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

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Outline

› 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)
Dielectric Loss (tan $\delta$)

- 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: $\text{SiO}_2$ and $\text{SiN}_x$
  - Convenient for fabrication
  - $\tan \delta \sim 10^{-3}$
  - Limits possible architectures & spectral resolving power
  - Requires the use of interdigitated capacitors (take a large area)
    → Need lower loss dielectrics
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, \((R_{\text{max}} \sim \frac{1}{\tan \delta})\), 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)
  - \( \tan \delta < 5 \times 10^{-6} \)
  - 200 times lower than SiO\(_2\) and SiN\(_x\)

› Hydrogenated amorphous silicon (a-Si:H)
  - \( \tan \delta < 5 \times 10^{-5} \)
  - Not as good as cSi but still 20 times lower than SiO\(_2\) and SiN\(_x\)

**Goal:** \( \tan \delta < 1 \times 10^{-4} \)
- 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 $\mu$m thick
  - Develop control experiment to measure $\tan \delta$, 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:

$$\frac{f_r(T) - f_r(0)}{f_r} = \frac{F\delta_{0}^{\text{TLS}}}{\pi} \left[ \text{Re} \Psi \left( \frac{1}{2} - \frac{\hbar \omega}{2j\pi k_B T} \right) - \log \frac{\hbar \omega}{2\pi k_B T} \right].$$ (5.74)
Goal: Evaluate wafer bonding effect on $F_{\delta 0}$ and $Q_i$

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 Fδ₀:

Quasiparticle creation due to input high power
cSi & a-Si:H: Other studies

› a-Si:H: Mazin et al. (2010)
  - $\tan \delta \in [2 \text{ - } 50] \times 10^{-6}$

› cSi: Weber et al. (2011)
  - $\tan \delta \in [1 \text{ - } 6] \times 10^{-6}$ (Surface oxide removed)
  - $\tan \delta$ derived from Qi

Mazin et al.

Weber et al.
5 μm cSi non-bonded wafer: Comparison

› Test results:
  – Loss tangent: $\delta_0 \in [1.2 - 1.6] \times 10^{-5}$
  – Internal quality factor: $Q_i \in [1.0 - 8.0] \times 10^5$ (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
  – $Q_i$:
    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 Fδ₀
5 μm cSi wafer bonded

› 2 devices tested:
  - Loss tangent: $F_{\delta_0} \in [6.0 - 12]e^{-5}$
  - Internal quality factor: $Q_i \in [3.0 - 8.0]e^4$

› Comparison with non-bonded 5um wafer:
  - Loss tangent: factor 4 worse than non-bonded
  - $Q_i$: 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.
2 μm cSi Wafer

› 1 device tested:
  - Loss tangent: $F\delta_0 \in [5.0 - 7.0]e^{-5}$
  - Internal quality factor: $Q_i > 1e6$

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

› Conclusion
  - Loss tangent a bit worse than with the 5 μm wafer
  - Very good $Q_i$
Conclusion & Perspectives

› 2 & 5 μm cSi non-bonded:
  – Loss tangent always < 8e-5
  – Internal quality factor > 1e5

› 5 μm cSi bonded:
  – Loss tangent always < 1.2e-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