Advanced ACTPol Multichroic Horn-Coupled Polarimeter Array Fabrication on 150 mm Wafers

Shannon M. Duff – NIST
for the Advanced ACTPol Collaboration

LTD16
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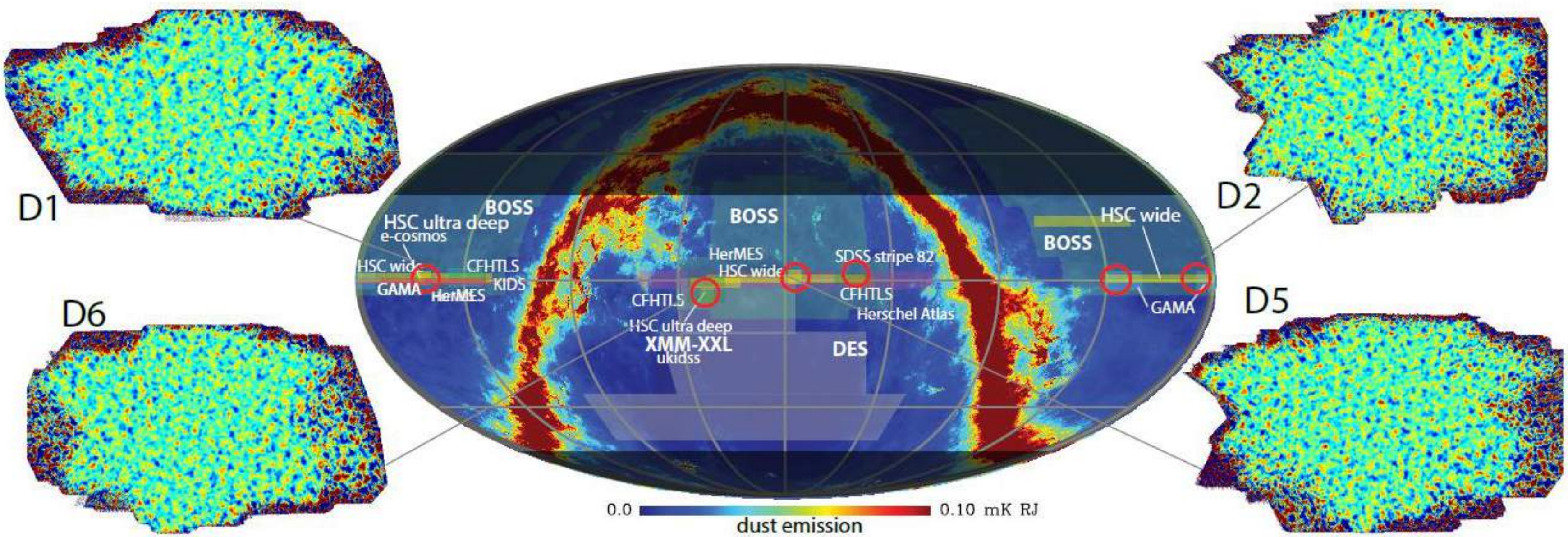
Grenoble, France

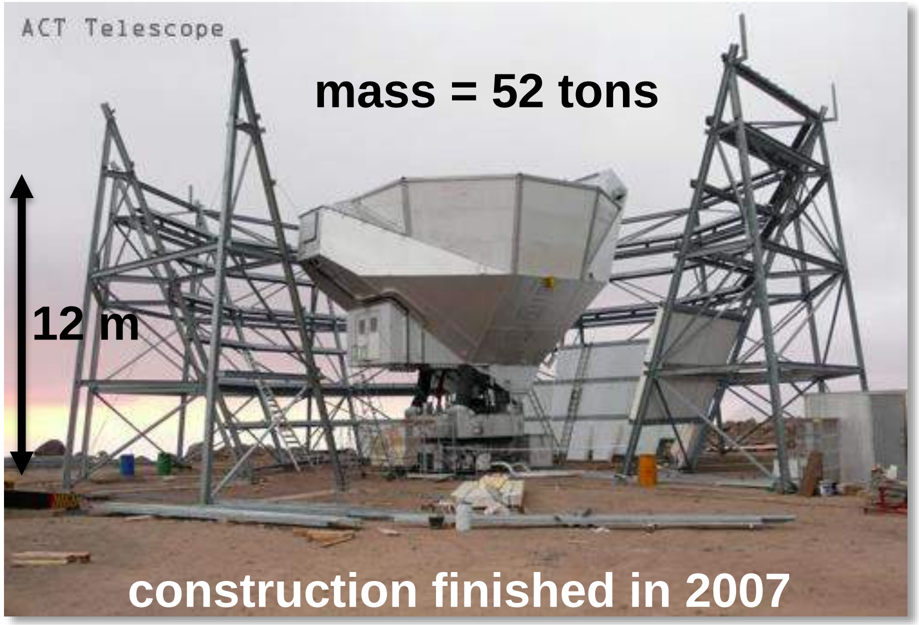
Why Long-λ Detectors for CMB?



Credit: Naess et. al.

- Already helped establish ΛCDM, allowing for new understanding of universe
- Technology to enable measurement of polarization and temperature anisotropies
  - Inflationary gravitational waves
  - Sum of neutrino masses

Atacama Cosmology Telescope (ACT)



Instrument Generations

1. MBAC (2008-2010)
   - 3 x 1000 pixel TES bolometer focal planes
   - 150 GHz, 220 GHz, 280 GHz
2. ACTPol (2013-2016)
   - 3 TES polarimeter focal planes
   - 2 x 500 pixel (1000 TES) 150 GHz polarimeters
   - 1 x 255 pixel (1020 TES) 90/150 GHz polarimeters
3. Advanced ACTPol (2016 onward)
   - Staged deployment of TES polarimeters in 5 bands
   - 1 x 503 pixel (2012 TES) 150/230 GHz polarimeters
   - 2 x 430 pixel (3440 TES) 90/150 GHz polarimeters
   - 1 x 40 pixel (160 TES) 28/41 GHz polarimeters

3rd Generation

- **Scaling (pixel count, bands per wafer, # wafers)**
- **Simplification (fabrication, layout)**
- **Production time (# wafers, fab time)**

4th Generation…

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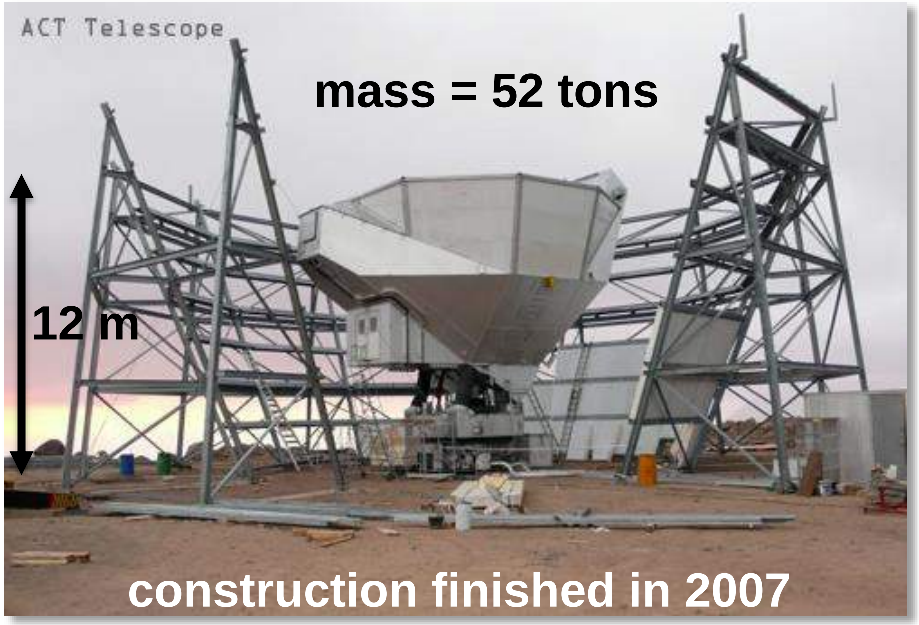

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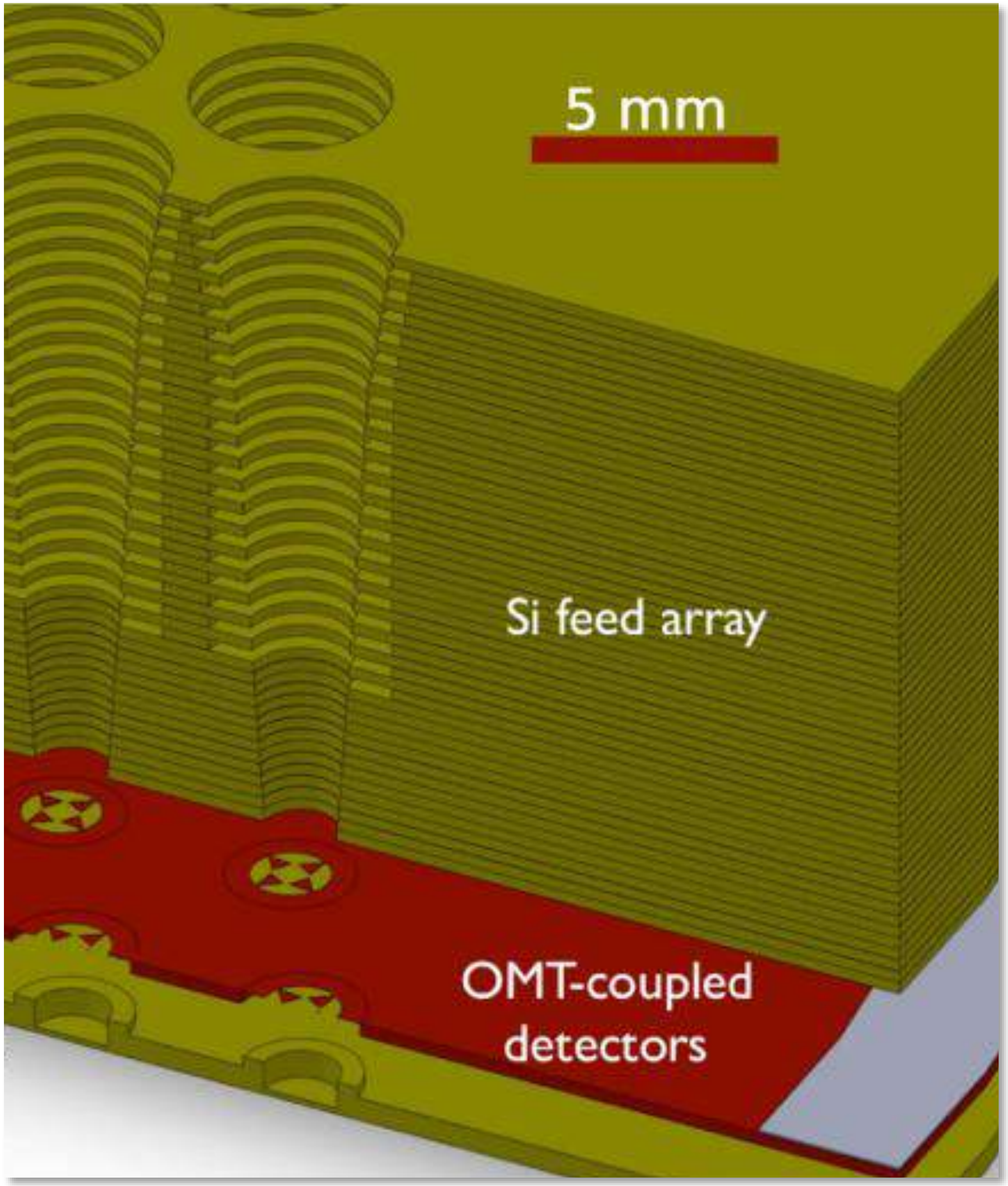
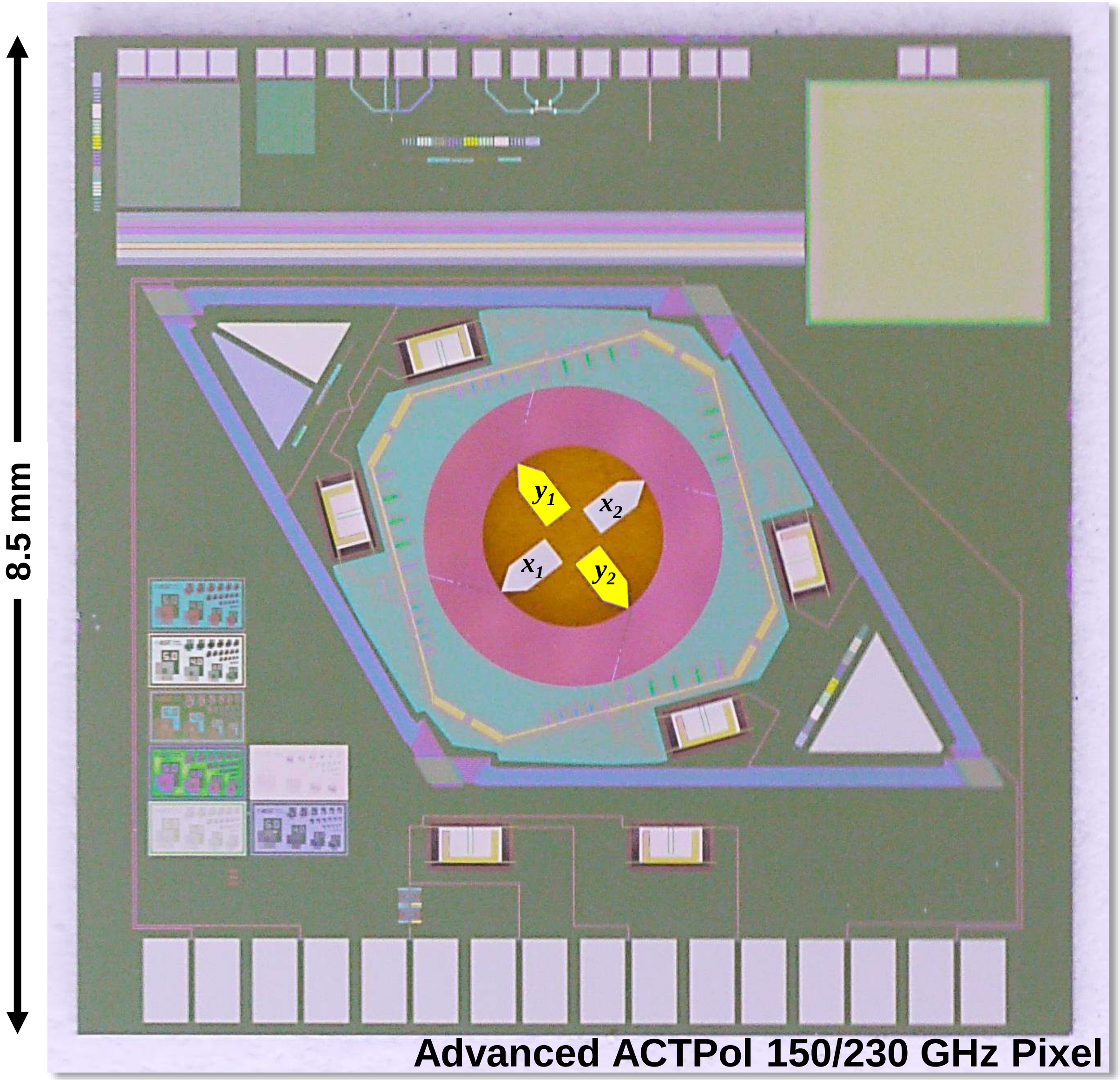
In same focal plane footprint, Advanced ACTPol to achieve 40% increase in mapping speed at 150 GHz + entirely new frequency band at 230 GHz!

Multichroic Feedhorn-Coupled Polarimeters

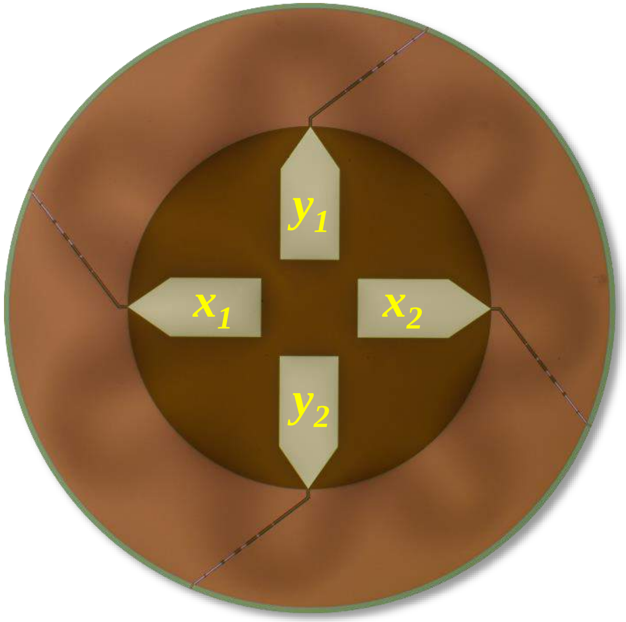


- Repeatable band edges
- Excellent noise performance
- ~1 ms time constants
- Excellent beam properties
- High coupling efficiencies

Multichroic Detector Cell



- Couple light from horn to TL via OMT, separate *x* & *y* linear polarizations



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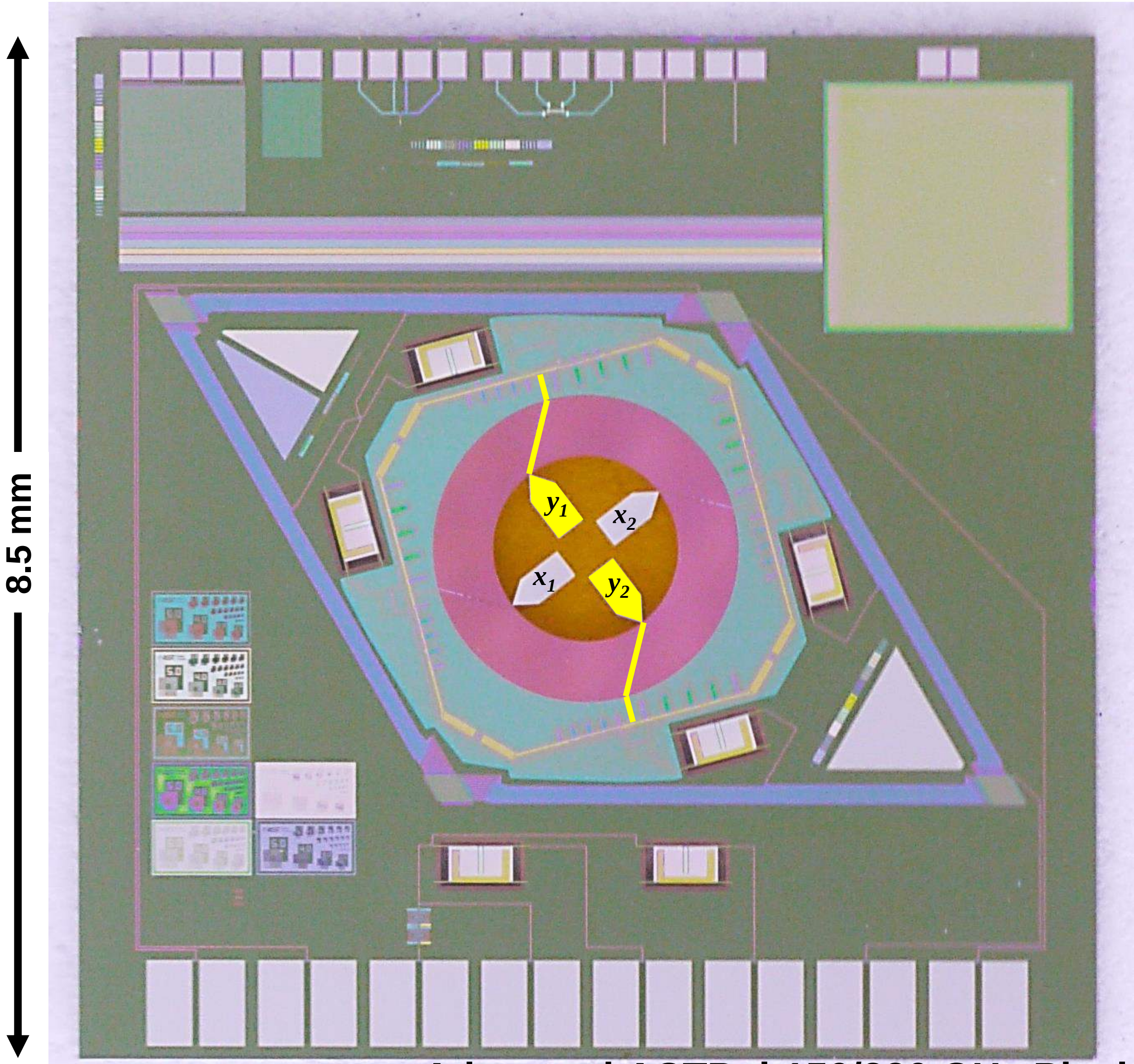
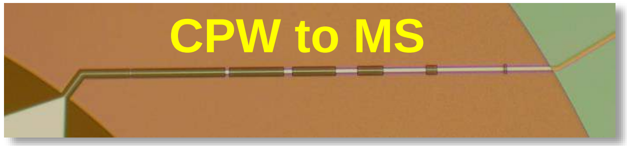
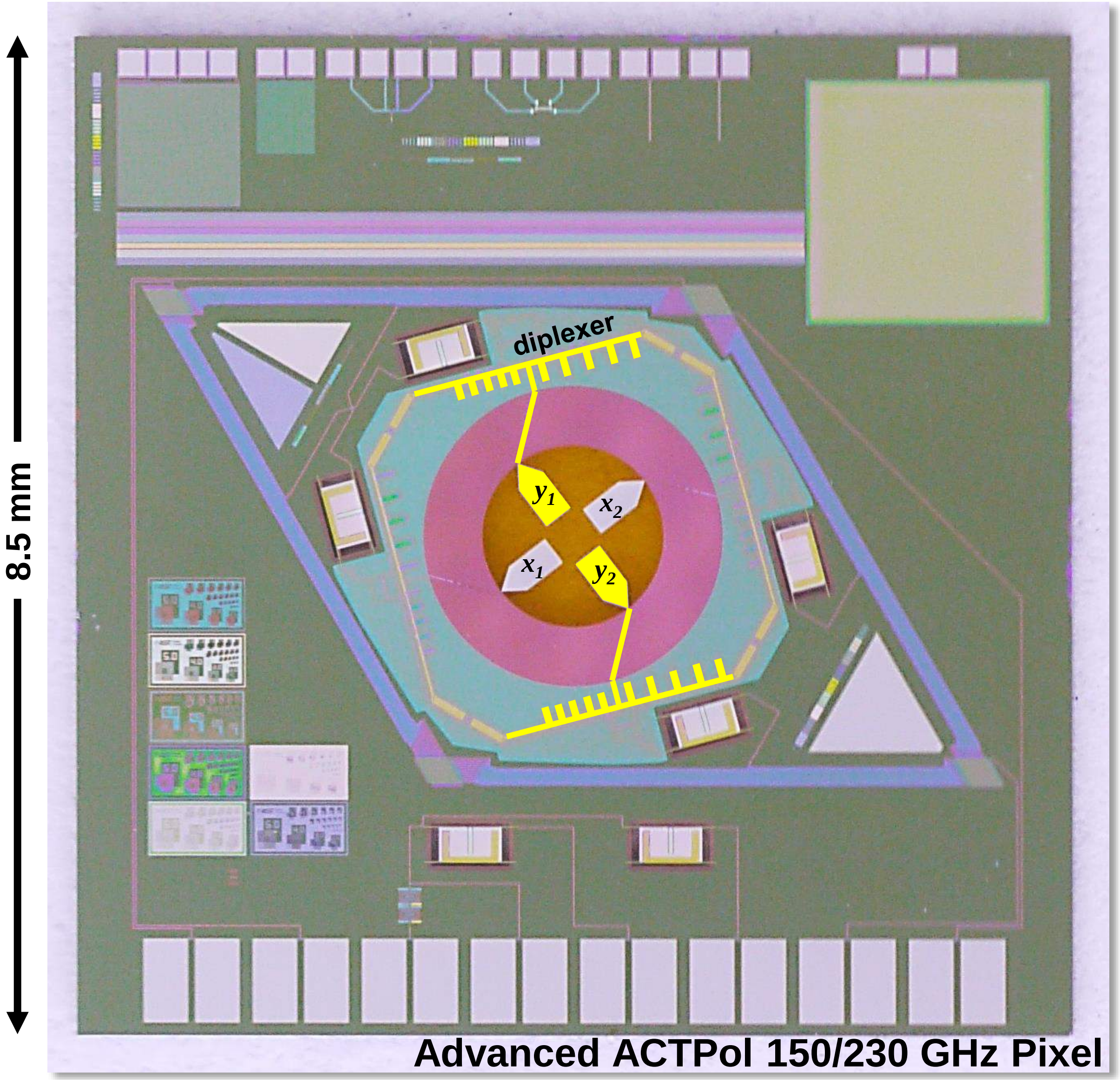


Advanced ACTPol 150/230 GHz Pixel

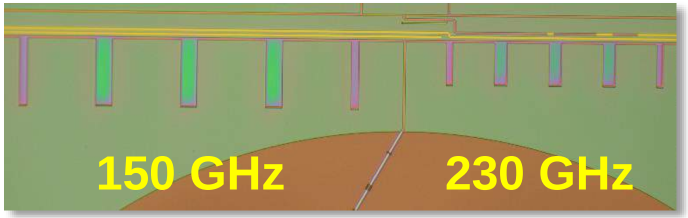
- Couple light from horn to TL via OMT, separate *x* & *y* linear polarizations
- CPW to MS transition



Multichroic Detector Cell



- Couple light from horn to TL via OMT, separate *x* & *y* linear polarizations
- CPW to MS transition
- Filter into two bands



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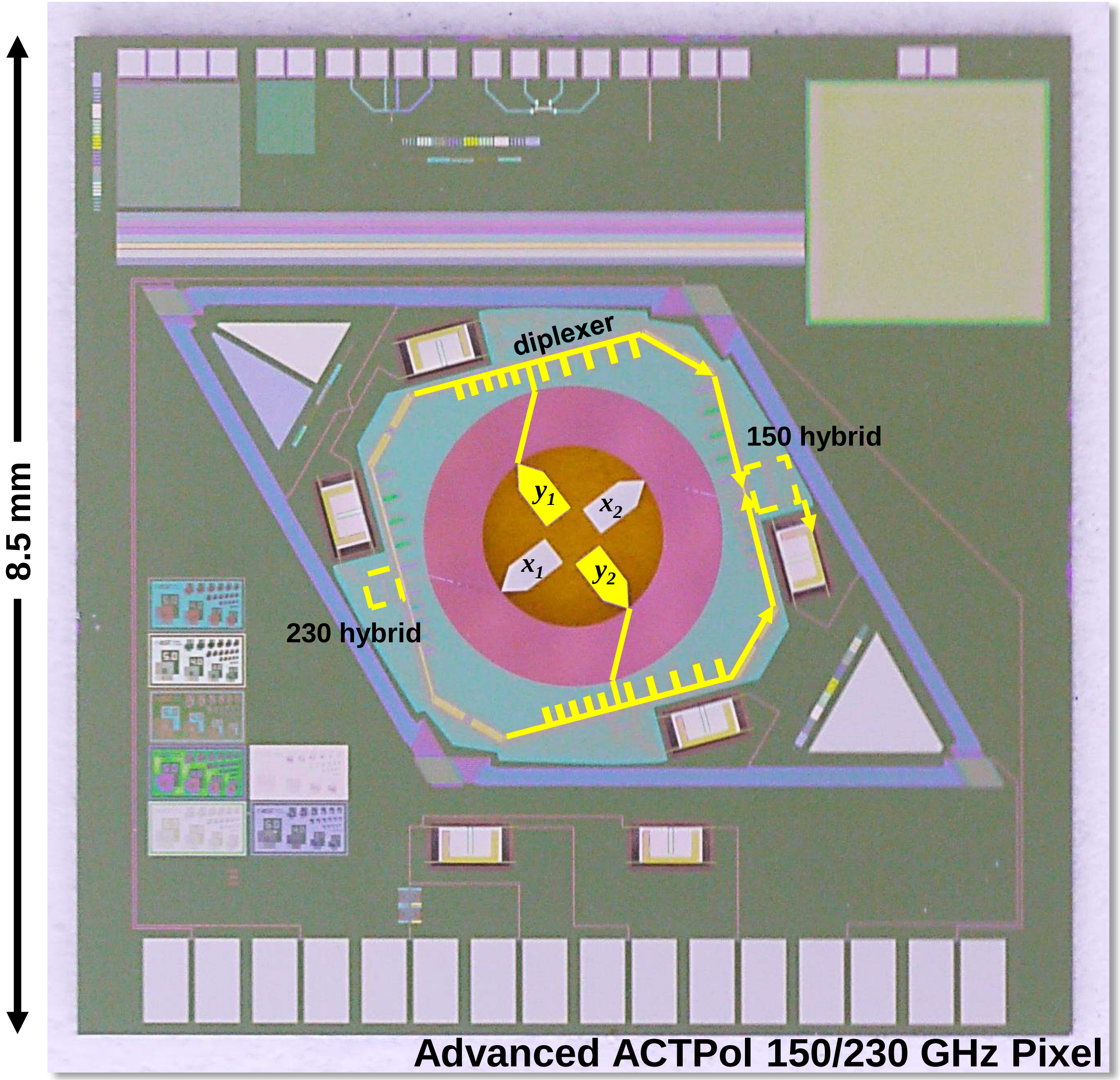
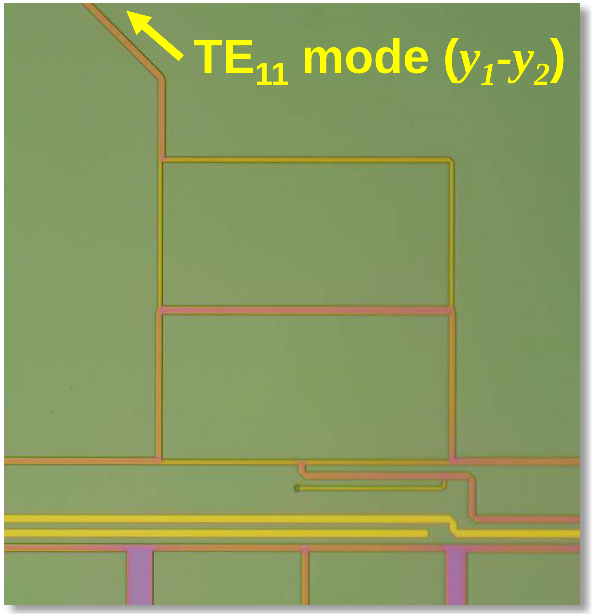


- Couple light from horn to TL via OMT, separate *x* & *y* linear polarizations
- CPW to MS transition
- Filter into two bands
- Combine lowest order mode/reject others



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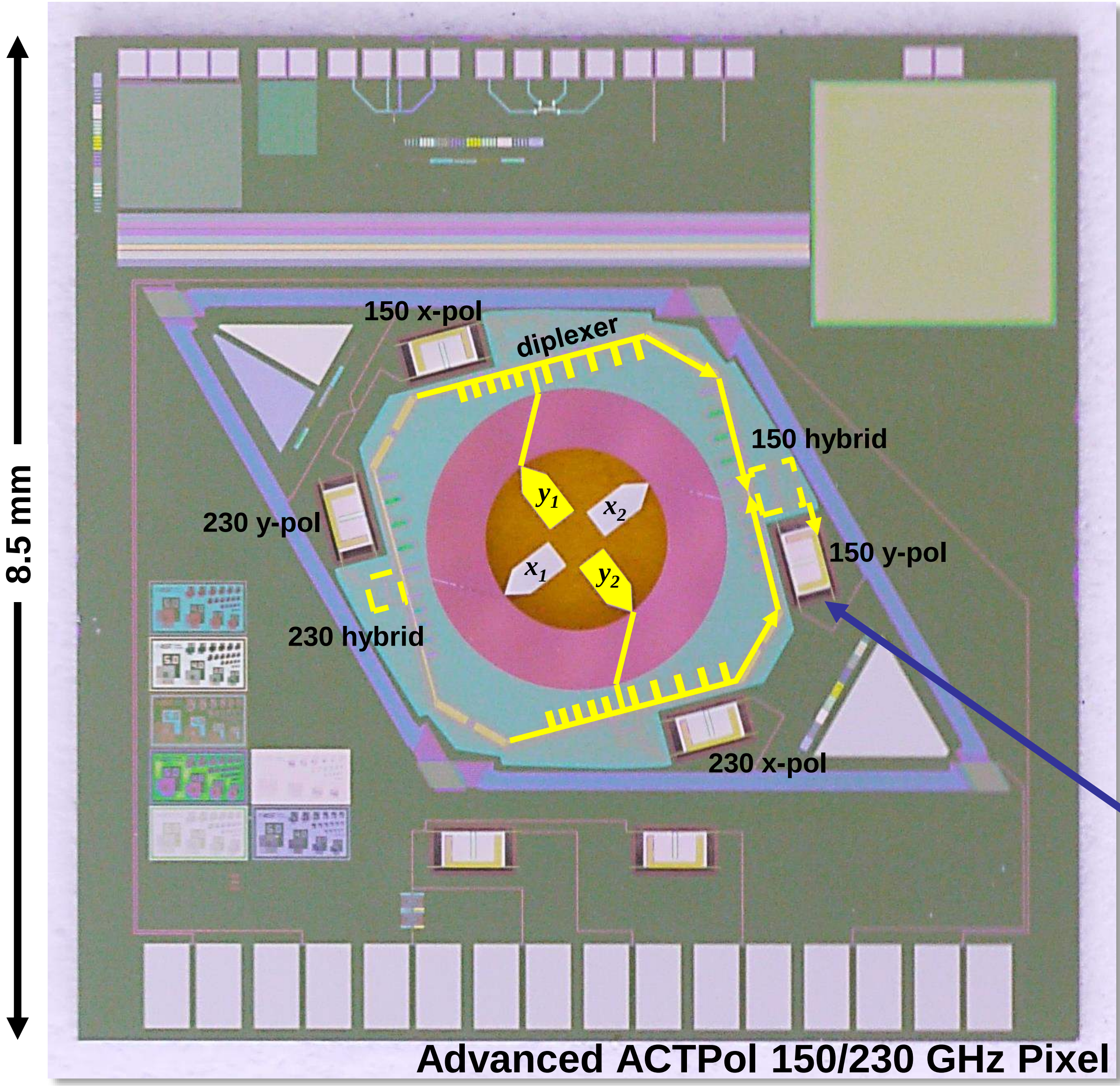
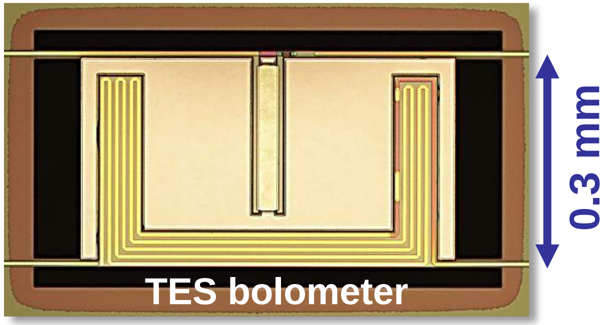


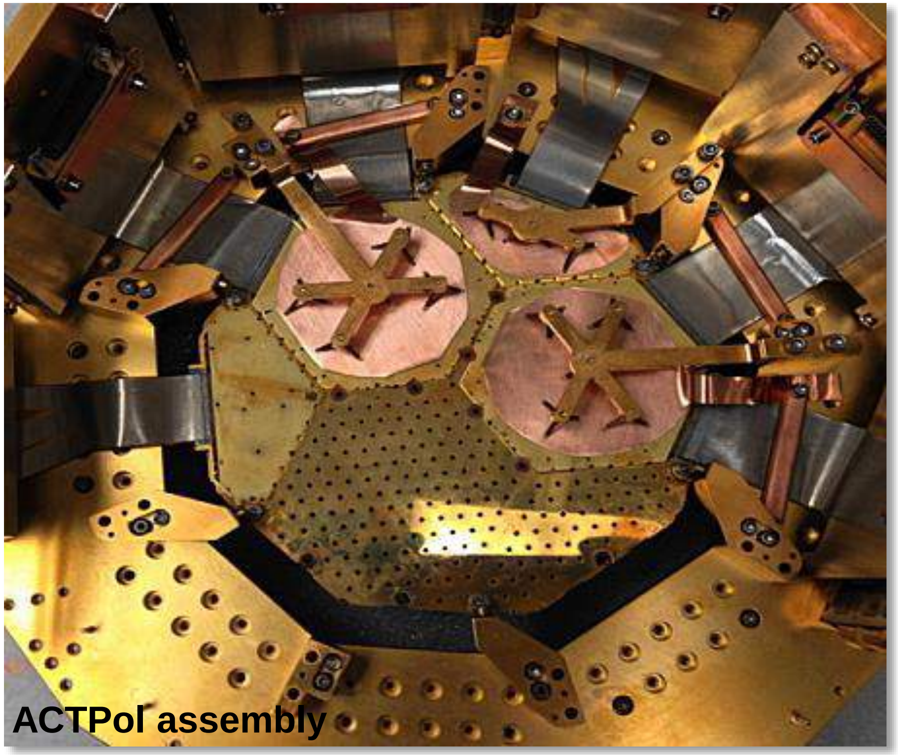
- Couple light from horn to TL via OMT, separate *x* & *y* linear polarizations
- CPW to MS transition
- Filter into two bands
- Combine lowest order mode/reject others
- TES detects polarization and bands



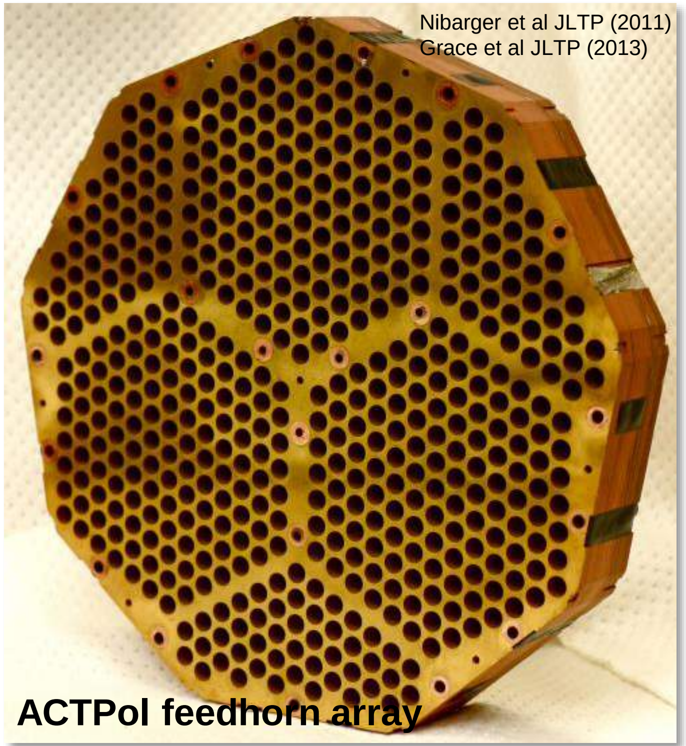
ACTPol Detectors

- Successful integration of first multichroic polarimeter arrays in the ACT (90/150 GHz)
- Polarimeter arrays fabricated on 3 inch wafers, tiled in assembly
- Feedhorns fabricated monolithically on 150 mm wafers

ACTPol 90/150 GHz detector array



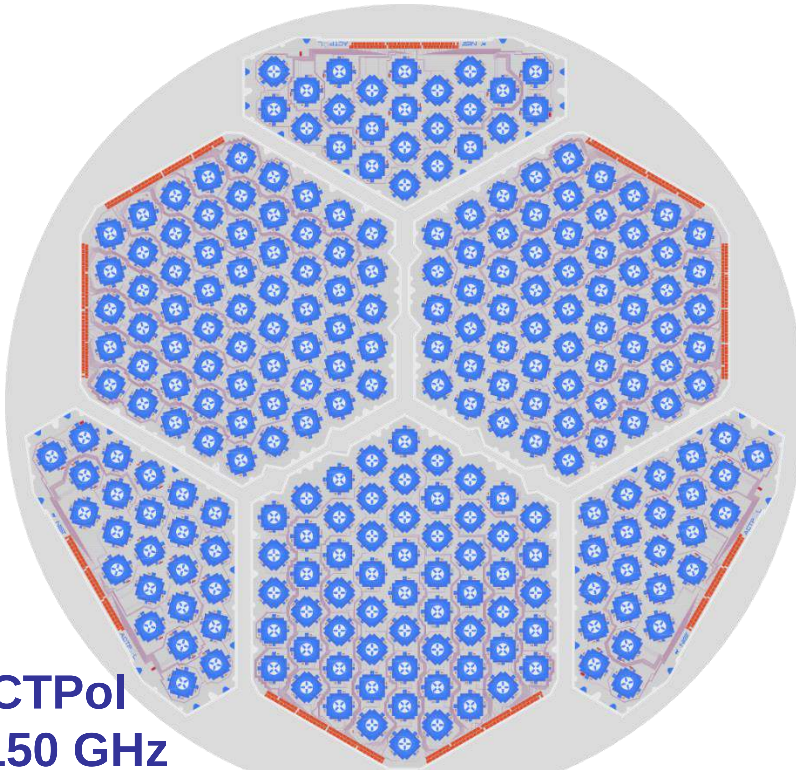
ACTPol assembly



Nibarger et al JLTP (2011)
Grace et al JLTP (2013)

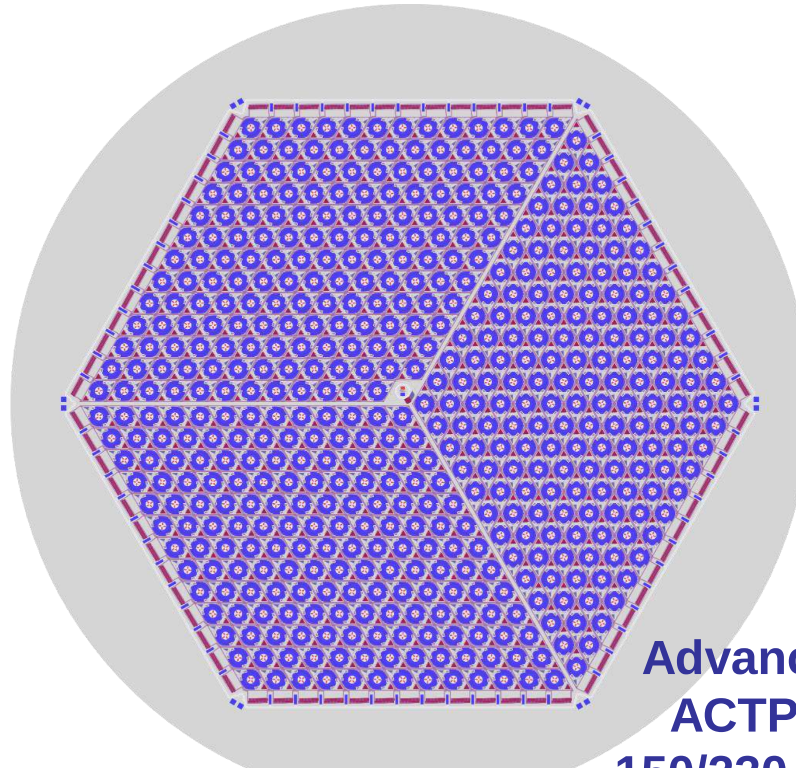
ACTPol feedhorn array

ACTPol to Advanced ACTPol



ACTPol
90/150 GHz

150 mm



Advanced
ACTPol
150/230 GHz

	Wafer Count	Pixel Count	TES Count
ACTPol 90/150 GHz	5 x 3 inch wafers	255	1020
Advanced ACTPol 150/230 GHz	1 x 150 mm wafer	503	2012

Simplifications and Improvements

	ACTPol	Advanced ACTPol	Simplifications & Improvements
Wafer count	5 x 3 inch	1 x 150 mm	Pixel density, cost, time
Unit steps	85 steps	63 steps	Risk, time, scalability
TES material	MoCu	AlMn	T_c uniformity, reproducibility, eliminates lithography step(s), post-deposition tuning
Dielectric material	SiO_x	SiN_x	Improves detection efficiency
Microwave components	Cross-over	Cross-under	Minimize reflections/crosstalk, eliminate 2 layers
Lithography	Stepper + contact printer	Stepper	Yield, dimensions, speed
Layout	Manual	Partially automated	Speed, flexibility, risk

150 mm Detector Arrays

- Historically, detector arrays fabricated on 3 inch wafers
- To scale to 3rd Generation+, necessary to move to 150 mm wafers
  - Sensitivity increases as detector arrays become more dense

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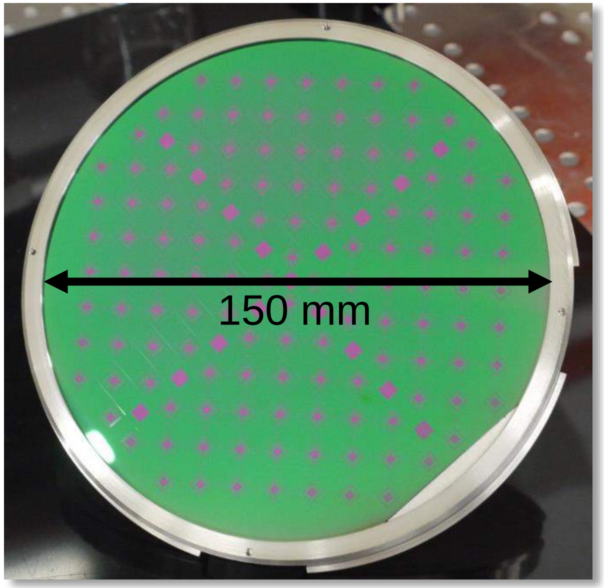
Uniformity



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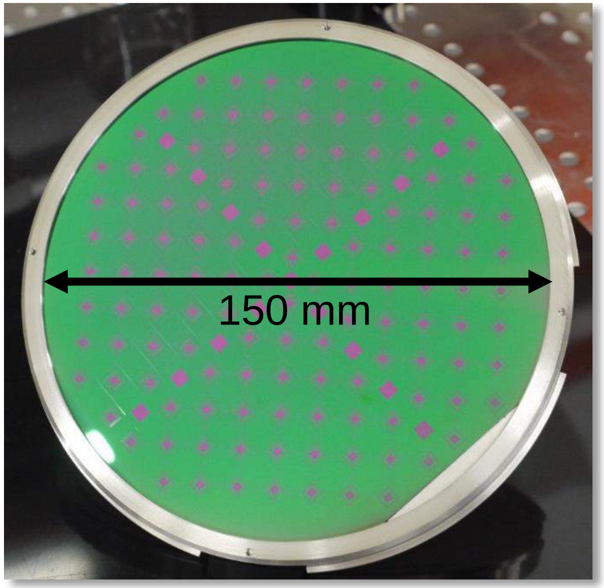
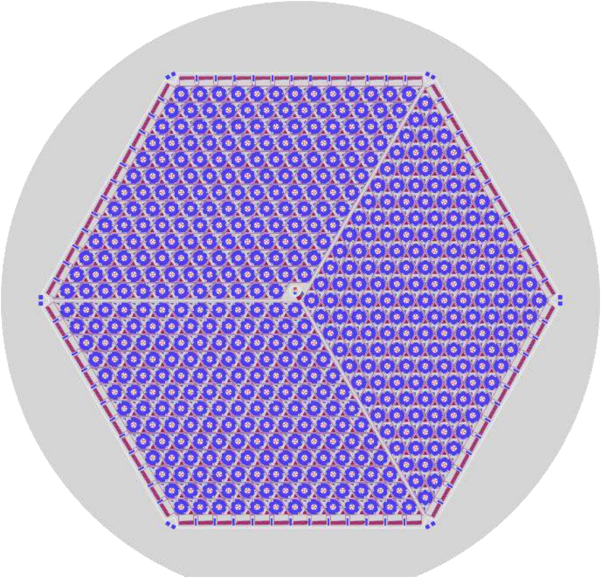


Wiring density



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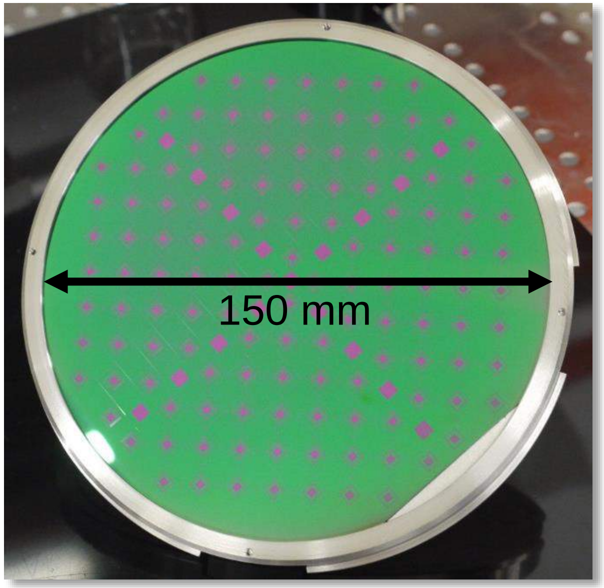

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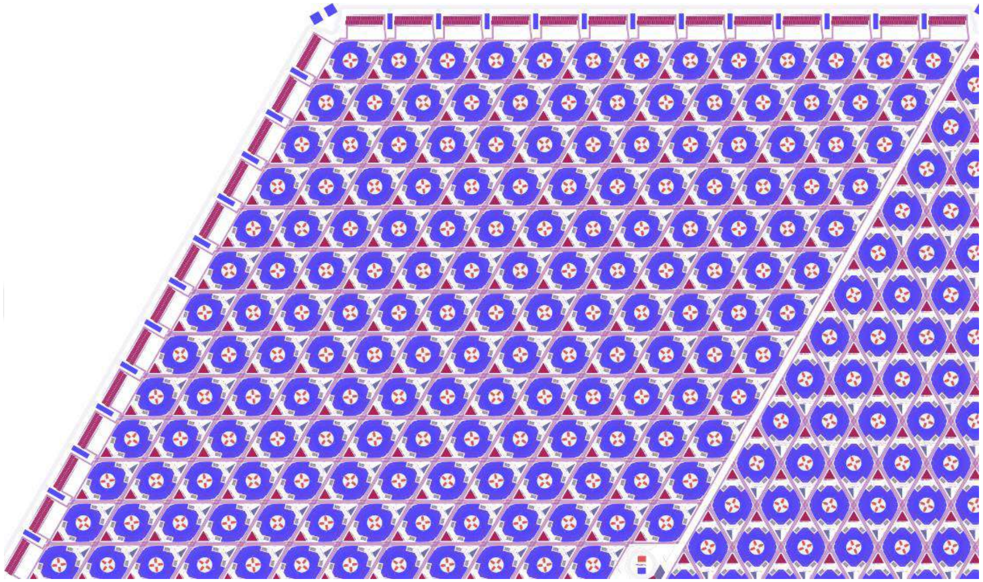

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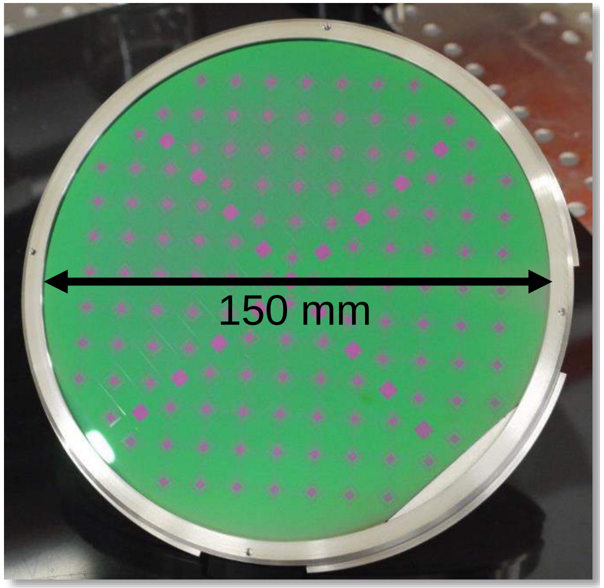

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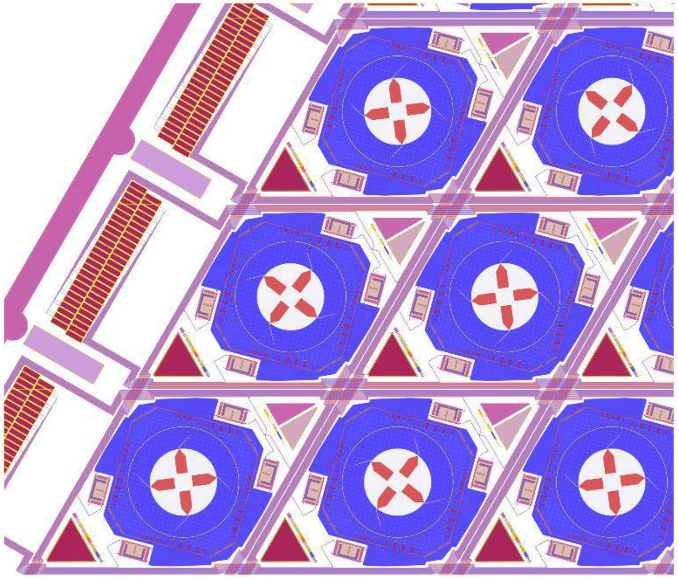

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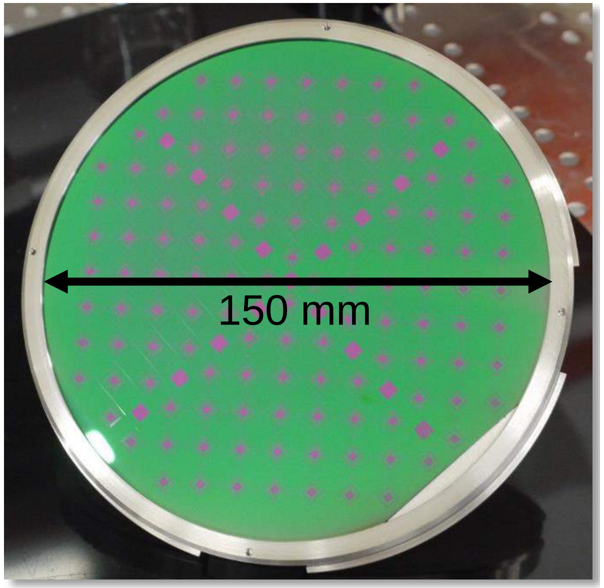

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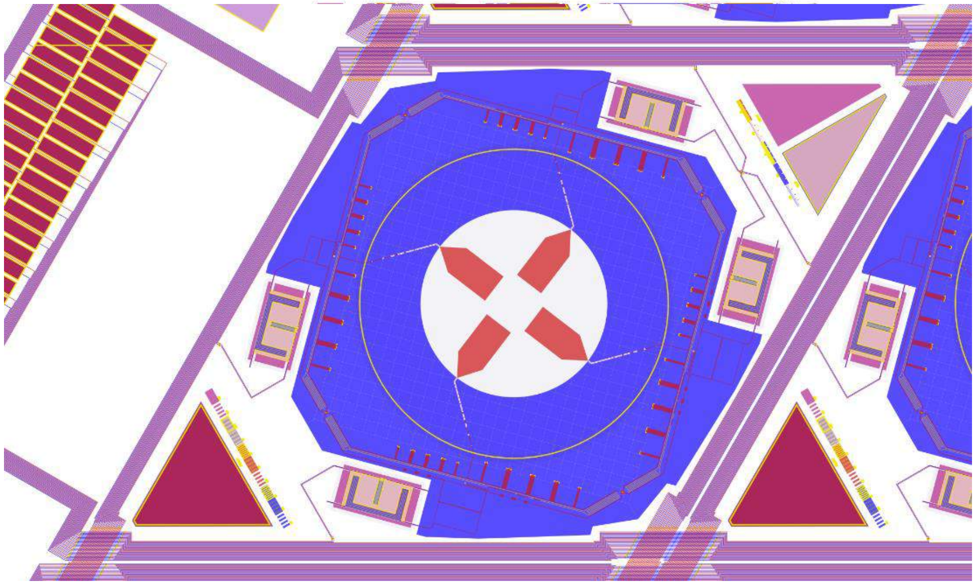

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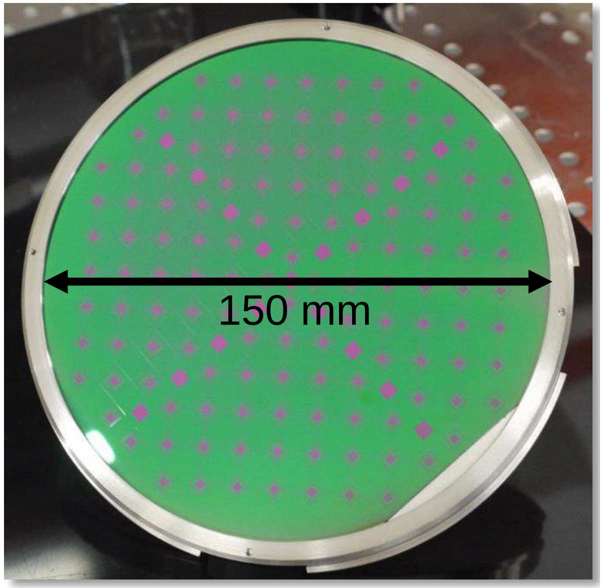
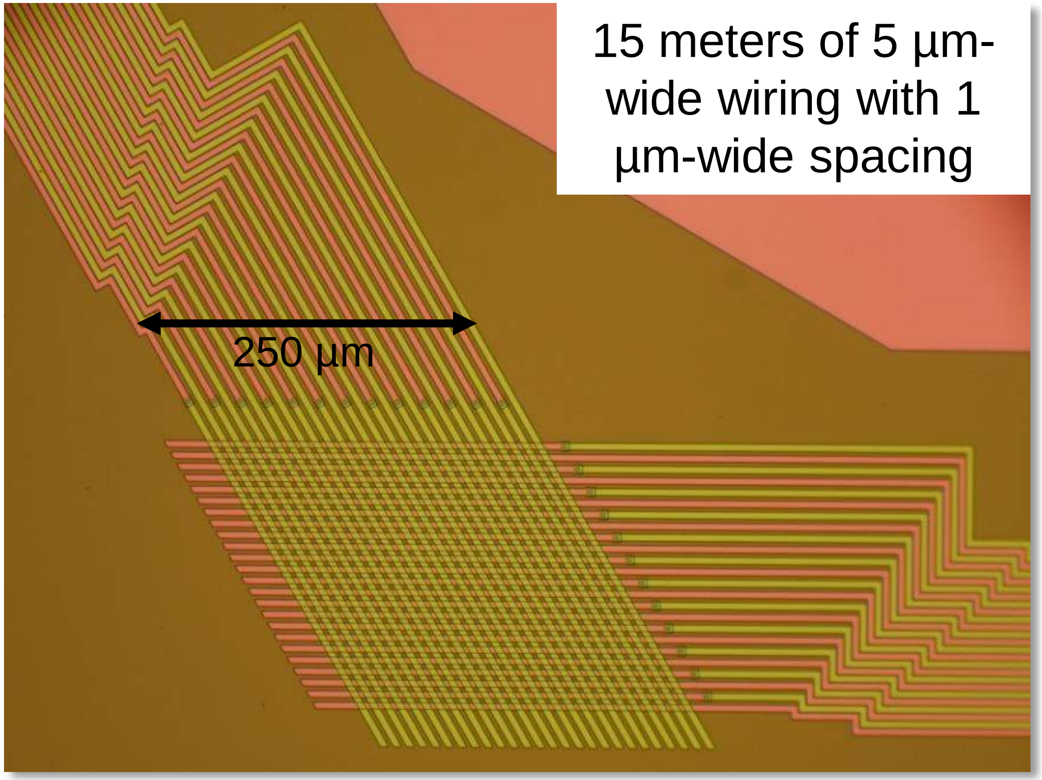
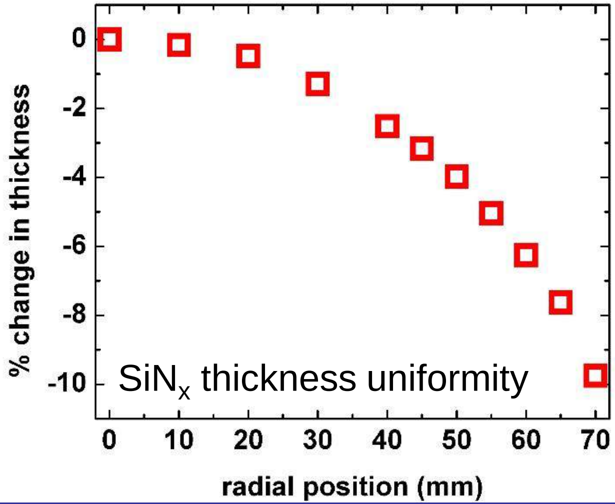
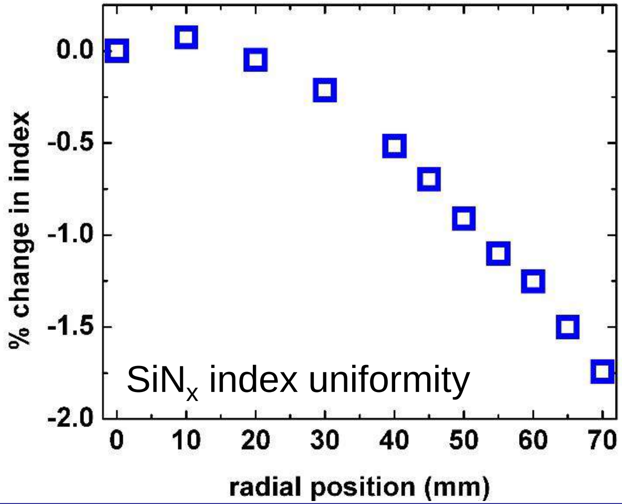




Process Control is Important

	Requirement	Methods
TES	5% T_c uniformity across wafer	AlMn composition
	10% R_n uniformity across wafer	AlMn thickness
Microwave components	Passband edges within ~1% of design	Dielectric thickness Dielectric constant Etch dimensions
Thermal properties	P_{sat}, τ within factor of 2 of design	LPCVD thickness TES leg etch dimensions TES material properties BLING thickness Backside etch (stop on oxide)

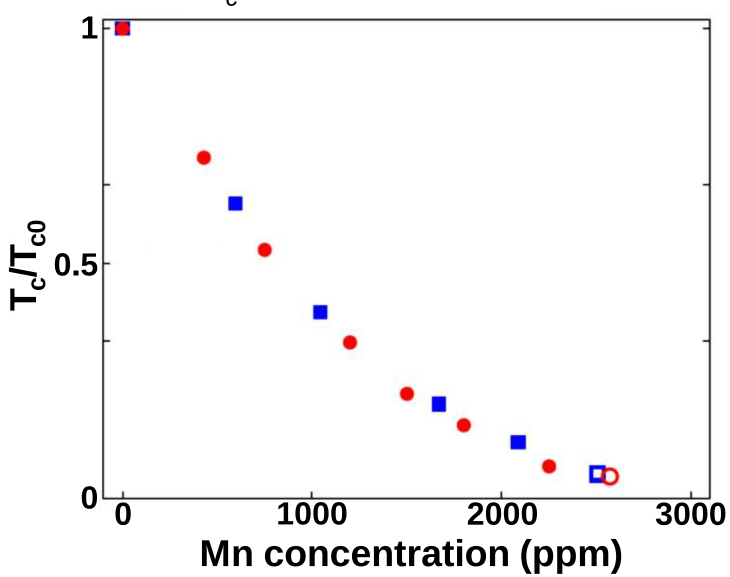




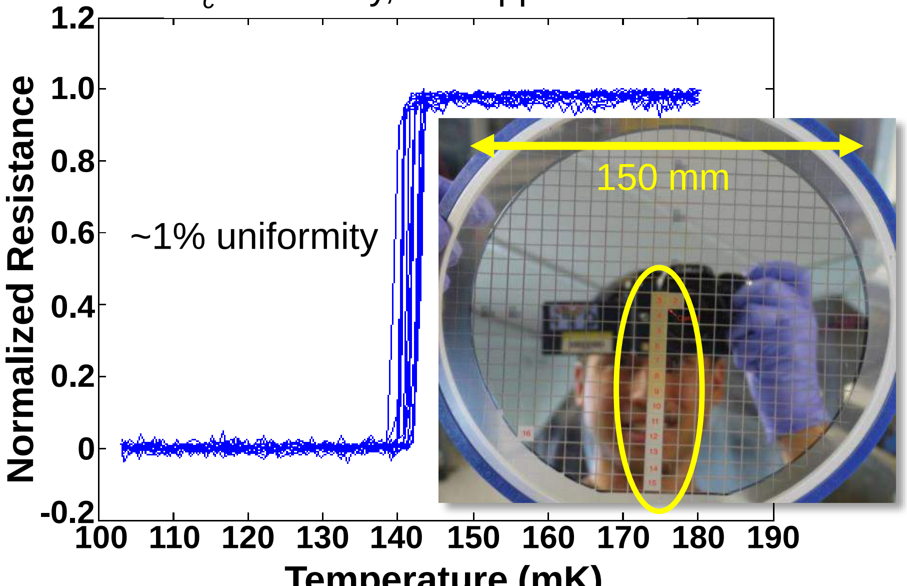
Why AlMn TESes?

- ACTPol TES material = MoCu bilayer
  - Dielectric adhesion to MoCu challenging
  - Thickness of Mo sets T_c → thickness uniformity across wafer *critical*
  - T_c = 150 mK requires thin (~65 nm) Mo film, reproducibility more difficult
  - T_c depends on MoCu interface
- Advanced ACTPol TES material = AlMn alloy (2000 ppm Mn in Al)
  - Concentration of Mn in Al sets T_c, thickness sets R_n
  - Fewer process steps

T_c vs Mn concentration



T_c uniformity, 2000 ppm AlMn



See also: Dale Li "Transition Edge Sensors for Advanced ACTPol"

Increase Detection Efficiency

- Lower dielectric loss → higher overall efficiency
- Fabricated Nb-SiO_x/SiN_x-Nb microwave resonators to probe dielectric properties
  - Necessary to appropriately design passbands and other microwave components

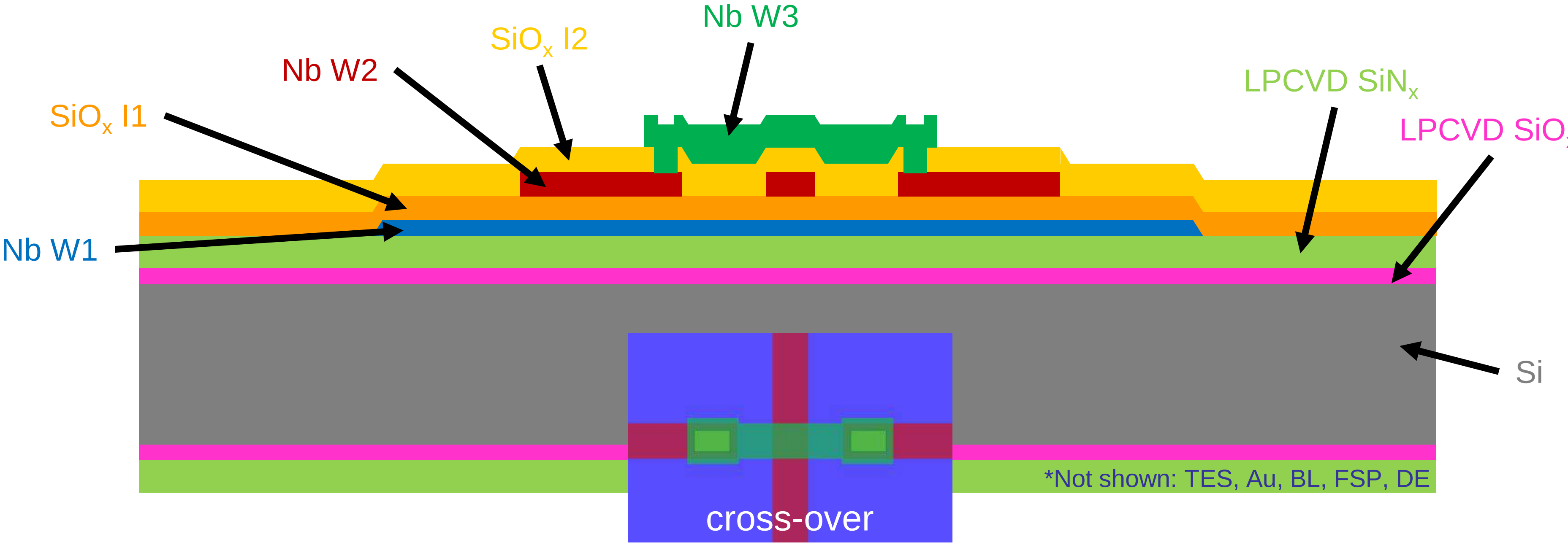
	Stoichiometry	Compressive stress [MPa]	Loss tangent
ACTPol SiO_x	Si-rich	150	2.0e-3
Advanced ACTPol SiN_x	stoichiometric	4	7.8e-4

Benefits of SiN_x

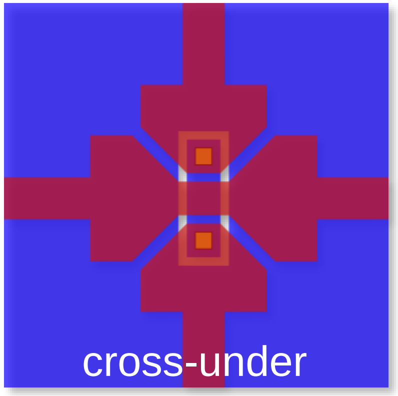
- Improvement in dielectric loss tangent by more than a factor of 2
- ~15% increase in overall detection efficiency

Simplifying Allows for Scaling

- ACTPol has 3rd wiring layer, only needed for 2 cross-overs per pixel



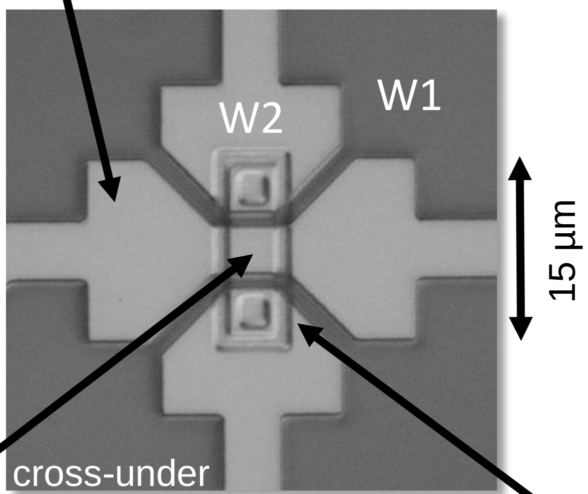
- To simplify fabrication process AND improve microwave performance, Advanced ACTPol eliminates 3rd wiring layer by implementing microwave cross-under



Optimized Microwave Cross-Under

- Cross-under achieves 2 things
  - Minimizes reflections and cross-talk
  - Simplifies fabrication by eliminating W3 layer

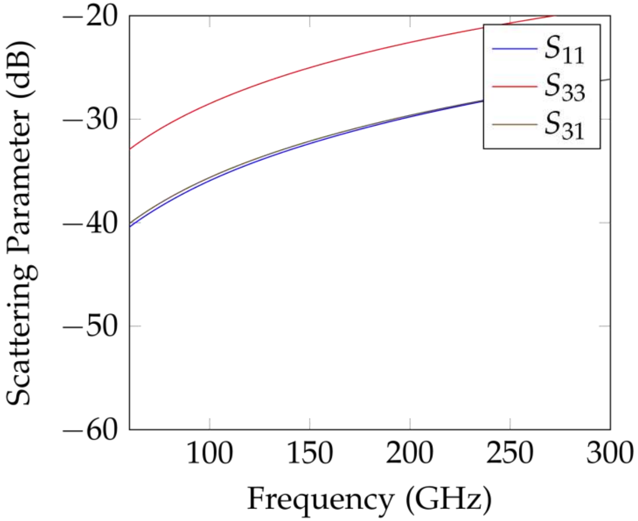
Wide microstrip adds extra capacitance to balance excess inductance



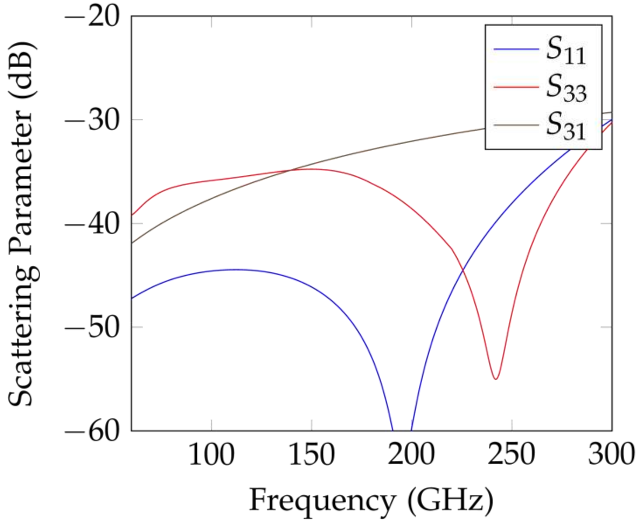
4 um wide microstrip in crossover region (reduces crosstalk)

Tapered section brings extra capacitance as close to midpoint as possible (reduces maximum reflection)

SiN_x Cross-Over Model

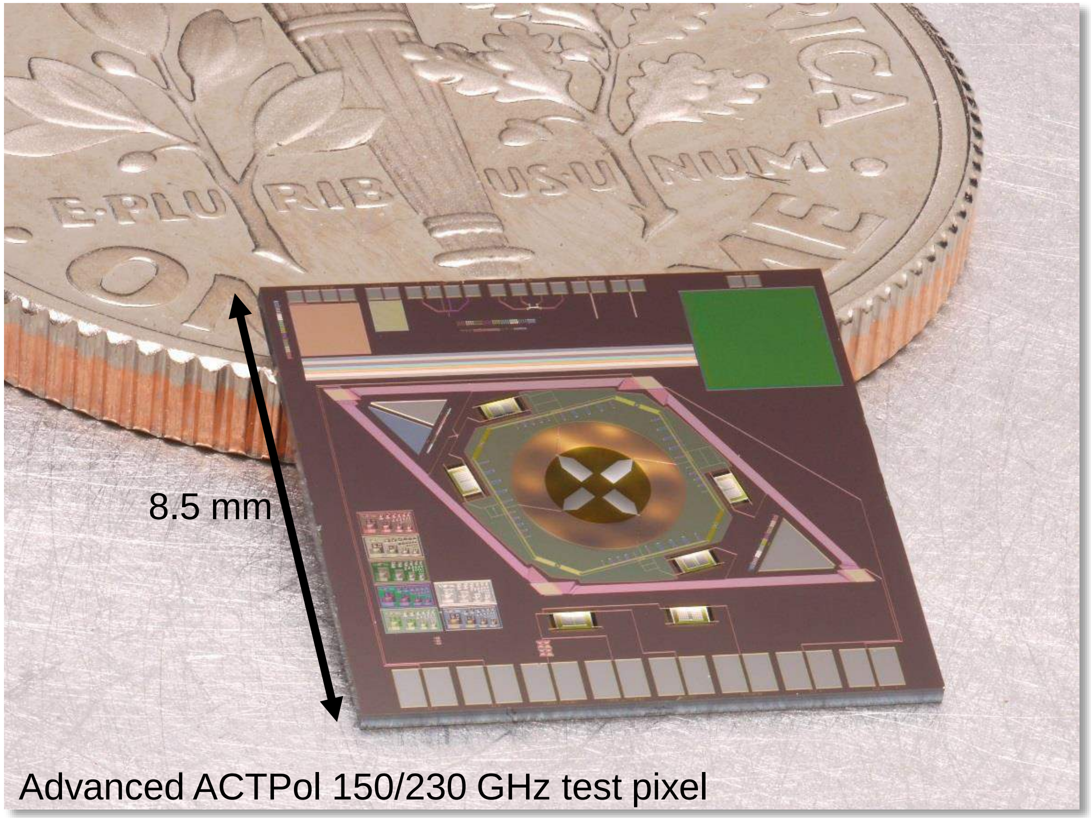


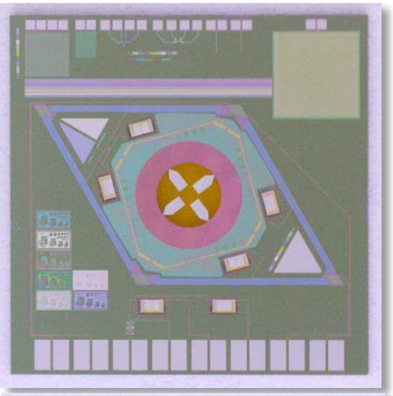
SiN_x Cross-Under Model



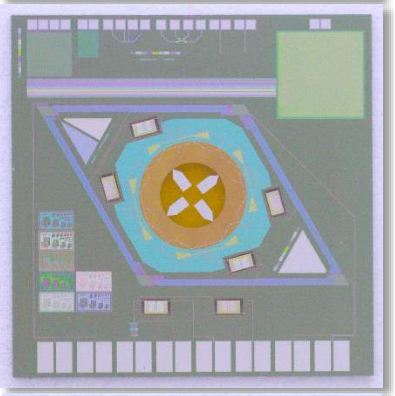
Multichroic Test Pixels

- In order to test and optimize Advanced ACTPol process improvements, must fabricate and characterize test pixels

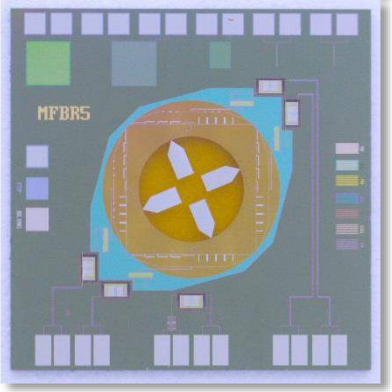




Advanced ACTPol 150/230 GHz test pixel 1

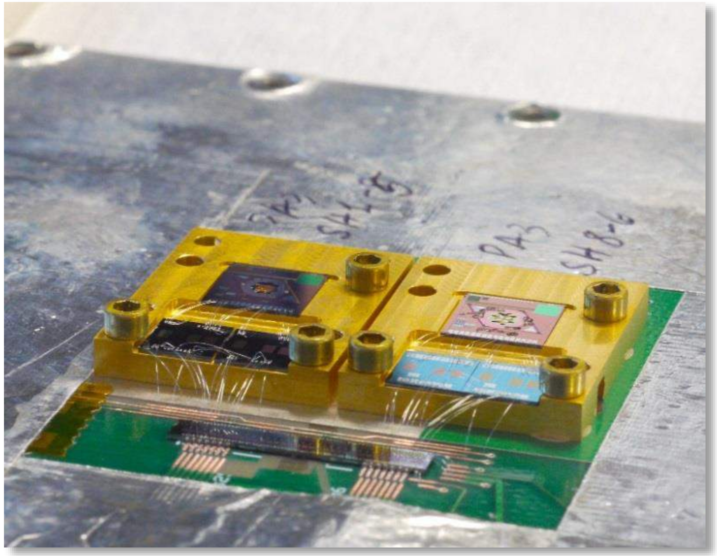


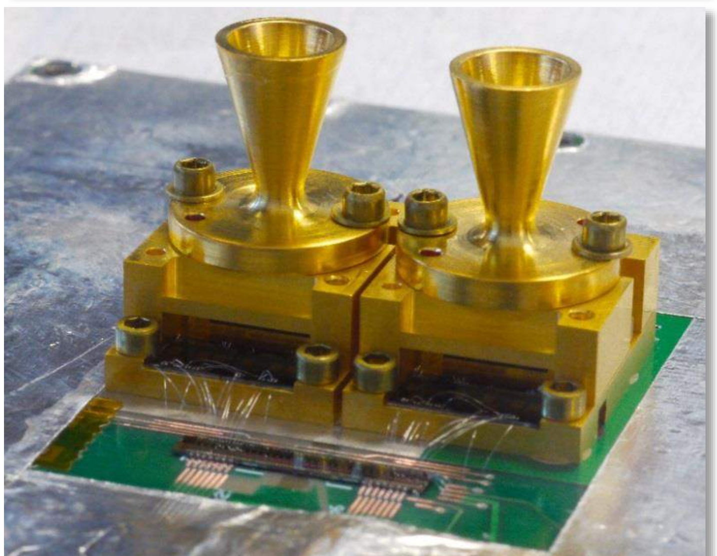
Advanced ACTPol 150/230 GHz test pixel 2

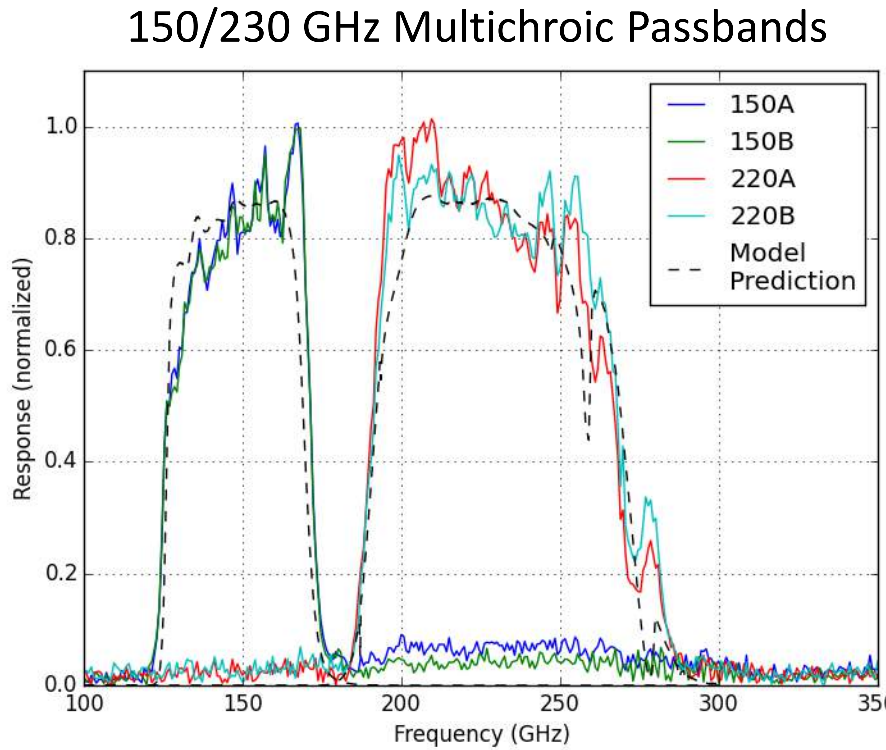


Advanced ACTPol 90/150 GHz test pixel

150/230 GHz Multichroic Test Pixels Work

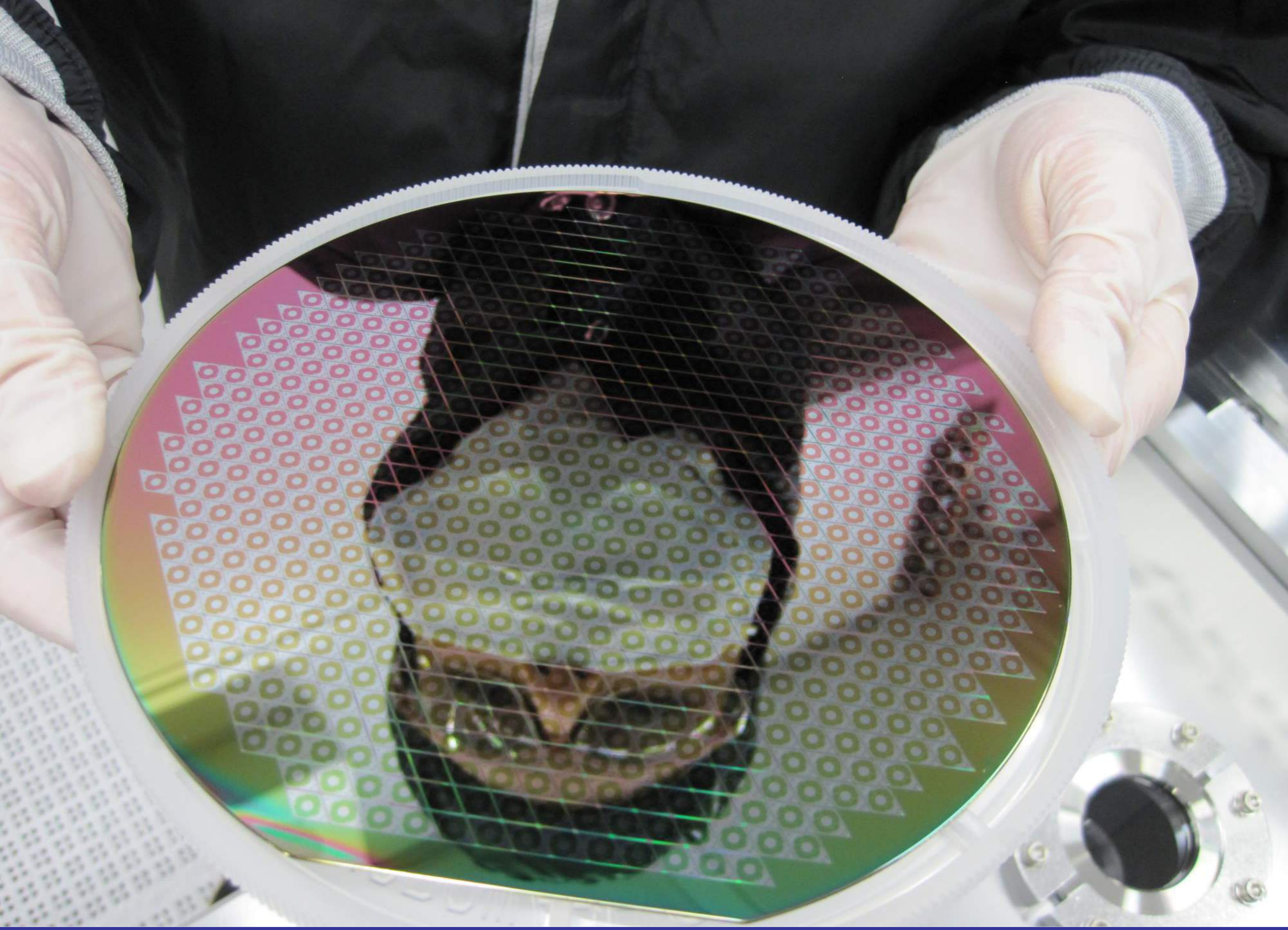






- Passbands near identical in X and Y
- Good agreement between prediction and measurement
- T_c, P_{sat}, τ, G, and noise as expected
- Early efficiency estimates promising

See also: Jason Austermann (poster), Hannes Hubmayr (talk), Shawn Henderson (talk)



Ready to Scale to 150 mm

- Simplification and optimization precedes scaling to manufacturable processes for next generation CMB experiments
  - Wafer count decreased → cost and time savings, increased pixel density
  - Total number of fabrication steps decreased → time savings, risk reduction
  - AlMn TESes → reproducible/uniform Tc, simplified fabrication
  - SiNx dielectric → improved detection efficiency, lower stress film
  - Microwave cross-under → minimized reflections/crosstalk, simplified fabrication
  - Full stepper lithography → increased yield, reproducible dimensions, time savings
  - Semi-automated layout → time savings, design change flexibility, risk reduction

Thank you!