Low-loss Microstrip Transmission Line Fabricated With Improved Liftoff Process

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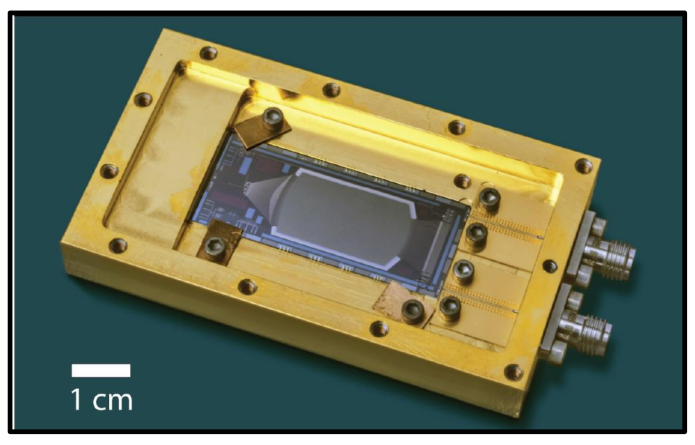
Abstract

The µ-Spec integrated spectrometer operating at ~500 GHz, employs thin film superconducting Nb microstrip transmission lines deposited directly on a thin (450 nm) single-crystal silicon dielectric. This single-crystal silicon layer is chosen as the dielectric layer due to its low intrinsic loss, with the goal of achieving both high-efficiency and precise phase control in a compact spectrometer architecture. To avoid roughening or etching through the thin single-crystal silicon dielectric a liftoff technique was developed for patterning these microstrip transmission lines and ground plane structures. This two-layer liftoff process was designed for use with sputter deposition and resulted in a US patent. Although this original technique provided precise control of linewidth, results of initial prototype spectrometer devices and separate diagnostic co-planer waveguide resonator devices showed that unexpected loss was being introduced due to the lift-off process. This extra loss was believed to be due to the "tails" (thin tapered regions) at the edge of the metal traces resulting from the sputtering process, as well as an amorphous oxide layer at the Nb-Si interface. We have since demonstrated an improved lift-off technique, which provides a clean metal-Si interface and removes the loss-inducing tails by a two-step selective etching method. This results in a decrease in microwave loss by more than an order of magnitude when measured in co-planar waveguide microwave resonator structures. We present these microwave test results and also SEM and TEM images of the microstrip interfaces and edge profiles before and after application of the improved process.

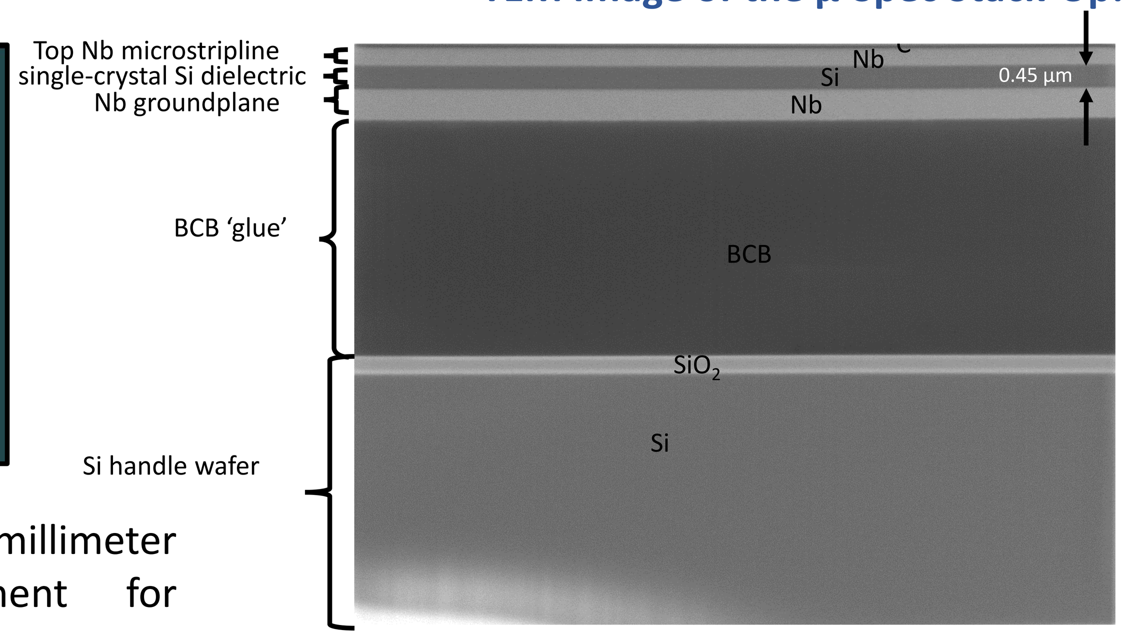
Motivation: High Microwave Loss in µ-Spec Prototypes

R=64 µ-Spec Prototype:



- µ-Spec is a integrated on-chip submillimeter spectrometer under development for astrophysical applications.
- µ-Spec is an analog to a diffraction-grating spectrometer, implemented on a Si chip with Nb microstrip transmission lines and Al/Nb microstrip Microwave Kinetic Inductance Detectors (MKIDs).
- Prototype R=64 µ-Specs have been demonstrated in the laboratory [1] and R=512 µ-Specs are planned for a cryogenic balloon-borne instrument, EXCLAIM.

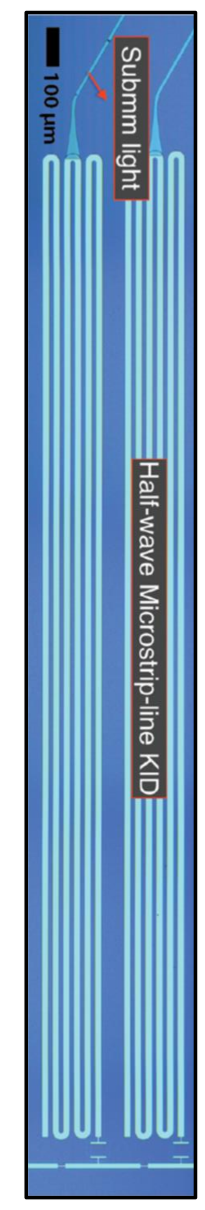
TEM Image of the µ-Spec Stack-Up:



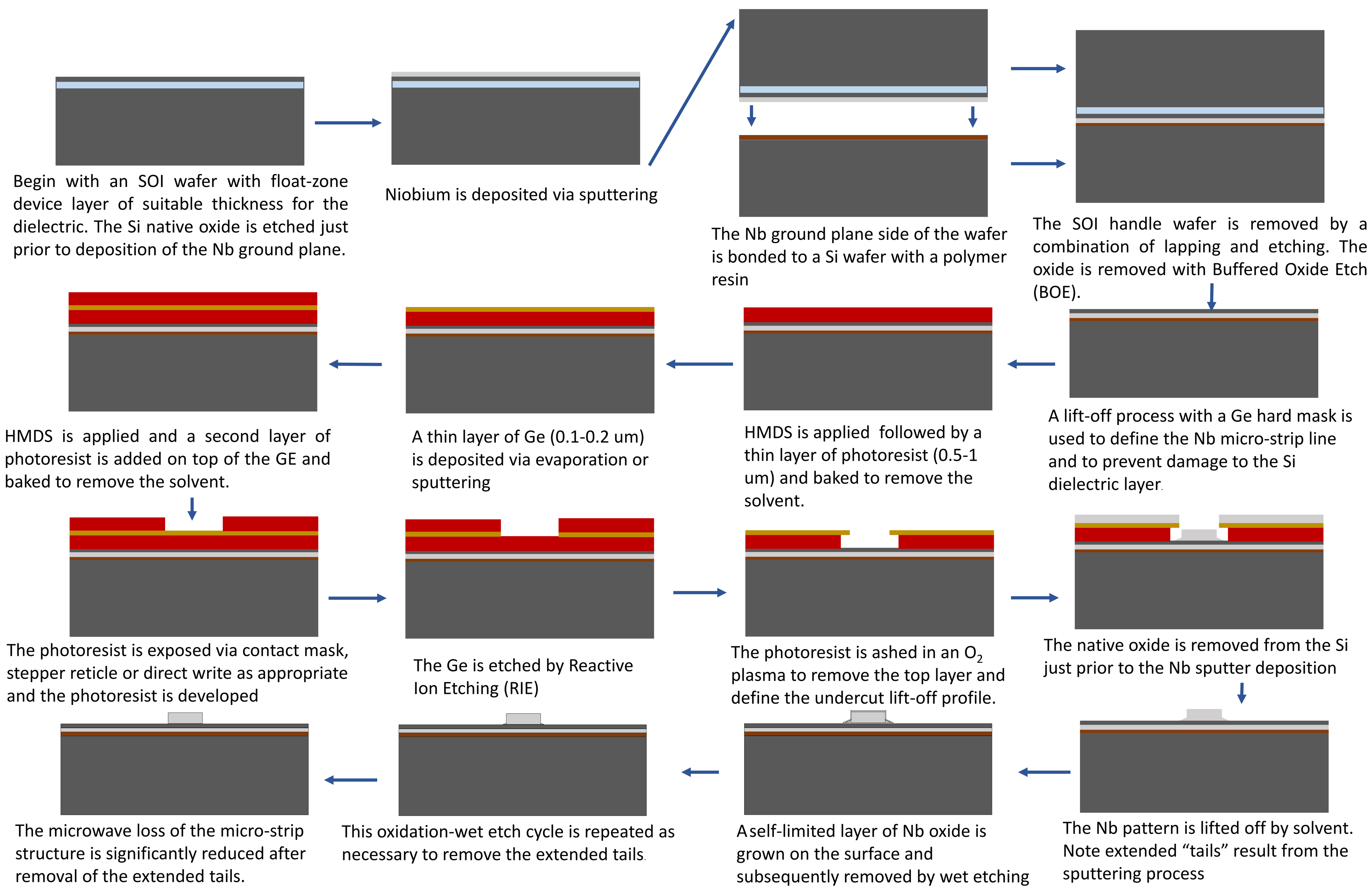
- The µ-Spec integrated spectrometer is realized by patterning superconducting Nb on both sides of a low-loss 450 nm thick single-crystal Si device layer of an Silicon-on-Insulator (SOI) wafer, using a flip-bonding process [2].
- To avoid etching or roughening the Si a precision Nb liftoff process was also developed [2] .
- The Nb ground plane also forms the ground plane of the Al/Nb microstrip MKIDs.

R=64 MKIDs:

- In R=64 prototypes, unexpected microwave loss was observed in the Al/Nb MKIDs with maximum internal quality factors Q_i of only ~40,000 at moderately high readout powers.
- From resonant frequency and Q_i vs. temperature and vs. readout power dependence, we determined the loss was dominated by Two-Level Systems (TLSs) [3], with $\tan\delta$ parameter ~1.5 x 10^{-4}.
- Similar loss was observed in both Al/Nb and Nb/Nb (dark) MKIDs, pointing to the Nb groundplane interface as the source of the high loss.

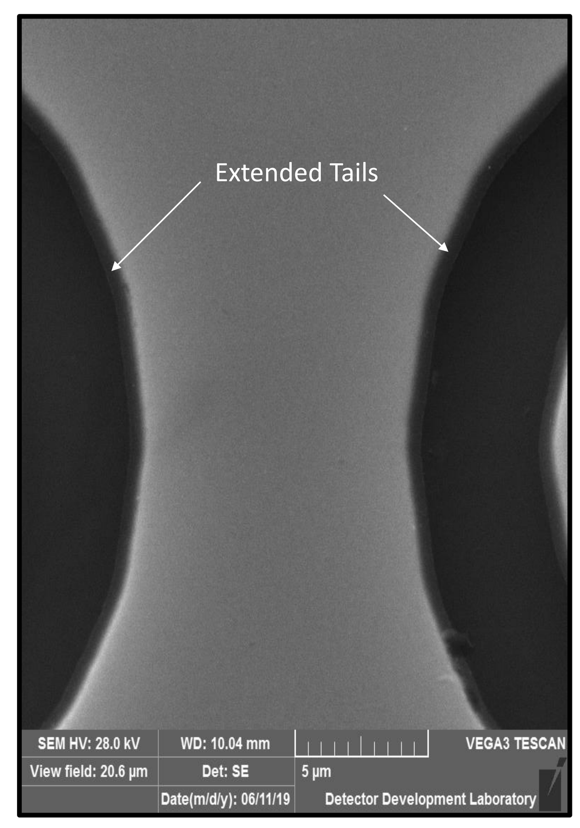


Liftoff Process & Modifications



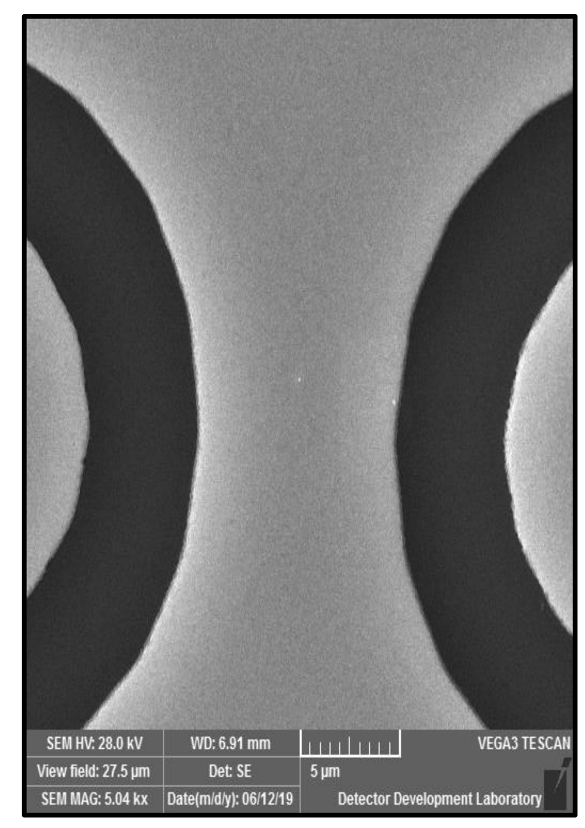
Tail Removal SEM Images

Before



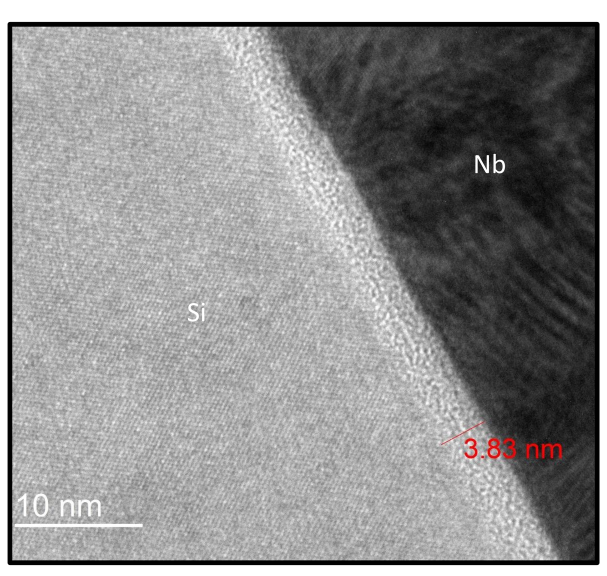
As deposited Nb lift-off pattern. Note the extended tail at the edges of the pattern which has been observed to result in higher loss and low Q in CPW resonator structures.

After

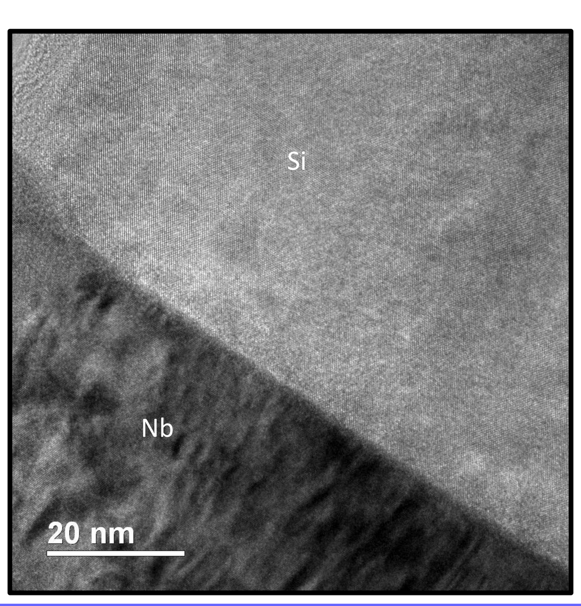


After successive oxidation and etch cycles the extended tails are removed and the resulting measured Q is significantly (more than10X) higher. See table below.

Si-Nb Interface



Before: TEM image showing the groundplane Nb-Si interface of an R=64 µ-Spec prototype. Here there is evidence of an amorphous layer which would be a source of TLS loss.

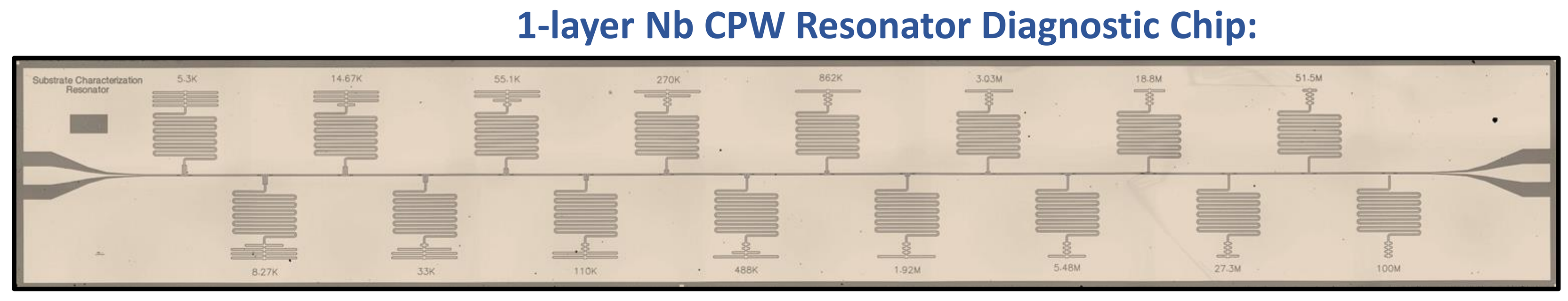


After: TEM image showing Nb-Si interface of CPW resonator R12C1, which underwent a modified Nb liftoff process. Here the contact is sharp with no evidence of amorphous layers.

Microwave Loss Study

- 1-layer Nb Coplanar-Waveguide (CPW) quarter-wave resonators with a 'fishbone' resonance frequency tuning structures [4] were used for a rapid-turn study of the impacts of process variations on microwave internal Q_i.
- Coupling Q values across the chip range from ~5,000 to ~500,000 and resonance frequencies are at ~3.5 GHz.
- The CPW readout feedline is the same layer and there are no additional layers or fabrication steps.
- Devices were tested at base temperatures, 7-30 mK, inside a magnetically-shielded and light-tight dilution refrigerator.

1-layer Nb CPW Resonator Diagnostic Chip:



Sample Comparison:

Sample ID	Device Type	Primary Process Differences	Microwave Q_i Readout power: -130 dBm	Microwave Q_i Readout power: -80 dBm	Film RRR
Nb etch (2 samples)	Fishbone CPW resonator	➢ Reactive ion etch of Nb	400,000-1,000,000	200,000-400,000	5.9
Nb R4C3	Fishbone CPW resonator	➢ Nb liftoff ➢ BOE clean prior to deposition ➢ Removal of sidewalls	200,000	100,000-150,000	5.7
Nb E06	Fishbone CPW resonator	➢ Nb liftoff ➢ Reverse bias prior to deposition ➢ Removal of sidewalls	150,000-350,000	100,000-200,000	5.0
Nb R13C1	Fishbone CPW resonator	➢ Nb liftoff ➢ BOE clean prior to deposition ➢ No removal of sidewalls	10,000-20,000	7,000-10,000	7.0
NbE05	Fishbone CPW resonator	➢ Nb liftoff ➢ No native oxide removal prior to deposition ➢ No removal of sidewalls	4,000-8,000	4,000-8,000	6.3

Summary

- Previous µ-Spec prototypes implemented a non-ideal Nb liftoff process, which resulted in an amorphous oxide layer at the Nb-Si interface, and a tapered sidewall profile, both which negatively impacted the microwave loss and sensitivity of the MKIDs.
- We found a combination of 1) substrate cleaning steps prior to the deposition and 2) a post-liftoff sidewall etch were both necessary to achieve low microwave loss in Nb films patterned into CPW resonators via liftoff.
- We hope to demonstrate high spectrometer efficiency and high internal quality factor microstrip MKIDs in next generation high resolution µ-Specs, which are currently under development for the EXCLAIM (EXperiment for Cryogenic Large-Aperture Intensity Mapping) balloon-borne instrument.

References

[1] Noroozian, Omid, et al. "µ-Spec: An efficient compact integrated spectrometer for submillimeter astrophysics." *26TH International Symposium on Space Terahertz Technology*. 2015.

[2] Patel, Amil, et al. "Fabrication of MKIDs for the MicroSpec Spectrometer." IEEE Transactions on Applied Superconductivity 23.3 (2013): 2400404..

[3] Gao, J., The physics of superconducting microwave resonators, Doctoral dissertation, California Institute of Technology, 2008.

[4] Stevenson, Thomas R., et al. "Superconducting films for absorber-coupled MKID detectors for sub-millimeter and far-infrared astronomy." IEEE Transactions on Applied Superconductivity 19.3 (2009): 561-564.