Titanium nitride lumped element kinetic inductance detector with parallel plate capacitors

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Introduction

Goal:
Develop a lumped element titanium nitride (TiNx) KID with low loss dielectrics (crystalline silicon: c-Si, and amorphous hydrogenated silicon: a-Si:H), for Cosmic Microwave Background (CMB) B-mode polarization and Sunyaev Zeldovich (SZ) effect observations, between 40 and 420 GHz

Motivation:
- Minimize direct absorption of optical power by KID capacitors: parallel plate capacitors (PPC)
- Operate down to 40 GHz for CMB observations: superconductor with Tc < Tc(Al) ➡ TiNx (0.6K < Tc < 4.2K)
- Minimize losses inside dielectric (for PPC and microstrip lines): Low loss dielectrics (tanδ < 1e-4): c-Si, a-Si:H
- Coherent reception elements (phased-array antennas, lens-coupled antennas, and feedhorns):
  ➡ Microstrip coupling of mm-wave optical power to detectors with a novel mm-wave coupler [1]

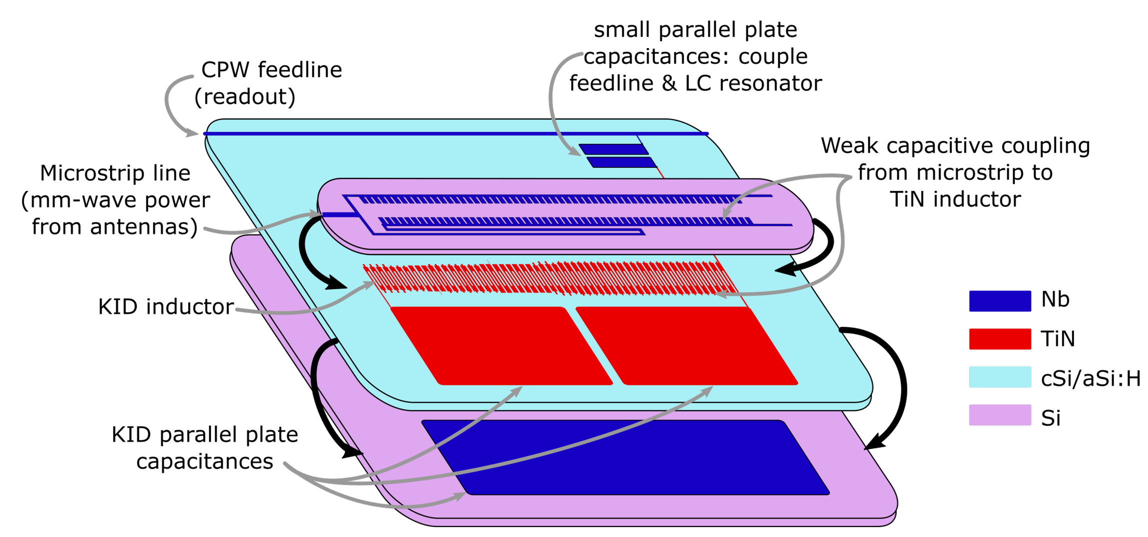
Our devices:
- TiNx resonances (between 50-100 MHz) and Nb LC resonances (between 1-3 GHz) with PPCs to characterize dielectric losses and TLS noise.
- Layer of 1 μm c-Si or 0.8 μm a-Si:H in between KID PPC's plates
- SOI wafer with c-Si layer bought from SEH (Shin-Etsu Handotai) using Soitec SmartCut process

Design

Main elements:
- KID PPC composed of Nb and TiNx plates separated by c-Si or a-Si:H

- Small Nb PPC couple CPW feedline & detector: another Nb plate on bottom layer, not visible on schematic

- mm-wave coupler:
Couple low impedance microstrip line to high-resistivity TiNx
Each Nb microstrip branch forms a PPC with the TiNx pattern below
Size of patterns designed to minimize current density variations over coupler length (approx. same amount of energy transmitted by each PPC)

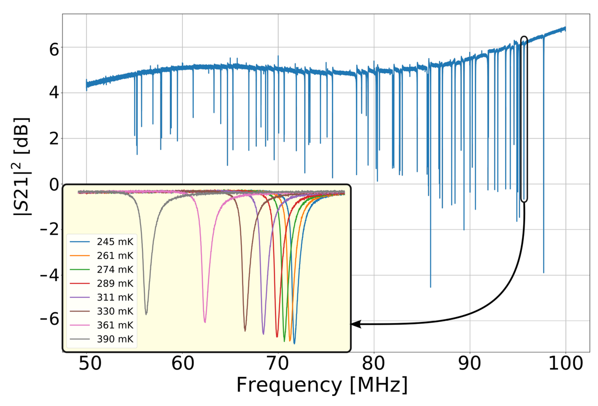


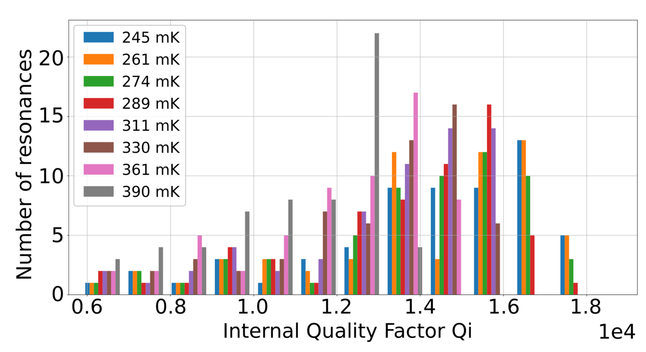
Dark measurements

c-Si

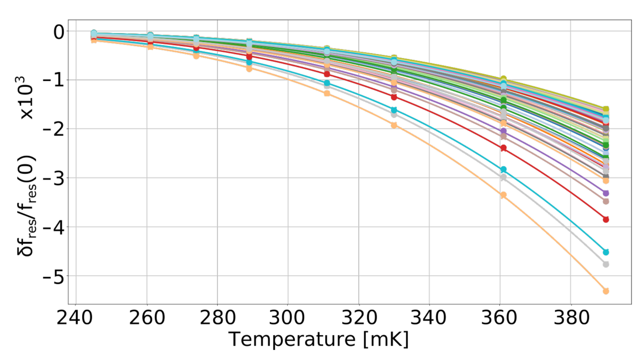
c-Si device:
- Resonances between 50 and 100 MHz
- 80 resonances designed, 76 observed

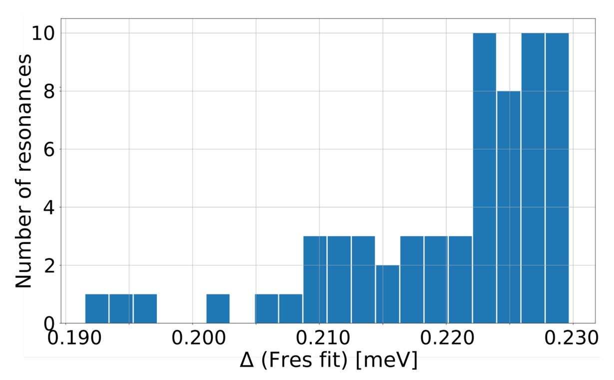
Internal quality factor: [1 - 2]e4
- Low Qi, but comparable to similar studies [2]





Mattis-Bardeen fit:
- Using δf_{res} vs. T for fit, as described in [3]
- No need for gap smearing
- α = 0.99 (set a priori), α and Δ are degenerate
- f_{res} measured ≈ f_{res} designed: α ≈ 0.99
- Assuming $\Delta_0 \approx 1.76\ k_B T_c$: Tc ≈ [1.4 - 1.5] K

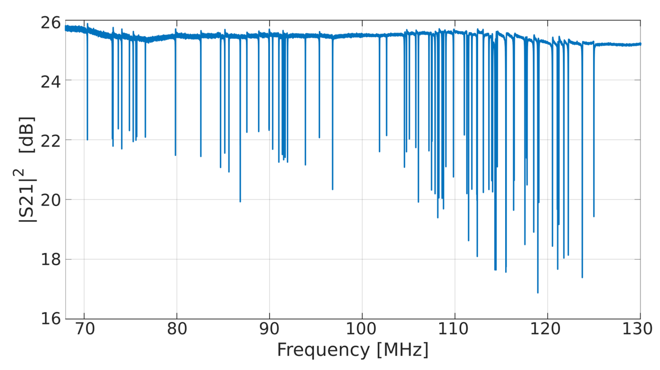


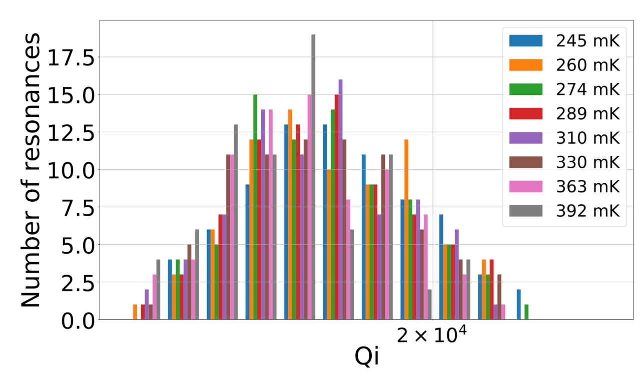


a-Si:H

a-Si:H device:
- Resonances between 70 and 125 MHz
- 80 resonances were designed, 80 observed!

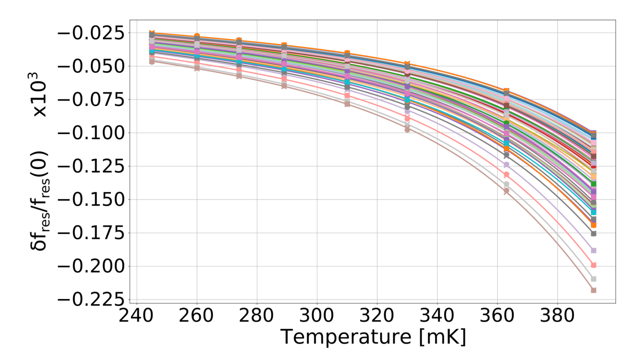
Internal quality factor: 2e4
- Low Qi, but comparable to similar studies [2]

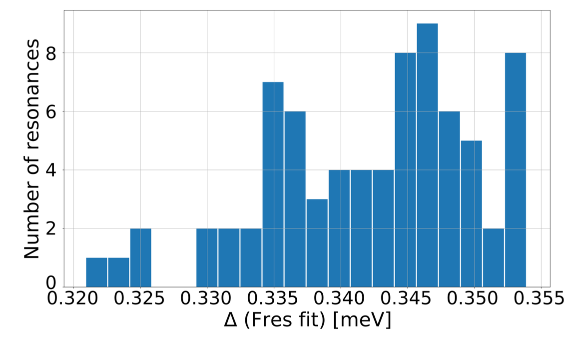




Mattis-Bardeen fit:
- Using δf_{res} vs. T for fit, as described in [3]
- Need for gap smearing
- α = 0.99 (set a priori), α and Δ are degenerate
- f_{res} measured ≈ f_{res} designed: α ≈ 0.99
- Assuming $\Delta_0 \approx 1.76\ k_B T_c$: Tc ≈ [2.2, 2.4] K

(High Tc accidental, due to retuning TiNx deposition)

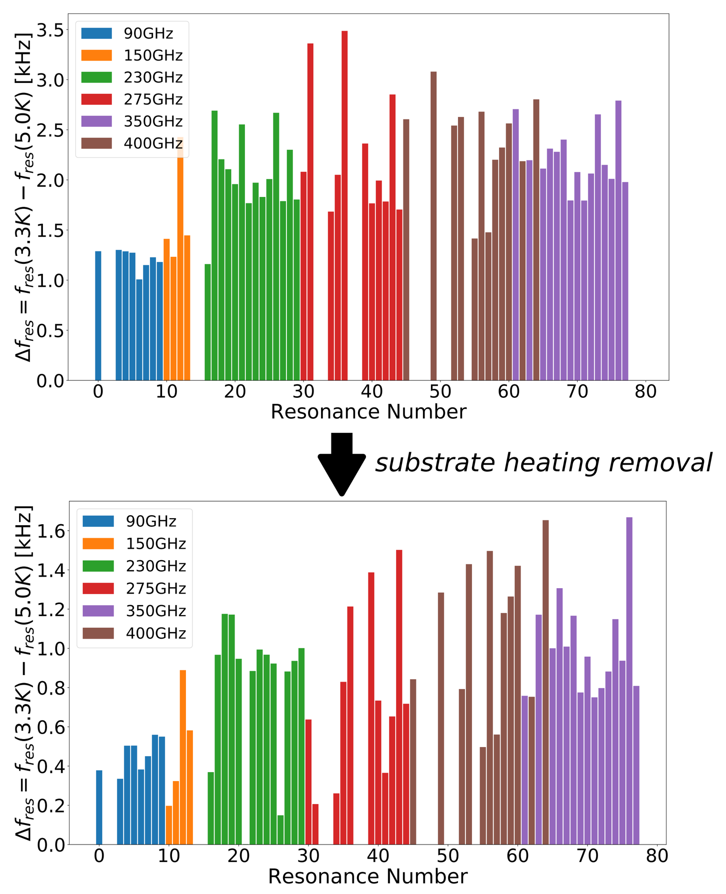




Cryogenic Black Body measurements

c-Si

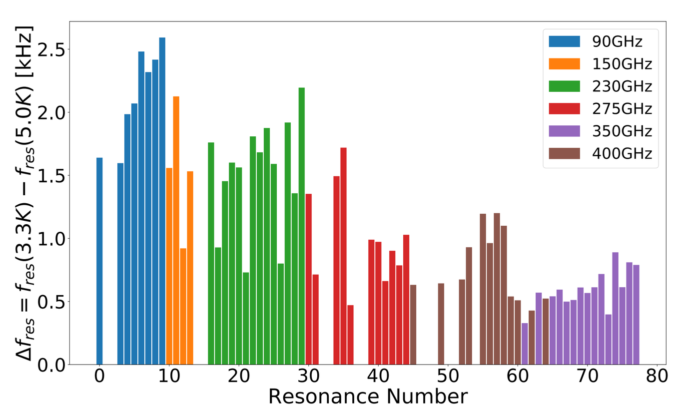
c-Si device:
- Slot antennas for [70 - 415] GHz (divided in 6 bands)
- Black body (BB) temperature from 3.3K to 5K
- 12 dark resonators: Not connected to antennas



Thermal frequency shift:
- All resonances shift (even dark ones)
- Nb LC resonances also shift

➡ Indicates small substrate heating: estimated to ≈ 3mK (in spite of good heat sinking with gold pads and wire bonds)
- Use dark TiNx resonances to remove substrate heating effect on frequency shift for all TiNx resonances

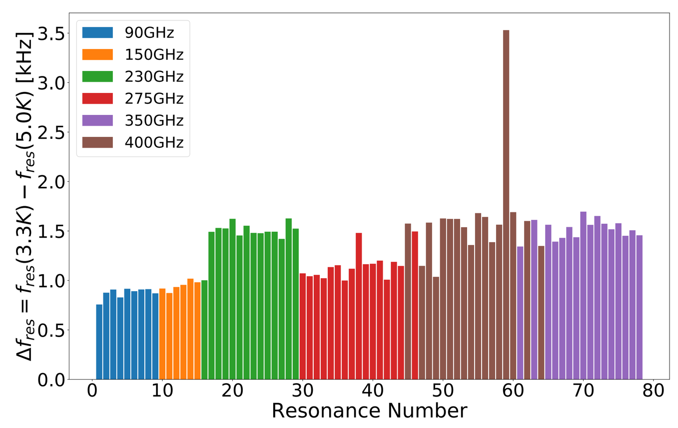
Expected frequency shift:
- With BB emission spectrum + resonators geometry/ materials + MB fits: possible to predict δf_{res}
- Predicted δf_{res} has similar level as observed δf_{res}, but the trend is very different.
- Due to high Tc, band 1 (70 - 110GHz) probably blind (photons not energetic enough to create quasi-particles)

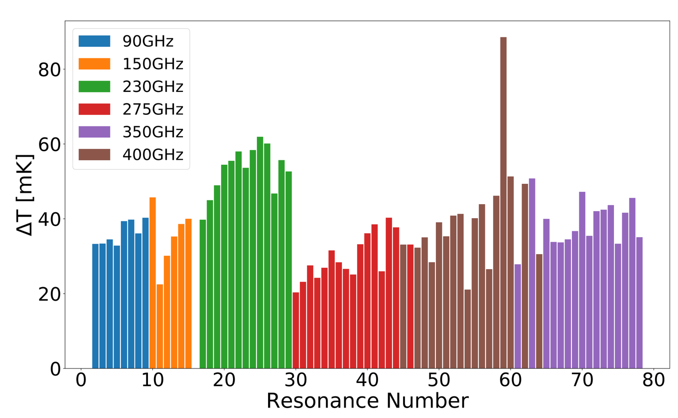


a-Si:H

a-Si:H device:
- Same as c-Si except:

No resonator connected to antennas (all dark)
Bad heat sink between substrate and focal plane
- δf_{res} probably due to substrate heating

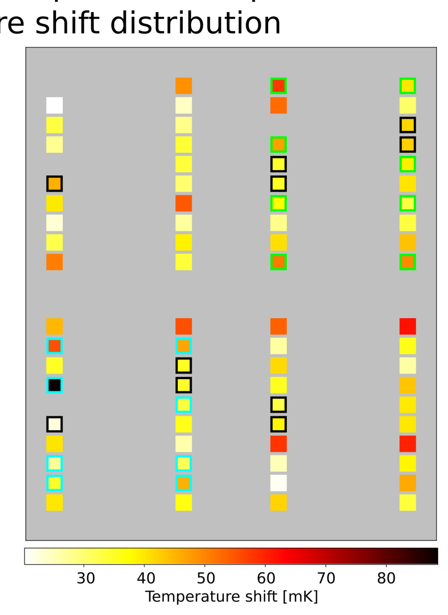




Thermal frequency shift:
- Nb LC resonances also shift

➡ δf_{res} due to substrate heating
- Nb δf_{res} corresponds to ≈ 30 mK
- TiNx δf_{res} corresponds to ≈ [20 - 60] mK
- Heating is about 10 times more than for c-Si, because of bad heat sink (no gold wire bonds)

Substrate heating mapping:
- We see all resonances, assuming they are ordered, we can map ΔT (corresponding to δf_{res}) at the surface of the KID
- No obvious pattern or explanation for temperature shift distribution



Conclusion

- Successful design, fabrication & test of two TiNx lumped element KID prototypes with parallel plate KID capacitors, TiNx inductor, and very low loss dielectrics (c-Si and a-Si:H)
- Good Mattis Bardeen fits for both devices with single gap and gap smearing models
- Cryogenic black body measurements: KID substrate is heated by the BB, which creates f_{res} shift. The c-Si device seems to also detect BB radiation, at expected level, but unexpected δf_{res} distribution accross channels
- Low Qi, not limited by losses inside dielectric (c-Si or a-Si:H): tanδ = 1e-5 measured with Nb resonators

Future work: Find what limits Qi, improve heat sinking of device substrate, make KIDs with lower Tc, measure TLS noise & sensitivity (NEP)

References

[1] C. Ji, A. Beyer, S. Golwala, J. Sayers, "Design of antenna-coupled lumped-element titanium nitride KIDs for long-wavelength multi-band continuum imaging," Proc. SPIE 9153, (2014)
[2] A. E. Lowitz, A. -D. Brown, T. R. Stevenson, P. T. Timbie, E. J. Wollack, "Design, fabrication, and testing of lumped element kinetic inductance detectors for 3 mm CMB Observations," Proc. SPIE 9153, (July 2014)
[3] J. Gao, The Physics of Superconducting Microwave Resonators, PhD Thesis, (2008)

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