National Aeronautics and Space Administration

Novel Low Loss Dielectric Development for Superconducting Microwave Devices

Principal Investigator: Chang Sub Kim (389); Co-Investigators: Daniel Cunnane (389), Andrew Beyer (389), Sunil Golwala (Caltech)

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Objective

Explore the potential of boron as a low-loss dielectric for superconducting microwave devices

Background

A key technology bottleneck in developing cryogenic microwave devices such as superconducting detectors for next-generation space telescopes **is microwave signal loss and noise from two-level states in dielectric layers.** The larger coordination number of boron (6) compared to silicon (4) implies lower loss (Figure 1), but boron as a dielectric material has been overlooked, having been investigated only at low frequencies (< 10 kHz) and temperatures > 4 K [2] where two-level system defects are secondary to thermal noise and other loss mechanisms. The experiment did, however, hit the measurement lower limit at low temperature, indicating that more investigations are necessar

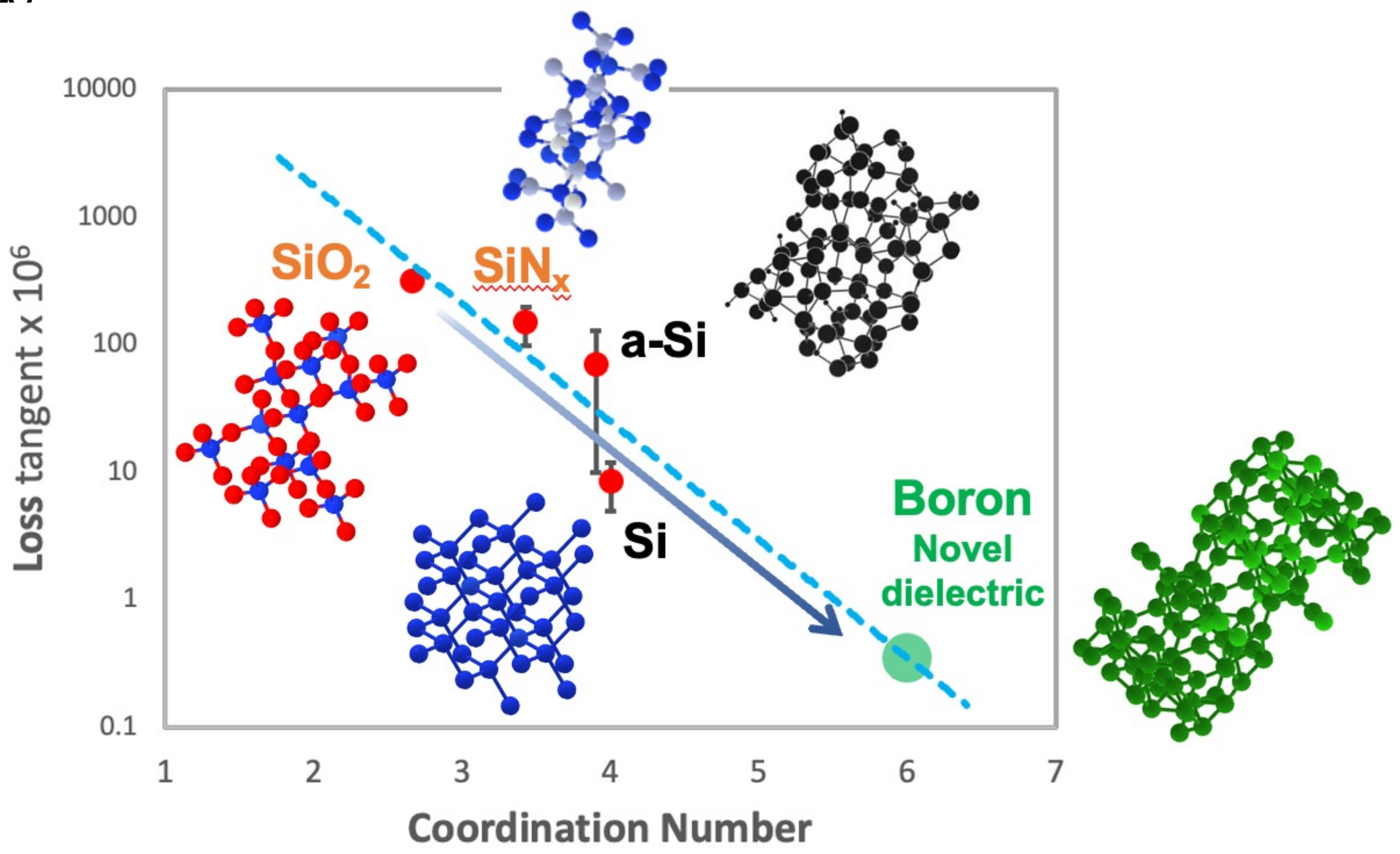

Figure 1. Loss decreases with increasing coordination number [1] in silicon-based dielectrics

Significance

- First-ever study on microwave dielectric loss/dangling bond characteristics of elemental boron
- Confirmed that sputtered boron has at least similar microwave dielectric loss compared to sputtered silicon-based dielectrics.
- Controlled the dangling bond defect density by a factor of 20 by eliminating substrate bias and slowing the deposition rate while increasing the kinetic energy of sputtered boron
- Next steps: use higher purity boron sources and control the kinetic energy of boron through HiPIMS and/or e-beam evaporation

Acknowledgments

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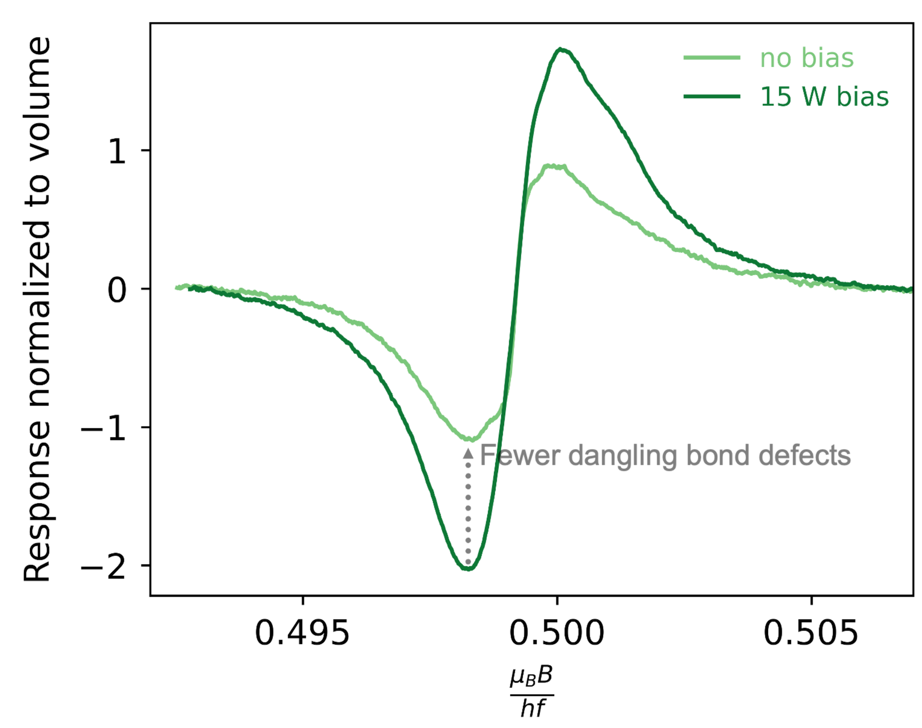
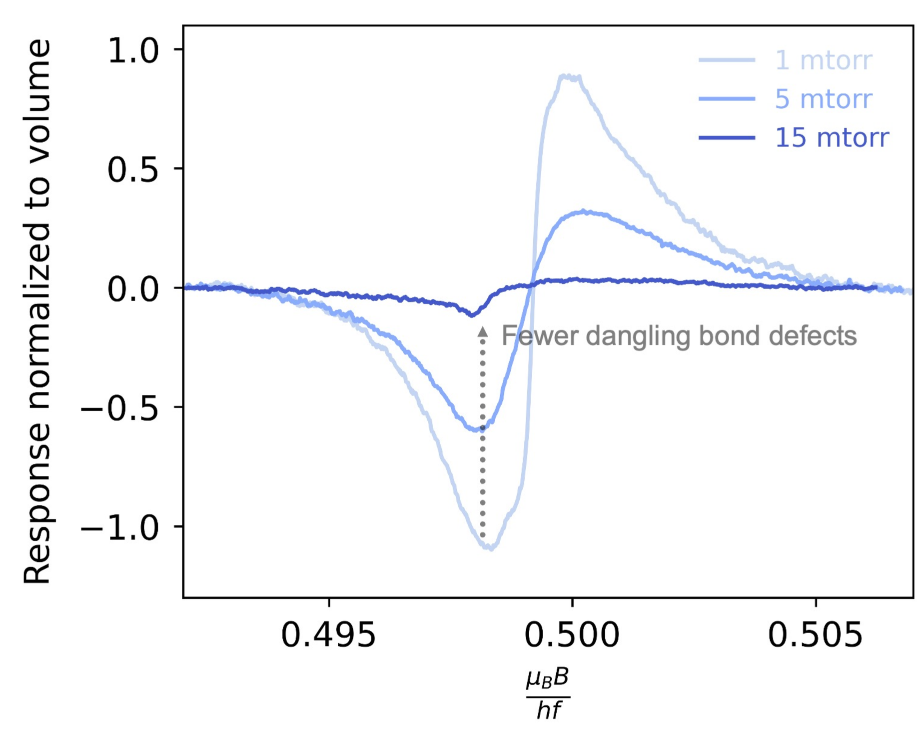
Approach & Results

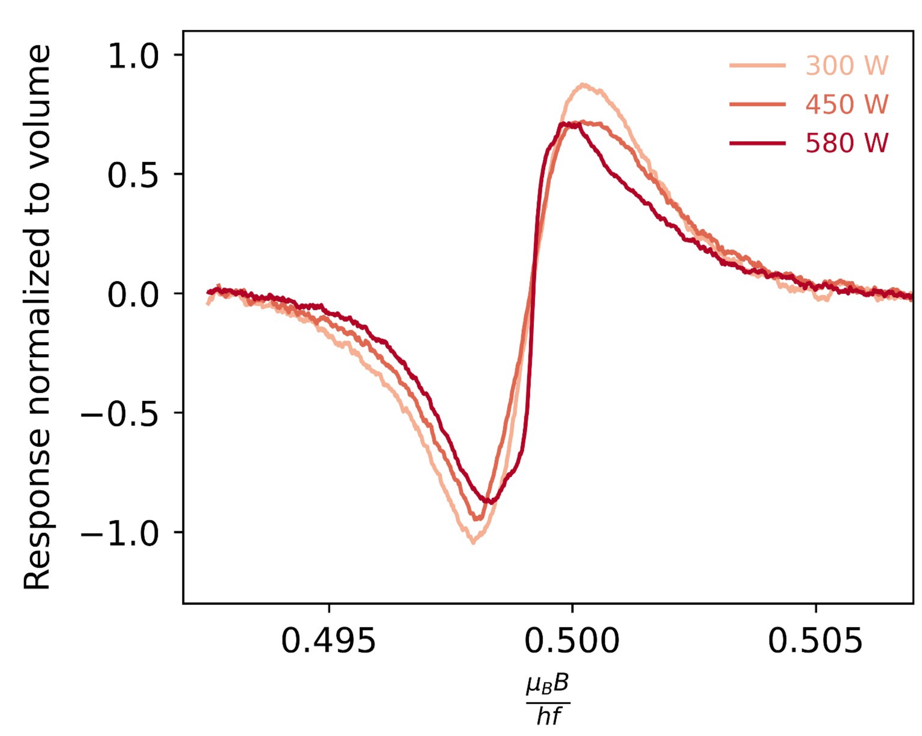
Lumped element LC resonators with a dielectric layer were fabricated using a niobium superconducting layer with a boron dielectric layer. Using a sub-Kelvin testbed at Caltech, initial RF loss measurements between 250 and 750 MHz at 260~370 mK showed dielectric loss tangents around $5.7\sim6\cdot10^{-3}$, comparable to sputtered amorphous silicon-based dielectrics. Multiple boron films with different deposition parameters needed to be tested in order to better optimize and understand the films. However, fabricating such microdevices and cooling down to sub-Kelvin temperatures for measurements are not easy tasks and were taking longer than expected. Because dielectric loss correlates with dangling bond (defect) density [3], we decided to do additional experiments in parallel: measuring dangling bond densities of boron films with different deposition parameters. Thin (65~150 nm) amorphous boron films were deposited by magnetron sputtering an elemental boron target at different RF powers and argon pressures, with and without substrate biasing. The number of dangling bonds in each film was then measured by electron paramagnetic resonance (EPR) spectroscopy.



Effect of RF substrate bias: Number of dangling bonds was higher with than without 15 W RF substrate bias, implying that the negative effect (substrate bias creating more defects in the film) outweighs the positive effect (substrate bias making the film denser).



Effect of deposition pressure
Higher pressure => mean free path of sputtered boron atoms gets shorter => lower deposition rate => more time for adsorbed boron atoms to diffuse along the surface and find the most energetically favorable space to sit in => fewer dangling bonds



Effect of RF power on boron target
Lower power results in lower kinetic energy, but also more time for adsorbed boron atoms to diffuse => net effect: dangling bond density remains roughly constant with sputtering power

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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

www.nasa.gov

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References:

[1] Aaron O'Connell, et al. "Microwave dielectric loss at single photon energies and millikelvin temperatures." Applied Physics Letters 92.11 (2008): 112903.
[2] F.N. Tavadze, et al. "Dielectric loss in boron." Journal of the Less Common Metals 67.1 (1979): 269-272.
[3] M. Molina-Ruiz, et al. "Origin of mechanical and dielectric losses from two-level systems in amorphous silicon." Physical Review Materials 5.3 (2021): 035601.

PI/Task Mgr. Contact Information:

Email: chang.sub.kim@jpl.nasa.gov