Results from X-Ray microcalorimeter arrays based on Thermal MKIDs (TKIDs)

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Technology & Funding Motivations

- Space-Borne – For *Physics of the Cosmos* NASA needs:
  - Priority #1: fast, low noise, megapixel X-ray imaging arrays with moderate resolution
  - Priority #2: large-format, high-spectral-resolution, small-pixel X-ray focal plane arrays
- Ground-Borne – Materials analysis:
  - Synchrotron beam-line studies and X-ray microanalysis where large solid angle is desired
  - Imaging extended x-ray sources with high temporal and spectral resolution

Funded Objectives

NASA APRA Funding for:

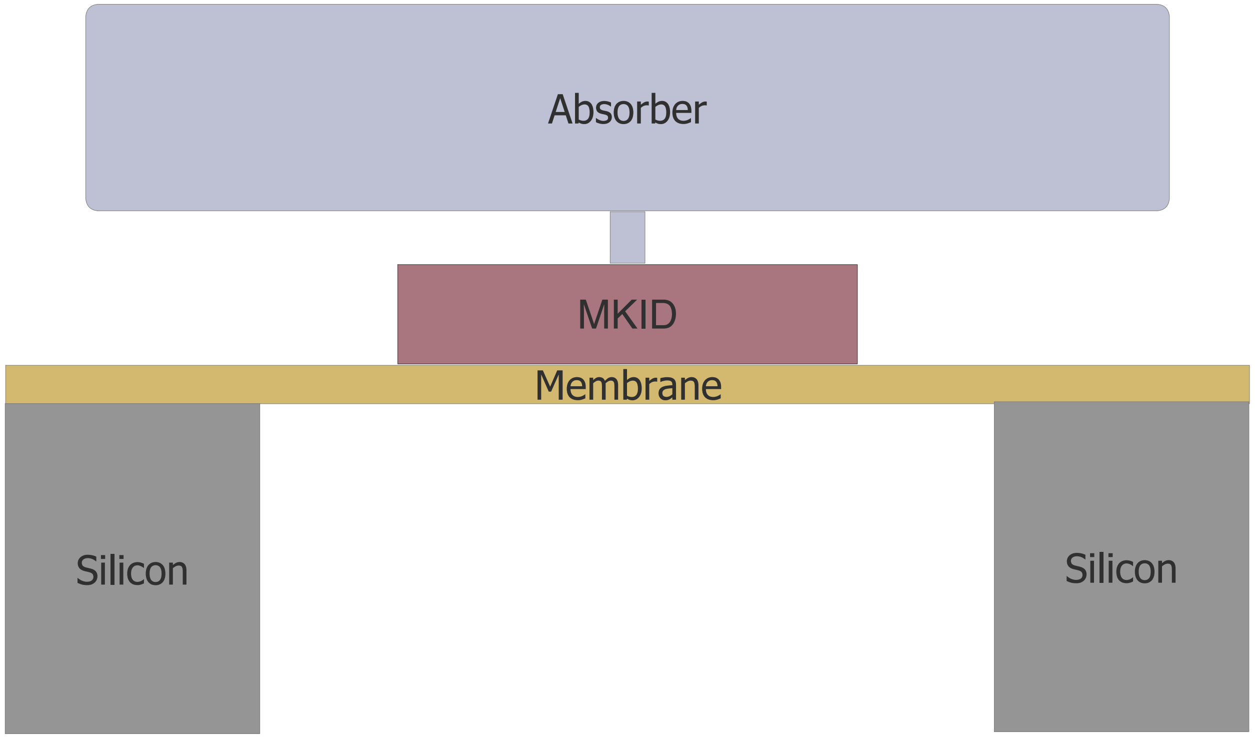
- X-Ray detector array, > 1,000 pixels
- Multiplex factor, 1 signal line : ≥ 250 pixels
- Soft x-rays, 0.2 - 10 keV
- Moderate energy resolution, $\Delta E \leq 5$ eV @ 6 keV
- Moderate fill factor, ≥ 75%
- Pixel quantum efficiency (QE), ≥ 95% @ 6 keV
- Microsecond photon arrival time resolution

Resources

- 1 Full-time postdoc
- UCSB Nanofab
- Dedicated UHV sputter system
- Two Dilution Fridges

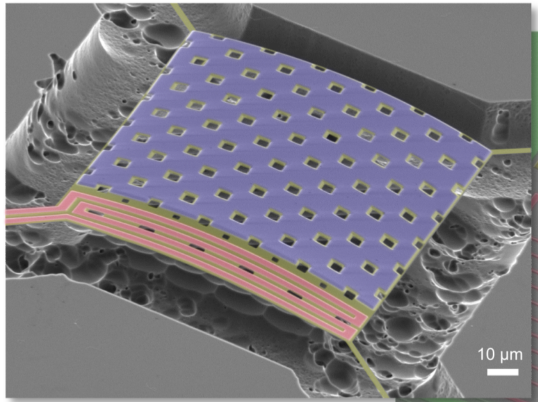
Approach

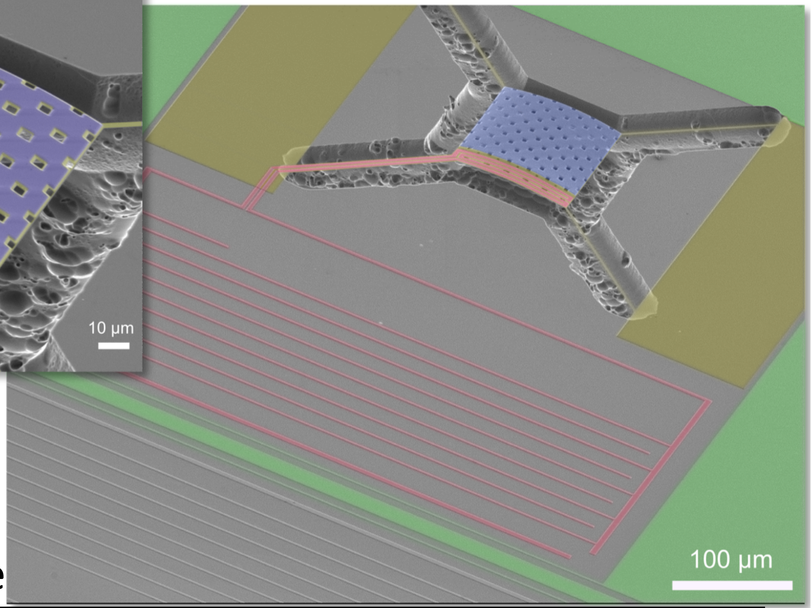
- Use microcalorimeter format to couple an x-ray absorber to an MKID.
- X-rays warm up absorber which warms up MKID.
- Use temperature rise to measure x-ray energy.



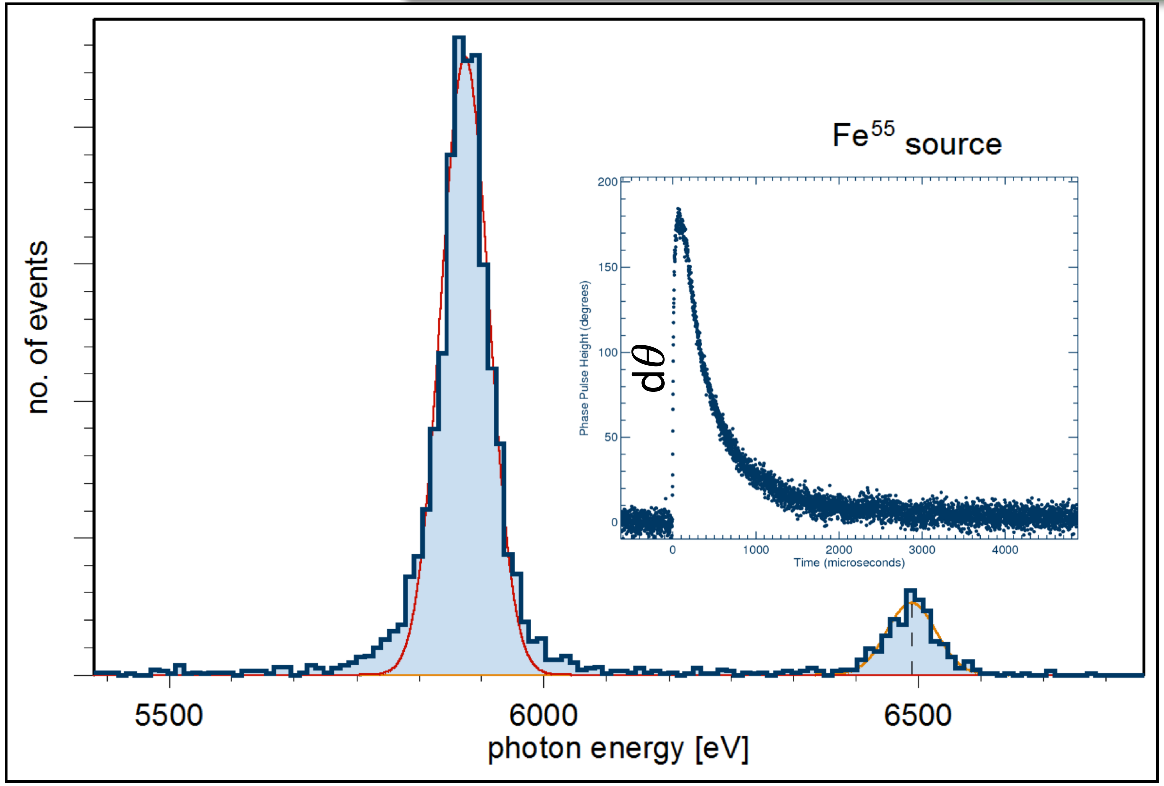
Progress so far…

- 75 eV at 5.9keV
  - Ulbricht *et al.*, APL, 106, 251103, 2015
- Long rise time, ≈45 μs, ⇒ degraded energy resolution
  - Probably due to perforated absorbers
  - Membrane conductance too low giving ≈500 μs fall times ⇒ low count rate
- Resonator phase sensitivity ($d\theta$ per dT) was too high resulting in easy saturation
- 2D format did not provide path for high fill factor and rapid absorber thermalization
- TiN_x or WSi_x sensor have large impact on total heat capacity



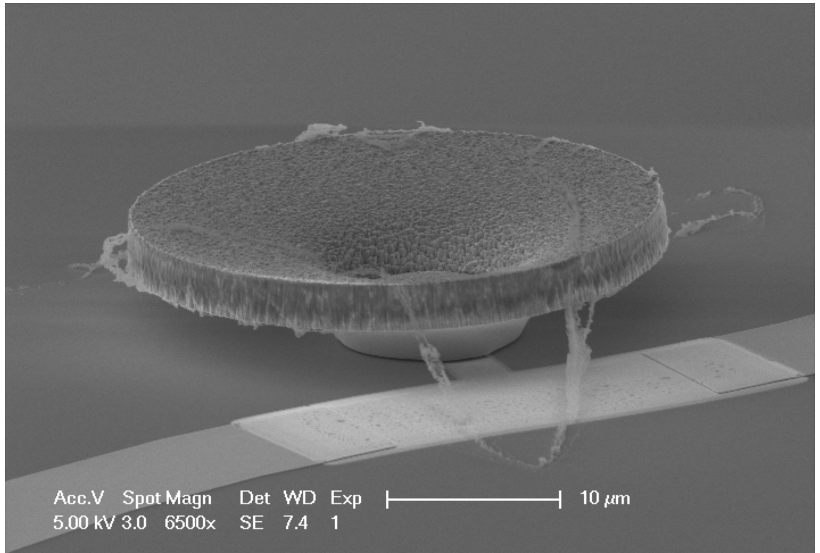


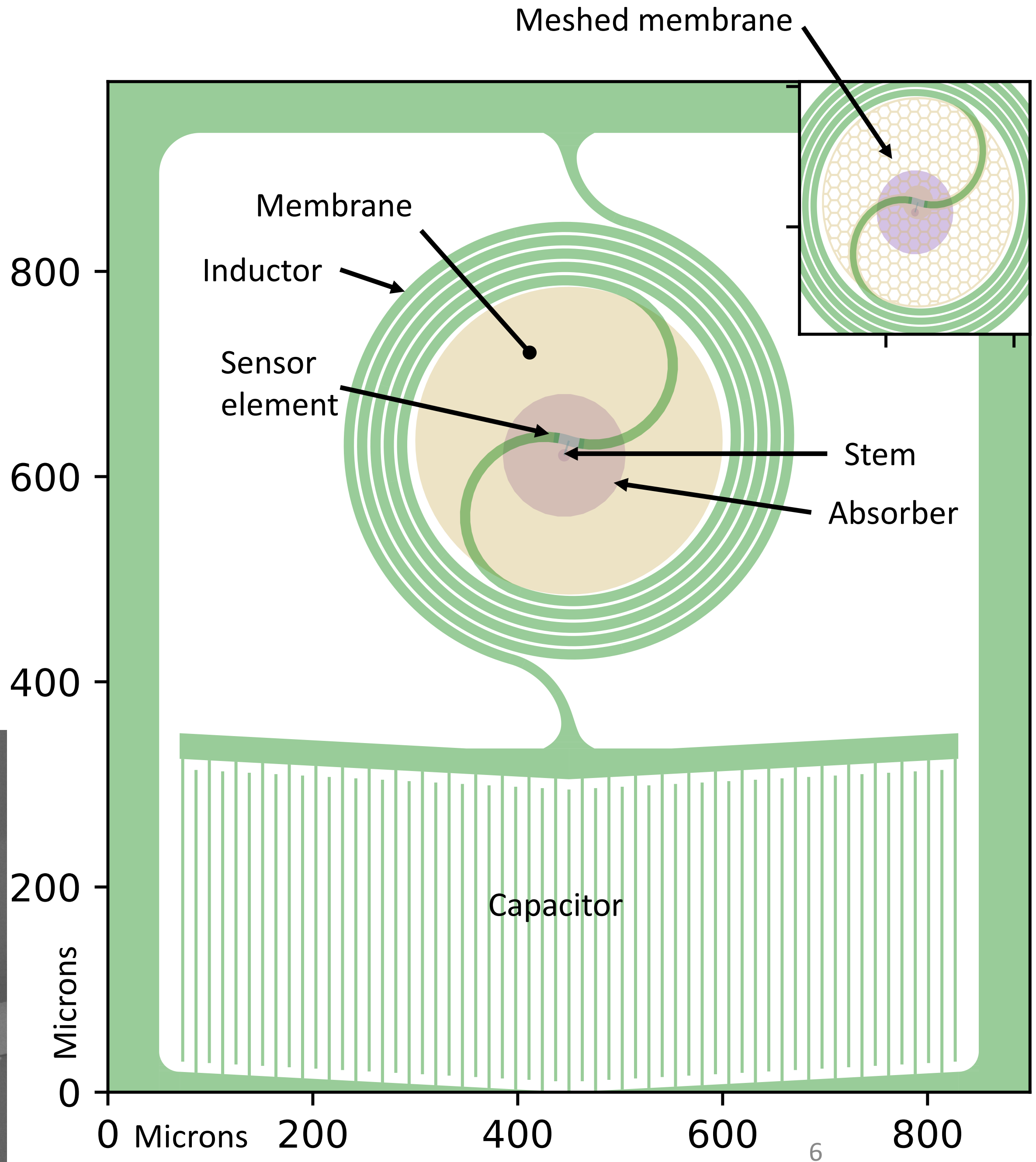
: TiN_x or WSi_x
: Si_3N_4 (etched with XeF_2)
: Ta absorber
: Nb feedline & GND plane



Next steps toward funded objectives

- Thick, cantilevered (3D) absorbers
  - Faster thermalization
  - X-ray stopping power
  - Admits high fill factor
- Hybrid resonators
  - Disentangle phase sensitivity, f_0 & Qc control, heat capacity, and readout power
- Suppress TLS noise using large capacitor and high readout power
  - Go to ~20x smaller pixels later

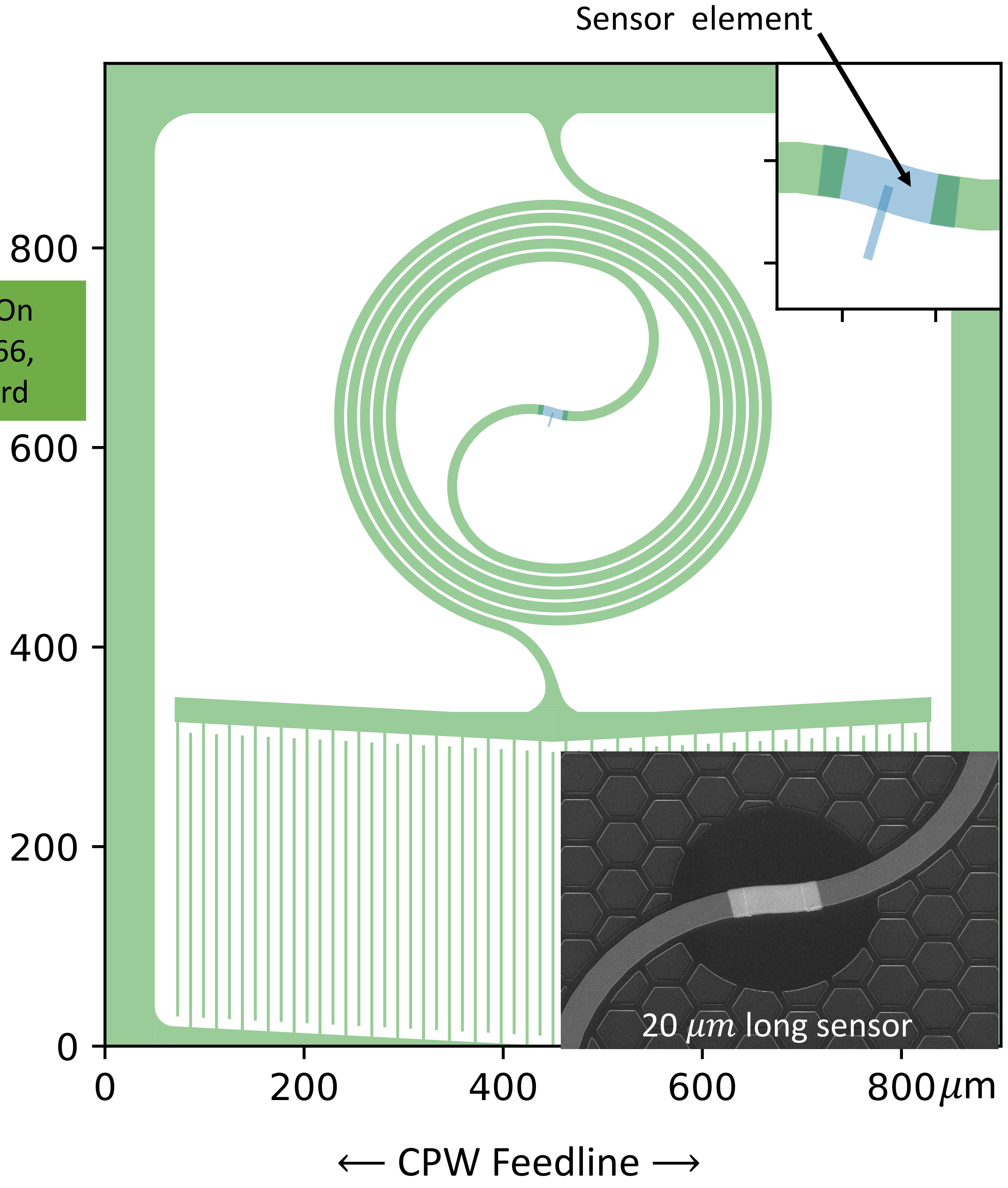




Resonator Design

- Wide inductor for high current operation
- Low T_c, High L_{Kin} 'Sensor element'
  - Hafnium
- High T_c, Low L_{Kin} ground, capacitor, inductor, feedline
  - Niobium
- Tapers and Fillets to control current density
- Q_c controlled by distance to feedline
- f_0 controlled by inductor length
  - Capacitor geometry/TLS-noise fixed across array
- Heat capacity of membrane + inductor fixed across array

See Poster On Hafnium #66, By G. Coiffard



MKIDs read out surface impedance changes

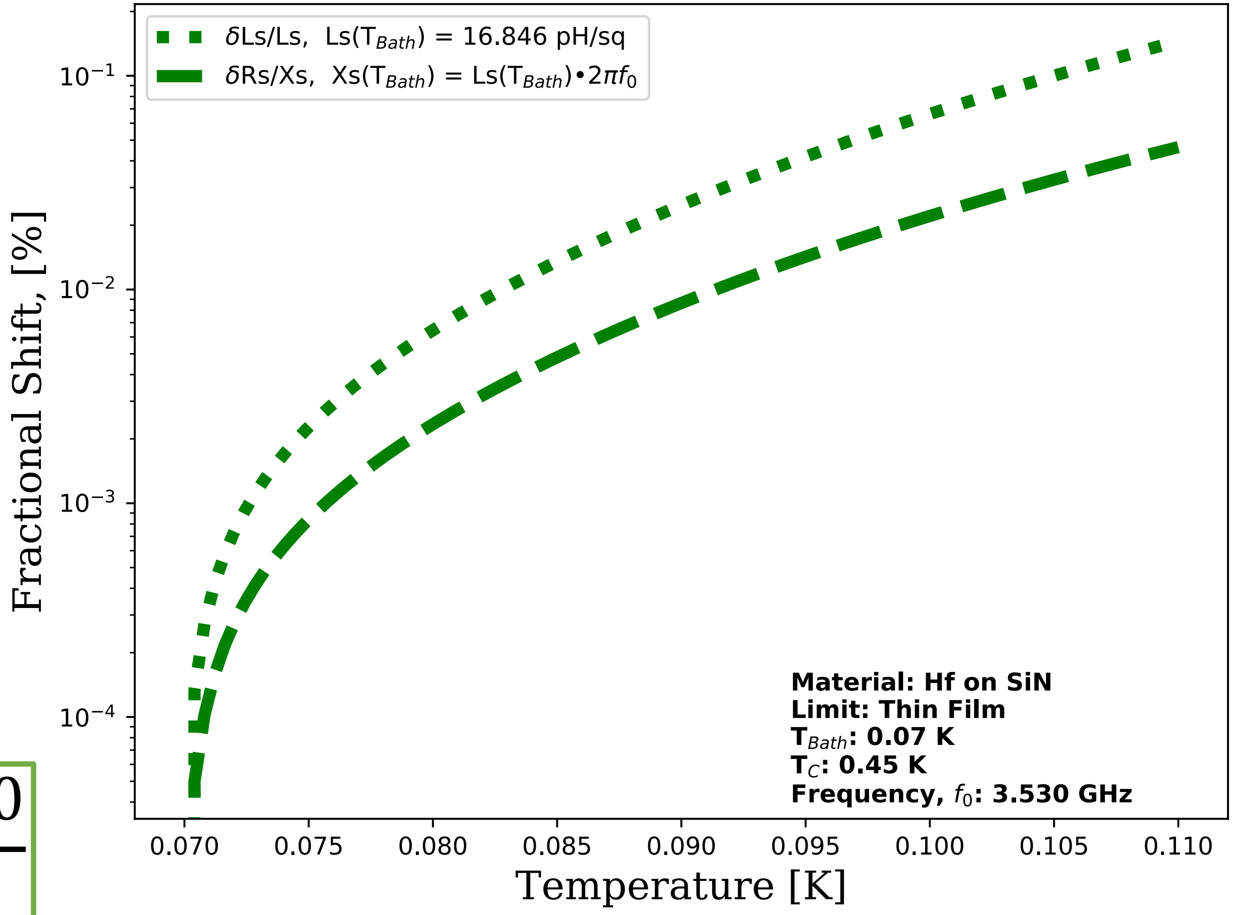
- Surface impedance:
  - $Z_S(T, \omega) = R_S + j\omega\, L_S$
  - R_S, L_S change with temperature
  - $L_{Kin} = g \bullet L_S$

- Resonant Frequency,

$$f_0 = \frac{1}{\sqrt{C\cdot(L_{\mathrm{Kin}}+L_{\mathrm{Mag}})}}$$

- Only $d\theta$ is measured

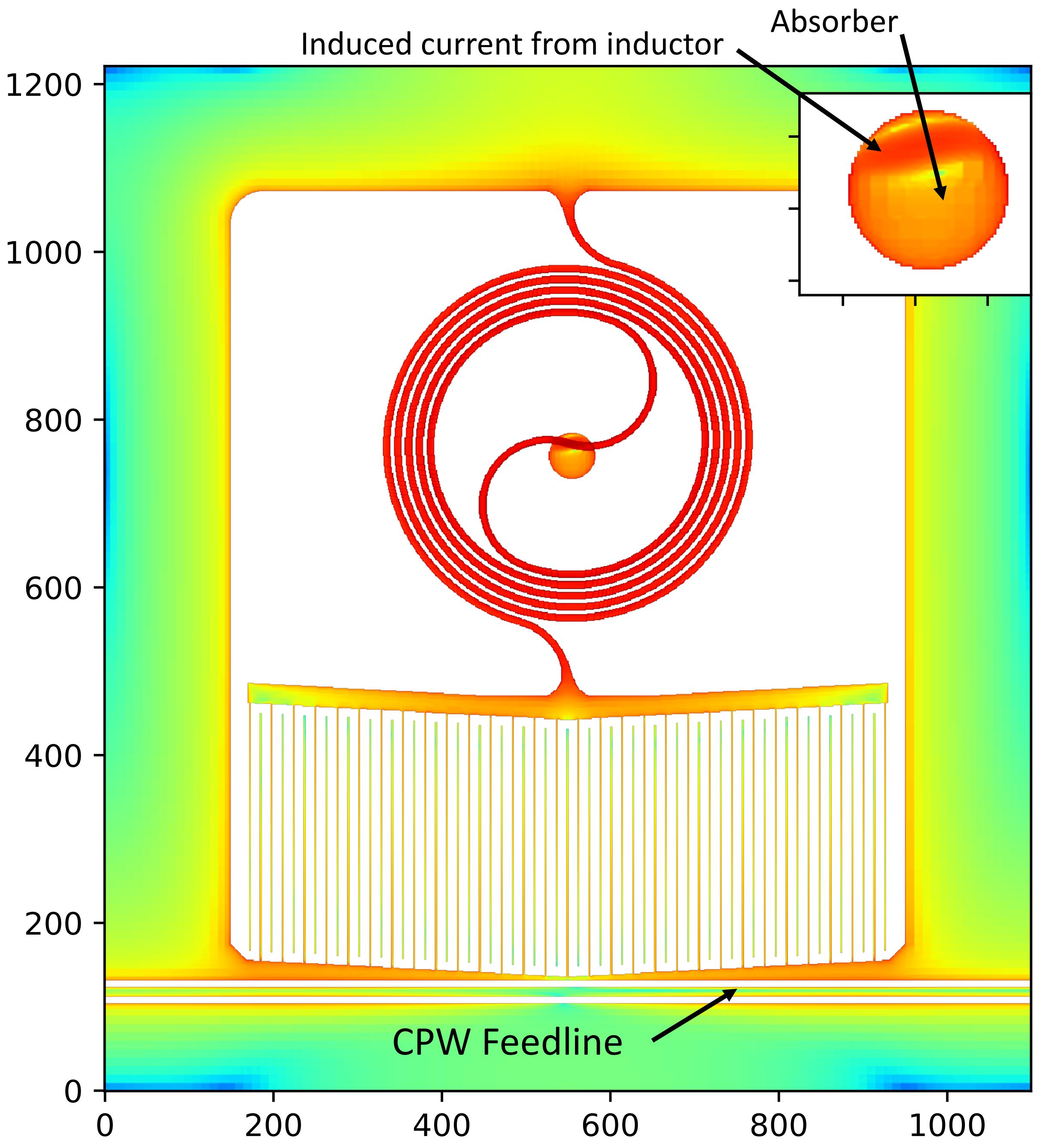
$$\boxed{d\theta^\circ = \frac{\delta f}{f_0}\frac{360}{\pi}}$$



Absorber Design 1

- Eddy currents must not diminish Q_i
  - Use superconductor
  - Possibly use normal metal top layer for better thermal conductivity

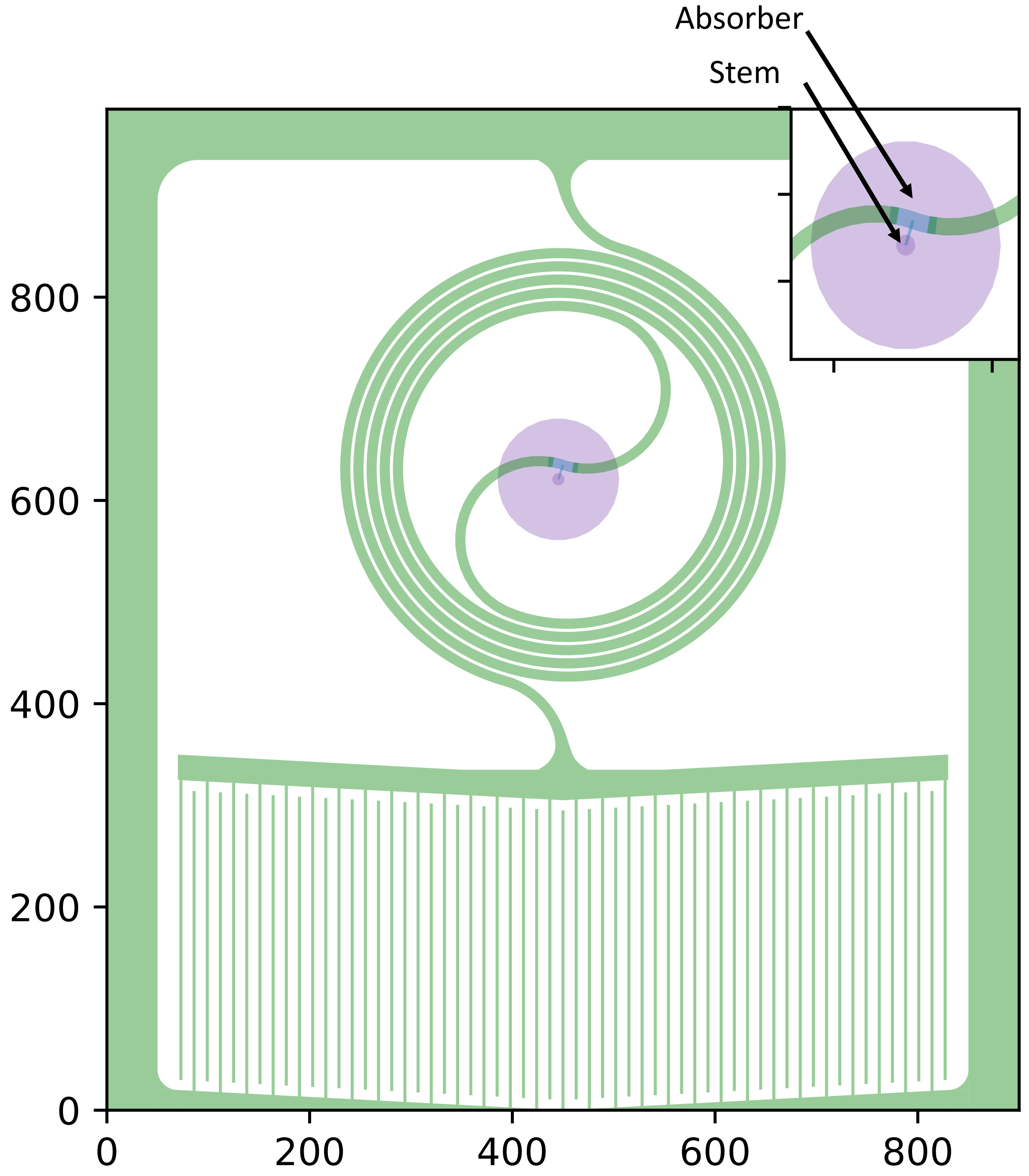
Q with 40 µm absorber, 4.2 µm above inductor, Qc ≈ 42000, $f_0 \approx 3.5$ GHz	
	Qi
Ta Absorber	$>10^6$
Au Absorber, (2e-9 Ω•cm)	50e3
Ta then Au (5 µm separation)	340e3



Absorber Design 2

- Need fast thermalization
  - Thermalization time << membrane cooling time, $\tau \approx C_{tot}/G$
  - How much does qp generation slows thermalization?
    - E.g. ~35 μs qp lifetime for Ta
- Use 'Stem' size to tune conductance to 'Sensor Element'
- Absorber thickness chosen to achieve QE objective

Minimum thickness, *t*, for 97% x-ray absorption at 6 keV	
Bi	7.41 µm
Ta	6.22 µm
Au	4.26 µm
Sn	9.06 µm



Sensor Element Design

- Estimate $d\theta$ response from absorber dT
  - dT is estimated from absorber heat capacity
- Tune sensor element geometry and thickness based on sensitivity/saturation goals

Assuming Ta absorber: Vol = $t \bullet \pi$ $(120/2)^2$ μm³; Hf Sensor: 120 nm thick; T_{bath} = 70 mK, Q ≈ 40,000

Sensor length	*@ 2 keV*		*@ 10 keV*	
	$\mathrm{d}f/f$	$\mathrm{d}\theta$	$\mathrm{d}f/f$	$\mathrm{d}\theta$
2 μm	2.1e-6	18˚	2.1e-5	190˚
6 μm	5.7e-6	52˚	5.9e-5	545˚
20 μm	1.8e-5	171˚	1.9e-4	1780˚

Sensor element and absorber geometry

Compute: f_0, Q @ T_{bath}
Using: Sonnet, $Z_s(T_{bath})$

↓

Compute: $\mathrm{d}f/f$ @ T_{bath} + dT
Using: Sonnet, $Z_s(T_{bath} + dT)$

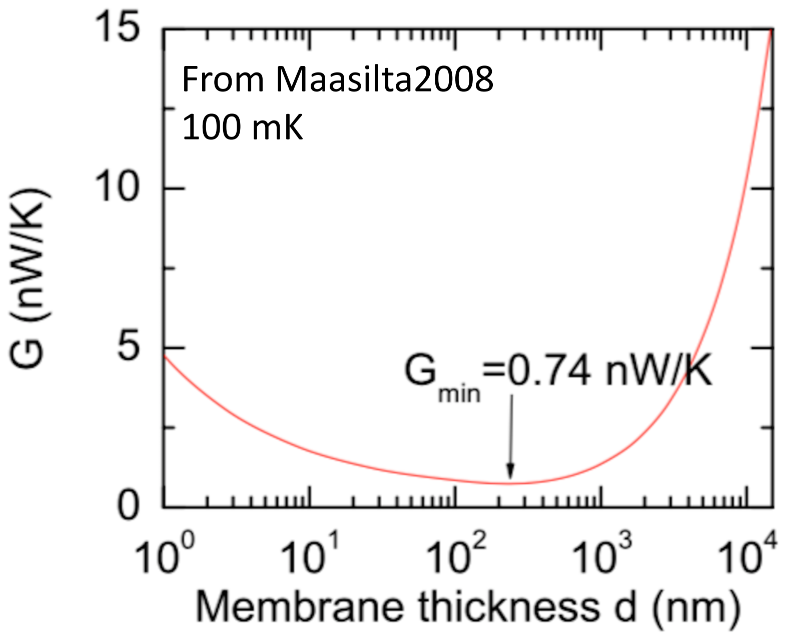
↓

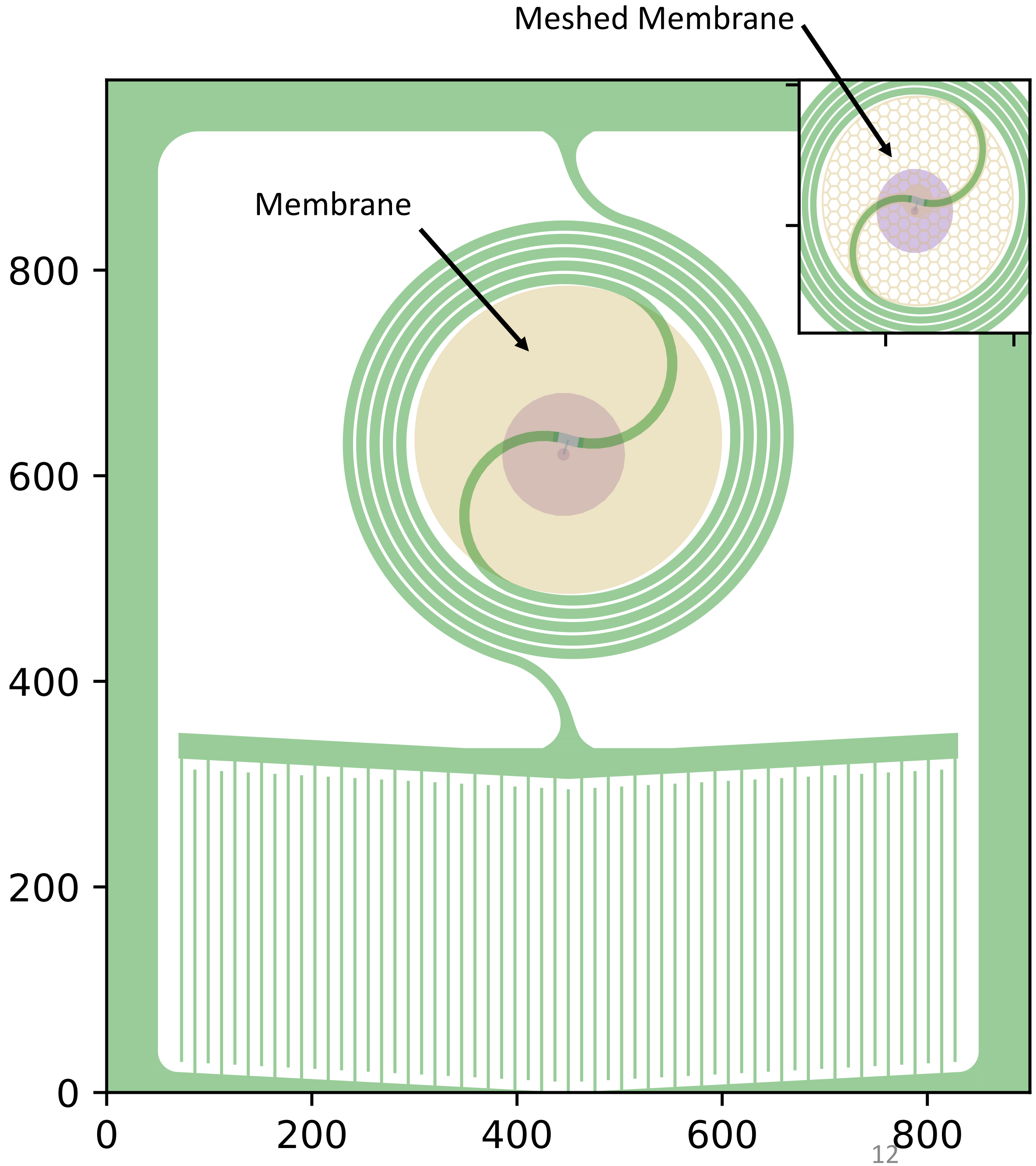
Compute: $\mathrm{d}\theta$
Using: $\mathrm{d}f/f$

Phase angle response, $\mathrm{d}\theta$

Membrane Design

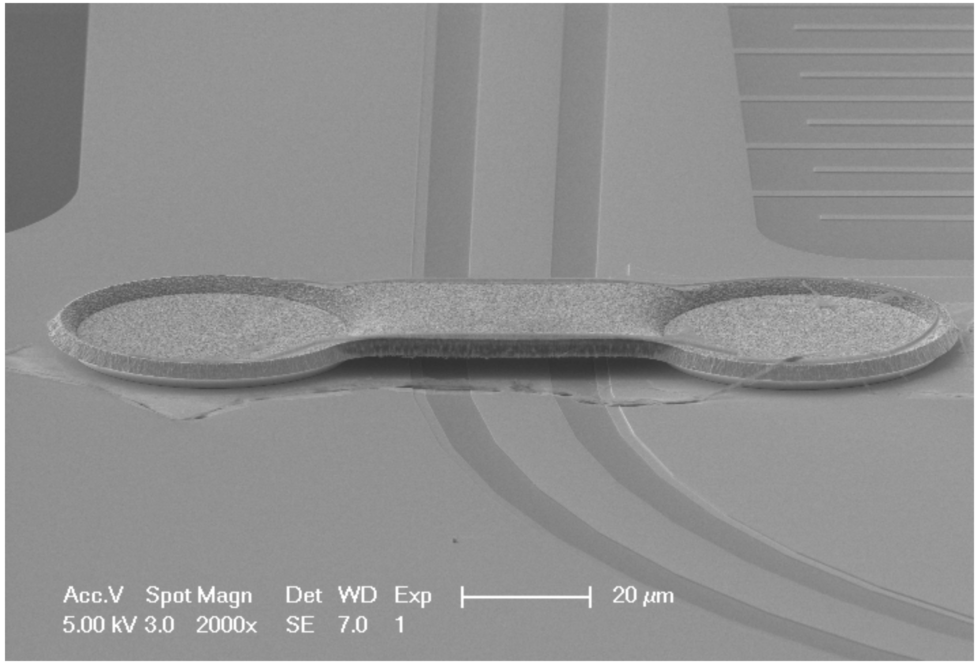
- Membrane thickness and patterning are used to control conductance
  - Using 250 nm thickness for low ballistic conductance limit

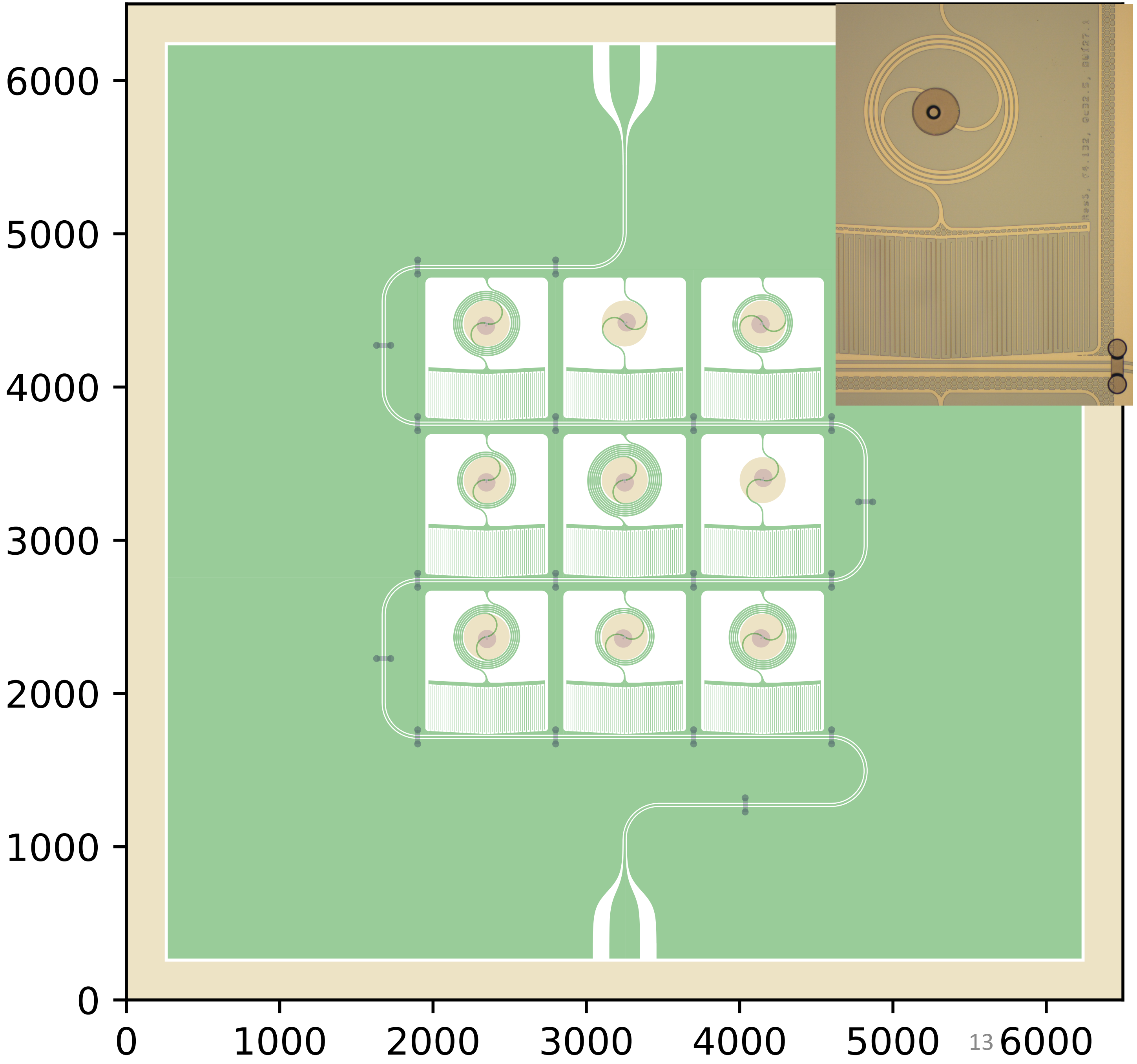




Test Die

- 9 Resonators
- Air bridges
- 3 – 6 GHz





Current Status:

- Process development and Fab
  - Membranes yield
  - Sensor to inductor contact
  - Absorber stress control
  - Absorber phase control
  - Cantilever cleaning
- Cooling down first devices!!
  - Seeing resonances need to improve Q_i

- END -

Readout of Surface Impedance

- Resonators shunt-coupled to feedline
- Surface impedances are proportional to the circuit impedances
  - R = g • R_S
  - L_{Kin}= g • L_S = α • L
  - L = L_{Kin} + L_{Mag}

$$\delta S_{21} = \frac{\delta V_{\text{out}}}{V_{\text{in}}} = \alpha \frac{Q^2}{Q_c}\left[\frac{\delta R_s}{X_s} + j\frac{\delta L_s}{L_s}\right]$$

- Only dθ is measured

$$\boxed{d\theta^\circ = \frac{\delta f}{f}\frac{360}{\pi}}$$

$$f_0 = \frac{1}{\sqrt{LC}}$$

$$\frac{1}{Q} = \frac{1}{Q_i} + \frac{1}{Q_c}$$