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Low-Loss, Low-Noise, Crystalline Silicon Dielectric for Superconducting Microstriplines & Kinetic Inductance Detector Capacitors

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Outline

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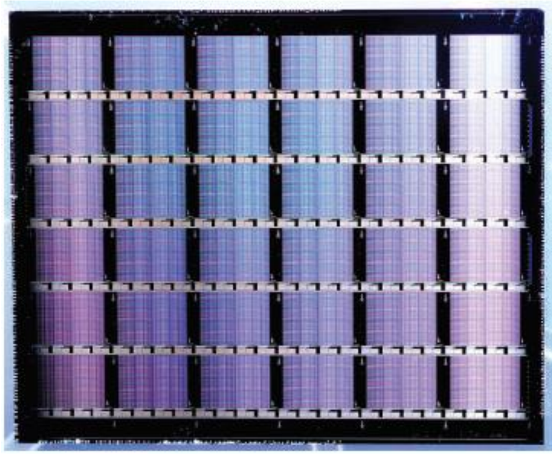
- Introduction
- Dielectric losses
- Crystalline Silicon wafers: Tests
- Conclusion and Perspectives

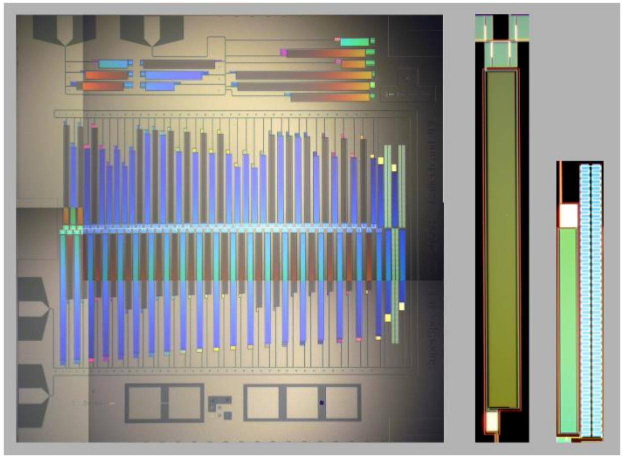
Introduction

- Technology developments in superconducting sensors for mm/submm astronomy require low-loss dielectric thin films:
  - Microstrip-coupled superconducting mm/submm detectors (e.g. Phased array antennas)
  - Superconducting spectrometers (e.g. SuperSpec)
  - Kinetic inductance detectors (KIDs) (e.g. MUSIC)

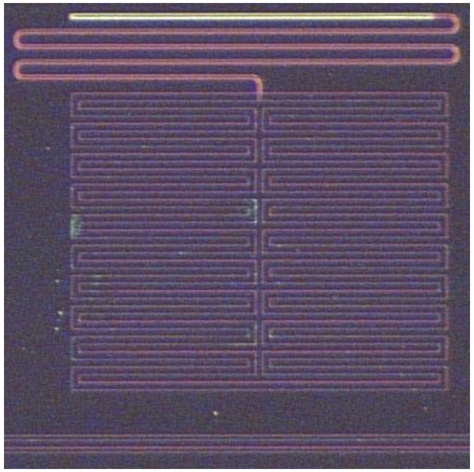
MUSIC phased array antenna



SuperSpec



KID interdigitated capacitor



Dielectric Loss (tan δ)

- Dielectric loss is critical and determines:
  - Optical loss in microstrip
  - Resolution of spectral channels
  - Two-level-system (TLS) dielectric fluctuation noise of KID capacitor

- Dielectric currently used: SiO_2 and SiN_x
  - Convenient for fabrication
  - Tan δ ~ 10^{-3}
  - Limits possible architectures & spectral resolving power
  - Requires the use of interdigitated capacitors (take a large area)

  → Need lower loss dielectrics

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Advantages of low loss dielectrics

- Phased-array antennas:
  - Move detectors away from antenna and shield from absorption of unfiltered (spatial or spectral) light.
  - Allows to simplify detector wiring, long wiring busses possible.
  - Multiscale antennas covering a decade of spectral bandwidth possible.

- Superconducting spectrometers:
  - Improve spectral resolution limit, ($R_{max} \sim 1/\tan\delta$), from 1e3 to 2e5

- KIDs:
  - Interdigitated capacitors (IDC) replaced by parallel-plate capacitors 40 times smaller in area. Currently, IDCs can be an appreciable fraction of focal plane area.

Low loss dielectrics candidates

- Crystalline silicon (cSi)
  - Tan δ $< 5e-6$
    → 200 times lower than SiO_2 and SiN_x

- Hydrogenated amorphous silicon (a-Si:H)
  - Tan δ $< 5e-5$
    → Not as good as cSi but still 20 times lower than SiO_2 and SiN_x

- **Goal**: Tan δ $< 1e-4$
  - Both materials would provide significant gains for KIDs noise
  - cSi has been developed and tested
  - a-Si:H studies exist in the literature

Conclusion

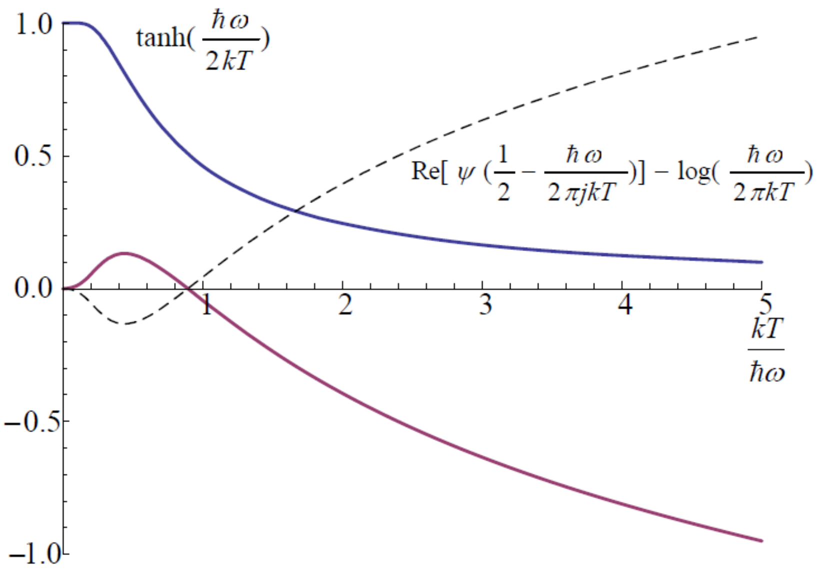
- Crystalline Silicon:
  - Very low loss dielectric
  - Important improvements possible for KIDs, superconducting spectrometers & phased array antennas
- Hydrogenated amorphous silicon:
  - Not as good as cSi but still 20 times better than SiO_2 and SiN_x
  - Not tested here but good low loss dielectric candidate
- Goal: Development of crystalline Silicon wafers
  - 2 and 5 μm thick
  - Develop control experiment to measure tan δ, Q factor, TLS noise
  - Test cSi with and without wafer bonding

cSi Wafers: Test

- Internal quality factor (Qi)
- Loss tangent ($F\delta_0$): from frequency shift measurement

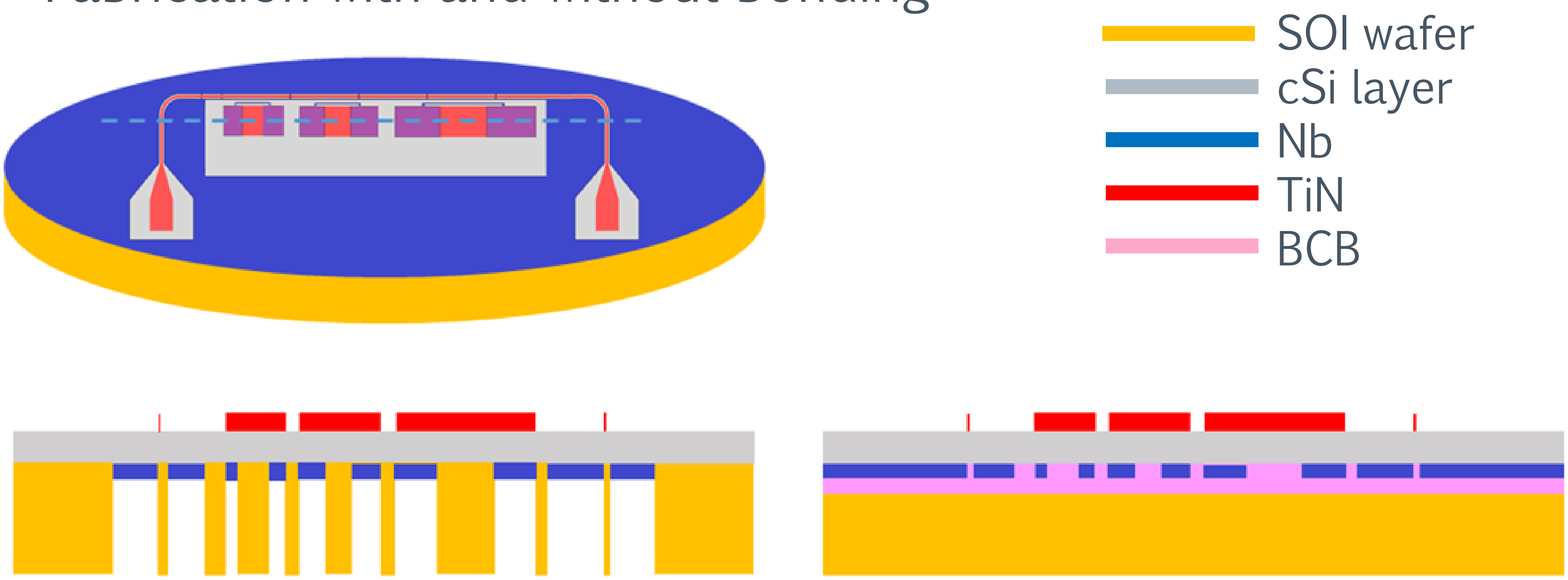
  Calculation of an approximate value of df/dT, deduction of the relation between df/f, f, and T using the formula from Jiansong Gao's thesis:

$$\frac{f_r(T) - f_r(0)}{f_r} = \frac{F\delta^0_{\mathrm{TLS}}}{\pi}\left[\mathrm{Re}\Psi\left(\frac{1}{2} - \frac{\hbar\omega}{2j\pi k_B T}\right) - \log\frac{\hbar\omega}{2\pi k_B T}\right]. \qquad (5.74)$$



cSi Wafers: Fabrication

- Goal: Evaluate wafer bonding effect on $F\delta_0$ and Qi
- LC resonators
- Fabrication with and without bonding

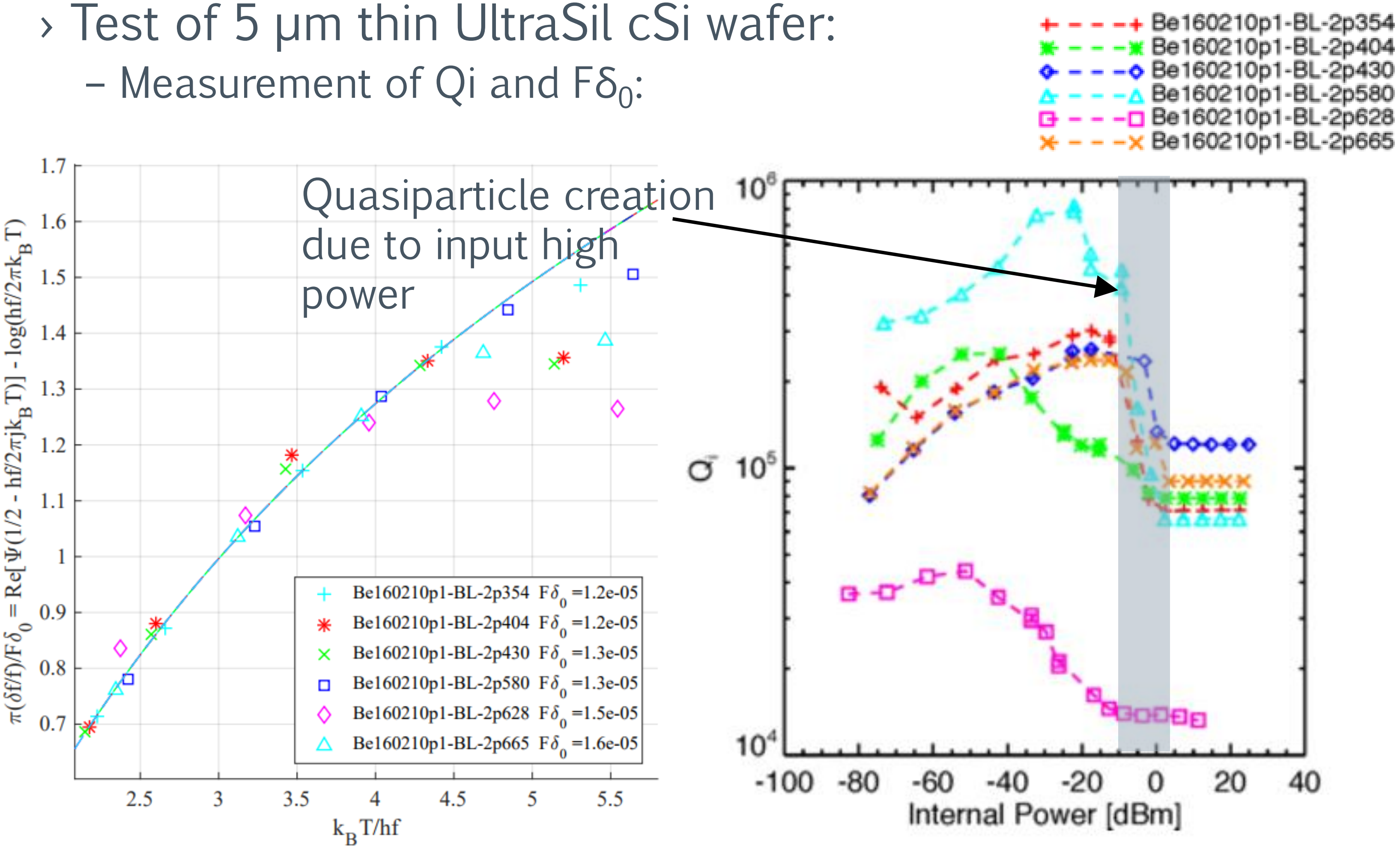


Without wafer bonding

With wafer bonding

5 µm cSi non-bonded wafer

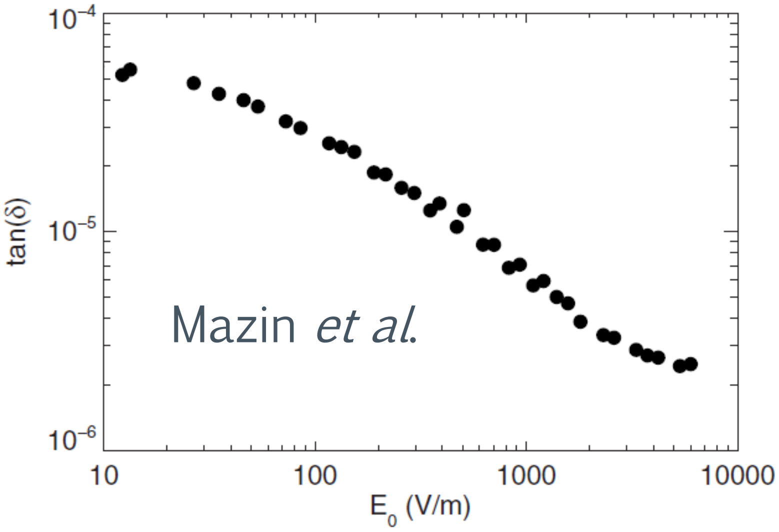
- Test of 5 µm thin UltraSil cSi wafer:
  - Measurement of Qi and Fδ_0:

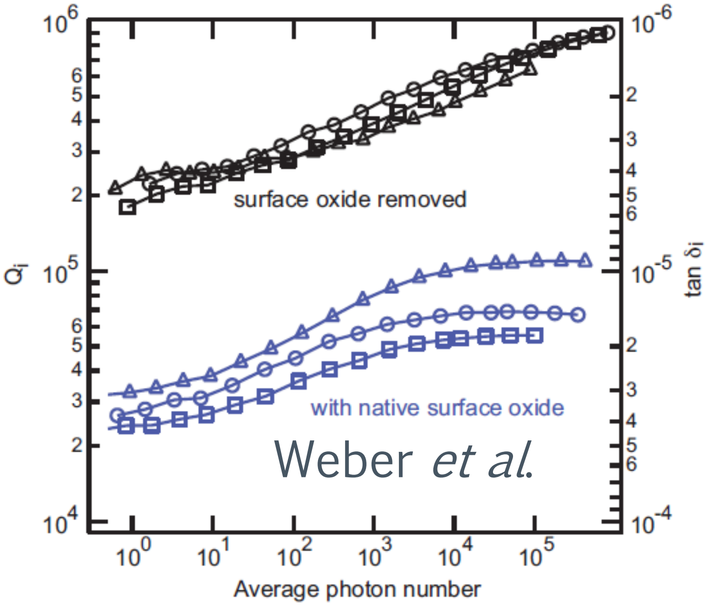


Quasiparticle creation due to input high power

cSi & a-Si:H: Other studies

- a-Si:H: Mazin *et al.* (2010)
  - tan δ ∈ [2 - 50]e-6
- cSi: Weber *et al.* (2011)
  - tan δ ∈ [1 - 6]e-6 (Surface oxide removed)
  - tan δ derived from Qi





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5 µm cSi non-bonded wafer: Comparison

- Test results:
  - Loss tangent: $F\delta_0 \in [1.2 - 1.6]$e-5
  - Internal quality factor: Qi $\in$ [1.0 - 8.0]e5 (except for 1 resonator)

- Comparison with other studies:
  - Loss tangent:

    3 – 10 times worse than Weber *et al.*

    Better than Mazin *et al.* (a-Si:H) at low powers, comparable at HP
  - Qi:

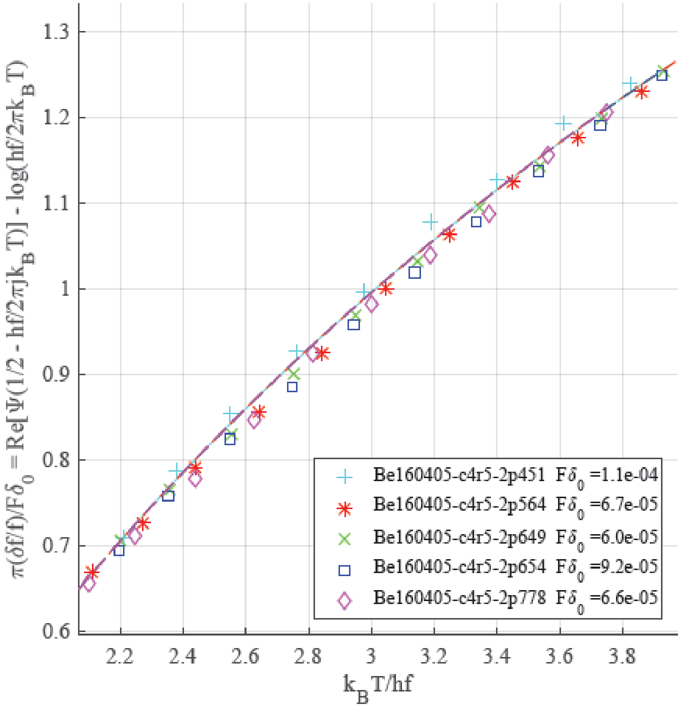
    3 times worse than Weber *et al.*

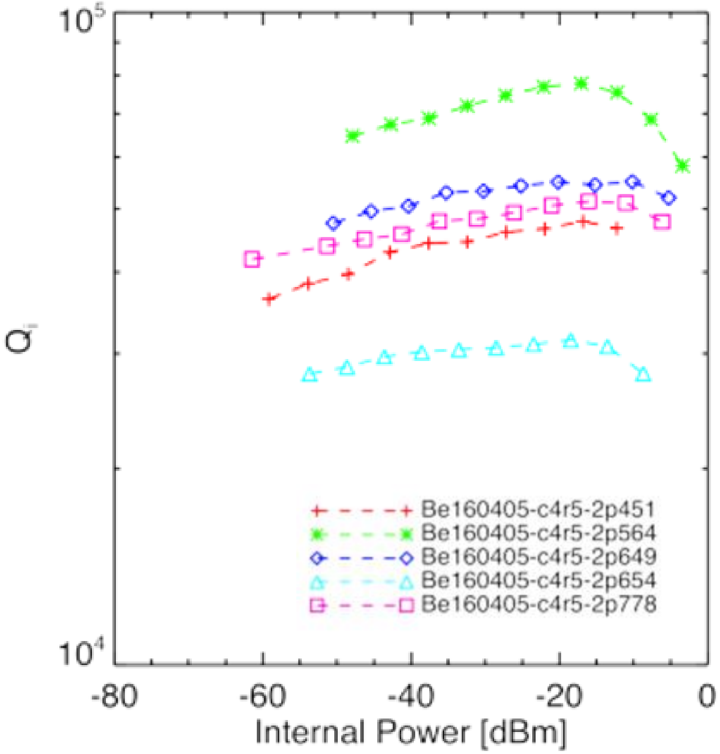
    Similar to Mazin *et al.* (a-Si:H)

- Conclusion:
  - Our results are comparable with the literature

5 µm cSi wafer bonded

- Goal: Evaluate influence of wafer bonding on Qi and $F\delta_0$





5 µm cSi wafer bonded

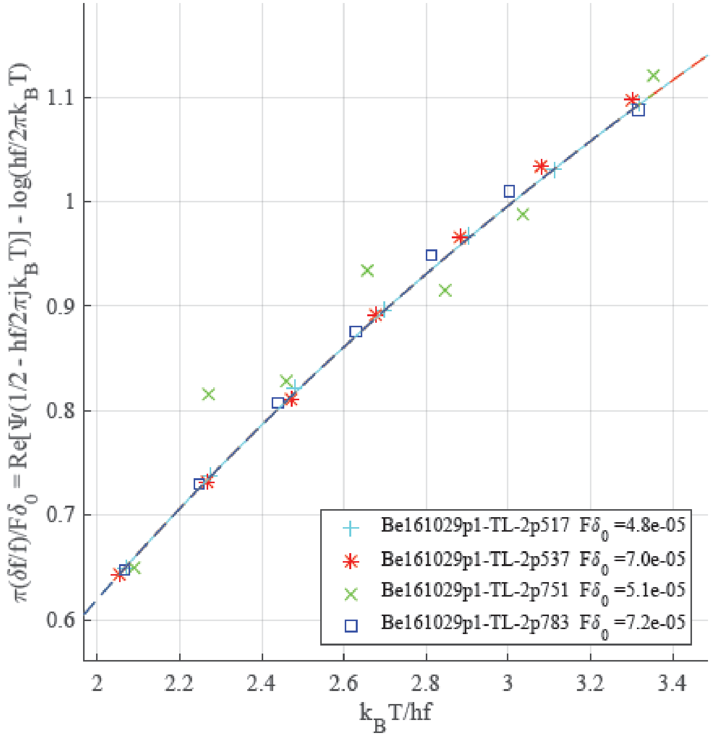
- 2 devices tested:
  - Loss tangent: $F\delta_0 \in [6.0 - 12]$e-5
  - Internal quality factor: Qi $\in [3.0 - 8.0]$e4

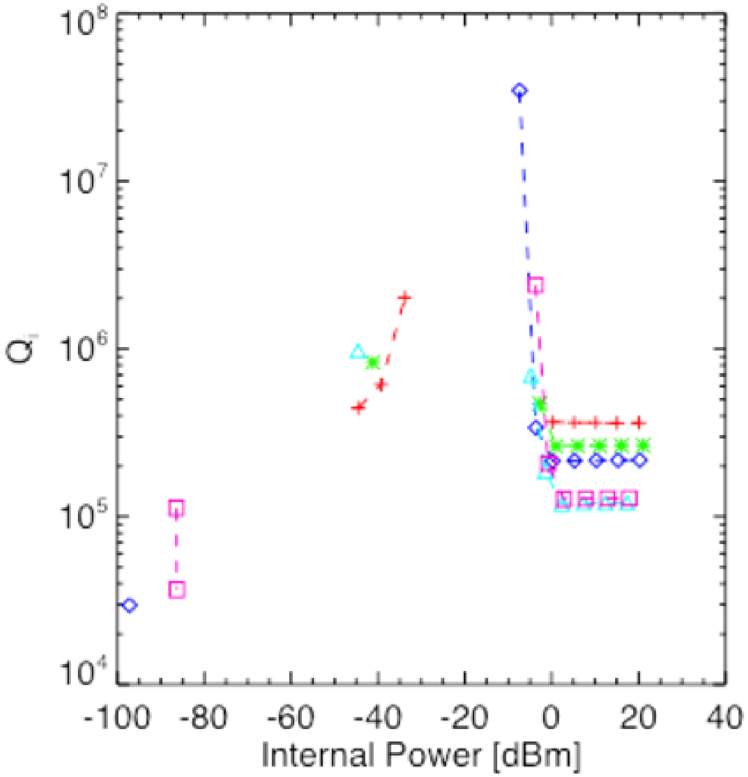
- Comparison with non-bonded 5um wafer:
  - Loss tangent: factor 4 worse than non-bonded
  - Qi: factor 10 worse than non-bonded

- Conclusion
  - The wafer bonding degrades the cSi characteristics
  - However, $F\delta_0$ is still about 10 times better than SiO_2 and SiN_x

2 µm cSi Wafer

- 2 µm thin UltraSil non-bonded cSi wafer.





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2 μm cSi Wafer

- 1 device tested:
  - Loss tangent: $F\delta_0 \in [5.0 - 7.0]\text{e-}5$
  - Internal quality factor: Qi $> 1\text{e}6$

- Comparison with non-bonded 5 μm wafer:
  - Loss tangent: factor 3 higher than 5 μm non-bonded
  - Qi: Better than 5 μm non-bonded

- Conclusion
  - Loss tangent a bit worse than with the 5 μm wafer
  - Very good Qi

Conclusion & Perspectives

- 2 & 5 µm cSi non-bonded:
  - Loss tangent always $< 8e\text{-}5$
  - Internal quality factor $> 1e5$
- 5 µm cSi bonded:
  - Loss tangent always $< 1.2e\text{-}4$
  - Internal quality factor $> 3e4$

- Results comparable to literature (cSi and a-Si:H).
- Better than currently used dielectrics (SiO_2 & SiN_x)
- TLS noise tests ongoing (planned for next week!)

- Very promising results. Test of thinner wafers planned