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RF Loss Tangent and Two-Level-System Noise of Amorphous Silicon Dielectrics for Mm/Submm/FIR Astronomy Applications

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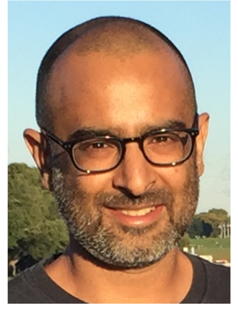


Goal: To develop reliable fabrication techniques for low-loss hydrogenated amorphous silicon (a-Si:H) dielectric films for

- low-noise, high-quality-factor superconducting resonators w/parallel-plate capacitors (PPCs)
- very low loss superconducting mm-wave microstripline

Results to date:

- RF loss tangent ~10^{-5}, dominated by residual two-level systems (TLS)
- TLS noise of PPC comparable to coplanar waveguide (CPW), interdigitated capacitor (IDC)
- Exploration of dependence on fab parameters, correlation with 300K diagnostics ongoing

Motivation

Superconducting technologies used in mm/submm/FIR photon detection and quantum computing would benefit from reliable fabrication techniques for low-loss/low-noise dielectrics:

RF (10s to 1000s of MHz):
superconducting resonators including KIDs

- usually use interdigitated capacitors (IDC) to minimize two-level-system (TLS) noise from nearby dielectric
- could benefit from parallel-plate capacitors (PPC):
  - prevent direct pickup of light in IDC
  - more compact capacitors (x10 to x100 C/area)
  - but need to demonstrate low δ_{TLS}

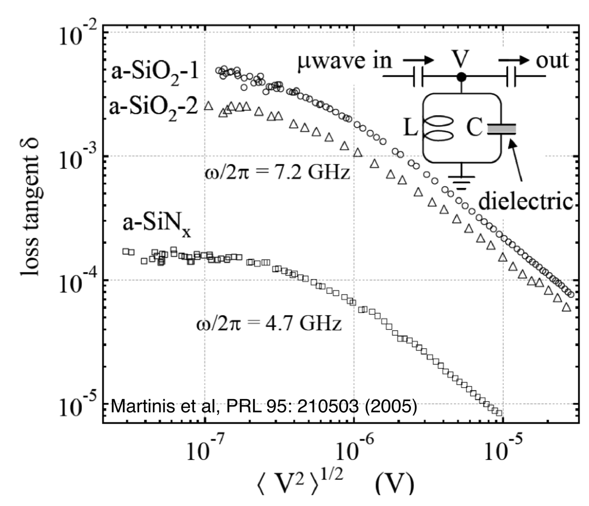
Mm/Submm/FIR (10s to 1000s of GHz):
Superconducting microstripline and filterbanks

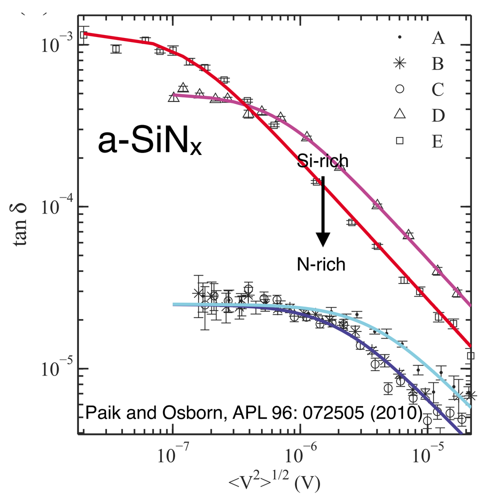
- state of the art is $\delta_{TLS} \approx 10^{-3}$:
  - limits length of microstripline used in superconducting phased-array antennas, lens-coupled antennas, and some feedhorn-coupled architectures
  - limits resolving power of spectrometer-on-a-chip architectures (SuperSpec, TIME, μ-Spec) to $R \approx 100$-1000
- $\delta_{TLS} \approx 10^{-4}$ to 10^{-5} could enable
  - shift of detectors to edge of focal plane to provide shielding and simplify readout wiring
  - sophisticated architectures, esp. multi-scale antennas with decade bandwidth
  - spectrometers that can resolve lines in Milky Way ($\Delta v/v \approx 10^{-3}$) and dwarf galaxies ($\Delta v/v \approx 10^{-4}$)

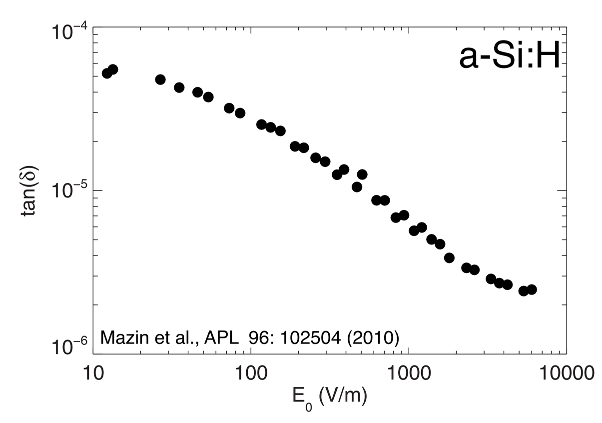
Prior Information on Silicon Dielectrics

The desired RF δ_{TLS} has been achieved in the literature:

- High coordination number (bonds per site) amorphous dielectrics show low loss, suggesting dangling bonds are the problem: Si-rich a-SiN_x, a-Si:H.
- Obtaining this performance nontrivial:
  - Large range in literature δ_{TLS} values
  - JPL a-SiN_x, a-Si:H historically have $\delta_{TLS} \approx 10^{-3}$

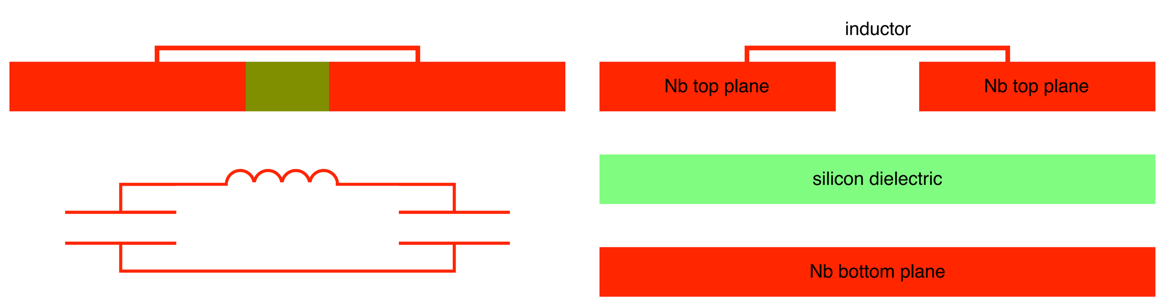






Test Device Design

Simple Nb LC PPC resonators at ~1 GHz to test range of a-Si:H fabrication recipes.



a-Si:H Deposition Recipes

Because historical JPL a-Si:H recipe showed relatively high loss, we tried substantially differing recipes, guided by desire to increase coordination number and/or reduce dangling bond density:

- High Ar content in deposition atmosphere: Ar mechanical impact to compress film, increasing coordination number (ref. Cunnane)
- Varying substrate temperature
- Using different machine at Caltech KNI (PECVD vs, ICP PECVD, both Oxford Plasmalab System 100)
- Using SiH_4 only (no H_2, no Ar)

Future Work

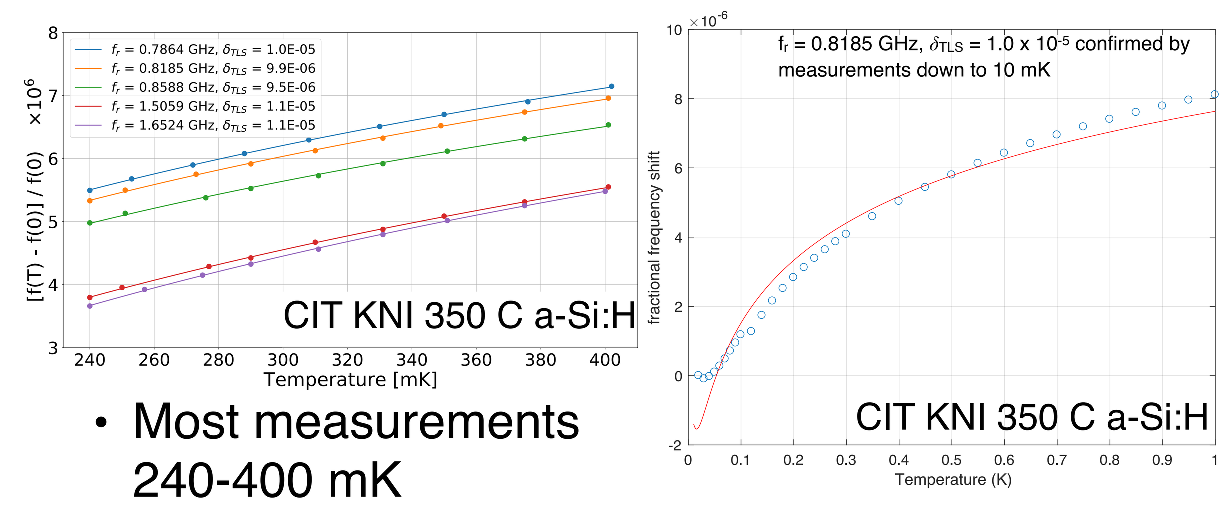
- Extensive survey of correlation of noise w/δ_{TLS}
- Investigate other recipes
- Other 300K diagnostics incl. Raman scattering
- mm-wave loss of select recipes

Low-Power Loss Tangent

Use TLS frequency shift vs. T to measure δ_{TLS}:

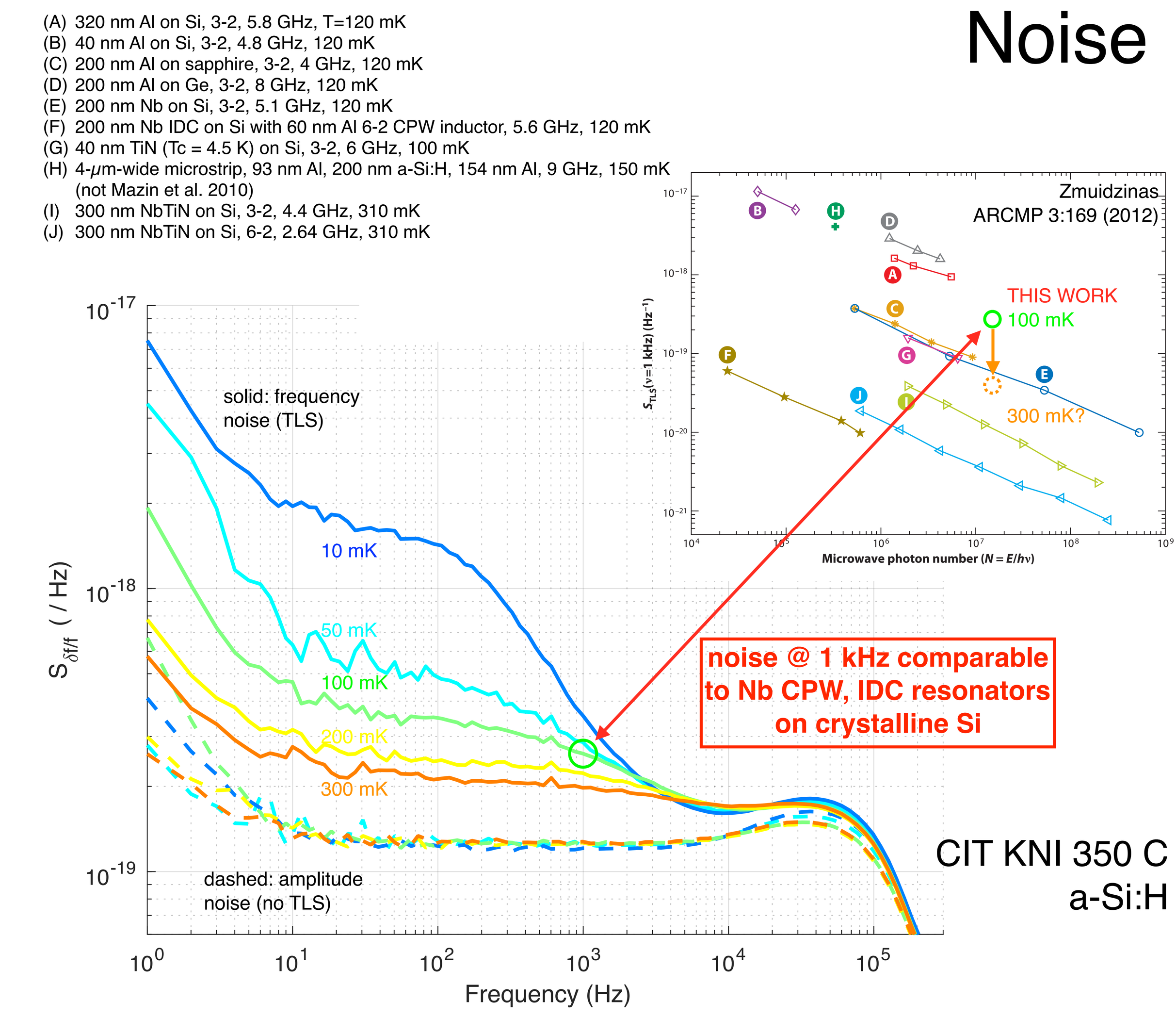
- No saturation of TLS: low-power limit
- $1/Q_{TLS} < \delta_{TLS}$ due to saturation
- Valid for predicting mm-wave loss (low power)

$$\frac{f_r(T) - f_r(T=0)}{f_r(T=0)} = \frac{F\delta_{TLS}}{\pi}\left[\mathrm{Re}\,\Psi\left(\frac{1}{2} - \frac{\hbar\omega}{2\,i\,\pi\,k_b\,T}\right) - \ln\frac{\hbar\omega}{2\,\pi\,k_b T}\right]$$



- Most measurements 240-400 mK
- $1/Q_i < \delta_{TLS}$ observed (high power meas.)
- **$\delta_{TLS} \approx 10^{-5}$ obtained reliably for multiple recipes**
  - Other recipes: lower T, SiH_4 only, JPL machine
  - One recipe: 0.5-1 x 10^{-4}
  - Historical JPL recipe still shows ~10^{-3}
- Confirmation to 10 mK for one a-Si:H device

Noise



Room Temperature Diagnostics

- Literature suggests high relative SiH peak from 300 K FTIR spectroscopy may imply low dangling bond fraction:
  - Initial good results did not hold up: "bad" spectra show low loss, "good" spectra show high loss
- Also investigated H concentration inferred from 640 cm^{-1} (wagging mode) and 663 cm^{-1} (stretching mode) peak integral: no correlation
- Next: Raman scattering to measure crystallinity