Commercially Fabricated Antenna-Coupled Transition Edge Sensor Bolometer Detectors for Next Generation Cosmic Microwave Polarimetry Experiment

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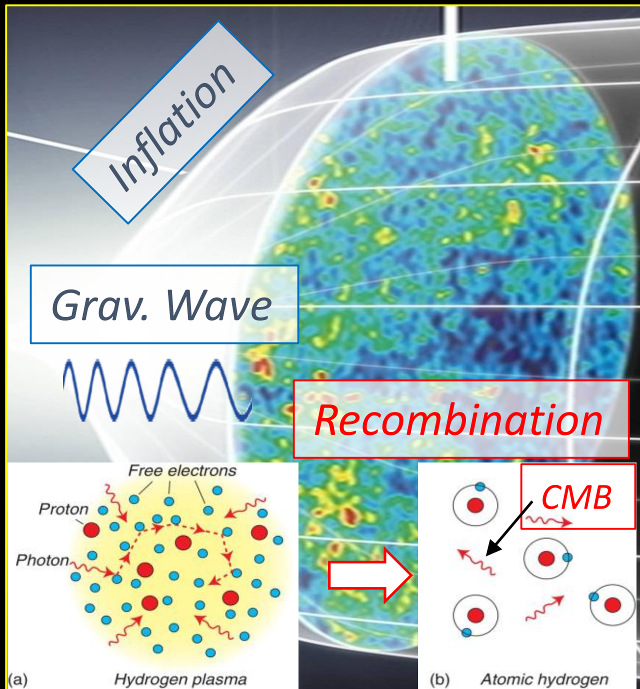
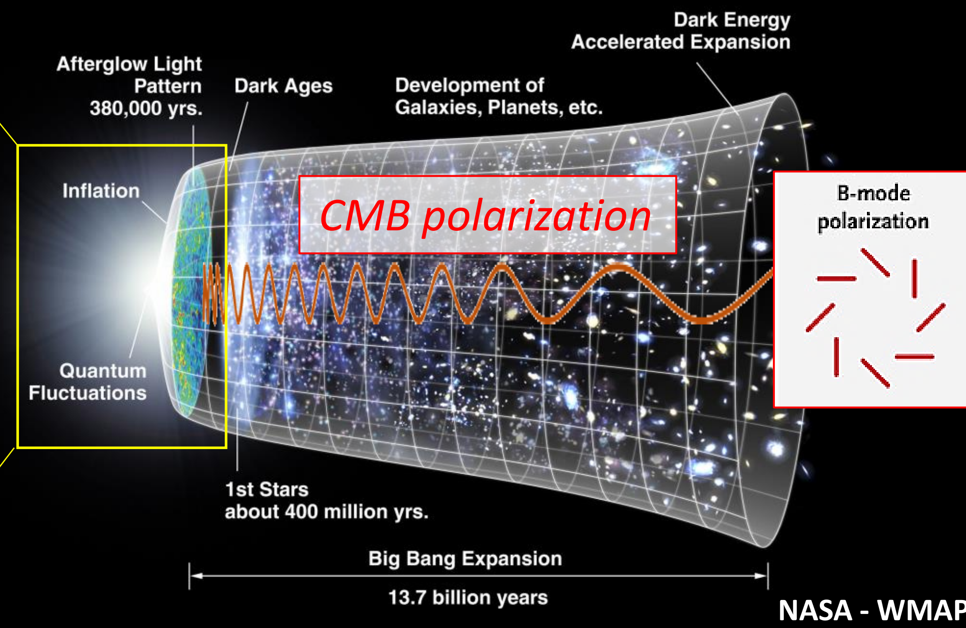
3) Cornell University
4) SeeQC-HYPRES, Inc.

Precision Cosmology with CMB





- Decades of efforts to characterize Cosmic Microwave Background radiation
  - Temperature anisotropy is characterized to cosmic variance limit (θ > ~0.1°)
  - Sub-percent constraints on cosmological parameters except for τ (opt. depth to reio.)

- CMB Polarization
  - Inflation: Large angular scale B-mode polarization pattern in the CMB
  - Light relics: History of relativistic particles. Alters CMB's power spectrum
  - Lensing: Cross-correlation with DESI, LSST. $\Sigma m\nu$

Current Experiments

Current experiments are on sky with ~10,000 detectors per telescope

Chile, Atacama


Atacama Cosmology Telescope


POLARBEAR/Simons Array


CLASS

Antarctica


South Pole Telescope

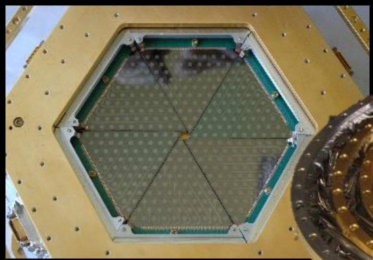
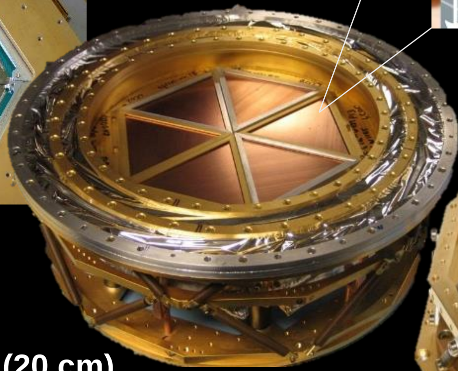
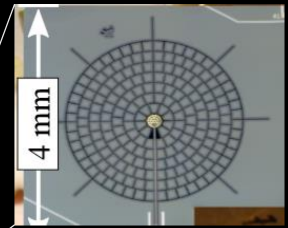
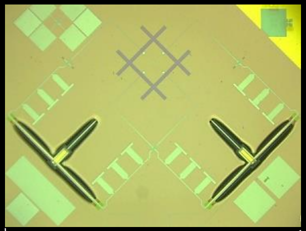
Bender (Wed)

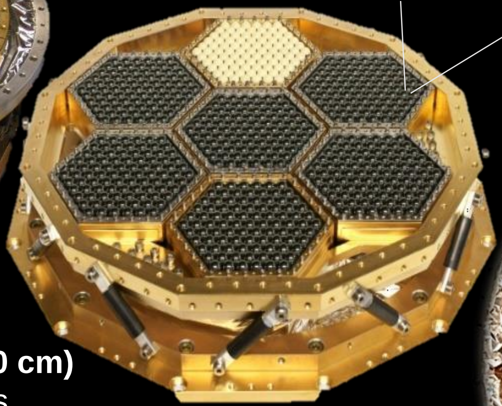
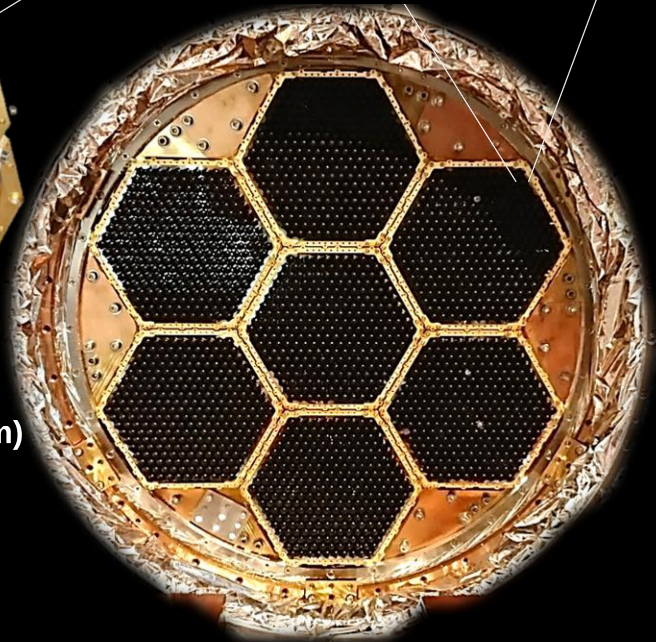

BICEP-2/Keck Array/ BICEP-3/ BICEP Array

Schillaci (Tue), Cukierman (Wed)


Spider

LTD

- Microfabricated antenna (horn, planar, phased array) coupled detectors
  - Transition Edge Sensor bolometer achieves photon-noise limited performance
- Increase optical throughput to improve sensitivity

Future Experiments

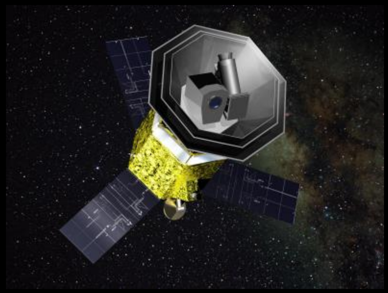
		# of detectors
~2011	Stage-2	~1,000
~2017	Stage-3	~10,000
~2020's	Stage-4	~500,000

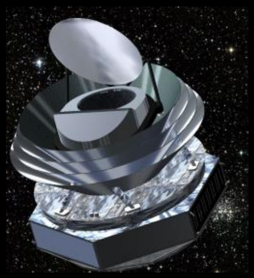
CMB experiment roadmap

- **Simons Observatory**
  - Chile, Atacama
  - 80,000 detectors
  - 2020 deployment
  - McCarrick, Dober (Wed)

- **CMB-S4 (Stage-4 CMB experiment)**
  - South Pole and Chile
  - ~500,000 detectors

- **Satellite Missions**
  - LiteBIRD - Sugai (Wed)
  - PICO





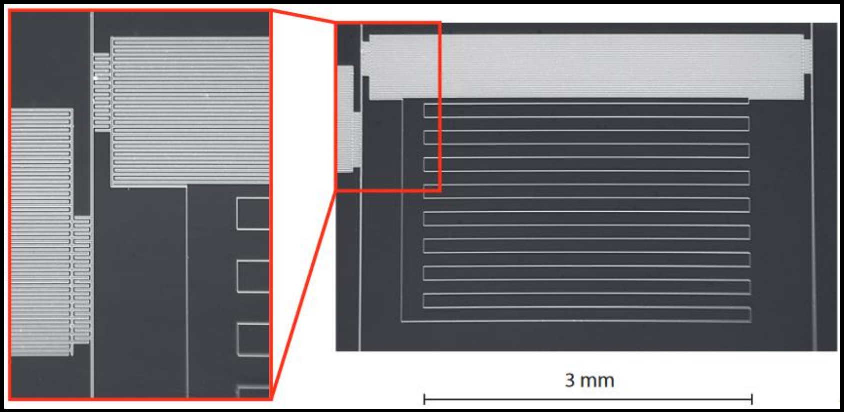
Challenge for next generation CMB experiment is understanding systematics even better and production throughput (especially for ground-based experiments)

Detector Production for Next Gen Experiment

Assume…

- 500 wafers in 2 years
- 2~3 sites fabricate detectors
- 75% yield…
- 40 fabrication weeks/year

Rate → 10 wafers per 3 weeks per site



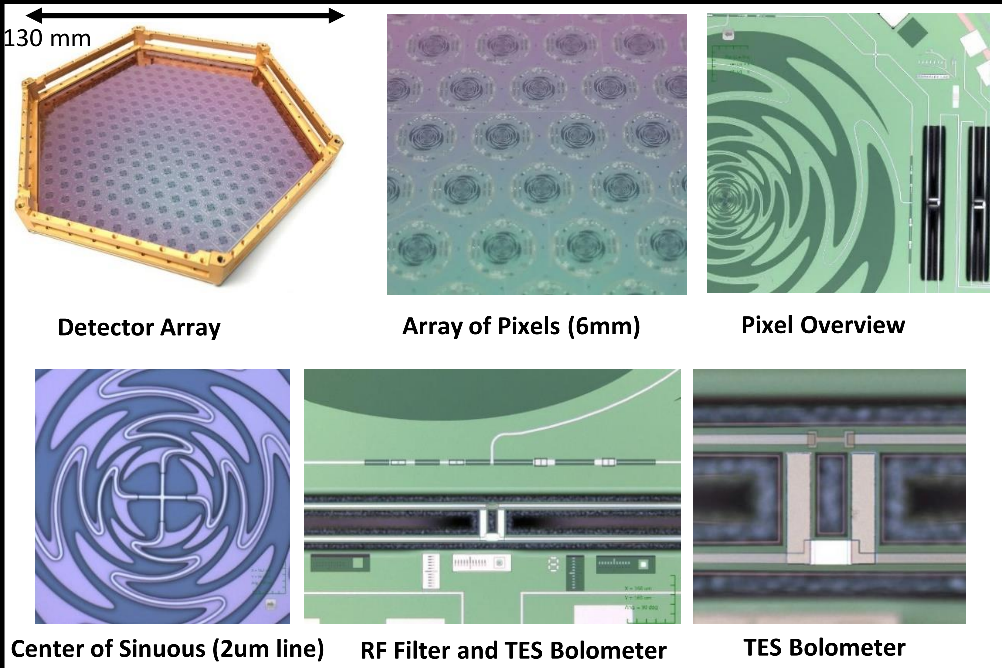
Commercial LEKID horn coupled detector fabricated by STAR Cryoelectronics (McCarrick et al 2014, arXiv:1407.7749)

Next generation ground based CMB experiment (CMB-S4) need to fabricate ~500 detector wafers
→ Orders of magnitude increase in wafer count from current experiments

Excitement in quantum computing expanded superconducting microfabrication capability in industry

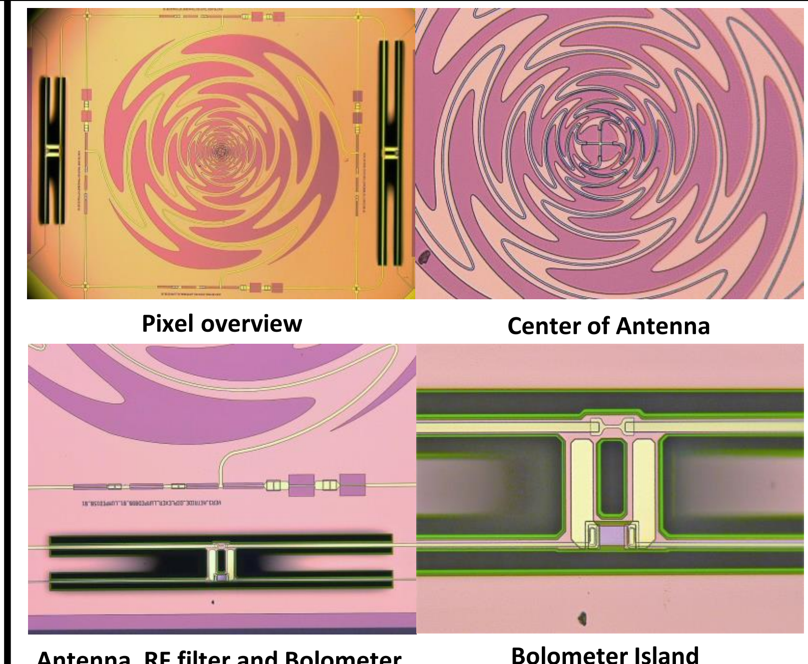
Can we merge industry's know-how on mass production and quality control and our knowledge of LTD to tackle production throughput challenge?

Commercially Fabricated TES bolometers



Detector Array | Array of Pixels (6mm) | Pixel Overview

Center of Sinuous (2um line) | RF Filter and TES Bolometer | TES Bolometer



Pixel overview | Center of Antenna

Antenna, RF filter and Bolometer | Bolometer Island

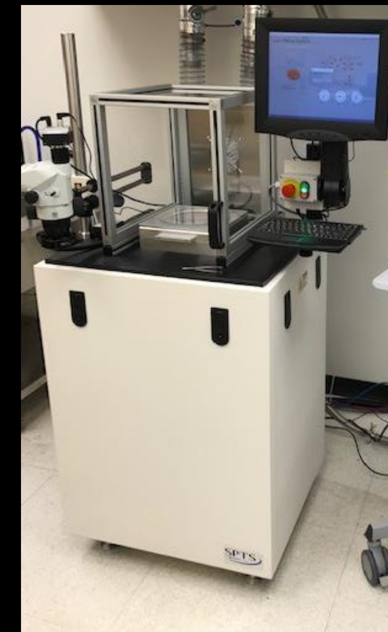
HYPRES The Digital Superconductor Company™ | SeeQC | STAR Cryoelectronics

- Strong support on knowledge/technology transfer from academia to industry - SBIR
- We worked with companies that specializes in superconducting microfabrication
  - HYPRES/SeeQC and STAR Cryoelectronics
- Successfully fabricated sinuous antenna coupled transition edge sensor detectors with both companies

My experience with HYPRES/SeeQC Inc.

Stepper lithography machine operated by dedicated engineer

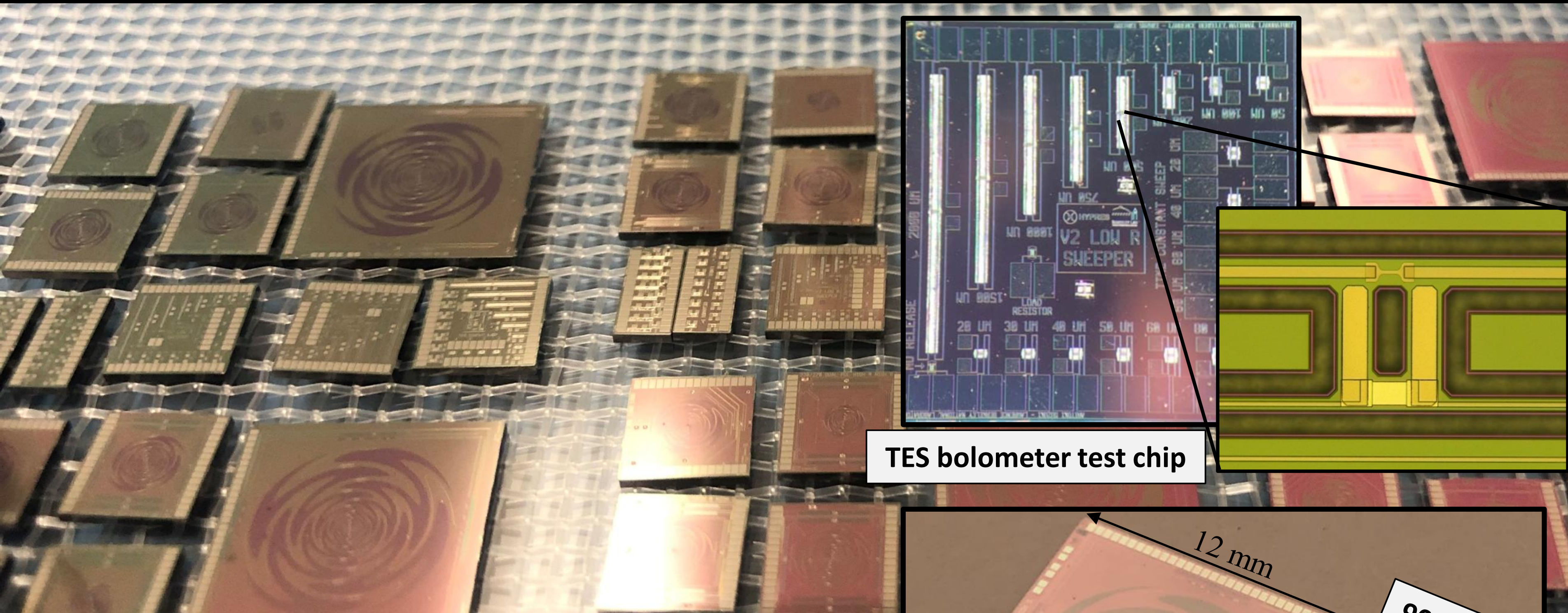
High throughput e-beam evaporator

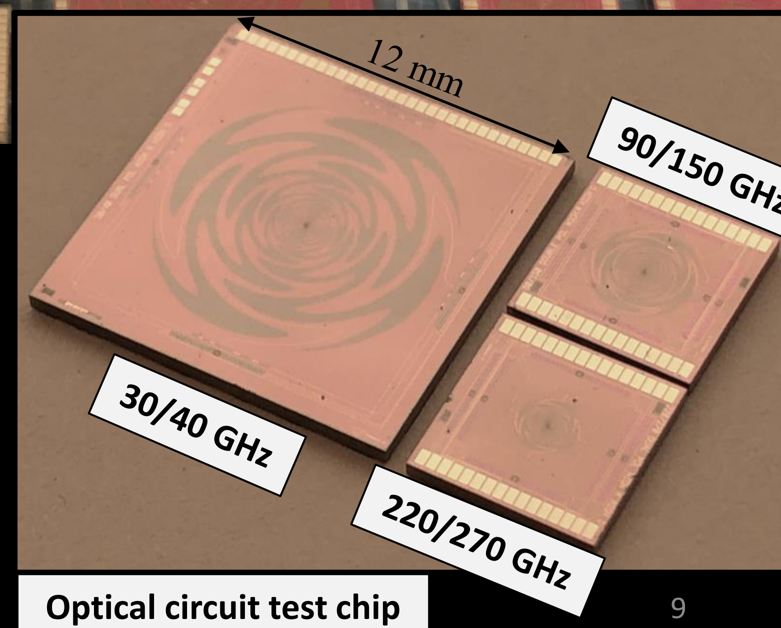


XeF2 machine Installed at SeeQC

- PhD Engineers that speak common superconducting fabrication language
- Controlled environment
- High throughput industrial equipment
- Many materials and steps are similar. 6-inch process.
- Some differences: Installed XeF2 machine and special alloy (AlMn)
- Exchanged detailed documentation and specification sheet

R&D Approach



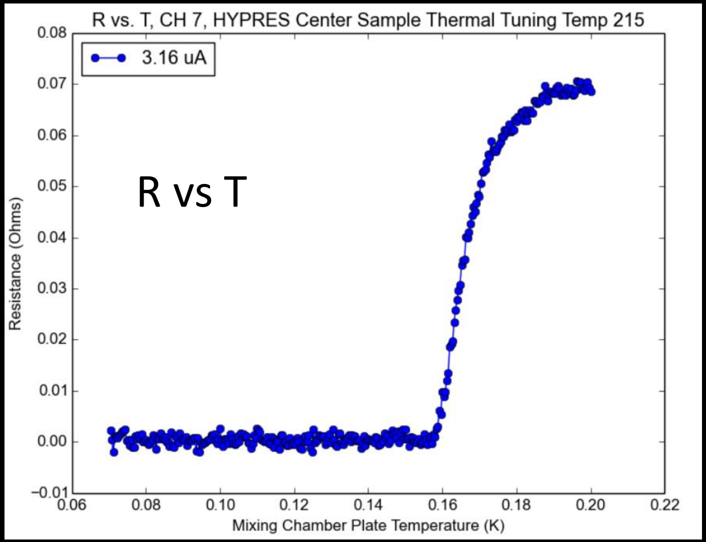


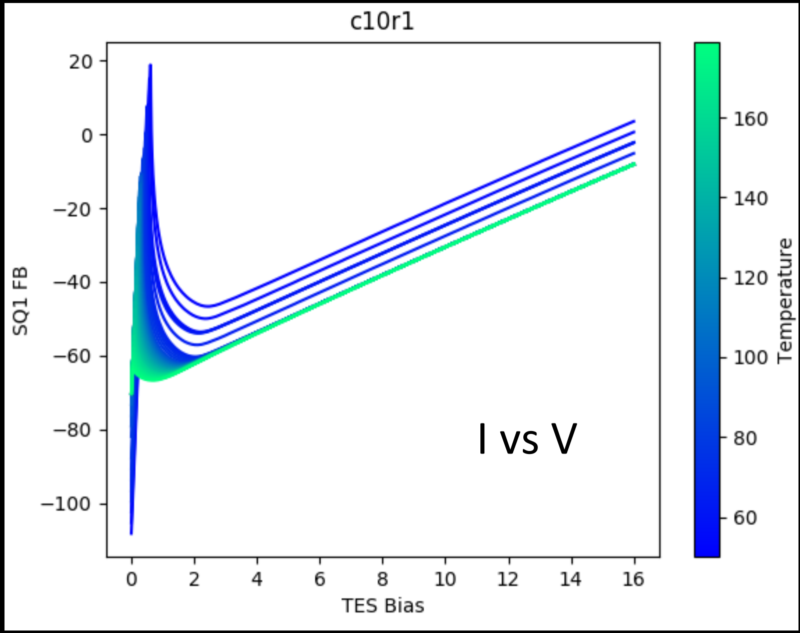
- Try out many different designs on one wafer
  - Converge on design quickly

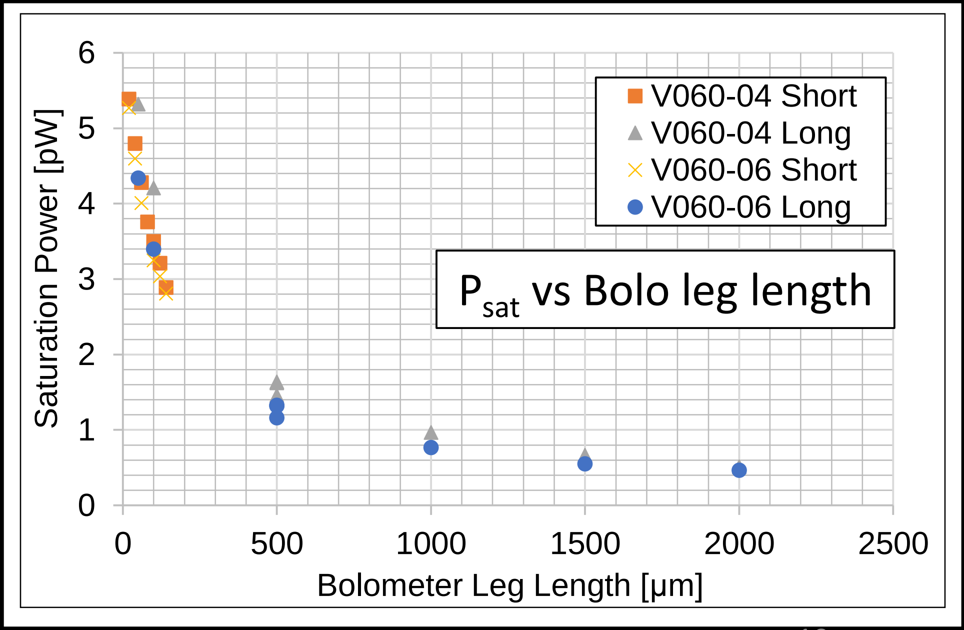
- Examples:
  - Bolometer leg length sweep
  - Optical chip with different band pass filters

Transition Edge Sensor Bolometer Performance

- **TES film development**
  - Installed aluminum-manganese targets at SeeQC
  - Dedicated a sputtering chamber
  - Found correct manganese concentration and annealing temperature for **Tc = 165 mK**
- **Bolometer leg length development**
  - Saturation power (P_{sat}) = 0.5 pW ~ 5.5 pW
  - Good range for CMB experiments

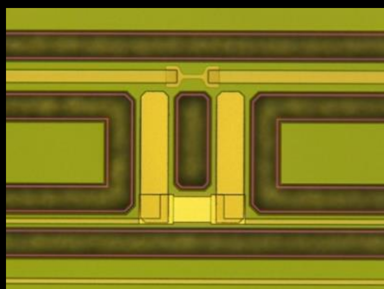






TES Bolometers for Multiple Readout Types

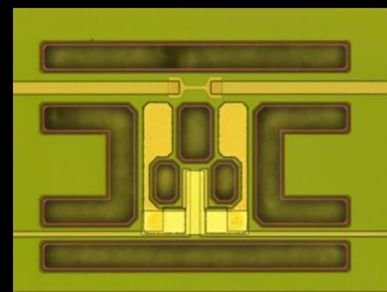
Frequency domain
Multiplexing Readout



TES bolometer
For fmux

R = 0.7 Ω

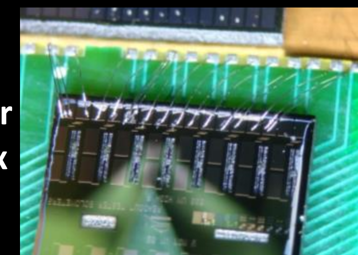
Time domain
Multiplexing Readout

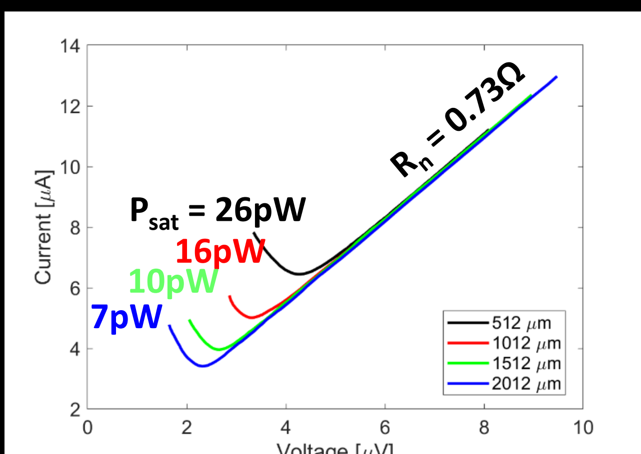


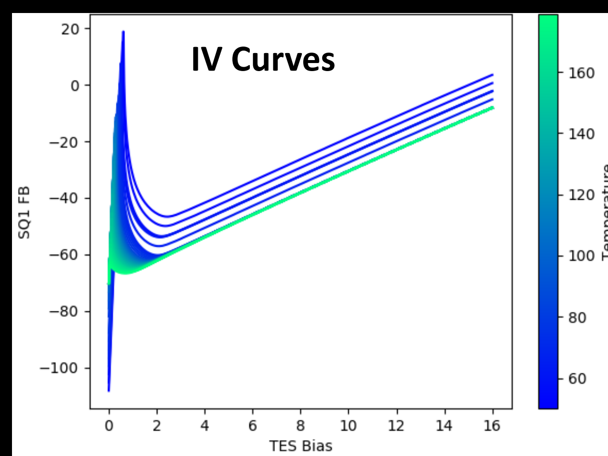
TES bolometer
for tdm/umux

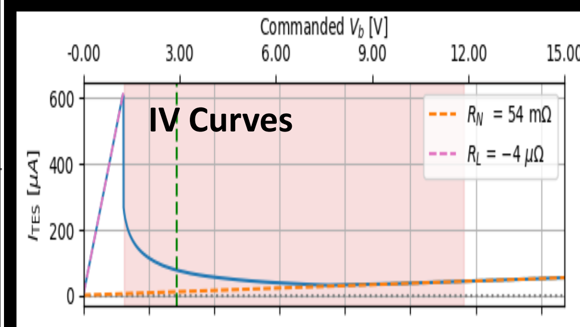
R = 8 mΩ

Microwave SQUID
Multiplexing Readout



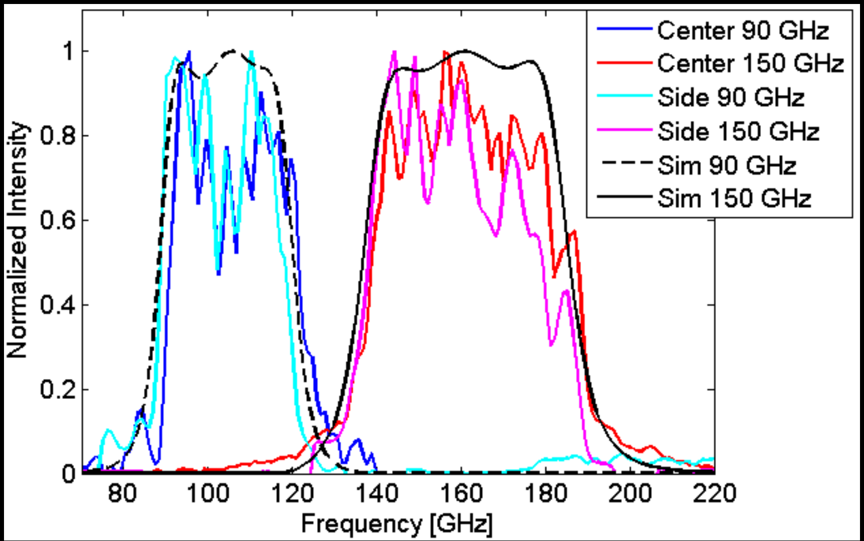




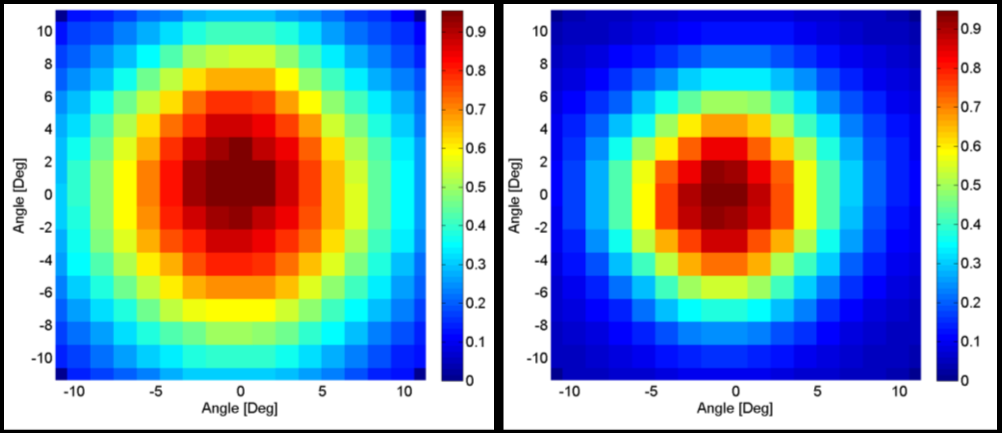


HYPRES/SeeQC detectors coupled to three readout technologies used by CMB experiments

Optical Performance



Spectra



90 GHz band 150 GHz band

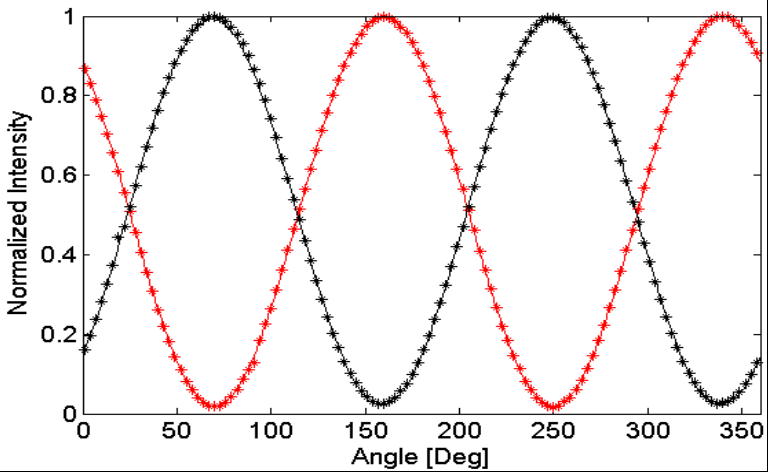
Beams

Dual frequency band, dual polarization pixel

Efficiency from outside of the dewar to bolometer

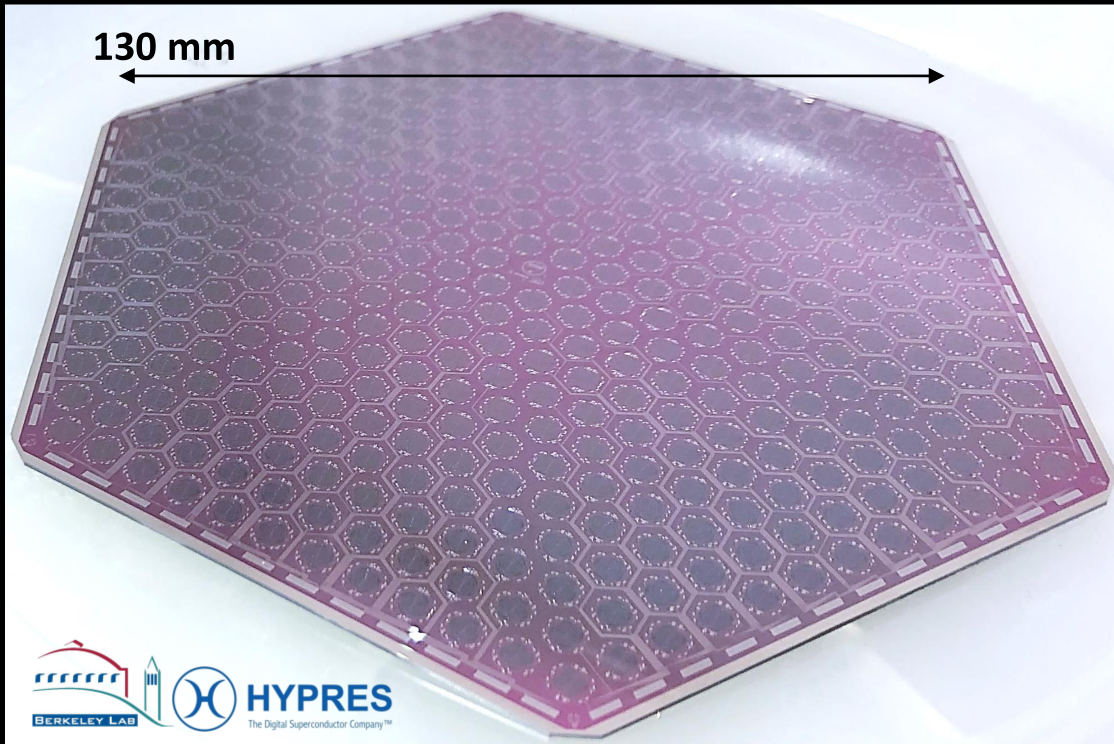
- 90 GHz band: ~70%
- 150 GHz band: ~50%

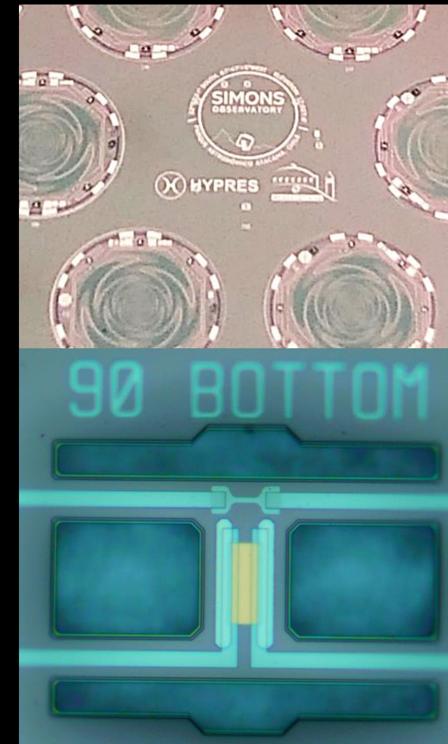
Increased optical efficiency by using silicon-rich silicon nitride film



Polarization (rotating wire grid)

Deployable Detector Array Fabrication

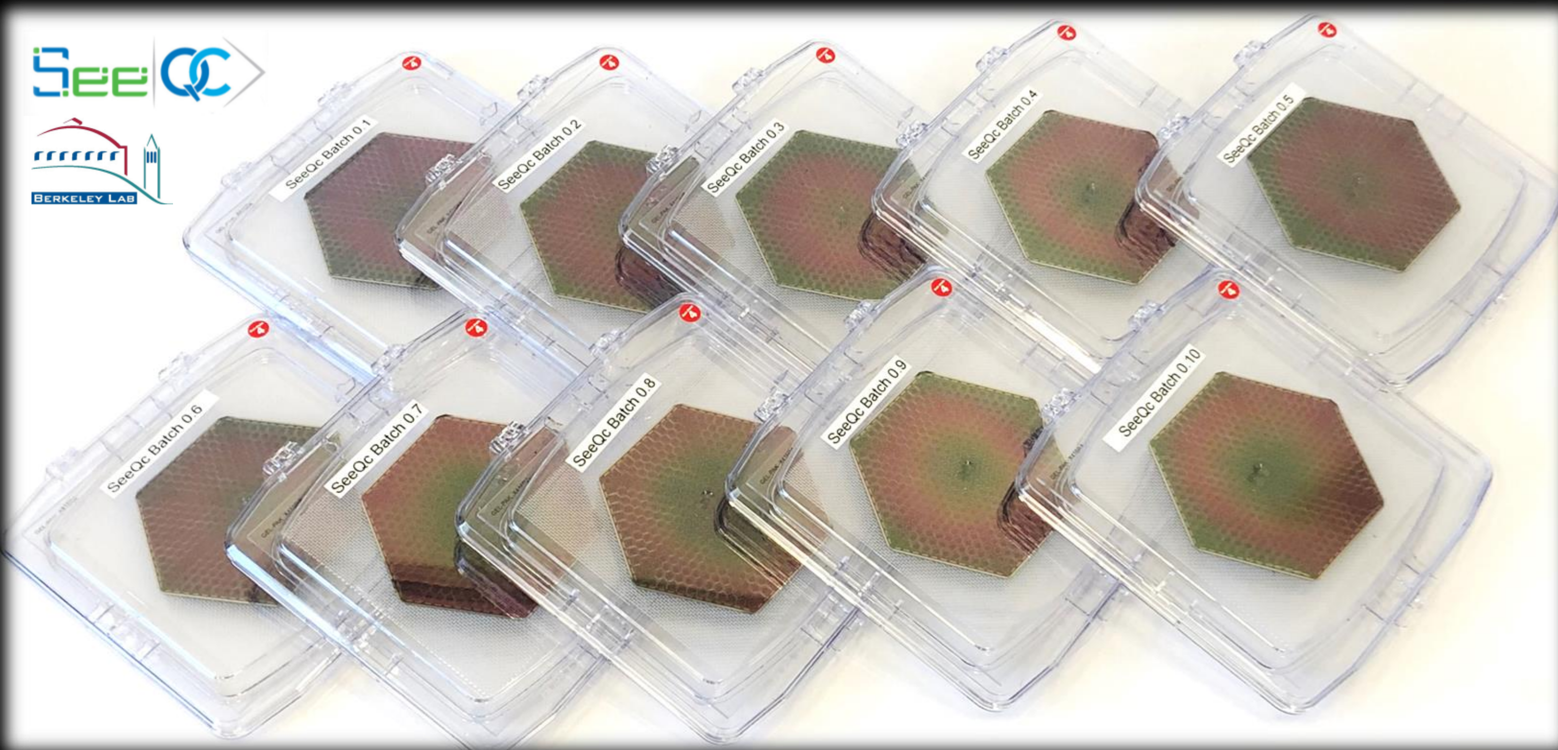




- We successfully fabricated detector array for Simons Observatory (SO) receiver
  - Fully SO compatible design. 90/150 GHz dual band dual polarized detector array

- Deploy HYPRES/SeeQC array as a demo once the array is fully vetted
  - Great way to raise Technology Readiness Level (TRL) of this approach

Batch Fabrication Demonstration



- Fabricated 10 wafer batch in 15 working days (3 weeks)
    - Achieved target, but want to go faster

- 15 working days include making monitor samples, metrology and documentation
- We identified bottle neck during the process – upgrading equipment to fabricate faster

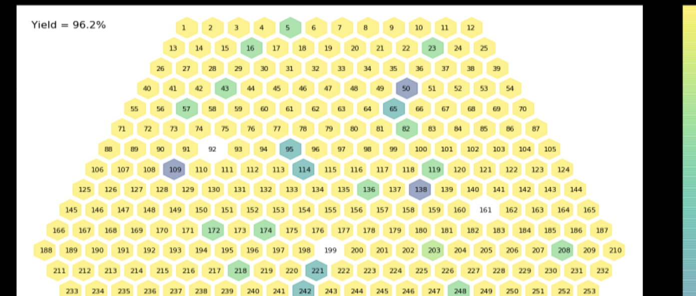
Metrology: Uniformity, Repeatability, Yield

Low stress PECVD SiNx (target 10,000 A)									
Wafer-ID	Top	Middle	Bottom	Left	Right	Monitor	Average	% stdev	Dev Target %
V08-Batch0.01	9935	9964	10024	9923	10021	9730	9973.4	0.47%	-0.266
V08-Batch0.02	9865	9961	9938	9862	9931	9791	9911.4	0.46%	-0.886
V08-Batch0.03	10038	10167	10053	9994	10069	10016	10064.2	0.63%	0.642
V08-Batch0.04	9991	9969	10082	9946	10057	10184	10009	0.58%	0.09
V08-Batch0.05	9870	9880	9943	9836	9913	9992	9888.4	0.42%	-1.116

Nb ground (target 3,000 A)										
Wafer-ID	Top	Middle	Bottom	Left	Right	Monitor	Average	% stdev	SheetR	Stress
V08-Batch0.01	3227	3209	3336	3288	3195	3137	3251	1.82%	0.57	-285
V08-Batch0.02	3188	3197	3291	3278	3185	3137	3227.8	1.62%	0.57	-285
V08-Batch0.03	3222	3211	3262	3172	3303	3141	3218.5	1.56%	0.57	-356
V08-Batch0.04	3237	3170	3244	3277	3166	3141	3205.833	1.52%	0.57	-361
V08-Batch0.05	3026	2995	3049	3064	2969	3028	3021.833	1.29%	0.6	-376
V08-Batch0.06						3028	3032.667	1.46%	0.6	-354
V08-Batch0.07						3093	3087.5	1.30%	0.6	-342
V08-Batch0.08						3093	3081.5	1.30%	0.6	-308
V08-Batch0.09						3095	3159.167	1.62%	0.58	-366
V08-Batch0.10						3095	3146	1.28%	0.58	-328

AlMn (target 5,000 A)				
Wafer-ID	Thickness	SheetR	Anneal tem	Stress
V08-Batch0.01	4837	0.105	215	
V08-Batch0.02	4837	0.105	215	310
V08-Batch0.03	4854	0.101	214	321
V08-Batch0.04	4854	0.101	214	331
V08-Batch0.05	5003	0.1	216	
V08-Batch0.06	5003	0.1	216	
V08-Batch0.07	4924	0.1	215	330
V08-Batch0.08	4924	0.1	215	326
V08-Batch0.09	4833	0.103	215	
V08-Batch0.10	4833	0.103	215	

DC probe (room temp) result



Metrology: Absolute thickness, uniformity & repeatability of films

Automated DC probing station

- 95% average warm DC yield – automated probe station
- Film property
  - Silicon nitride — within 1% of target thickness, < 1% uniformity
  - Niobium — within 8% of target thickness, < 1.8% uniformity
  - AlMn — within 3% of target thickness, sheet resistance vary by < 5%
- Next step is to cryogenically test detector arrays (so far tests were done at pixel level)

Summary

The CMB polarization measurement is entering very exciting era.
Challenges for next generation experiments are:
production throughput and understanding systematics

We have fabricated antenna-coupled TES detector array to show that partnering with industry is a great way to tackle production throughput challenge

Next:

- Test detector arrays in cryogenic environment
- Expand to low (30/40 GHz) and high (220/280 GHz) frequency range
- Explore detectors with different optical coupling
- Explore to see if we can apply SeeQC's capability to other LTD needs