Mask Aligner vs Maskless Aligner

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Mask aligners since 2004
Maskless aligners since 2017
Still learning!

Outline

- Introduction
- Tools
- Pros and Cons
- Alignment
- Resolution
    - At optimal conditions
    - When things change
- Resist profile
- Problems/Solutions
- Conclusions

Introduction

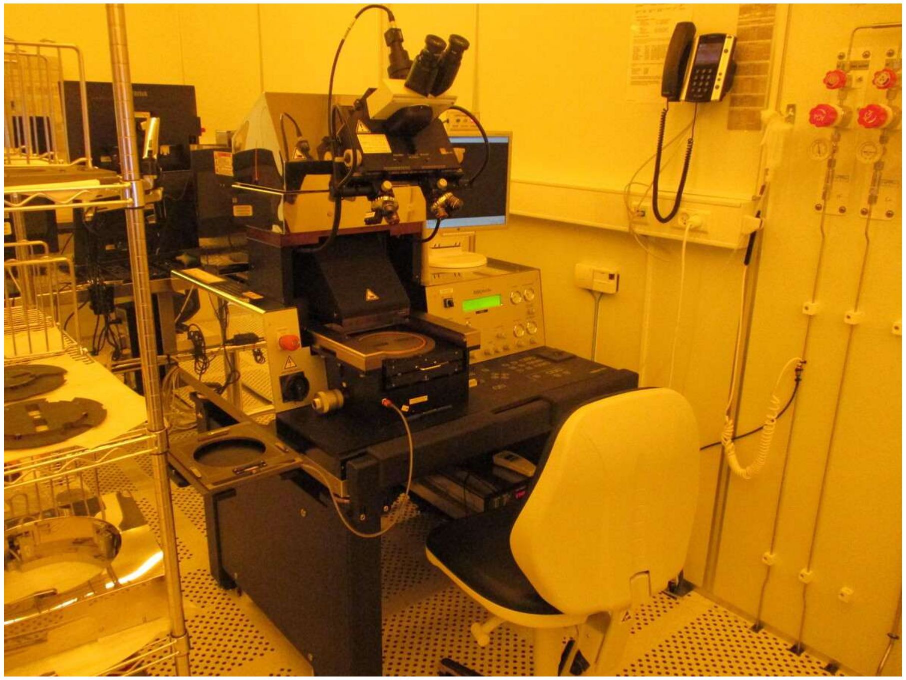
- Motivation: Did we lose something in the shift from Mask Aligner to Maskless Aligner?

- Answering this question required a lot of exposures and a lot of inspection. The resulting slides are quite information-dense, and the pictures are all monochrome. Bear with me, there is something more colorful at the end ☺

- I will not repeat the UV-lithographic process or explain the details of the exposure technologies. I will assume everybody in the audience has experience with the UV-lithographic process and aligners.

Tools – Mask Aligner

- "MA6-2"
  - SUSS MA6/BA6 (2014)
  - 500W Xe-Hg arc lamp
  - 365nm (i-line filter)
  - Intensity 10mW/cm^2
- "MA6-1"
  - SUSS MA6 (1999)
  - 350W Hg arc lamp
  - 365nm (i-line filter)
  - Intensity 10mW/cm^2



Mask Aligner MA6-2

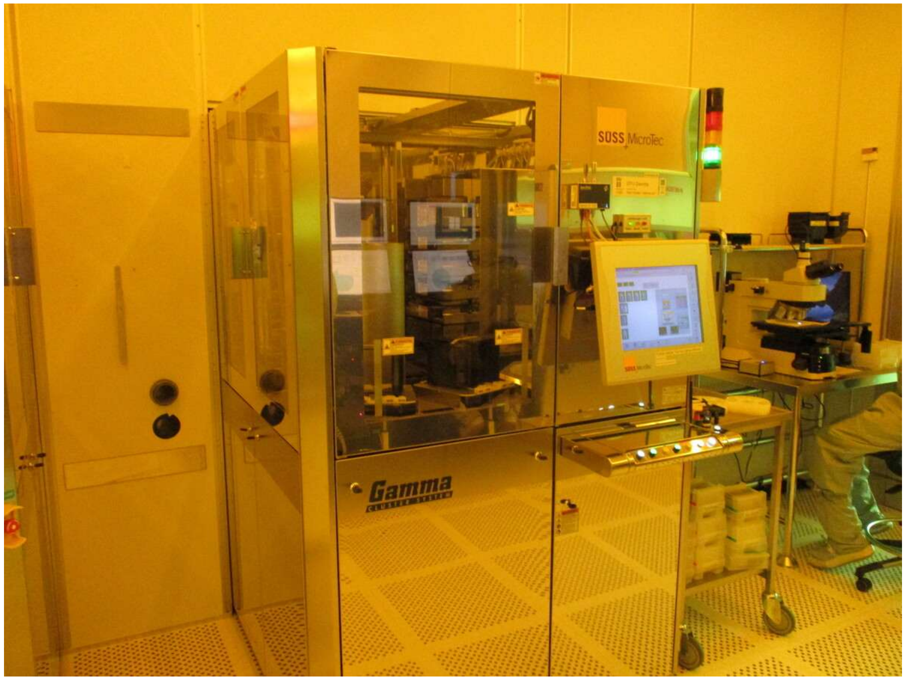
Tools – Maskless Aligner

- “MLA2”
  - – Heidelberg MLA150, WM II (2018)
  - – 375 nm laser diode source
  - – Optical auto-focus
- “MLA1”
  - – Heidelberg MLA100 (2016)
    - Discontinued model, now µMLA
  - – 365 nm LED source
  - – Pneumatic auto-focus

Maskless Aligner MLA2

Tools – The rest of the process

- 100mm Si wafers, SSP <100>
- Resist
  - AZ 5214E (image reversal)
  - AZ MiR 701 (positive)
  - AZ nLOF 2020 (negative)
- Spin coating
  - SUSS Gamma coater cluster (2014)
  - In-line HMDS priming
- Development (incl. PEB, if relevant)
  - SUSS Gamma developer cluster (2014)
  - AZ 726 MIF (2.38% TMAH)
- Inspection
  - Microscope: Olympus MX63 (2025)
  - SEM: Zeiss Supra 40 VP (2010)



Spin coater Gamma UV

Pros and Cons

Pros

- Mask Aligner
  - **Throughput**: exposure time 10-100s for any size
  - Relatively simple hardware
  - Visual alignment (easier to spot errors)
- Maskless Aligner
  - **Flexibility**: change design on the fly
  - Easy parameter optimization
  - Easy alignment without exposing marks
  - Possibility to adapt to distortion from processing or other exposure equipment

Cons

- Mask Aligner
  - **Mask gets dirty** when used, leading to loss of resolution and/or yield
  - Long lead-time of photomasks
  - Alignment marks are always exposed
- Maskless Aligner
  - **Speed**: exposure time 10-100min for a full 100mm substrate
  - Exposure defects: stitching, aliasing
  - Possible dehydration of resist due to autofocus air

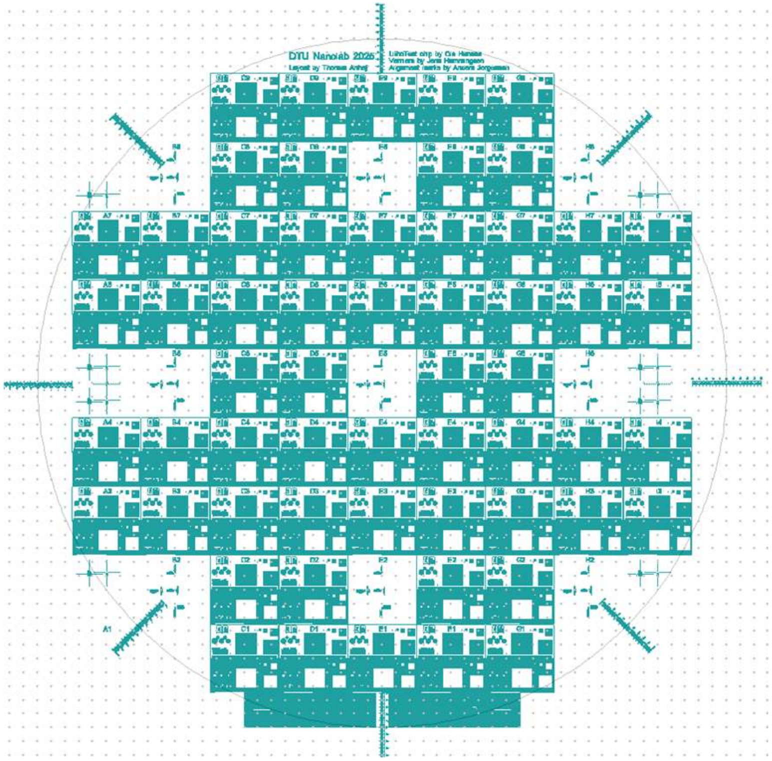
Alignment

	Mask Aligner	Maskless Aligner
Flat	0±0.05°	0±0.2°
Center	**X** 0±25µm	**X** 0±100µm
	Y 350±430µm *)	**Y** 0±100µm
TSA (expose, develop, align, expose, develop)	Spec: ±2µm	Spec: ±0.5µm
	X 0.76±0.45µm	**X** 0.16±0.25µm
	Y -0.14±0.30µm	**Y** 0.06±0.23µm
BSA (align, expose, flip 180°, align, expose, develop)	Spec: ±5µm	Spec: ±1µm
	X 0.10±0.73µm	**X** -0.30±0.60µm
	Y 0.08±0.70µm	**Y** -0.13±0.38µm

Flat and center: average of 3 wafers

Overlay accuracy: average of 9 points on 3 wafers

*) Due to the 32.5±2.5mm spec on the flat length



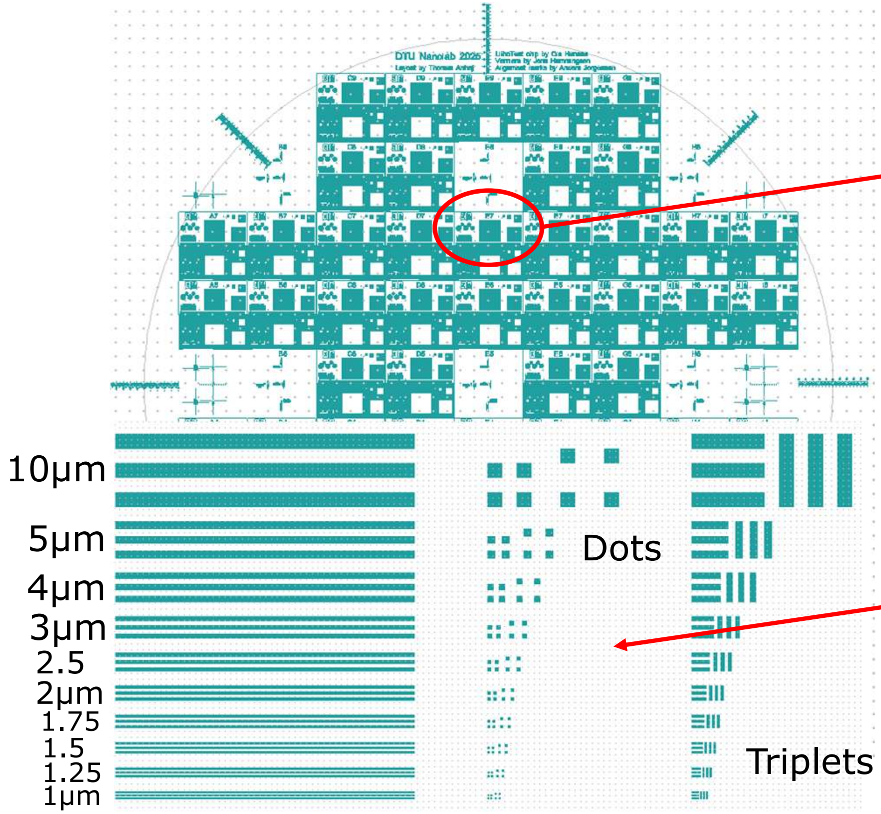
Interested in this design? E-mail taran@dtu.dk

Resolution

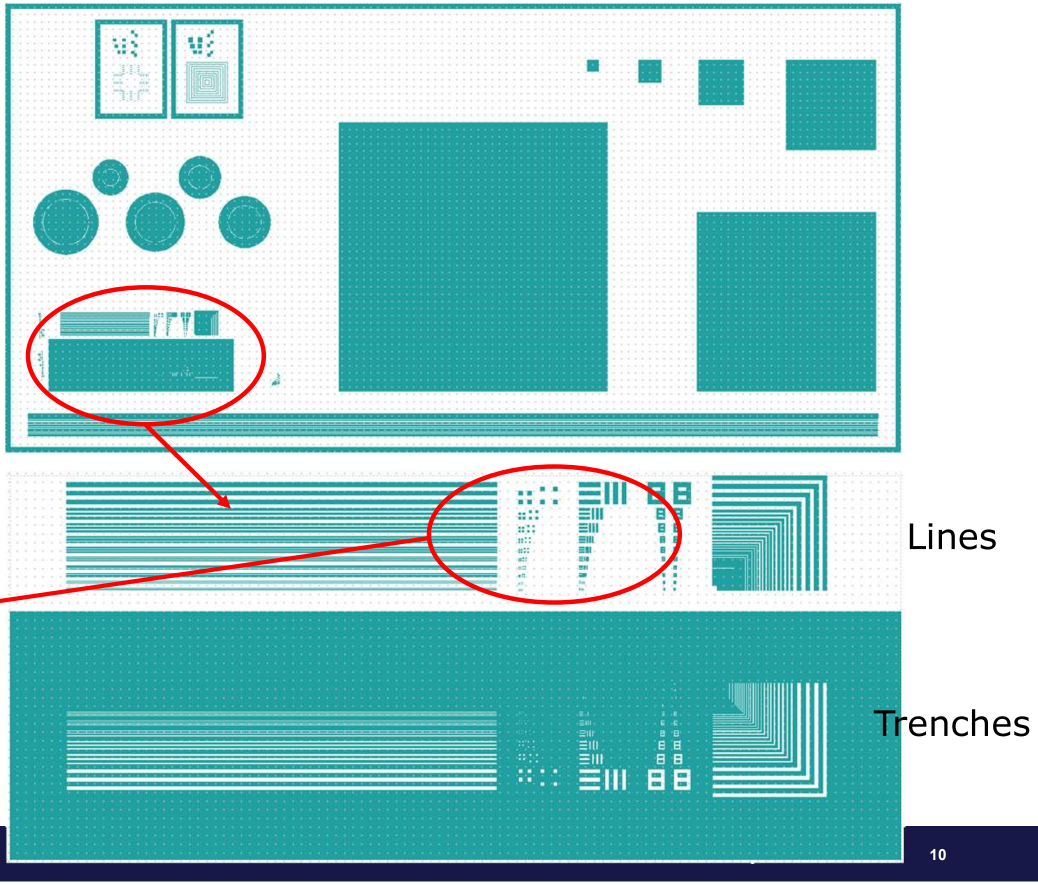
- At optimal conditions
- When things change

Resolution – design

Mask for Mask Aligner



Chip for Maskless (5x10mm)



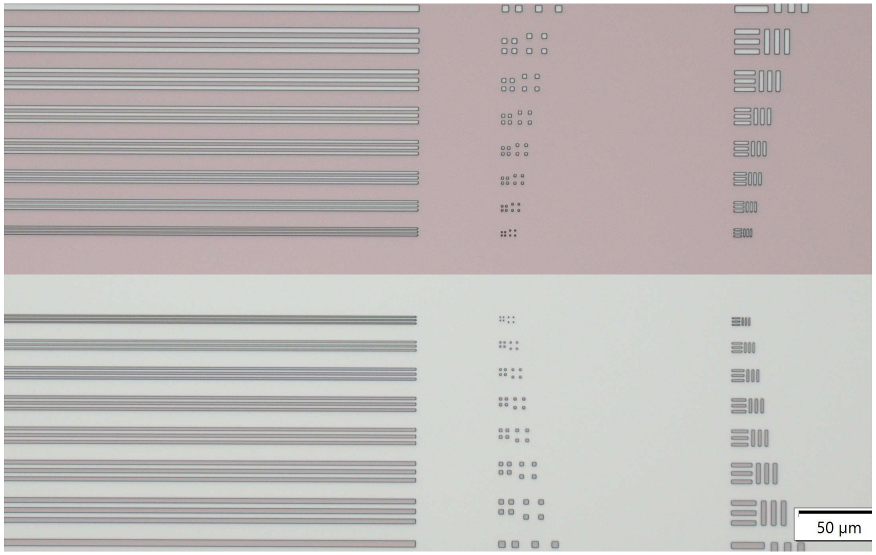
Resolution – method

- Spin coat 1.5µm AZ 5214E with HMDS pre-treatment, soft bake 60s@90°C
- Expose
  - Mask Aligner (MA6-2)
    - Dose test in vacuum contact using a “pie wheel” and the multiple exposure function
    - Optimal dose: 100mJ/cm^2 (365nm at 10mW/cm^2)
  - Maskless (MLA2)
    - Dose-defocus matrix using Series mode
    - Optimal dose: 90mJ/cm^2 (375nm)
    - Optimal defoc: 2

- Develop 60s, single puddle (AZ 726 MIF), DIW rinse, N_2 dry
- Optical microscope inspection of lines and dots, to establish the optimal dose (and defoc) as the point where the resolution is highest, looks similar for lines and trenches, and the print looks 1:1 (lowest bias)
- SEM inspection of triplets (top-view, tilted) for selected wafers

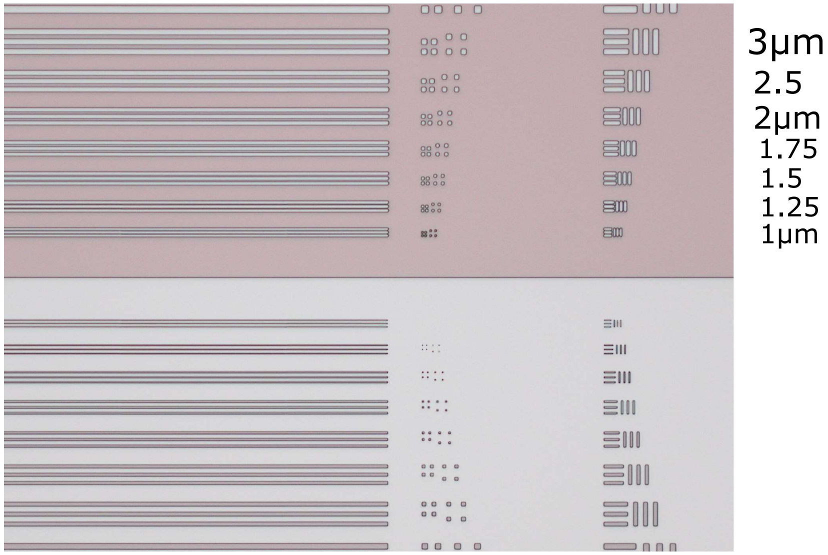
Resolution – at optimal conditions

Mask Aligner



Resolution 1µm. Theory: 0.8µm in 1.5µm resist.

Maskless Aligner

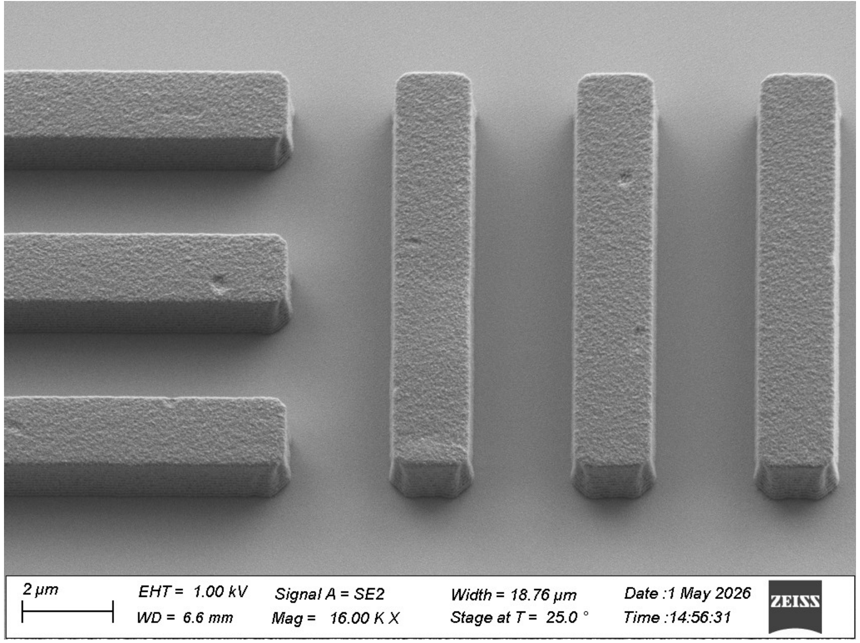


Resolution >1µm. Spec: 1µm in 0.5µm resist.

Resolution – at optimal conditions

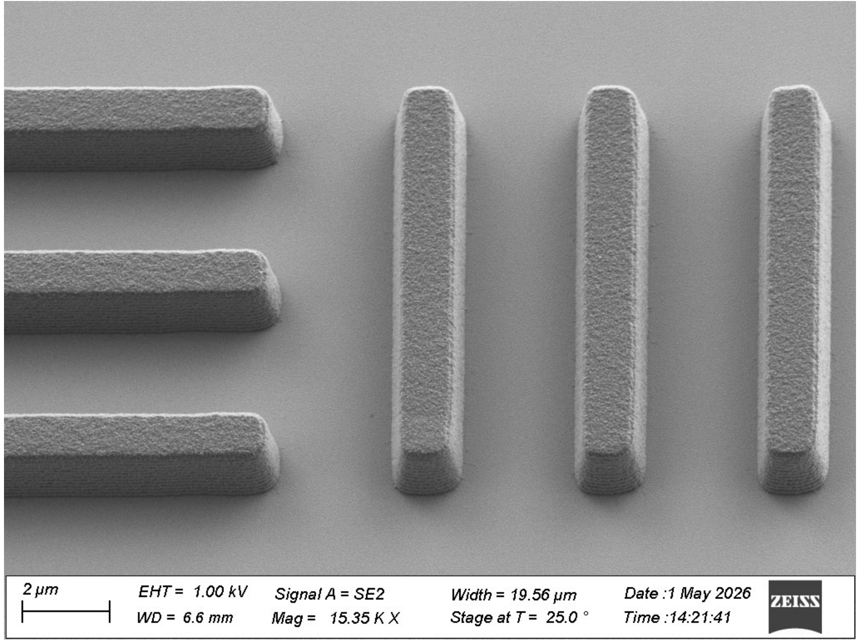
2µm triplets, imaged at 25° tilt

Mask Aligner



Nice straight sidewalls. Evidence of proximity?

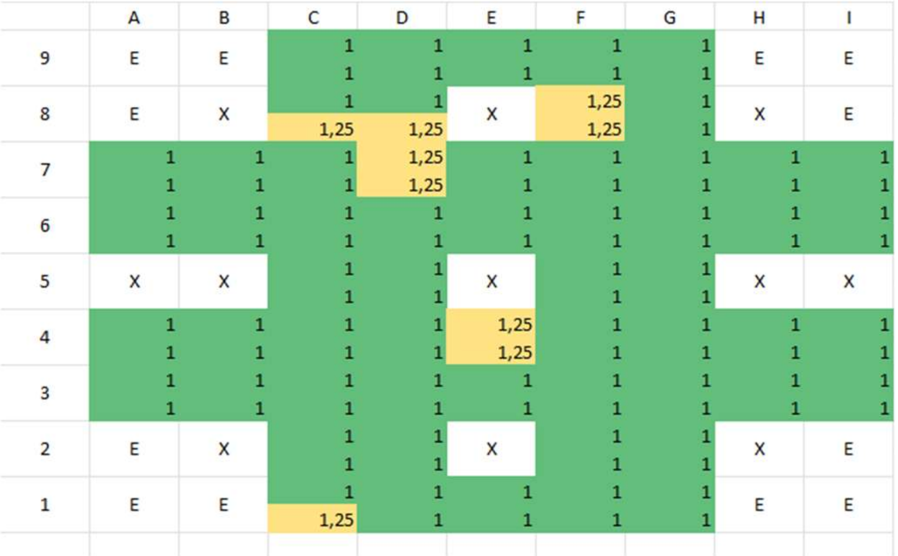
Maskless Aligner



Positive sidewalls. Clear bias (exposed > design)

Yield at optimal conditions

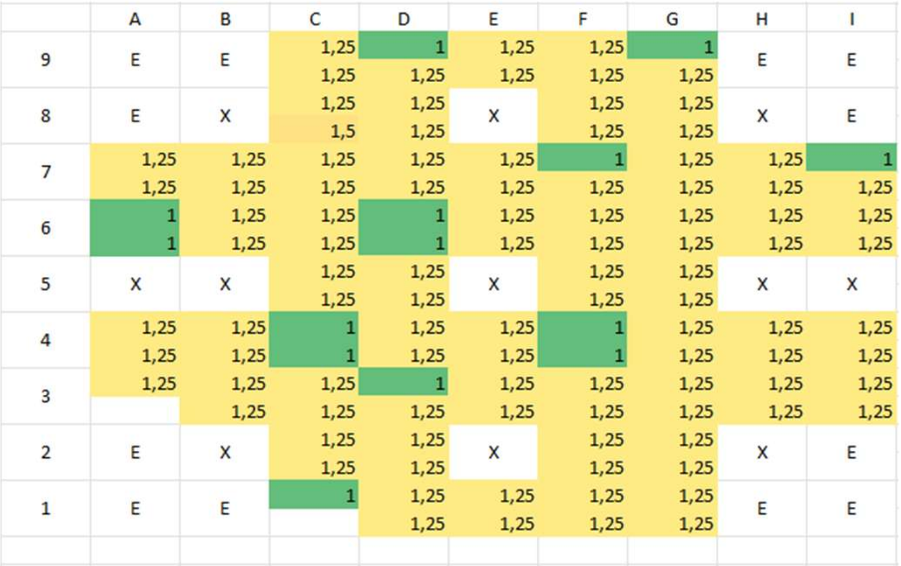
Mask Aligner



	A	B	C	D	E	F	G	H	I
9	E	E	1 1	1 1	1 1	1 1	1 1	E	E
8	E	X	1 1,25	1 1,25	X	1,25 1,25	1 1	X	E
7	1 1	1 1	1 1	1,25 1,25	1 1	1 1	1 1	1 1	1 1
6	1 1	1 1	1 1	1 1	1 1	1 1	1 1	1 1	1 1
5	X	X	1 1	1 1	X	1 1	1 1	X	X
4	1 1	1 1	1 1	1 1	1,25 1,25	1 1	1 1	1 1	1 1
3	1 1	1 1	1 1	1 1	1 1	1 1	1 1	1 1	1 1
2	E	X	1 1	1 1	X	1 1	1 1	X	E
1	E	E	1 1,25	1 1	1 1	1 1	1 1	E	E

Yield at 1µm: 92%. Average resolution: 1.0±0.1µm
Hard contact: 89% at 1.25µm; 1.2±0.4µm

Maskless Aligner



	A	B	C	D	E	F	G	H	I
9	E	E	1,25 1,25	1 1,25	1,25 1,25	1,25 1,25	1 1,25	E	E
8	E	X	1,25 1,5	1,25 1,25	X	1,25 1,25	1,25 1,25	X	E
7	1,25 1,25	1,25 1,25	1,25 1,25	1,25 1,25	1,25 1,25	1 1,25	1,25 1,25	1,25 1,25	1 1,25
6	1 1	1,25 1,25	1,25 1,25	1 1	1,25 1,25	1,25 1,25	1,25 1,25	1,25 1,25	1,25 1,25
5	X	X	1,25 1,25	1,25 1,25	X	1,25 1,25	1,25 1,25	X	X
4	1,25 1,25	1,25 1,25	1 1	1,25 1,25	1,25 1,25	1 1	1,25 1,25	1,25 1,25	1,25 1,25
3	1,25	1,25 1,25	1,25 1,25	1 1,25	1,25 1,25	1,25 1,25	1,25 1,25	1,25 1,25	1,25 1,25
2	E	X	1,25 1,25	1,25 1,25	X	1,25 1,25	1,25 1,25	X	E
1	E	E	1	1,25 1,25	1,25 1,25	1,25 1,25	1,25 1,25	E	E

Yield at 1.25µm: 99%. Average resolution: 1.2±0.3µm

Resolution – when things change

Mask Aligner

- Exposing in vacuum contact yields only a few good prints, then the mask must be cleaned.
- As the mask gets dirty, particles and resist introduce proximity gap effect which lowers the resolution.
- Switching to hard or soft contact helps but introduces proximity gap effect (diffraction) which lowers the resolution.

Maskless Aligner

- The optimal defocus value is known to drift over time in Maskless aligners.
- Drift in the optical/pneumatic auto-focus system or physical changes to the writehead nozzle, due to resist contamination or substrate collisions, cause the optimal defocus value to change.
- But how much is too much?

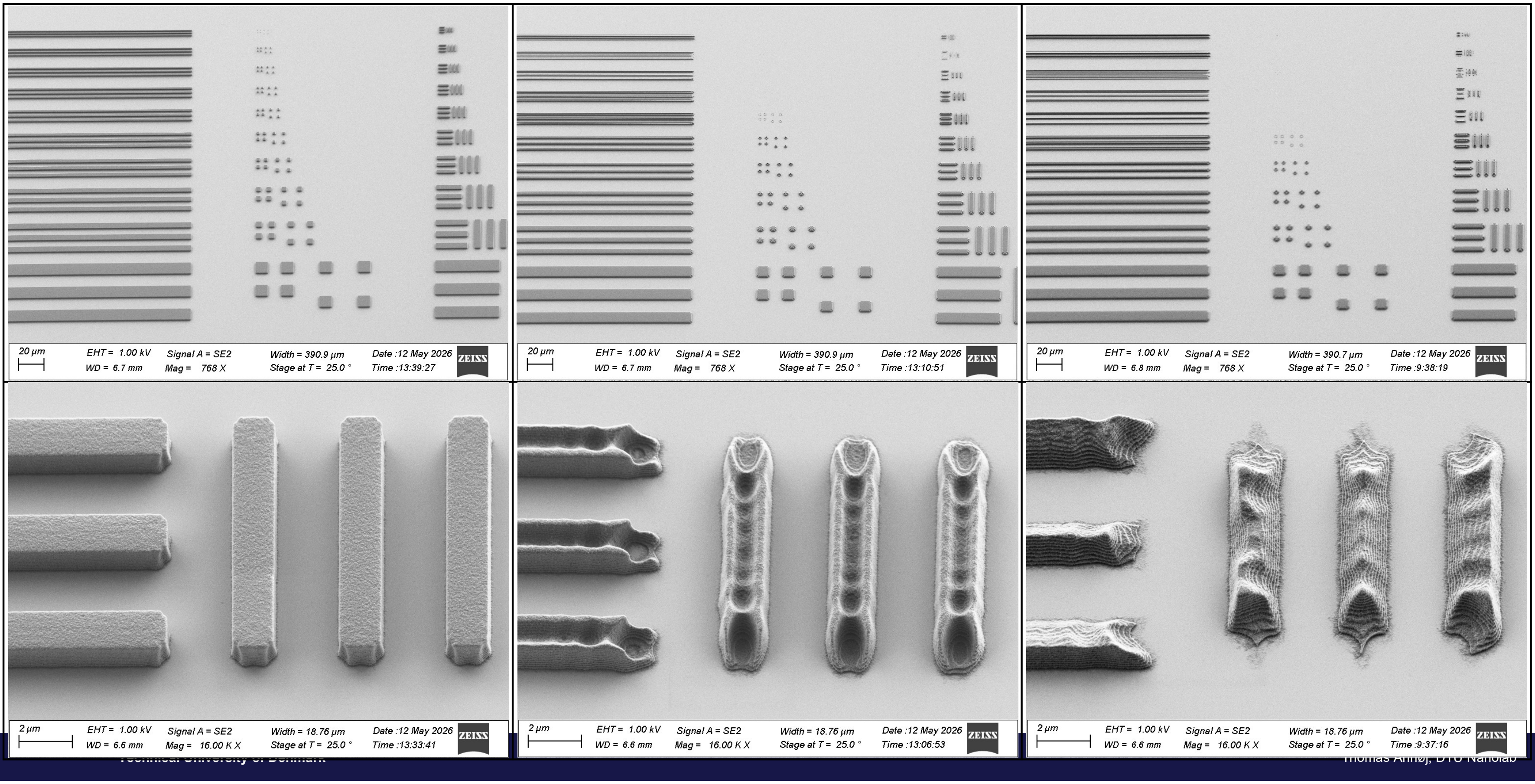
I’m ignoring the dose and focusing on the thing that seems to change most.

When things change – Mask Aligner (MA6-1)

Vacuum contact Soft contact 10µm proximity

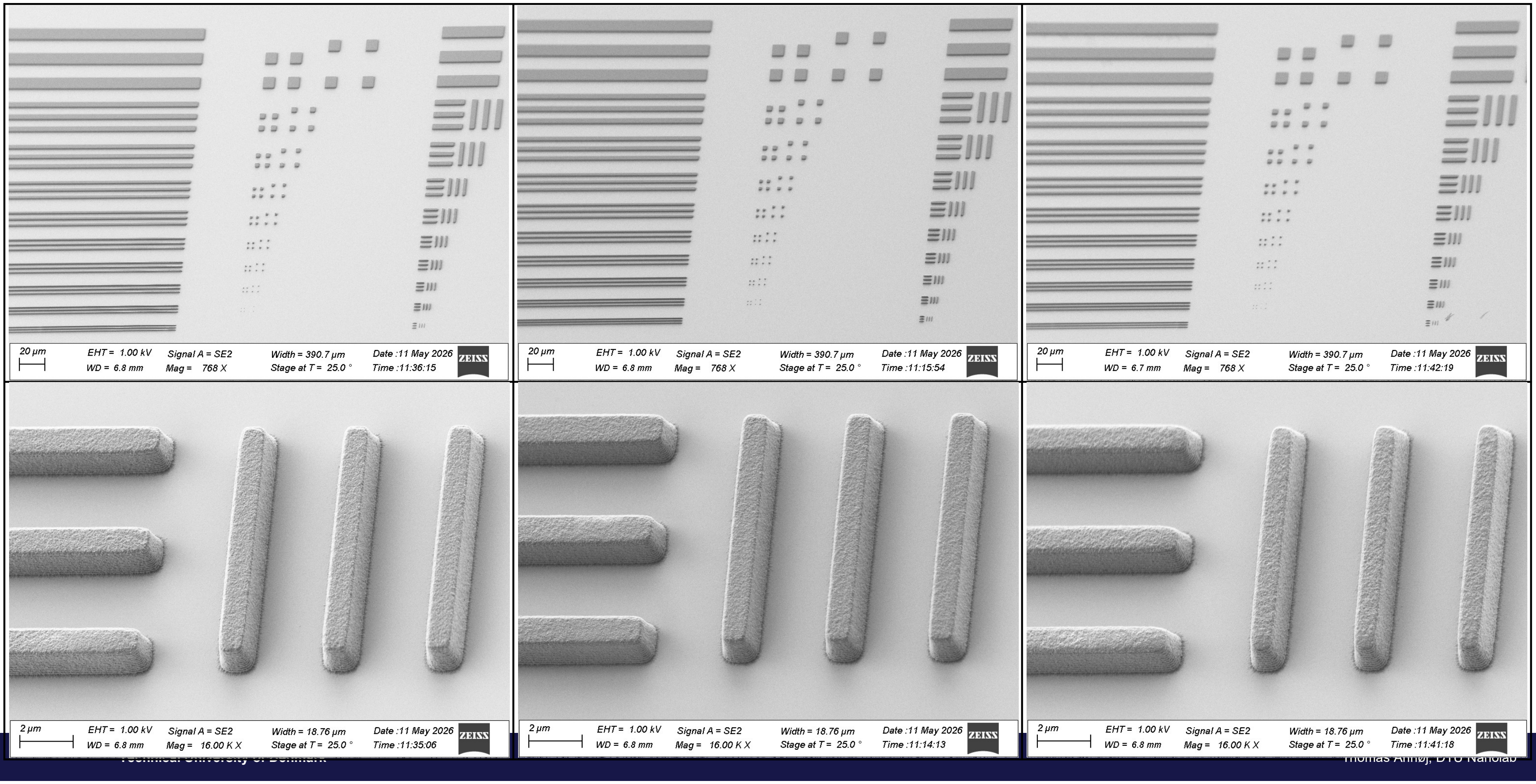
2µm

triplets



When things change – Maskless Aligner

Optimal defoc-3 | Optimal defoc | Optimal defoc+3



2µm

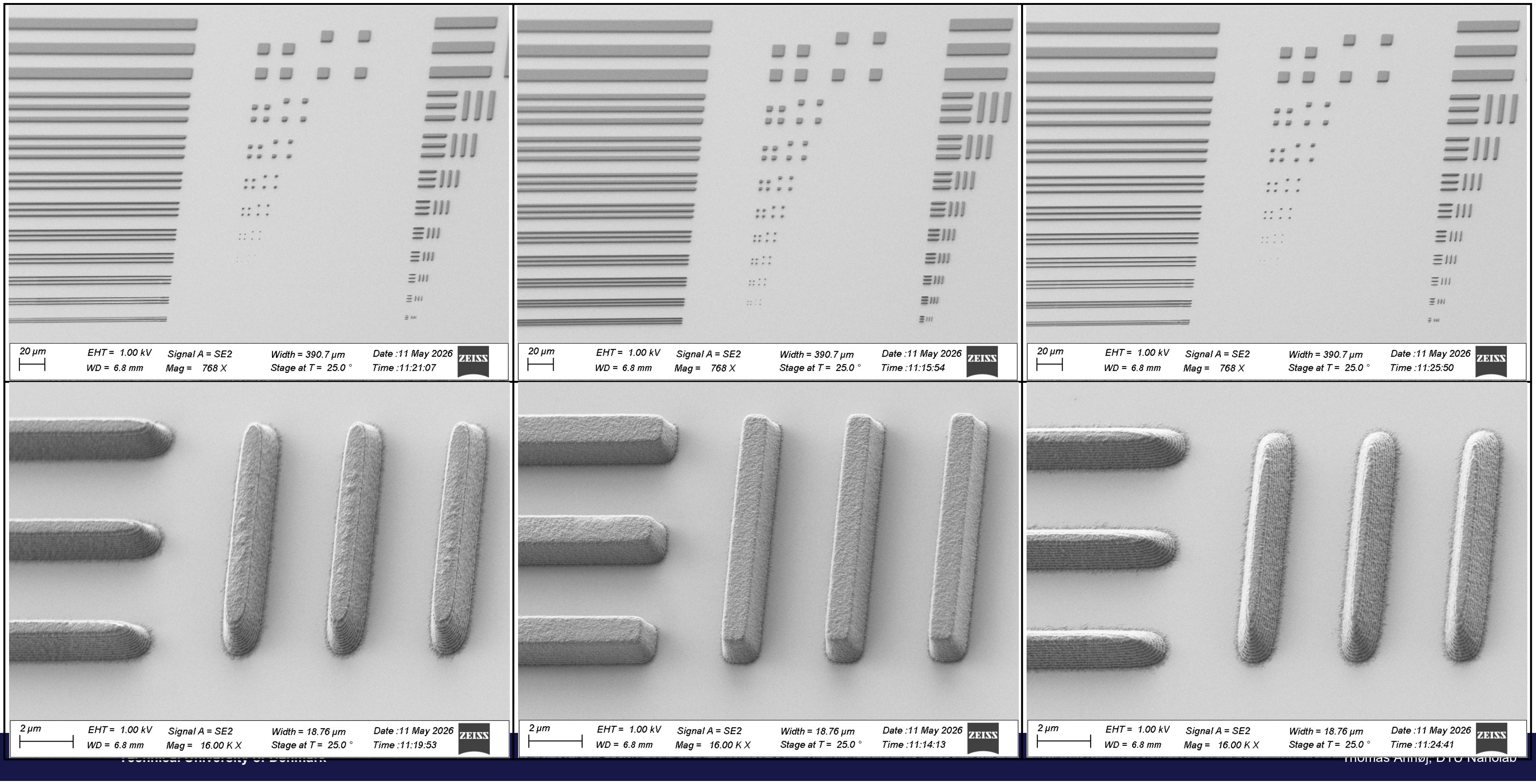
triplets

When things change more – Maskless Aligner

Optimal defoc-10 Optimal defoc Optimal defoc+10

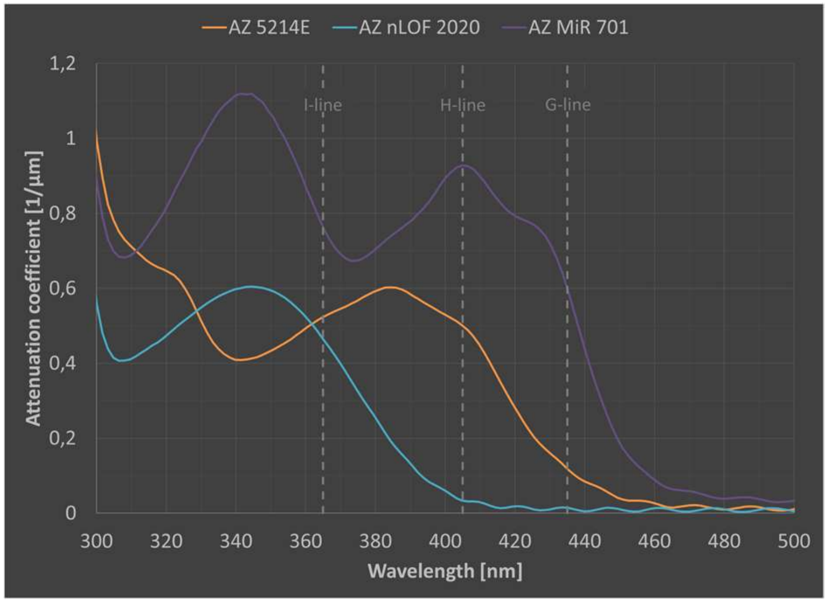
2µm

triplets



Resist profile

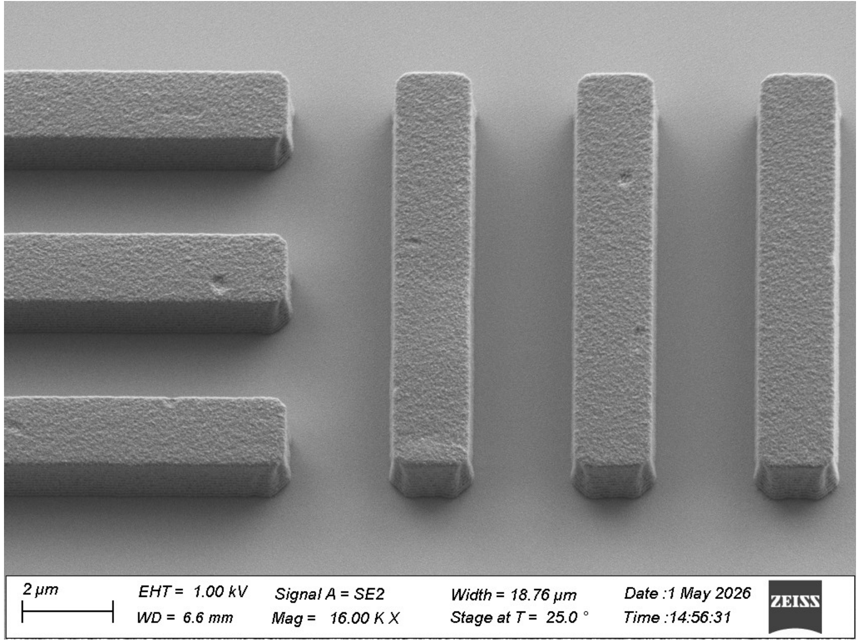
- AZ 5214E (image reversal resist, but positive process)
  - Mask Aligner vs Maskless Aligner
- AZ MiR 701 (positive tone)
  - Mask Aligner vs Maskless Aligner
- AZ nLOF 2020 (negative tone)
  - Mask Aligner vs Maskless vs Maskless



Resist profile – AZ 5214E (positive tone)

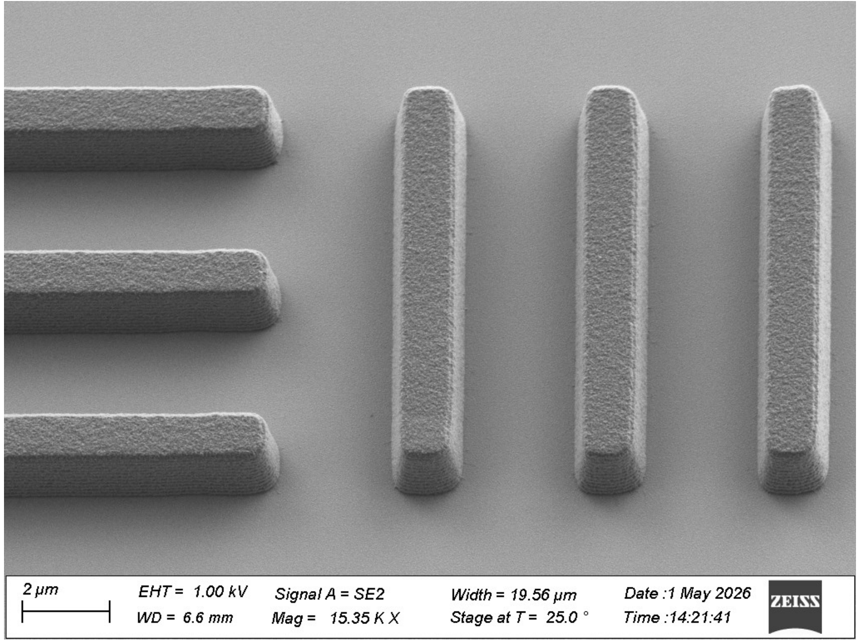
1.5µm AZ 5214E, SB 60s@90°C, developed 60s single puddle AZ 726 MIF

Mask Aligner (100mJ/cm^2, vacuum)



1µm resolution. Straight sidewalls. Rough resist.

Maskless Aligner (90mJ/cm^2, defoc 2)

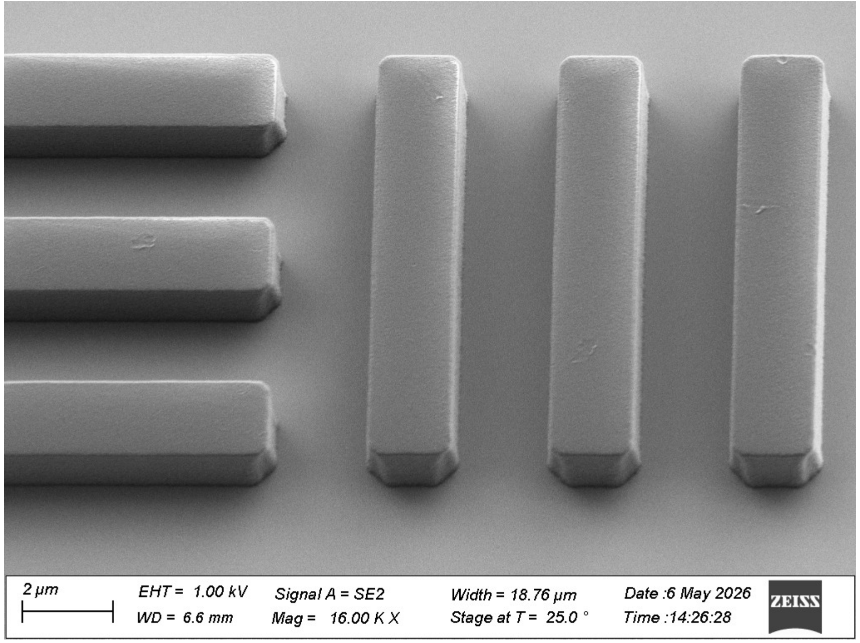


1.25µm resolution. Positive sidewalls. Clear bias.

Resist profile – AZ MiR 701 (positive tone)

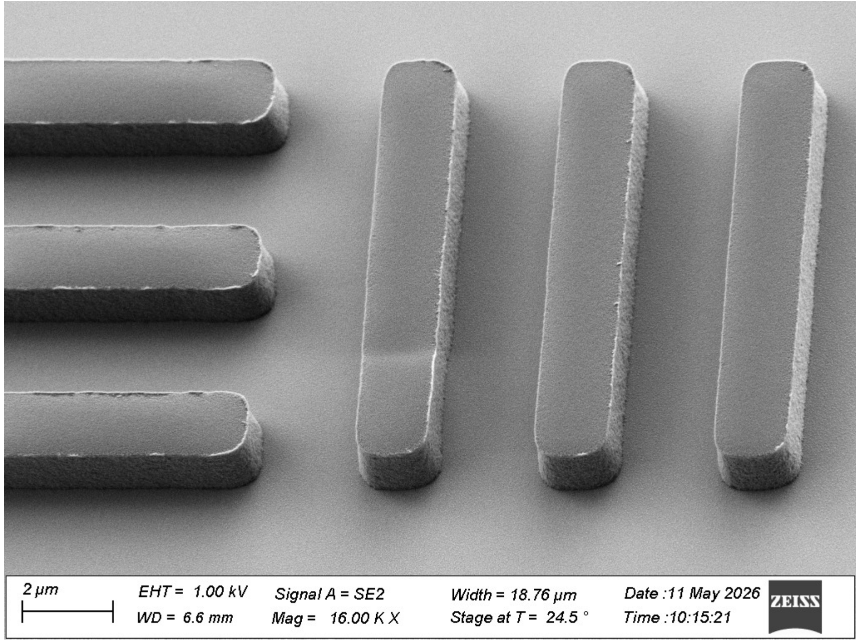
1.5µm AZ MiR 701, SB 60s@90°C, PEB 60s@110°C, developed 60s single puddle AZ 726 MIF

Mask Aligner (220mJ/cm^2, vacuum)



Very similar to AZ 5214E. Smooth resist surface.

Maskless Aligner (275mJ/cm^2, defoc 2)

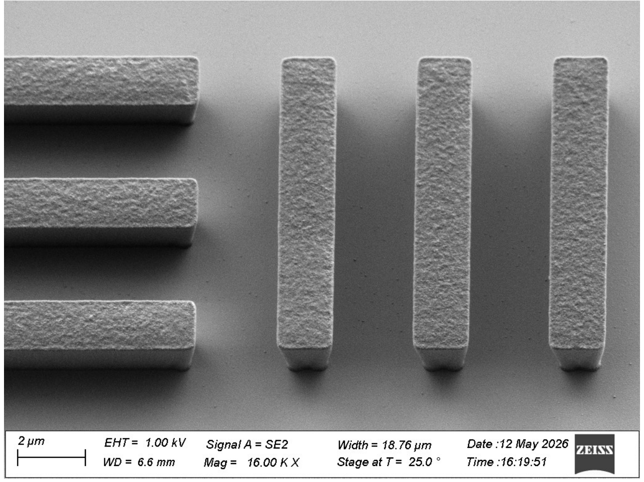


Resolution 1µm. Straight sidewalls. Less bias.

Resist profile – AZ nLOF 2020 (negative tone)

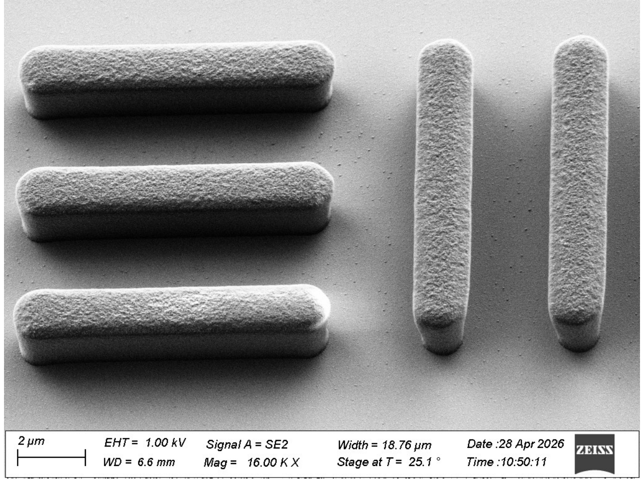
2µm AZ nLOF 2020, SB 60s@110°C, PEB 60s@110°C, developed 60s single puddle AZ 726 MIF

MA6-2, 365nm (150mJ/cm^2, vacuum)



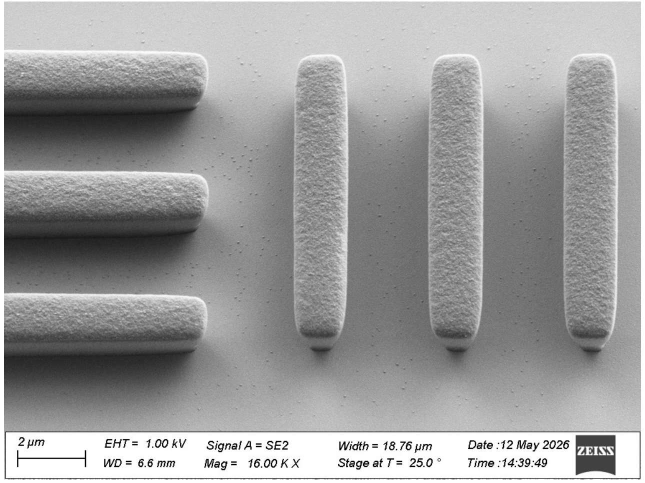
Very nice resolution, 1µm.
250nm undercut.

MLA2, 375nm (450mJ/cm^2, defoc 0)



1.25µm resolution, round corners.
250nm undercut.

MLA1, 365nm (220mJ/cm^2, defoc -4)



2µm resolution, round corners.
500nm undercut.

Resist profile – Sidewall angle

Resist	Exposure tool	Exposure parameters	Sidewall angle	Effect of dose	Effect of gap/defoc
AZ 5214E 1.5µm	MA6-1	100mJ/cm^2, vacuum	1-3°	Decreases with increasing dose	Increases significantly with proximity gap
	MLA2	90mJ/cm^2, defoc 2	8-10°	Decreases with increasing dose	Constant at optimal defoc ±3, increases at higher values
AZ MiR 701 1.5µm	MA6-2	220mJ/cm^2, vacuum	4-5°	Decreases with increasing dose	
	MLA2	275mJ/cm^2, defoc 2	2-4°	Seems constant with dose	Seems constant with defoc
AZ nLOF 2020 2µm	MA6-2 (365nm)	150mJ/cm^2, vacuum	- 6-7°	Seems constant with dose	Not visible due to loss of resolution
	MLA2 (375nm)	450mJ/cm^2, defoc 0	- 5-6°	Seems constant with dose	Maybe a slight increase towards positive defoc values
	MLA1 (365nm)	220mJ/cm^2, defoc -4	- 11°	Increases with decreasing dose	Maybe a slight increase towards negative defoc values

Resist profile – Line width (bias)

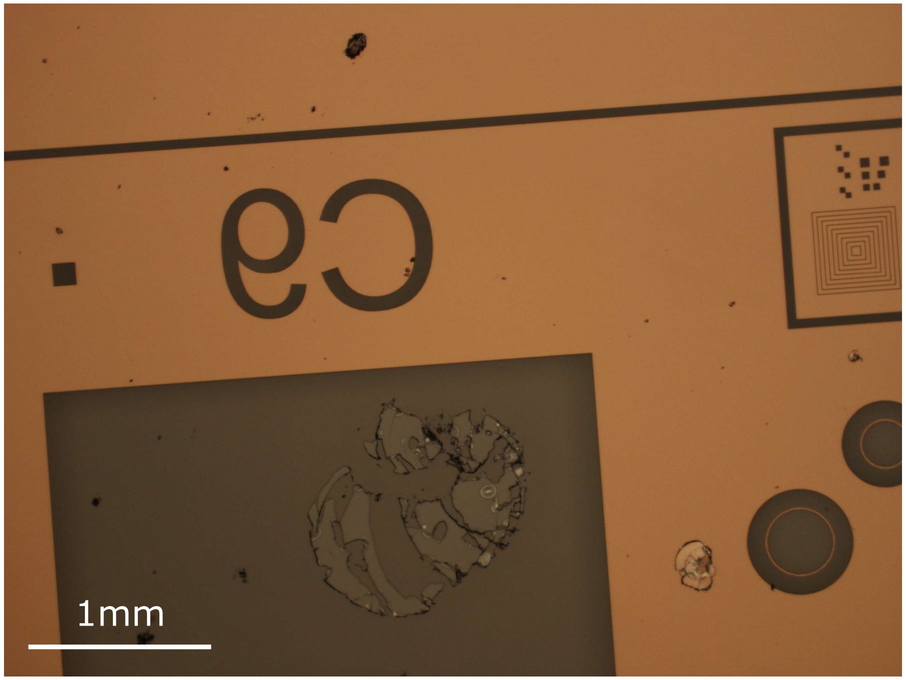
Resist	Exposure tool	Exposure parameters	Width of 2µm line	Effect of dose	Effect of gap/defoc
AZ 5214E 1.5µm	MA6-1	100mJ/cm^2, vacuum	1.9µm	Decreasing with increasing dose, 1:1 at 95mJ/cm^2	Increases with proximity gap
	MLA2	90mJ/cm^2, defoc 2	1.6µm	Decreases with increasing dose, 1:1 below dose to clear	Constant at optimal defoc ±10
AZ MiR 701 1.5µm	MA6-2	220mJ/cm^2, vacuum	2.0µm	Decreasing with increasing dose, 1:1 at 250mJ/cm^2	
	MLA2	275mJ/cm^2, defoc 2	1.8µm	Decreases with increasing dose, 1:1 below dose to clear	Max at optimal defoc, decreases at ± values
AZ nLOF 2020 2µm	MA6-2 (365nm)	150mJ/cm^2, vacuum	1.7µm	Increasing with increasing dose, 1:1 at 190mJ/cm^2	Seems to decrease with gap
	MLA2 (375nm)	450mJ/cm^2, defoc 0	1.7µm	Increases with increasing dose, 1:1 at 550mJ/cm^2 (extrapolated)	Seems constant with defoc
	MLA1 (365nm)	220mJ/cm^2, defoc -4	1.6µm	Increases with increasing dose, 1:1 at 270mJ/cm^2 (extrapolated)	Maybe a slight increase towards negative defoc values

Problems and Solutions

- Mask Aligner
  - Dirty masks
  - Wedge Error Compensation
- Maskless Aligner
  - Stitching
  - Jaggies (aliasing)
  - Resist dehydration

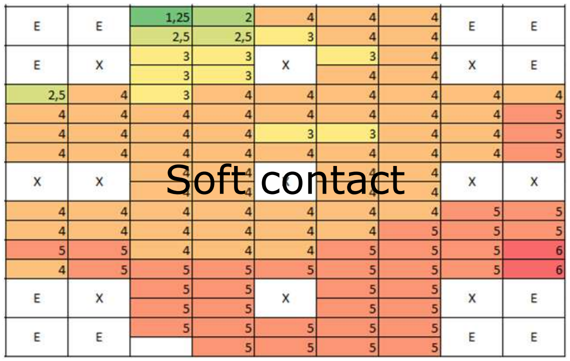
Problems – Mask Aligner: dirty mask

- Resist sticking to mask
  - The resist seems to stick most to the open areas (glass areas)
  - Large pieces of resist should be removed with solvent before cleaning with acid
  - A long period of drying after cleaning (overnight) seems to reduce sticking
  - According to Cleanroom lore, HMDS treatment after cleaning reduces sticking. This was not tested as part of this investigation.



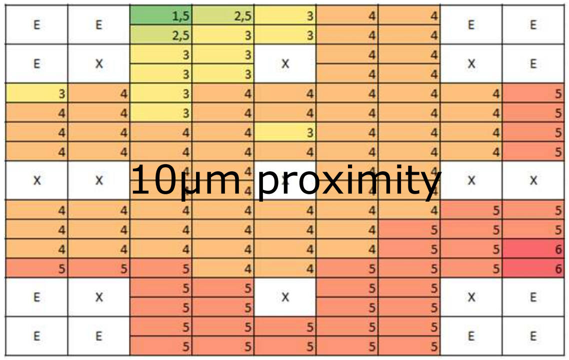
Problems – Mask Aligner: Wedge Error Compensation

- During this investigation, it was noticed that the result of soft contact looked surprisingly similar to 10µm proximity. Both had an average resolution of 4.2µm and a similar distribution.
- Due to concerns about the 10-year-old hardware, a service visit was arranged. The WEC head was found to be in decent condition, so the result after a full WEC head service was about the same.
- The service technician suggested to increase the WEC pressure, from 0.15bar to 0.4bar. This improved the result significantly, to an average resolution of 2.2µm.



Soft contact

E	E	1,25	2	4	4	4	E	E
		2,5	2,5	3	4	4		
E	X	3	3	X	3	4	X	E
		3	3		4	4		
2,5	4	3	4	4	4	4	4	4
4	4	4	4	4	4	4	4	5
4	4	4	4	3	3	4	4	5
4	4	4	4	4	4	4	4	5
X	X	4	4	X	4	4	X	X
		4	4		4	4		
4	4	4	4	4	4	4	5	5
4	4	4	4	4	4	5	5	5
5	5	4	4	4	5	5	5	6
4	5	5	5	5	5	5	5	6
E	X	5	5	X	5	5	X	E
		5	5		5	5		
E	E	5	5	5	5	5	E	E
			5	5	5	5		

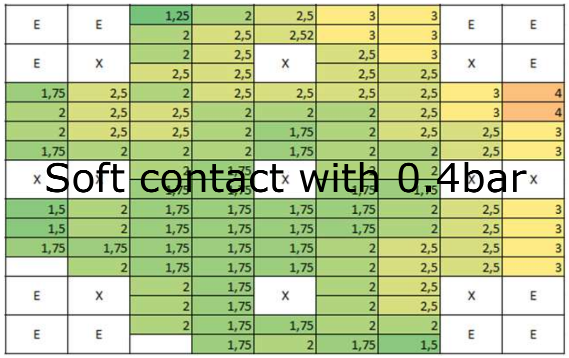


10µm proximity

E	E	1,5	2,5	3	4	4	E	E
		2,5	3	3	4	4		
E	X	3	3	X	4	4	X	E
		3	3		4	4		
3	4	3	4	4	4	4	4	5
4	4	3	4	4	4	4	4	5
4	4	4	4	3	4	4	4	5
4	4	4	4	4	4	4	4	5
X	X	4	4	X	4	4	X	X
		4	4		4	4		
4	4	4	4	4	4	4	5	5
4	4	4	4	4	4	5	5	5
4	4	4	4	4	4	5	5	6
5	5	5	4	4	5	5	5	6
E	X	5	5	X	5	5	X	E
		5	5		5	5		
E	E	5	5	5	5	5	E	E
		5	5	5	5	5		

Soft contact after service

E	E	1	2	3	4	4	E	E
		2	2	3	4	4		
E	X	3	3	X	4	4	X	E
		3	3		4	4		
2	3	2,5	3	4	4	4	4	5
2,5	3	3	3	3	4	4	4	5
2,5	3	3	3	3	4	4	4	5
2,5	3	3	4	4	4	4	5	5
X	X	3	4	X	4	4	X	X
		4	4		4	4		
3	4	4	4	4	4	4	5	5
3	4	4	4	4	4	5	5	5
4	4	4	4	4	4	5	5	6
	4	4	4	4	4	5	5	6
E	X	4	4	X	4	5	X	E
		4	4		5	5		
E	E	5	5	5	5	5	E	E
			5	5	5	4		

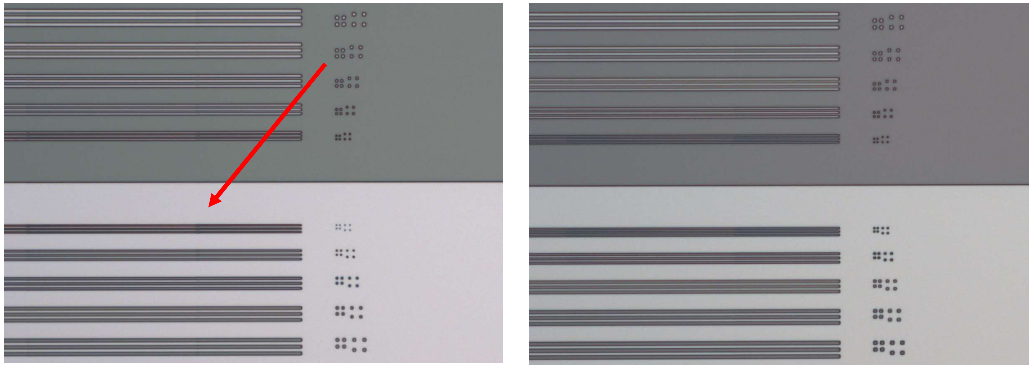


Soft contact with 0.4bar

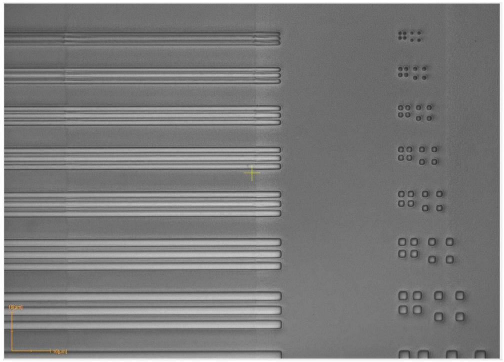
E	E	1,25	2	2,5	3	3	E	E
		2	2,5	2,52	3	3		
E	X	2	2,5	X	2,5	3	X	E
		2,5	2,5		2,5	2,5		
1,75	2,5	2	2,5	2,5	2,5	2,5	3	4
2	2,5	2,5	2	2	2	2,5	3	4
2	2,5	2,5	2	1,75	2	2,5	2,5	3
1,75	2	2	2	1,75	2	2	2,5	3
X	X	2	1,75	X	2	2	X	X
		1,75	1,75		1,75	1,75		
1,5	2	1,75	1,75	1,75	1,75	2	2,5	3
1,5	2	1,75	1,75	1,75	1,75	2	2,5	3
1,75	1,75	1,75	1,75	1,75	2	2,5	2,5	3
	2	1,75	1,75	1,75	2	2,5	2,5	3
E	X	2	1,75	X	2	2,5	X	E
		2	1,75		2	2,5		
E	E	2	1,75	1,75	2	2	E	E
			1,75	2	1,75	1,5		

Problems – Maskless Aligner: stitching

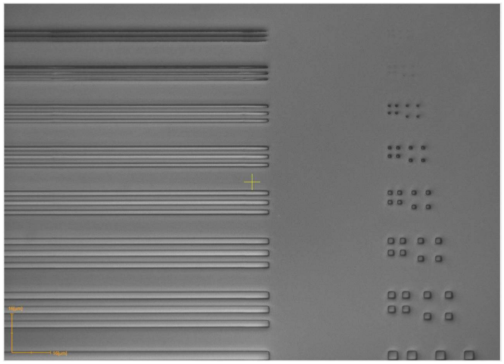
- Slight overlap or gap between the stripes during exposure leads to vertical line defects in the developed pattern. Can also be caused by a slight angle between the image and the stage.
- Sometimes the hardware needs to be adjusted by Heidelberg.
- In negative resist, lines are often visible after PEB and development. These are mostly aesthetic, but for AZ nLOF 2020, they can be removed by increasing the post-exposure bake time.



Before and after zoom module service



Dose 500, PEB 1min

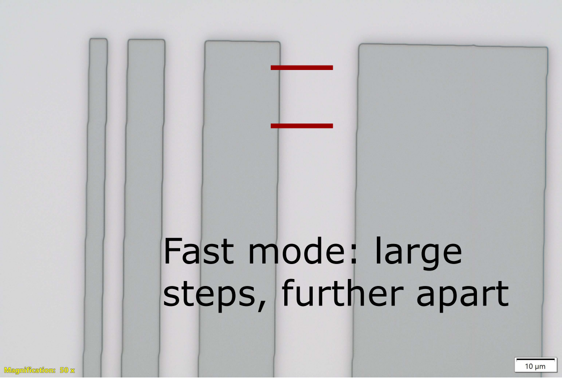


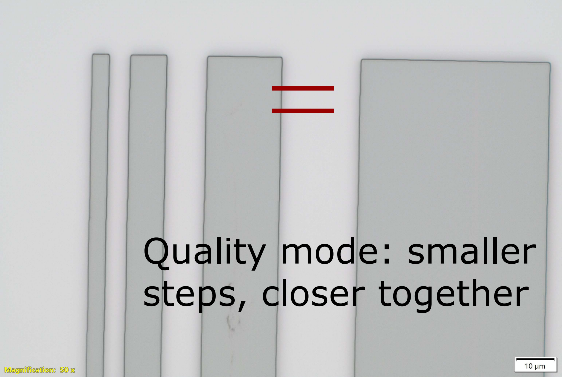
Dose 350, PEB 2min

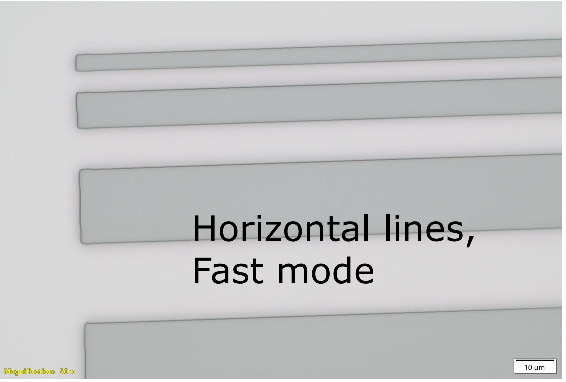
Problems – Maskless Aligner: jaggies (aliasing)

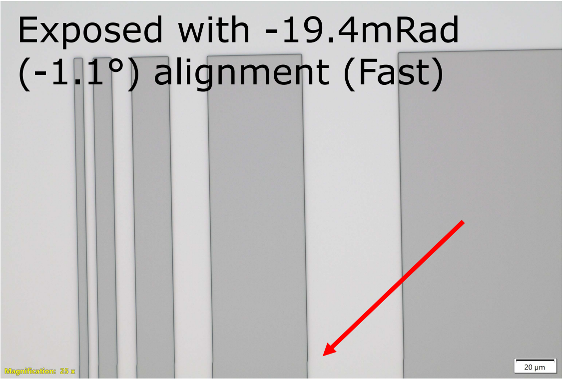
- When a design is exposed with alignment (flat or overlay), straight lines become stepped due to pixel aliasing effects. Such steps are called “jaggies”.
- The distance between steps decreases with increasing alignment angle
- The size of the steps depends on the exposure mode (fast vs. quality)
- The effect is much more pronounced for vertical lines than for horizontal lines
- For best result, expose using quality mode and minimize alignment angle

All patterns are rotated ±1° in design


Fast mode: large steps, further apart

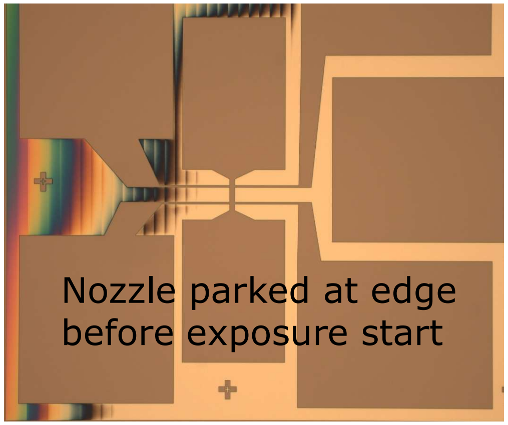

Quality mode: smaller steps, closer together

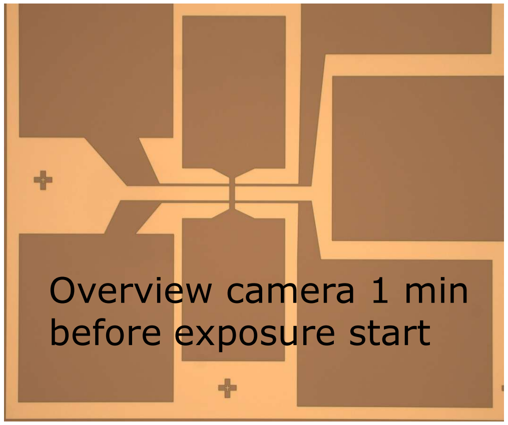

Horizontal lines, Fast mode

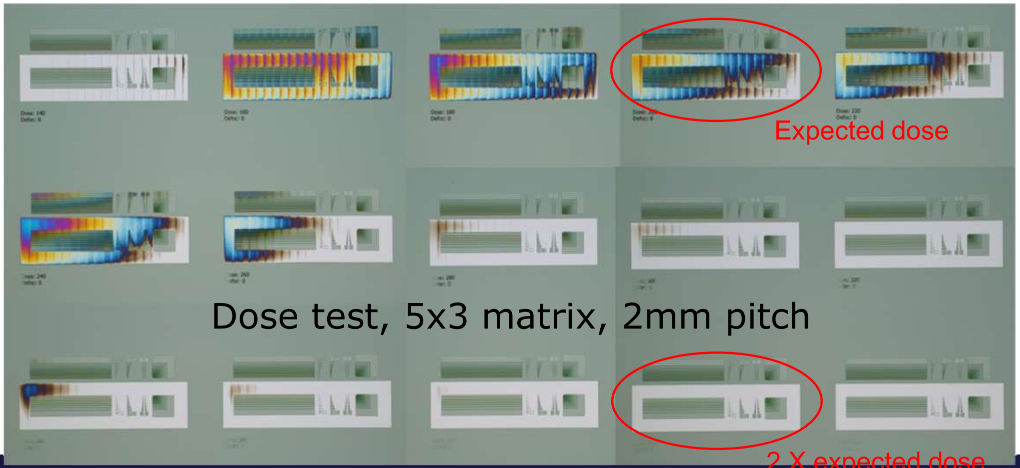

Exposed with -19.4mRad (-1.1°) alignment (Fast)

Problems – Maskless Aligner: dehydration

- DNQ-based resists (e.g. AZ MiR 701) rely on moisture in the resist film to complete the photo-chemical process. The clean dry air used for pneumatic autofocus can dehydrate the resist before or during the exposure, causing incomplete development.
- The effect depends on the coating process. A fully out-baked resist film doesn't seem to be affected (provided the cleanroom humidity is sufficiently high).
- Small chips: use the overview camera to park the substrate away from the nozzle for 1-2min before exposure start
- Dose test:
  - Labeling makes it worse
  - Increasing the distance between each dose (pitch) helps
  - Solution: extend the test design ≥40mm vertically (along the Y-axis), either during conversion, or by including a sub-resolution structure in the design


Nozzle parked at edge before exposure start


Overview camera 1 min before exposure start



Dose test, 5x3 matrix, 2mm pitch

Conclusions

- Alignment
  - Maskless Aligner wins, due to the convenient and versatile alignment method, the possibility to correct for distortion, as well as the possibility to correct machine shifts in the software
- Resolution
  - Mask Aligner is superior, but resolution deteriorates quickly with exposure mode
- Yield
  - Maskless Aligner has the upper hand (uniformity across the wafer, probably also repeatability)
- Sidewall angle
  - Highly dependent on specific resist
    - AZ 5214E: Mask aligner is best (straight sidewalls)
    - AZ MIR 701: Maskless aligner is best (straight sidewalls)
    - AZ nLOF 2020: Maskless aligner is best (highest undercut), but only at 365nm
- Bias
  - Mask Aligner has the least bias, and it can be removed by varying dose
  - Maskless Aligner always has bias (resist lines smaller than design), but there is a CD bias correction option in the conversion software

Thank you for listening.
Questions?