Improving tunnel junction yield in arrays of CMB TESs cooled by NIS refrigerators

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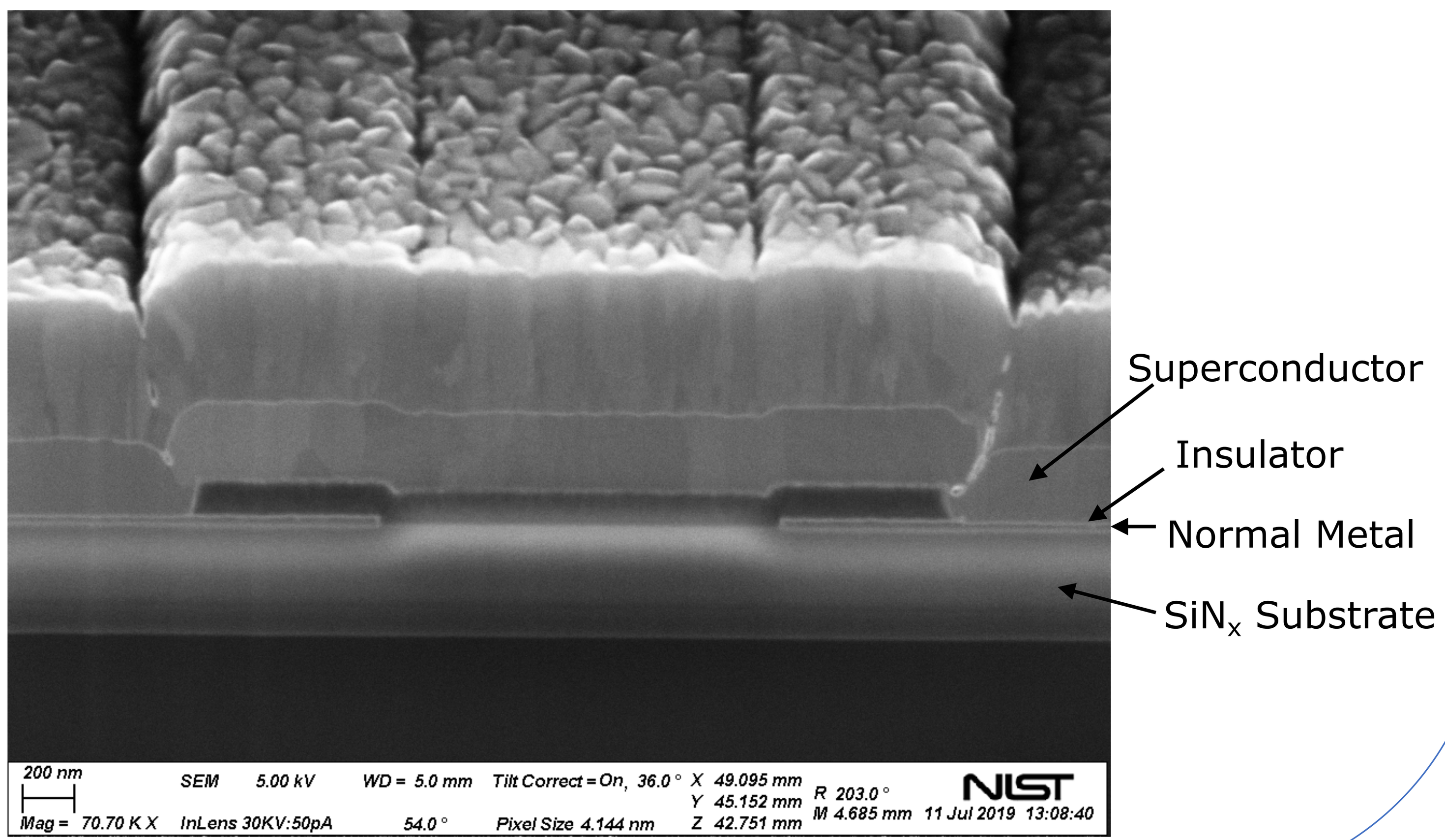
1. NIS REFRIGERATORS – WHAT AND WHY?

In millimeter and submillimeter (mm/submm) wavelength astronomy, low temperature detectors are now essential for many observations, such as polarization studies of the cosmic microwave background (CMB). These detectors are often superconducting devices with optimized performance at ~150 mK. Observations in the mm/submm are plagued by water absorption in the atmosphere, an issue some experiments mitigate with balloon or satellite missions.

A pumped ^{3}He refrigerator alone provides a base temperature of 300 mK. Adiabatic demagnetization refrigerators and dilution refrigerators are popular choices for cooling a testbed from 300 mK to below 100 mK. These refrigeration technologies are well established, but can be heavy and expensive.

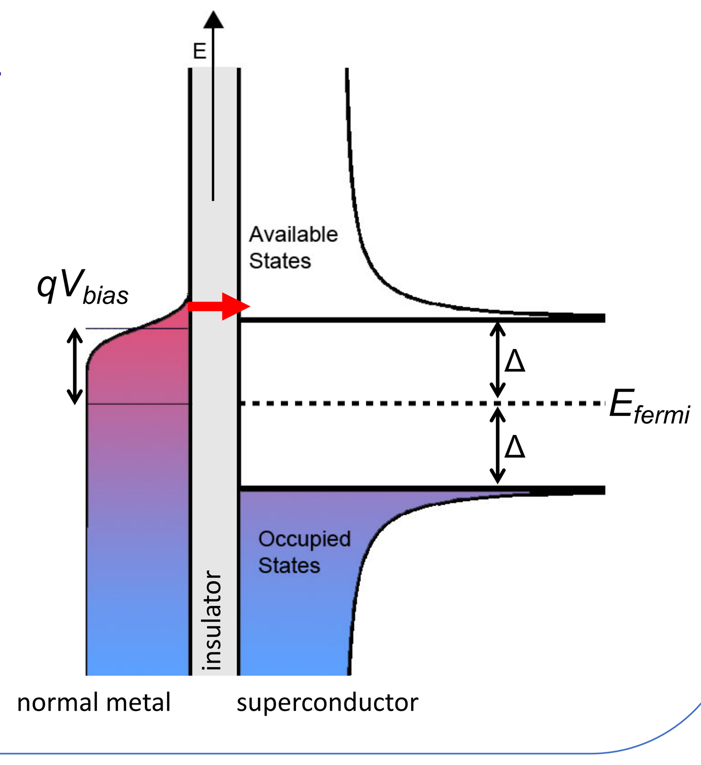
We propose a potential alternative to these technologies, well-suited for balloon- and space-based experiments. A **Normal metal – Insulator – Superconductor** junction, when properly voltage biased, siphons off hot electrons from the normal metal into the superconductor, cooling the electrons in the normal metal. We aim to cool mm/submm detectors from the pumped ^{3}He bath temperature of 300 mK to 150 mK using NIS refrigerators alone.



2. SOLID STATE ON-CHIP COOLING

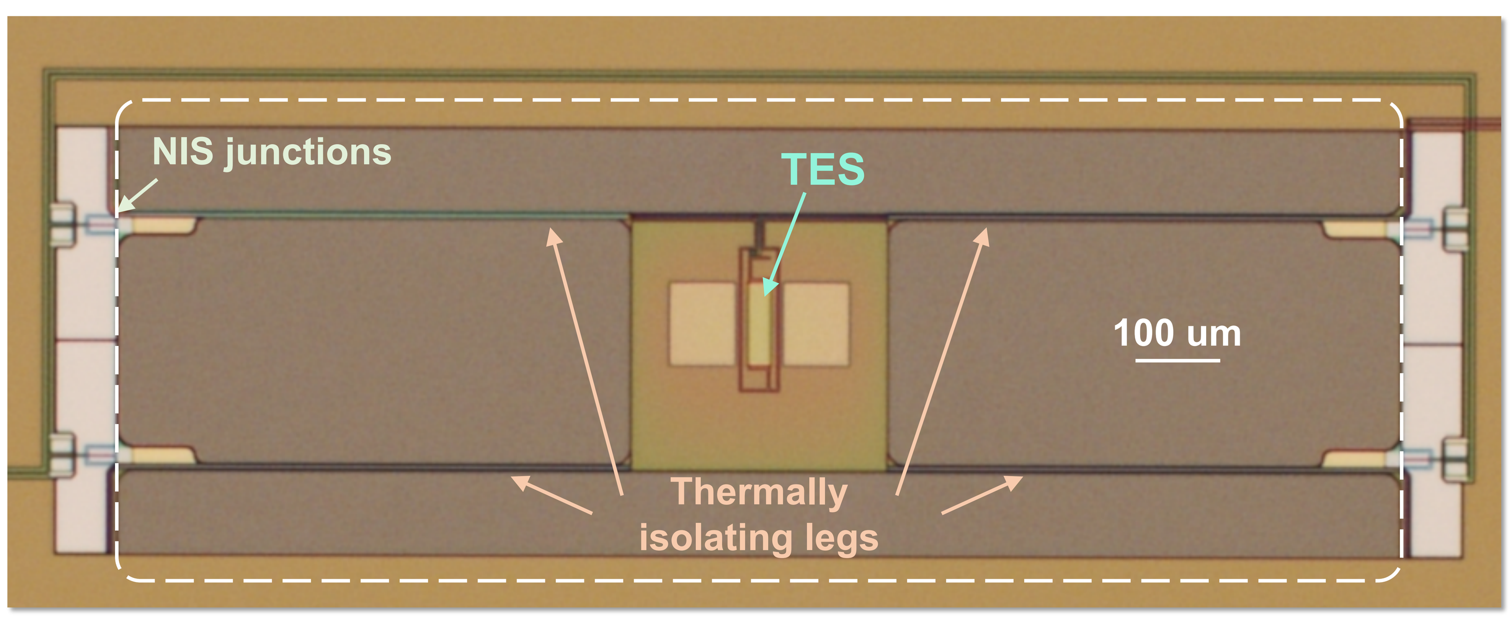
Due to thermal smearing of the occupation of states, the hottest electrons in the normal metal preferentially tunnel across the insulating barrier into the superconductor. Peak cooling occurs when the normal metal is voltage biased at ~0.9Δ/e, where Δ is the superconducting energy gap [2].

These devices are fabricated onto a detector wafer, providing localized solid-state cooling that only requires one DC bias line. NIS refrigerators have been shown to contribute negligible noise to the TES.



3. NIS-TES INTEGRATED DEVICES

We have fabricated integrated NIS-TES devices with TESs similar to those deployed on SPIDER [1], a balloon-born CMB polarimeter. We integrate 8 NIS junctions on a TES bolometers, two per leg.



REFERENCES

[1] A.S. Bergman *et al.*, "280 GHz Focal Plane Unit Design and Characterization for the SPIDER-2 Suborbital Polarimeter," *Journal of Low Temperature Physics*, vol. 193, no. 5-6, pp. 1075-1084, Dec. 2018.

[2] G. C. O'Neil, P. J. Lowell, J. M. Underwood, and J. N. Ullom, "Measurement and modeling of a large-area normal-metal/insulator/superconductor refrigerator with improved cooling," *Phys. Rev. B*, vol. 85, no. 13, pp. 4504, April 2012

4. IMPROVING SUBSTRATE ROUGHNESS

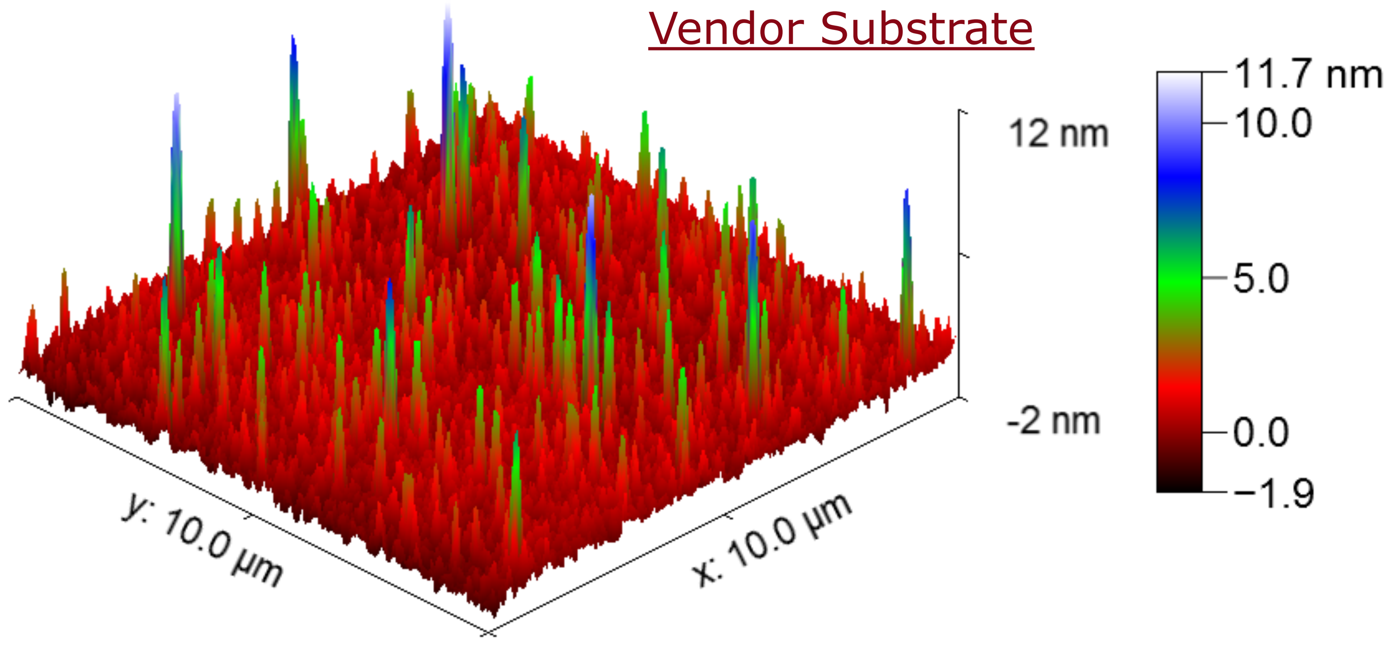
The first batch of integrated devices were fabricated on commercially-produced very low stress SiN_x substrate. The high Si content lead to Si islands as high as 11 nm tall. This created shorts between the normal and superconducting films through the few-nm-thick insulating layer, leading to the low junction yield of ~50%.

To reduce the number of shorts, we grew a substrate with slightly less Si content. The index of refraction of the lower-Si substrate is n=2.2, compared to n=2.27 of the vendor substrate (n scales positively with Si content in SiN_x). We measured a large improvement in roughness with the new substrate, from a height RMS = **0.75nm** (peak ~**12nm**) to RMS < **0.4nm** (peak ~**5nm**).

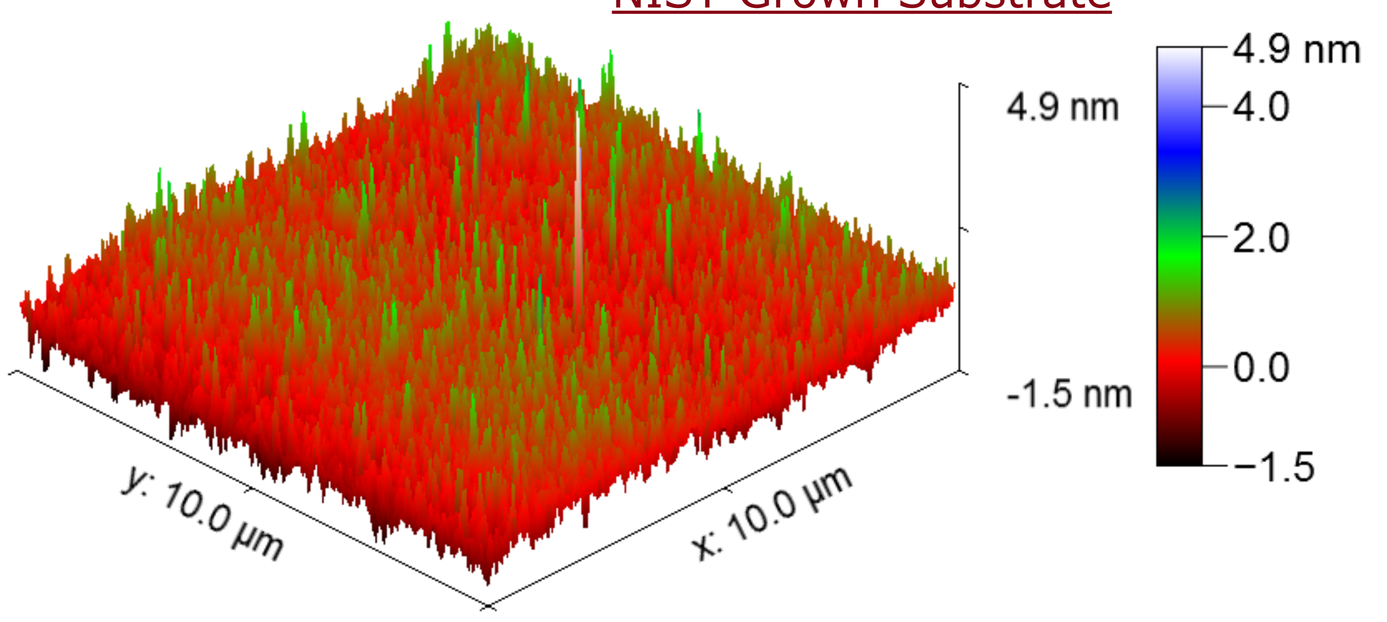
Lower Si content in SiN_x produces a higher stress material. In changing the Si content in the substrate, there is a the potential to decrease TES mechanical yield due to leg bowing from material stress. By lowering the Si content a small amount, we increased the junction yield while maintaining the TES yield.

AFM Scans of Substrates

Vendor Substrate



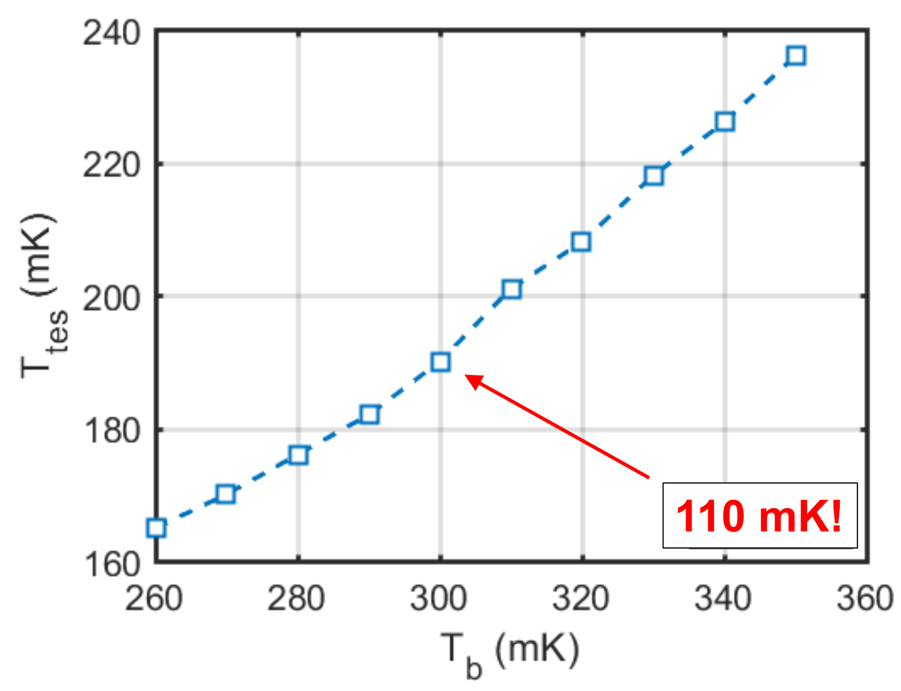
NIST-Grown Substrate



5. GREATER JUNCTION YIELD, FUTURE WORK

Fabrication on our new, smoother substrate yielded **100%** (24/24) of junction-only devices.

A device fabricated on the rougher substrate with non-optimal geometry achieved cooling from **300 mK** to **190 mK**. A new batch of integrated NIS-TES devices have been fabricated, and testing is under way.



Cooling from 300 mK to 160 mK (140 mK cooling) would be sufficient for balloon missions such as SPIDER. With an optimized geometry and 100% junction yield, we project **141 mK** of cooling with the new devices.