roughness Loss Comparisons

- If Q_{HP}^{-1} is due to phonon scattering off the rough surface alone:[18]

$$Q_{\mathrm{HP}}^{-1} = Q_{\mathrm{scat}}^{-1} = \frac{2n\sigma^2}{h^2}, n \notin \mathbb{Z}$$


Profilometry (1SP InP)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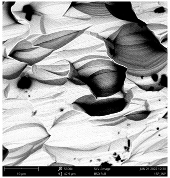
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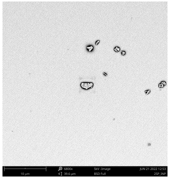
SEM Image (2SP InP)

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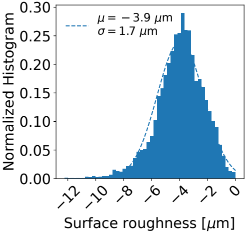
- If Q_{HP}^{-1} is due to increased surface area alone – participation argument:

$$\frac{p_{\mathrm{etched}}}{p_{\mathrm{polished}}} = \frac{S_e}{S_p} = 1.04, \frac{Q_{\mathrm{HP,e}}}{Q_{\mathrm{HP,p}}} = 1.35$$

Profilometry (1SP InP)



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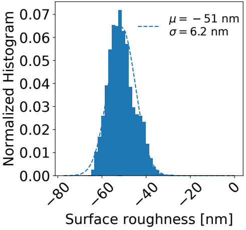
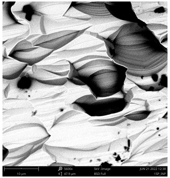


SEM Image (1SP InP)



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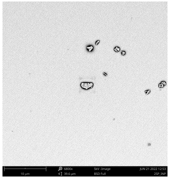

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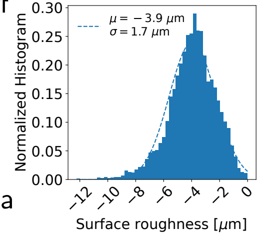
- Need other model(s) to explain high power and low power loss differences

Profilometry (1SP InP)



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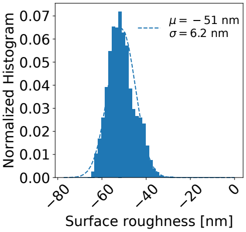
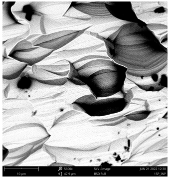
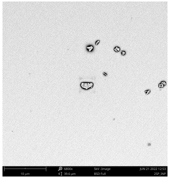


SEM Image (1SP InP)



SEM Image (2SP InP)



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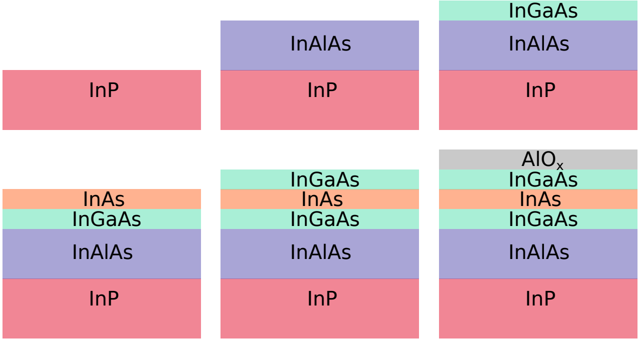
[18] Galliou et al., Scientific Reports **3**, 2132 (2013).

Next Steps

- Remeasure 1SP InP to lower powers, measure another 2SP InP sample, compositional surface studies of 1SP and 2SP InP

Next Steps

- Remeasure 1SP InP to lower powers, measure another 2SP InP sample, compositional surface studies of 1SP and 2SP InP
- Measure the remaining components of the coupler stack, one-by-one



InP

InAlAs
InP

InGaAs
InAlAs
InP

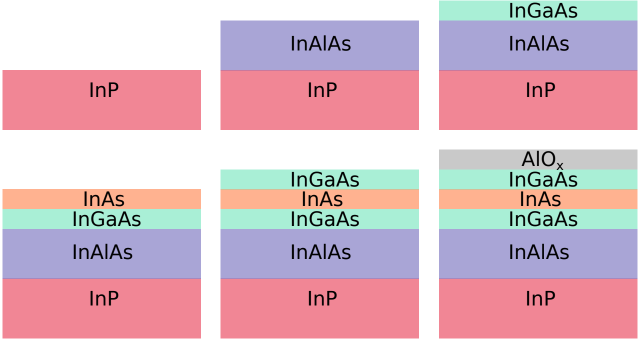
InAs
InGaAs
InAlAs
InP

InGaAs
InAs
InGaAs
InAlAs
InP

AlO_x
InGaAs
InAs
InGaAs
InAlAs
InP

Next Steps

- Remeasure 1SP InP to lower powers, measure another 2SP InP sample, compositional surface studies of 1SP and 2SP InP
- Measure the remaining components of the coupler stack, one-by-one
- Measure other materials of interest to SQMS (TaO_x, Nb_2O_5)



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- 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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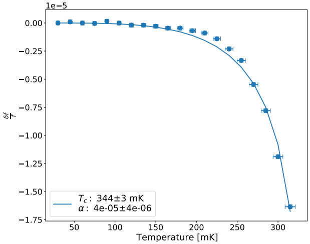
Mattis-Bardeen Theory

- Fractional frequency shift from Mattis-Bardeen theory, two fluid model[19,20]

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

- Kinetic inductance fraction is related to the magnetic participation ratio by[21]

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



Planar Al CPW Resonator on InP (NYU)

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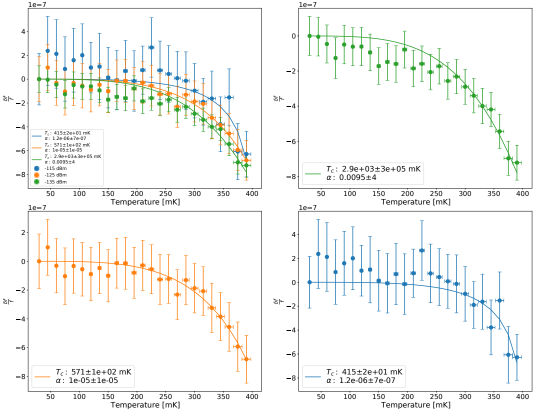
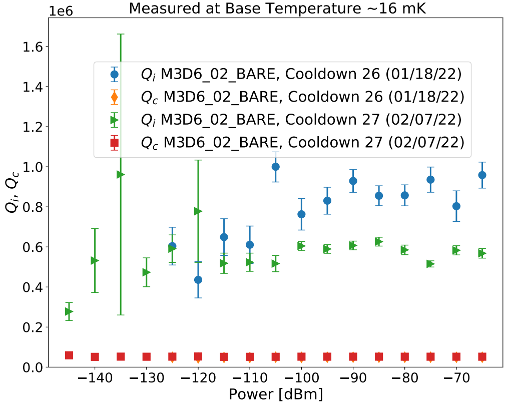
Temperature Dependence & Bare Cavity Results

Frequency Shifts, 1SP InP: Mattis-Bardeen Fit



Temperature Dependence & Bare Cavity Results

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



Summary of Ongoing Loss Measurements

TABLE I. TLS Loss Model Fit Parameters

Sample	$F\delta_{\mathrm{TLS}}{}^{0} \times 10^{-6}$	n_c	β	$Q_{\mathrm{HP}} \times 10^{5}$
Cavity #1 + Si/$\mathrm{SiO_x}$	-	-	0.27(7)	12.50(8)[a]
Cavity #1 + 1SP InP	1(2)	$2(4)\times10^{7}$	0.10(7)	4.92181(3)
Al CPW on 1SP InP	2(1)	$4(8)\times10^{6}$	0(1)	0.192(3)
Cavity #1 + 2SP InP, Cryoconcept 1	11(1)	$2(1)\times10^{-1}$	1.0(4)	7.3(8)
Cavity #1 + 2SP InP, Cryoconcept 2	9.7(7)	$4(2)\times10^{-2}$	0.44(1)	5.8(7)
Cavity #1 + 2SP InP, Gold DR 29	6.7(8)	$3(2)\times10^{-2}$	0.7(2)	5.5(3)
Cavity #1 + 2SP InP, Gold DR 32	3.8(5)	$3(4)\times10^{-1}$	0.9(8)	8(1)
Bare Cavity #2	-	-	-	-
Cavity #2 + Si/$\mathrm{SiO_x}$	-	-	-	-
Cavity #2 + 1SP InP	-	-	-	-
Cavity #2 + 2SP InP	-	-	-	-

[a] Overcoupled cavity measurements, $Q_c \ll Q_i$