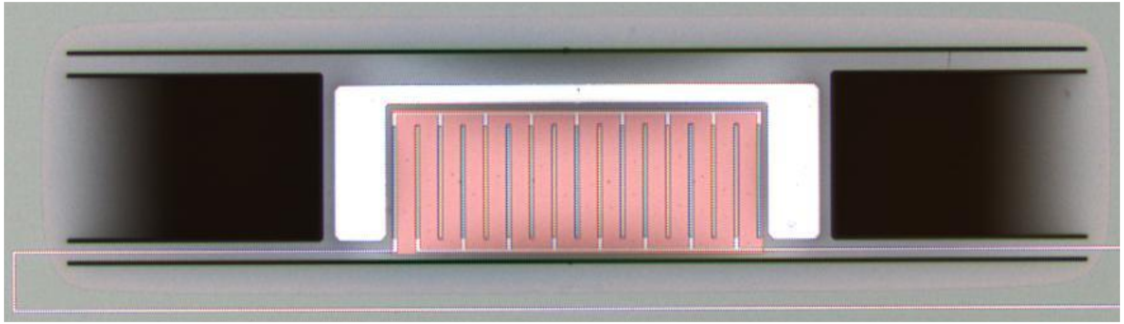
Versatility of superconducting Hafnium for transition edge sensor bolometers



CPAD 2023 - SLAC

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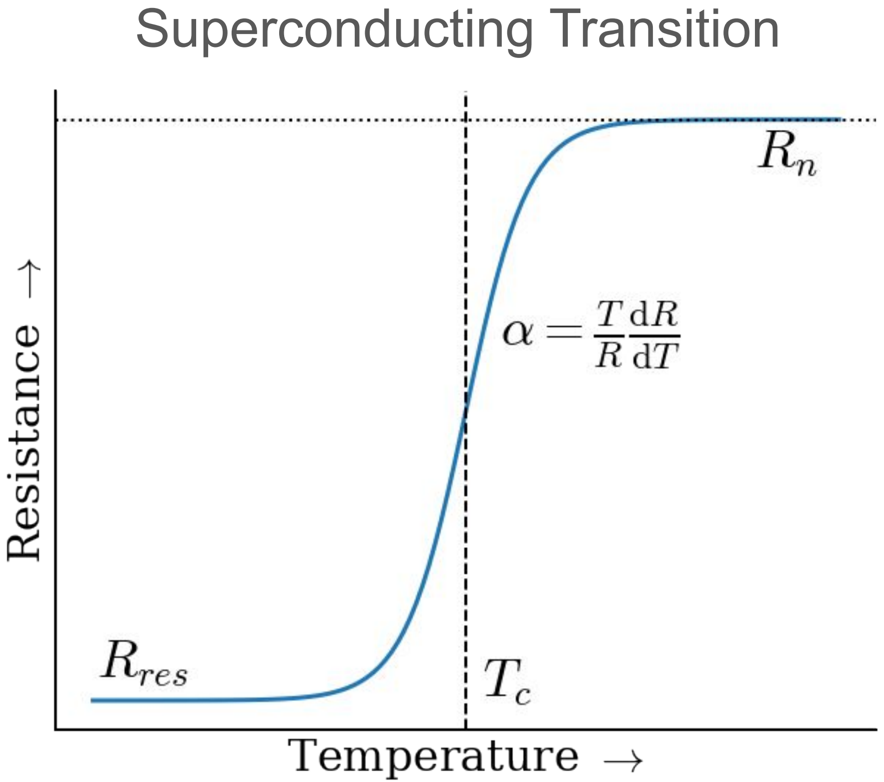
BERKELEY LAB seeqc STAR CRYOELECTRONICS

TES bolometer parameters



Typical CMB targets:

- T_c ~ 165 mK
- R_n ~ 0.01 Ω , ~ 1 Ω
- $\alpha \gtrsim 100$

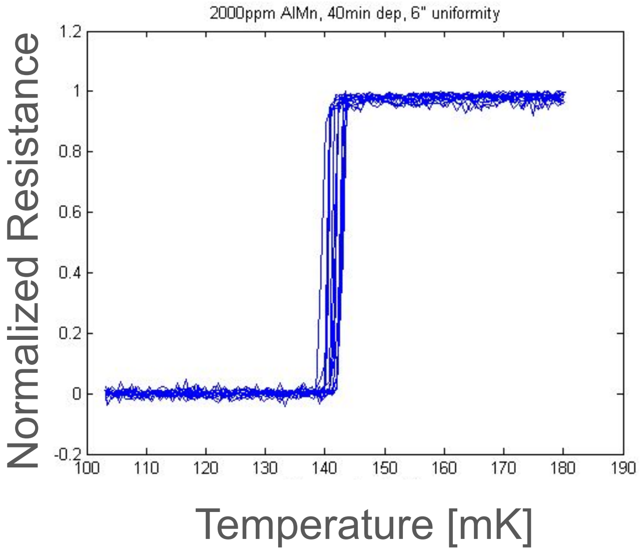
➢ Compatible with detector fab
➢ Reproducible
➢ Uniform across wafer
➢ Does not degrade over time

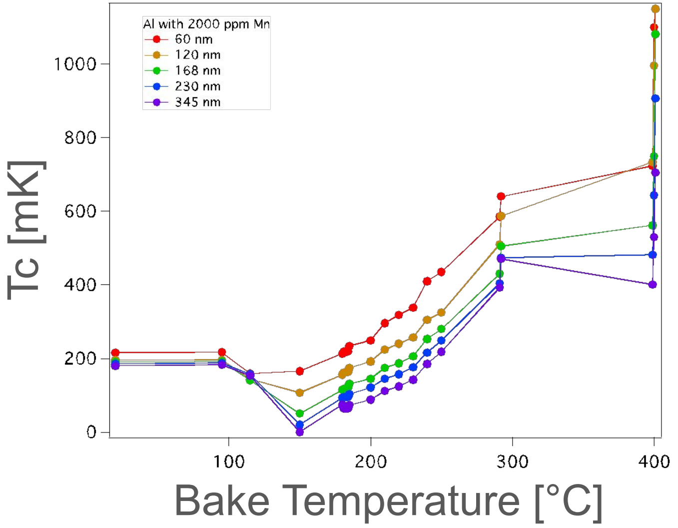
Example of TES material: Aluminum Manganese

Dale Li et al. (2016)

- Steep transition
- High uniformity across wafer
- Sensitive to fabrication temperature

- Mn dopant coarsely sets T_c
- Film thickness affects T_c
- Bake temperature fine-tunes T_c

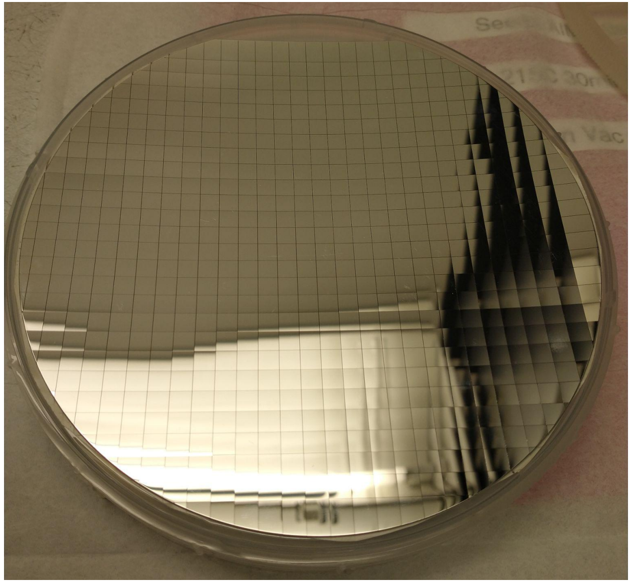




Hafnium: an attractive alternative

- Single element
- ~1 Ω/□ sheet resistance
  (250 nm film, measured at 1 K)
- Tunable T_c ~ 130 - 400 mK
  - Heated sputter deposition
  - Ideal range for CMB experiments

^{72}Hf



Example Hf detector efforts

Superconducting tunnel junctions: Kraft et al. (1998)

- Photon counting spectrometers for application in astrophysics
  - 100 nm Hf film, T_c ~ 130 mK

TES calorimeters: Adriana Lita et al. (2009)

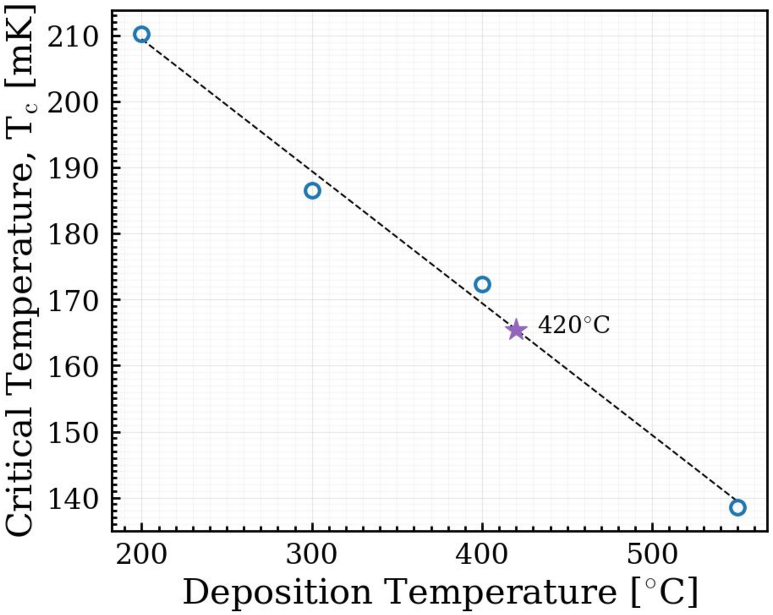
- Hf calorimeter: “transition broadened considerably”
  - Hf film as deposited: 30 nm, T_c ~ 195 mK, ΔT ~ 3 mK, R_n ~ 12 Ω
  - TES buried under SiN
  - Final TES T_c ~ 140 - 190 mK

MKID: Nicholas Zobrist et al. (2019) & Gregoire Coiffard et al. (2020)

- Successful demonstration of Hf OIR MKID arrays
  - Q_i ~ 77,000
  - T_c = 395 mK, ΔT ~ 5 mK
    - ➢ Room temp deposition

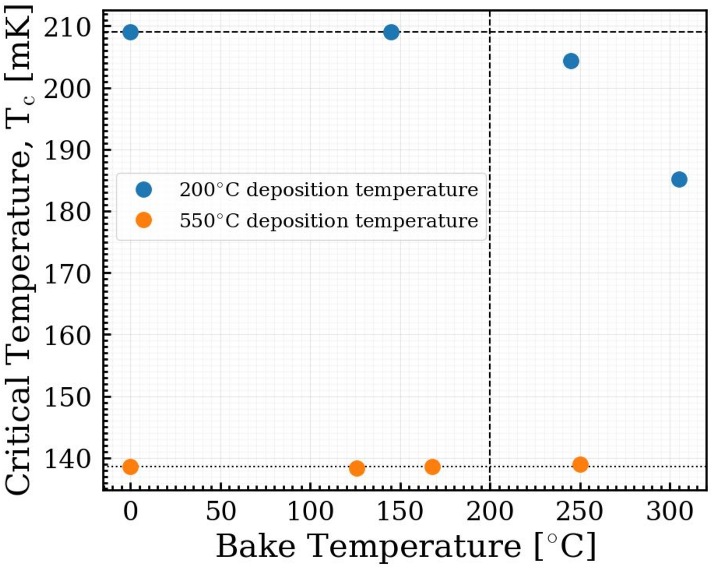
Heated sputter deposition

Tunable critical temperature



Robust against heating

- ➢ Stable and unchanged T_c



TES bolometer fabrication process

0) 675 μm Si Wafer
   + SiN (2.0 μm, low-stress) + SiO_2 (0.45 μm)

1) Hf: sputter 247 nm @ 500°C
   Cl_2 plasma etch, DI termination

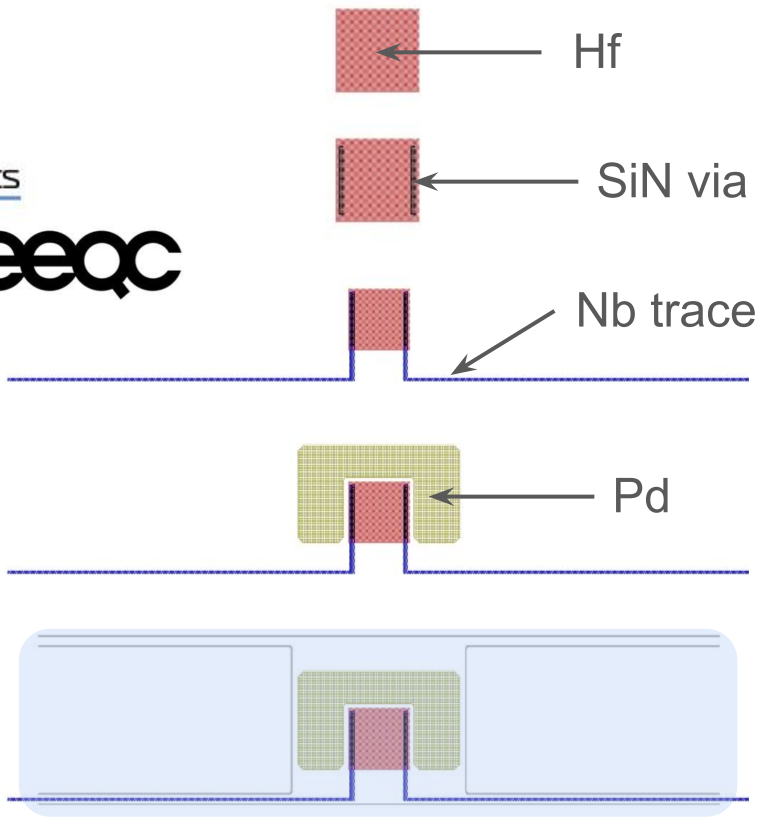
2) SiN: PECVD 500 nm
   N2 preclean, CHF_3 + O_2 plasma etch

3) Nb: sputter 600 nm @ room temp
   Cl_2 plasma etch, DI termination

4) Pd: 1 μm e-beam evaporation

5) DRIE release bolometer

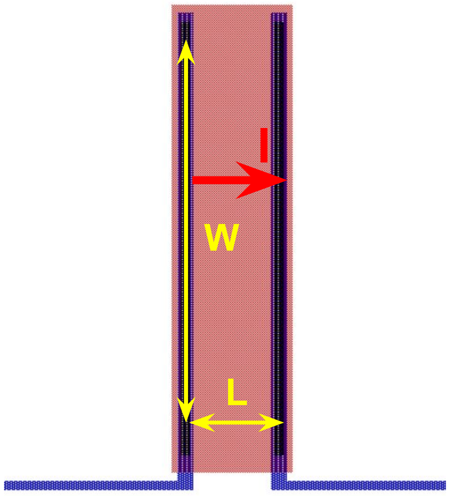
6) Stealth dicing



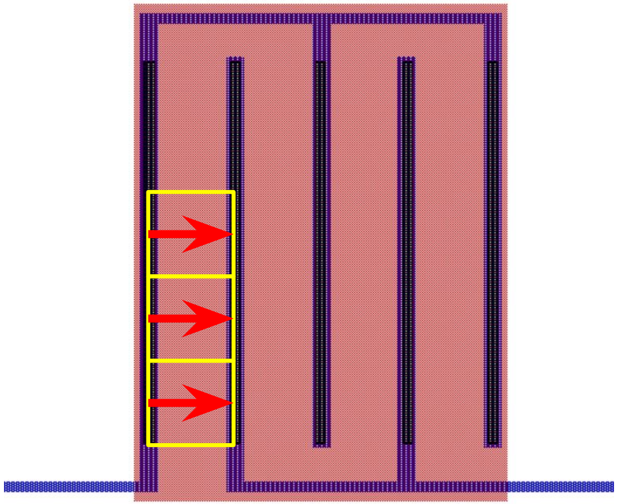
Designing low R_n

- Unpatterned ~ 250 nm film
  - $R_n \sim 1\ \Omega/\square$ (~ 1 K measurement)
- Reduce R_n via interdigitated design
- Design R_n to range from $1\ \Omega \rightarrow 17\ m\Omega$

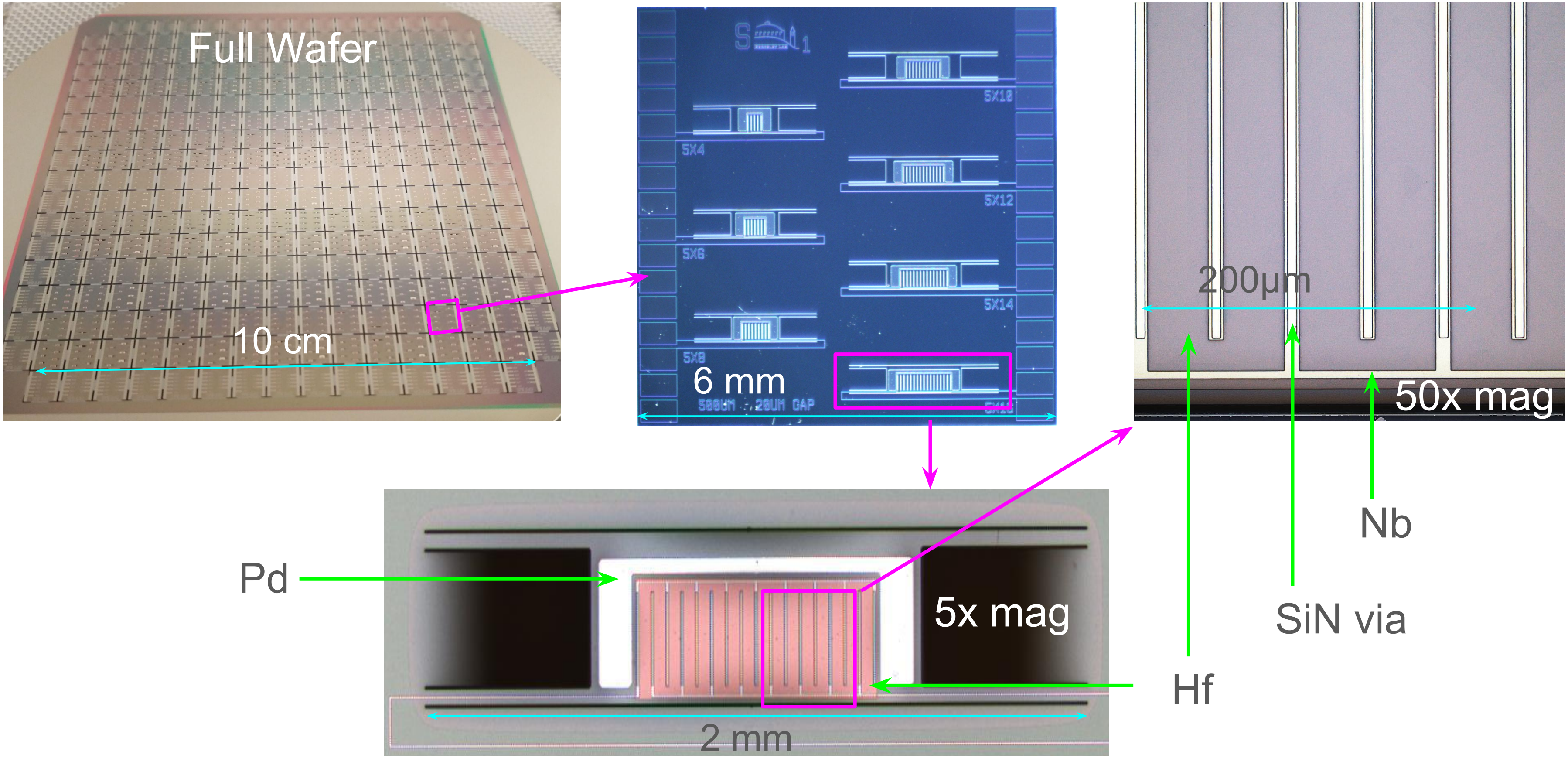
$R_n \propto L / W$



$R_{tot} \sim R_{\square} / N_{sq}$

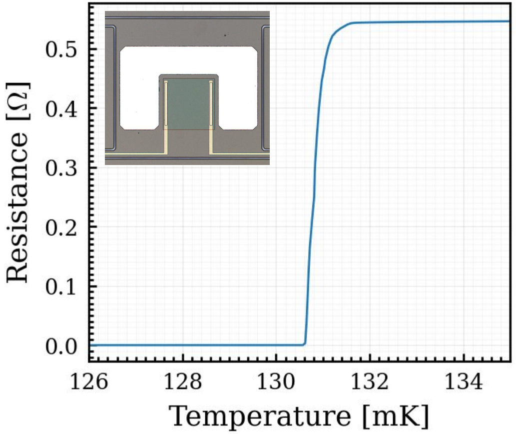


Prototype wafer



Results - achieving stable T_c, high α, low R_n

High-R_n style

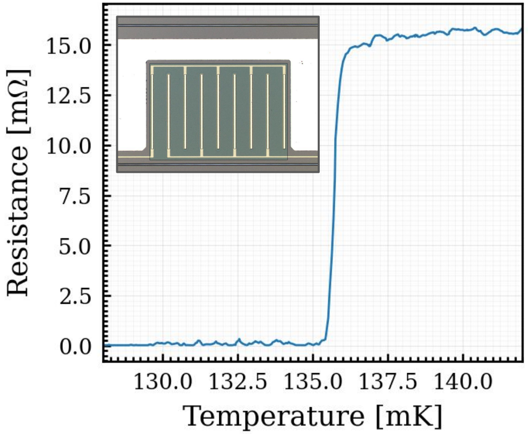


R_n = 0.55 Ω

$\alpha_{0.5Rn}$ ~ 380

T_c = 131 mK

Low-R_n style



R_n = 16 mΩ

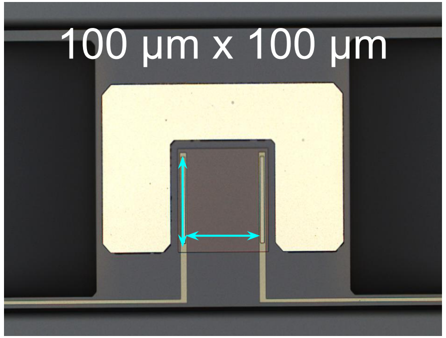
$\alpha_{0.5Rn}$ ~ 270

T_c = 136 mK

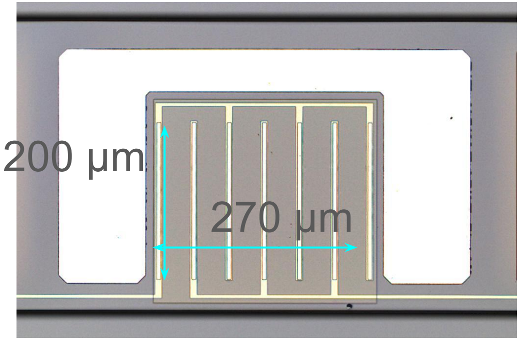
- ✓ Unchanged T_c (~ 5 mK variation across wafer)
- ✓ Smooth & steep transition
- ✓ Low R_n via interdigitated design

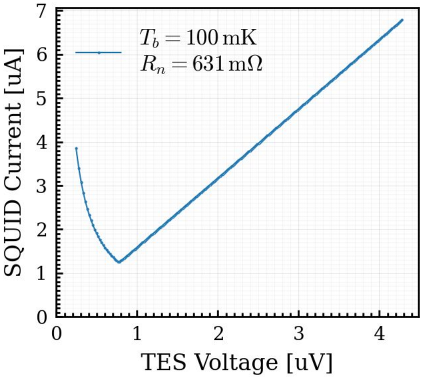
Results - achieving stable T_c, high α, low R_n

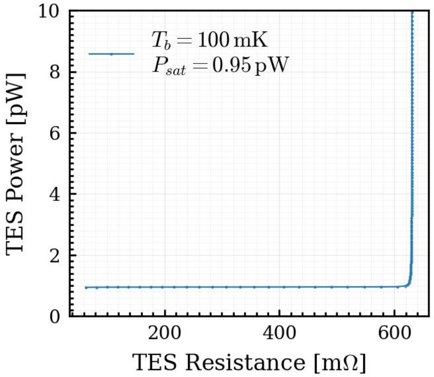
High-R_n style (630 mΩ)

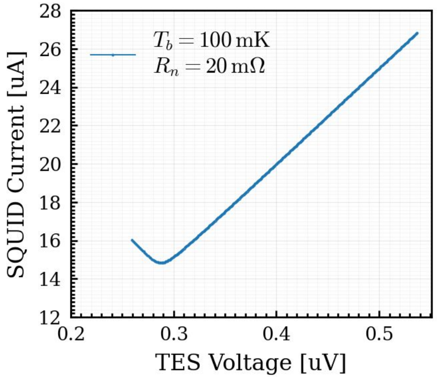


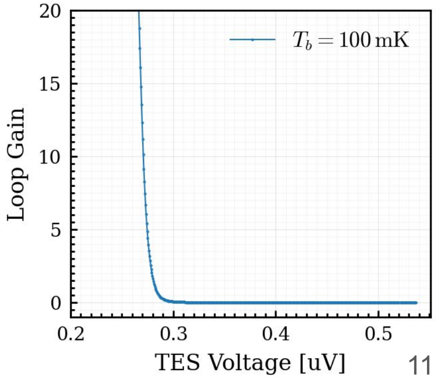
Low-R_n style (20 mΩ)







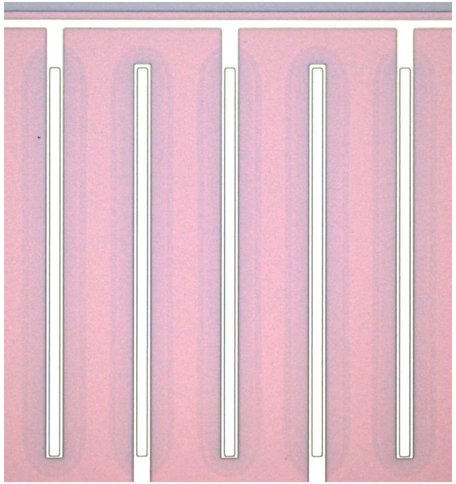




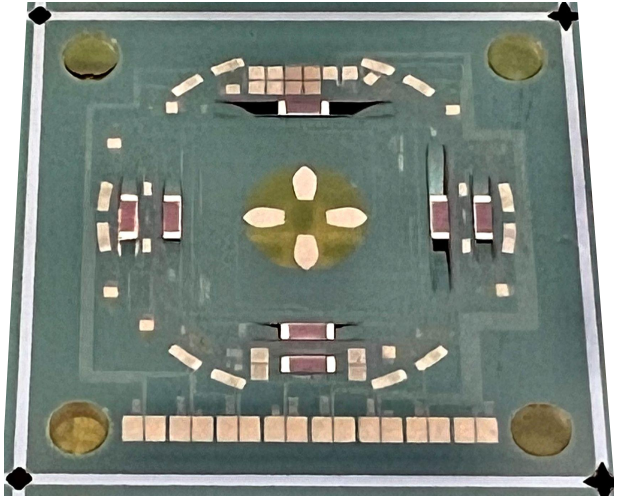
Achieving high yield

- Stress in Nb film → Hf delamination
- Solution: Al lift off, fabricated full CMB detector stack
- Good superconducting contact & no halos

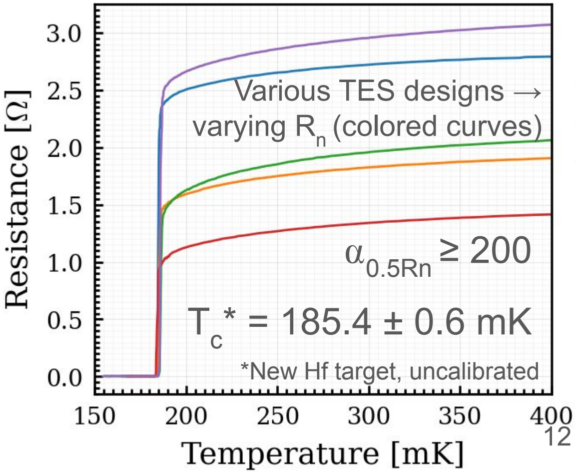
Delamination around Nb contact



Full CMB detector stack



Good superconducting contact



Summary

Hf is an attractive detector material

- T_c is tunable and stable with heated deposition
- α: steep transition with high loop gain
- Interdigitated design effectively reduces R_n
- Successful fabrication of a full CMB detector stack

Thank You.

Abstract

Several current and next generation cosmic microwave background (CMB) polarimetry experiments employ transition edge sensor (TES) bolometers whose operating temperature is ~100 milli-Kelvin, requiring a critical temperature (T_c) around 170 milli-Kelvin. Aluminum Manganese (AlMn) has been successfully used as the superconducting metal by several groups for CMB experiments. However, achieving a repeatable and stable T_c requires careful thermal management that puts bounds on fabrication processes. We studied an alternative superconducting metal – Hafnium (Hf) is an attractive alternative as its bulk T_c is well matched to our needs and can also be deposited as a thin film as demonstrated by the microwave kinetic inductance detector (MKID) community. One critical differentiation between past Hf MKID fabrication processes and our own, is our use of a heated sputter deposition that enables us to finely tune the T_c to our desired target. Furthermore, the T_c remains robust against subsequent exposure to heat as long as the initial deposition temperature is not exceeded. As the deposition temperatures are high (ranging from 300℃ - 550℃, depending on the desired T_c), there is ample thermal budget for continued fabrication processes while maintaining a stable T_c. Additionally, by using an interdigitated geometry we are able to precisely design the normal resistance of the TES to anywhere between 1 Ohm and 10 milli-Ohm, making these TESs compatible with CMB experiments that use both time-domain as well as frequency-domain and microwave multiplexing readout systems. We present our findings of a Hf based TES bolometer designed for CMB experiments.