CMB-S4 Detector Layout Discussion

Aritoki Suzuki Lawrence Berkeley National Laboratory

March 10th 2021

Layout Options

Detector arrays from NIST



Hexagon

Rhombus

Square

	Hexagon	Rhombus	Square
ANL	SPT3G	CDFG	
JPL			BICEP2, Keck Array, BICEP3, Spider
LBNL-Seeqc	PB2 layout, SO layout, CDFG		
NIST	ACTpol, SPTpol	AdvACT, SO, AliCPT, LiteBIRD	Spider
SLAC			
UCB	APEXSZ, EBEX, PB1, PB2, SO, CDFG		LiteBIRD

Features

Hexagon	Rhombus	Square
 All site's equipment is naturally compatible 	 All features can be printed with stepper 	 All site's equipment is naturally compatible
	 Works well with steppers with rotation 	
 Use direct write for non-contact 	capability	All features can be printed with stepper
lithography for wiring layer	 Requires x3 masks and x3 litho steps 	
	for steppers without rotation	 Array size per wafer and pixel packing
 Wiring on single Nb layer, no cross-over 	 Direct write is possible, litho time? 	density is lower than hex/rhombus design
TES bolometers for different frequencies	Crossovers for wiring layers	 Wiring/cable routing can be done as
are routed to same sides, repeated		nexagon or rnombus design
pattern	 TES bolometers from single frequency is mapped to one side 	

	Stepper with rotation	Direct write
ANL	No	Yes
JPL	No	Yes
LBNL-Seeqc	No	Yes (procuring)
NIST	Yes	Yes
SLAC	Yes (procuring)	Yes (procuring)
UCB	No	Yes

Interface with Readout – 100 mK Components



Readout team can work with both types

Direct Write

Detector arrays from UC Berkeley



- UC Berkeley used direct write system (MLA 150) to fabricate CDFG wafers
- Detector features and wiring printed successfully with direct write
- Clear field exposure takes 45~50 minutes per layer for MLA 150 (faster direct write)
 - I-line resist (1.0 um thick, 200mJ/cm^2 dosage)

Pixel pitch/ Detector count

Hexagonal layout

Туре	Pixel Pitch [mm]	Pixel Count
LAT HF	5.200	469
SAT HF	5.200	469
LAT MF	5.200	469
SAT MF	8.930	169
LAT LF	14.900	61
SAT LF	26.800 or 30.000	19
LAT 20 GHz	19.150	37

Rhombus layout

Туре	Pixel Pitch [mm]	Pixel Count
LAT HF	5.300	432
SAT HF	5.300	432
LAT MF	5.300	432
SAT MF	9.400	147
LAT LF	15.700	48
SAT LF	31.100	12
LAT 20 GHz	21.100	27

• Pixel pitch and pixel count is quantized for fixed wafer size

- Assumed CDFG wafer size
- For hexagonal design, I selected a design with higher pixel count, but lower count with larger pixel is possible

• Next step is to verify pixel pitch and count works

- Quick layout study in back up slide suggest this works
- Make sure detector structures for each site fit within detector area

• Then study mapping speed, beam truncation point and beam shape for given pixel size

• Flow up/across WBS to make sure this is okay

Detector Components



Tightest layout (LAT MF) shown

Detector Components



Different bandpass filter designs



Lumped filter (JPL)



Lumped filter (ANL, LBNL-Seeqc, UCB)

- Different sites developed RF design that best suit their equipment/ fab process
 - Example: UCB moved from stub \rightarrow lumped filter to improve cross wafer uniformity
 - RF design that works for one site may NOT work well for other sites
- Not all components are absolutely necessary. Example is an hybrid
 - NIST have done comparison test with and without hybrid. Report in future CDFG meetings

Wafer Size



- CDFG wafer **118.800 mm side to side**, largest area where many site feel comfortable about film quality
- Wafer pitch assumption from SAT: **124 mm**
- 2.6 mm outside of each side of detector wafer left to grab onto detector wafer, wire readout cable etc.
 - Is this enough?

Hexagonal array, densest layout check



- Hexagonal layout LAT MF is the densest layout
- Assumed 118.8 mm (CDFG wafer size), 5.2 mm pixel pitch, 469 pixels, 4 optical TES per pixel
- Enough space between pixels for all wires to come out (details in back up slide)

Discussion Points

- CMB-S4 is different from past experiments in that multiple fabrication sites will deliver detector wafers for the project
 - Compatibility with multiple sites will be important for backup/contingency
- What should we make same across sites, what should we leave to sites to decide?
 - Same across sites
 - Wafer size, thickness
 - Pixel location (shape, pitch), pixel count
 - Wire bond pad location, wire bond pad assignment
 - Performance specs (Rn, Tc, time constant, bandpass, yield)
 - Leave to fab sites to decide
 - How to achieve performance spec (Rn, Tc, time constant, bandpass)
- Hexagonal layout can be fabricated by all sites
 - Readout can accommodate TES orders
 - Direct write (MLA 150) can write wiring layer in 50 min
 - Detectors fit for the tightest (LAT MF) design
 - \rightarrow Can we study if all designs be hexagonal layout?
- Important things to do
 - Module team: 124 mm wafer pitch enough? This can drive detector wafer size
 - Discuss about RF designs (ex: hybrid, filters), check RF designs for different sites fit
 - Pixel pitch & count → horn size → efficiency, beam size & ellipticity study → mapping speed → science requirement

Appendix

Rhombus Wafers







90/150GHz 428 pixels

NIST's experience with rhombus array layout

Shannon Duff, NIST

February 3, 2021



Why rhombus layout?

- ACTPol to Advanced ACTPol improvements
 - ACTPol implemented hex layout and relied on contact lithography for wiring - resulted in many lithography defects and reworked steps = lost time, lower yield
 - Advanced ACTPol goal to use stepper for 100% of frontside lithography resulted in rhombus-shaped pixels, repeating wiring bus
- Gene Hilton says: "modern microelectronics works well because you do the same thing over and over again"
 - 100% stepper lithography was the only way to achieve this for Advanced ACTPol
- Rhombus layout now used for Advanced ACTPol, Simons Observatory, and AliCPT



Key benefits of rhombus array layout

- No contact lithography results in improved yield ullet
 - Improvements in direct write lithography tools may allow for lithography 0 without 100% step-and-repeat patterning
 - However, throughput could be problematic without using faster resists
- Inspection is very simple lacksquare
 - Gridded layout makes it very easy to find non-repeating defects across array Every other defect would be eliminated due to thorough reticle inspection
- Very easy to route each frequency band to a single side of array
 - E.g., 90 GHz to 3 edges and 150 GHz to 3 edges preferential for readout in some cases
- Benefits of stepper overlay and resolution lacksquare
- 100% automated layout and stepper jobfile creation Pixels from all three rhombii can use exact same set of masks -• uniformity in dimensions
 - Can use same pixel mask images for fabricating single pixels
- Integration of dark TES bolometers between rhombii
 - Radial distribution of dark parameters 0



Crossovers (unders)

- Each pixel intersection has many W1/W2 crossovers
 Requires deposition and etch processes that do not result in "stringer shorts"
- Requires robust via process
 - Test structures confirm deposition and etch process success
- NIST processes are robust against issues with crossovers
 - Total number of crossovers (need ~half to yield based on design of wiring bus) ■ 2304/pixel ■ ~995,000/array





Hexagonal layout study

Summary

LAT HF	5.20 mm pitch	469 pixels
SAT HF	5.20 mm pitch	469 pixels
LAT MF SAT MF	5.20 mm pitch 8.93 mm pitch	469 pixels 169 pixels
LAT LF SAT LF	14.90 mm pitch 26.80 mm pitch 30.00 mm pitch	61 pixels 19 pixels or 19 pixels

LAT 20 GHz 19.15 mm pitch 37 pixels

LAT MF5.2 mm pitch 469 pixelsLAT HF5.2 mm pitch 469 pixelsSAT HF5.2 mm pitch 469 pixels

- These types share commonality that readout limits how many pixels can be readout
- We can use same pixel layout for all three types. Inner detector RF structures will be different
- LAT MF is the tightest to design because of the larger RF structure size. Next four slides show how LAT MF can be packed into the current wafer size.



- Assumed same wafer outline as current NIST's design
- 469 detector pixels
- 5200 um pitch





- 469 detector pixels
- 5200 um pitch
 - 78 pixels in 1 triangle area
- TES wiring from 66 pixels has to go through 11 green channels
 - TES wiring from 6 pixels per channel
 - Assume 4 TESs/pixel
 - Assume 5 um line + 5 um gap
 - 480 um required
 - Assumed 500 um reserved for wiring
- 5200 um 500 um = 4700 um hex area available for detectors (blue area)





- Everything do fit within 4700 um hex
- Used OMT diameter from NIST's design
- Assumed differential lumped termination at TES bolometer

SAT MF 8.93 mm pitch 169 pixels



- Assumed same wafer outline as current NIST's design
- 169 detector pixels
- 8930 um pitch
- Use same RF structure as LAT MF



- Use same RF structure as LAT MF
- Plenty of space (all white area) for wiring
- Same wire bond pad locations as LAT MF
 - Can eliminate unused pads to save space
- RF active area fit nicely within bond pad areas

LAT LF 14.90 mm pitch 61 pixels



- 61 pixel = 244 TES
- Pitch 14,900 um
- Detector structure area 12,900 um hex
- Wire bond pads on one side can support 312 TES
 - Wire all TES to one side
 - One side is enough to readout entire wafer
- 2000 um gap for wires to go through
 - 1 gap can support wires for 100 TES
 - 4 gaps available at a choke point
 - Enough space to wire out entire TES to one side



- Assumed 10 mm opening for DRIE holes
 - Depending on this opening size, we may need to adjust pitch or wire bond pad location

SAT LF 26.80 mm pitch 19 pixels or 30.00 mm pitch 19 pixels



- 26.80 mm pitch, 19 pixels
- Plenty of room for all parts.
- See idea on the next slide to take advantage of this.



- 30.00 mm pitch, 19 pixels
- This idea works because RF structure for SAT LF fits in much smaller area than pixel pitch
- Horn array will be bigger (machined out of aluminum), but coupling wafer etc will still stay within nominal 6-inch wafer size

LAT 20 GHz 19.15 mm pitch 37 pixels



- 37 pixel, single color = 74 TES
- Pitch 19,150 um
- Wire bond pads on one side can support 312 TES
 - Wire all TES to one side
 - One side is enough to readout entire wafer



- Assumed 13 mm opening for DRIE holes
 - Depending on this opening size, we may need to adjust pitch or wire bond pad location

Hexagonal/Rhombus layout on circular wafer

BLAST-TNG Production Arrays



250 µm Array 1836 Detectors

350 µm Array 938 Detectors 500 µm Array 544 Detectors

• Austermann, 2017