Metrology Requirements for Nanoimprint Lithography

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What am I doing here?

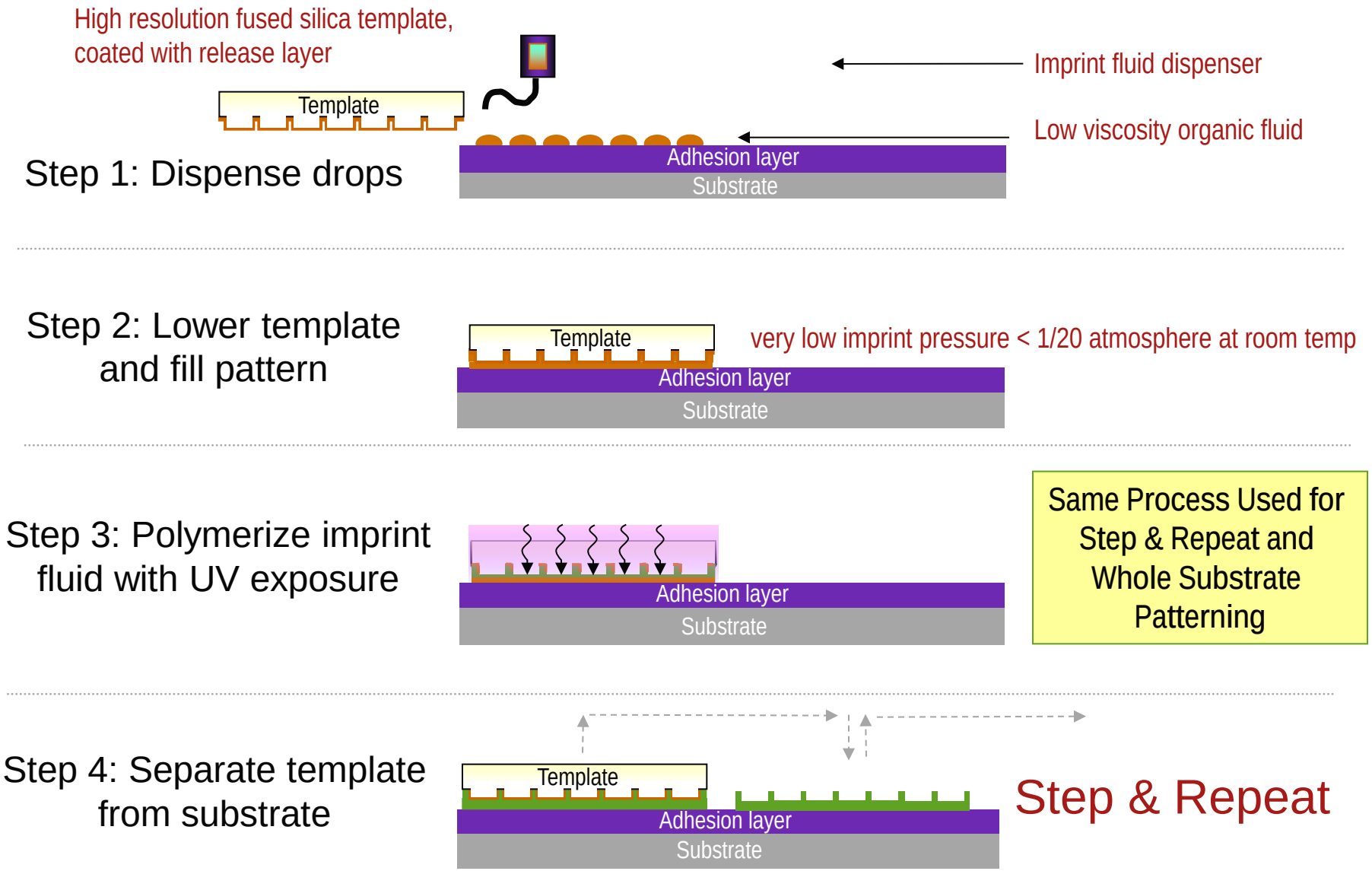
- Canon has developed a novel Nanoimprint Lithography capability which has unique challenges relative to more standard 4x reduction methods
- The purpose of this presentation is to introduce our technology, highlight some of the challenges and get folks thinking about metrology methods suitable for this technology*
- In this presentation, we will discuss two inkjet-based applications that require advanced measurement methods

**But promise not to derive anything from Maxwell's equations during the talk*

Nanoimprint Basics

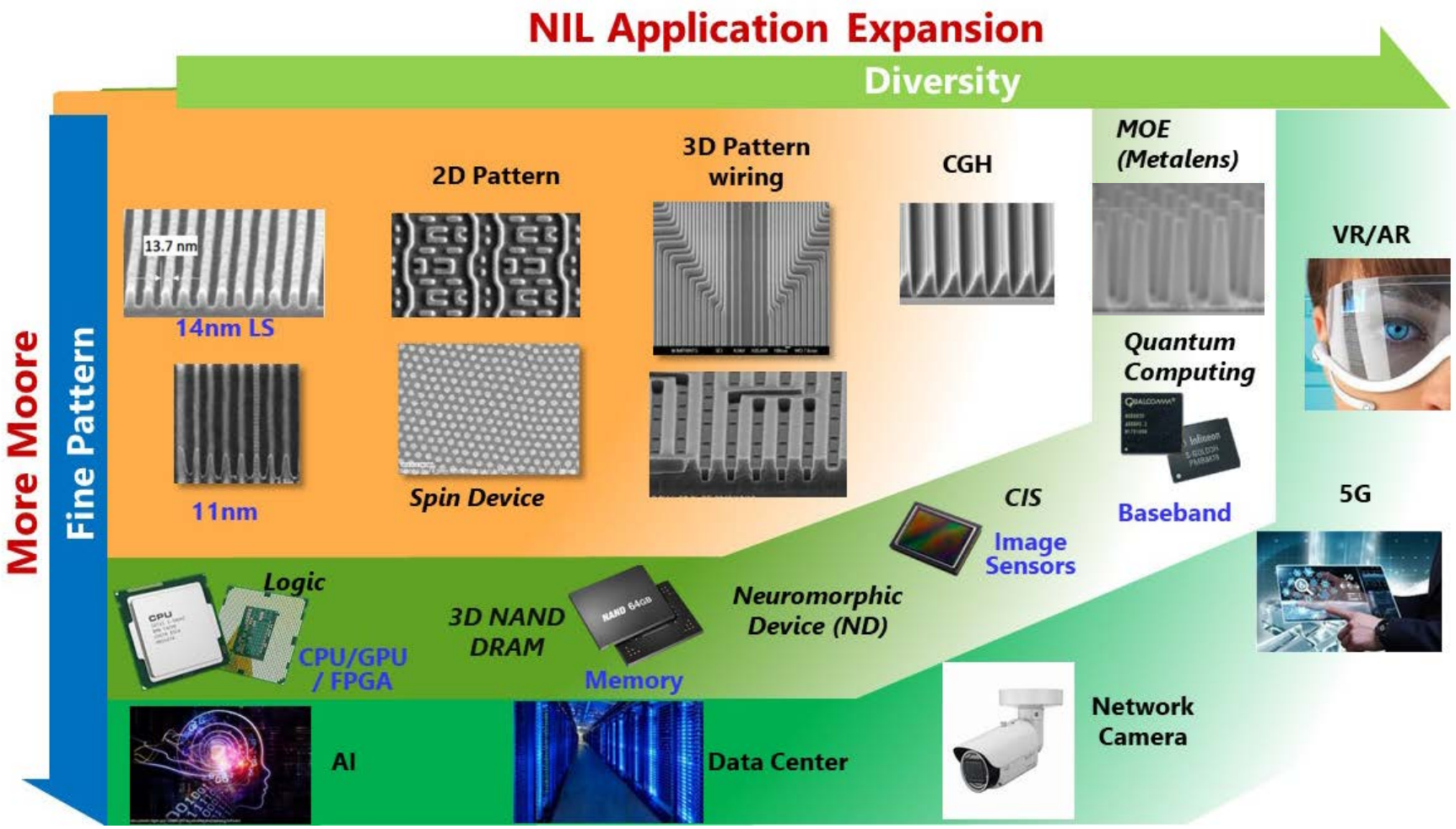
Canon's Approach to Nanoimprint (NIL)

- The Canon NIL process uses a transparent mask and jetted resist to create pattern
- This method enables an easier approach to overlay and optimizes the residual layer thickness uniformity beneath the imprinted features
  - First introduced by Grant Willson in 1999

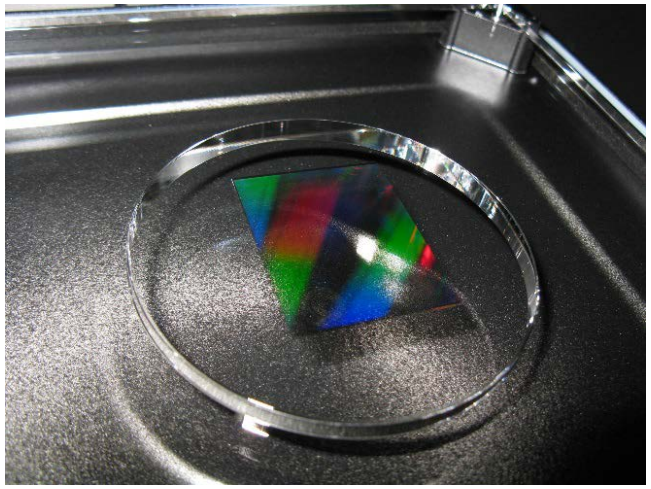


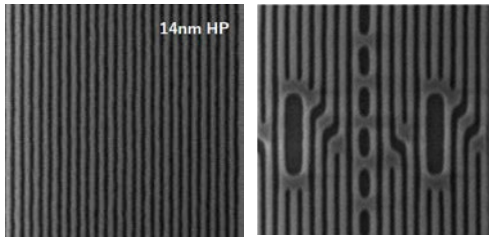
NIL Application Space

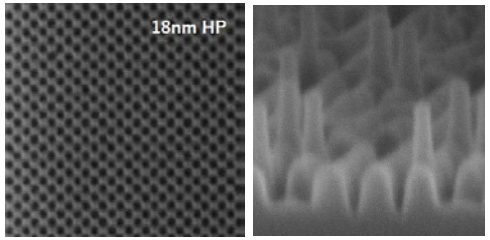
- Unlike other lithographic methods, NIL provides the pattern flexibility and a cost structure at address a much larger application space
- But any application requires a supporting ecosystem to enable a suitable production solution

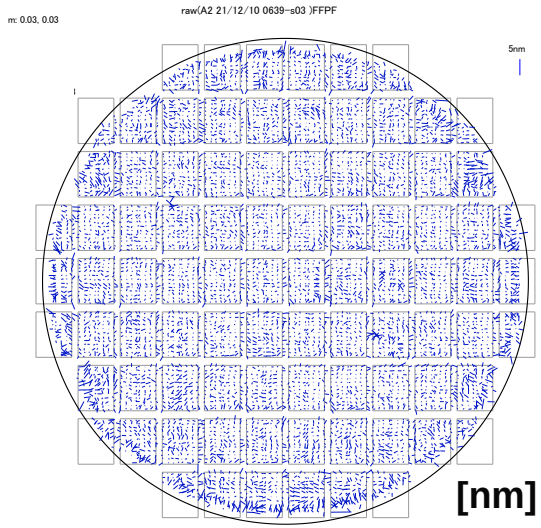


NZ2C performance







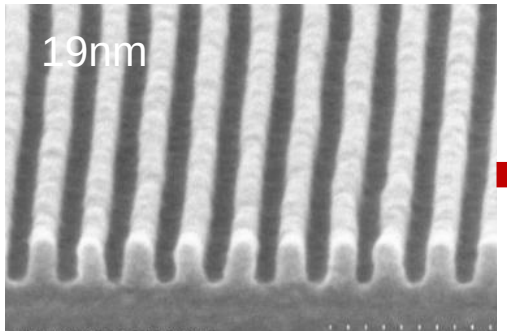


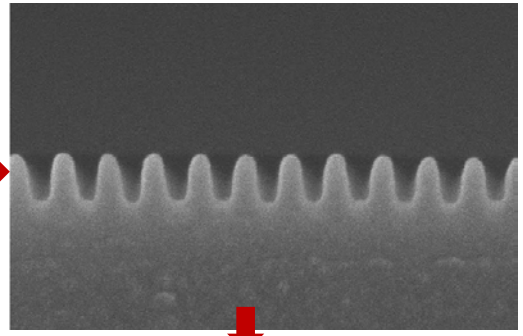
5nm

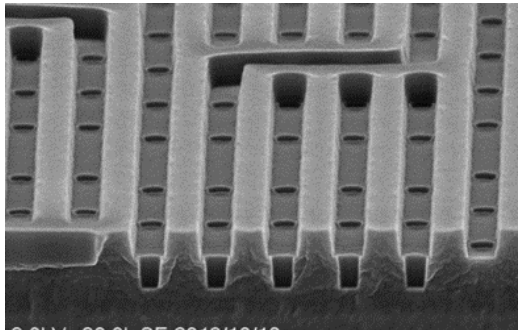
[nm]

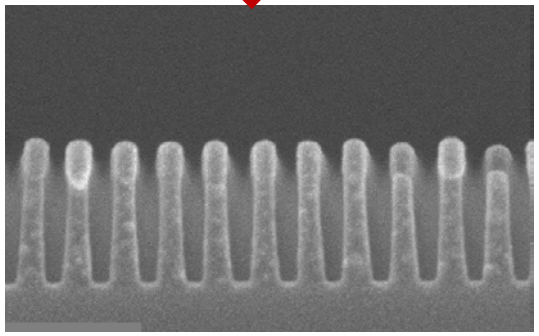
FPA-1200 NZ2C
NIL to ArF-IML
Evaluated with 96 locations per field
Full field + partial field

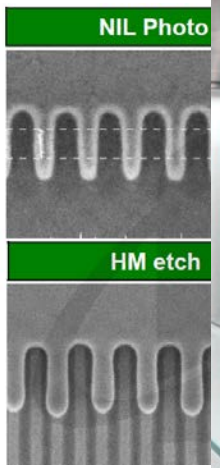
m+3σ	X	Y
Best Wafer	2.20	2.10
Average	2.42	2.24

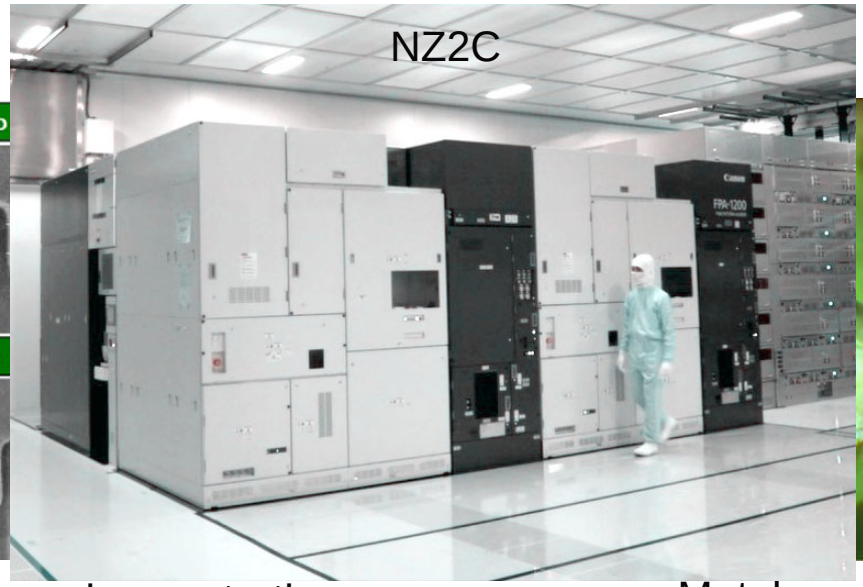


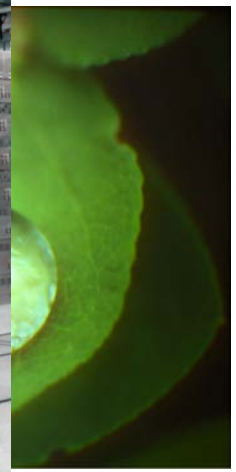










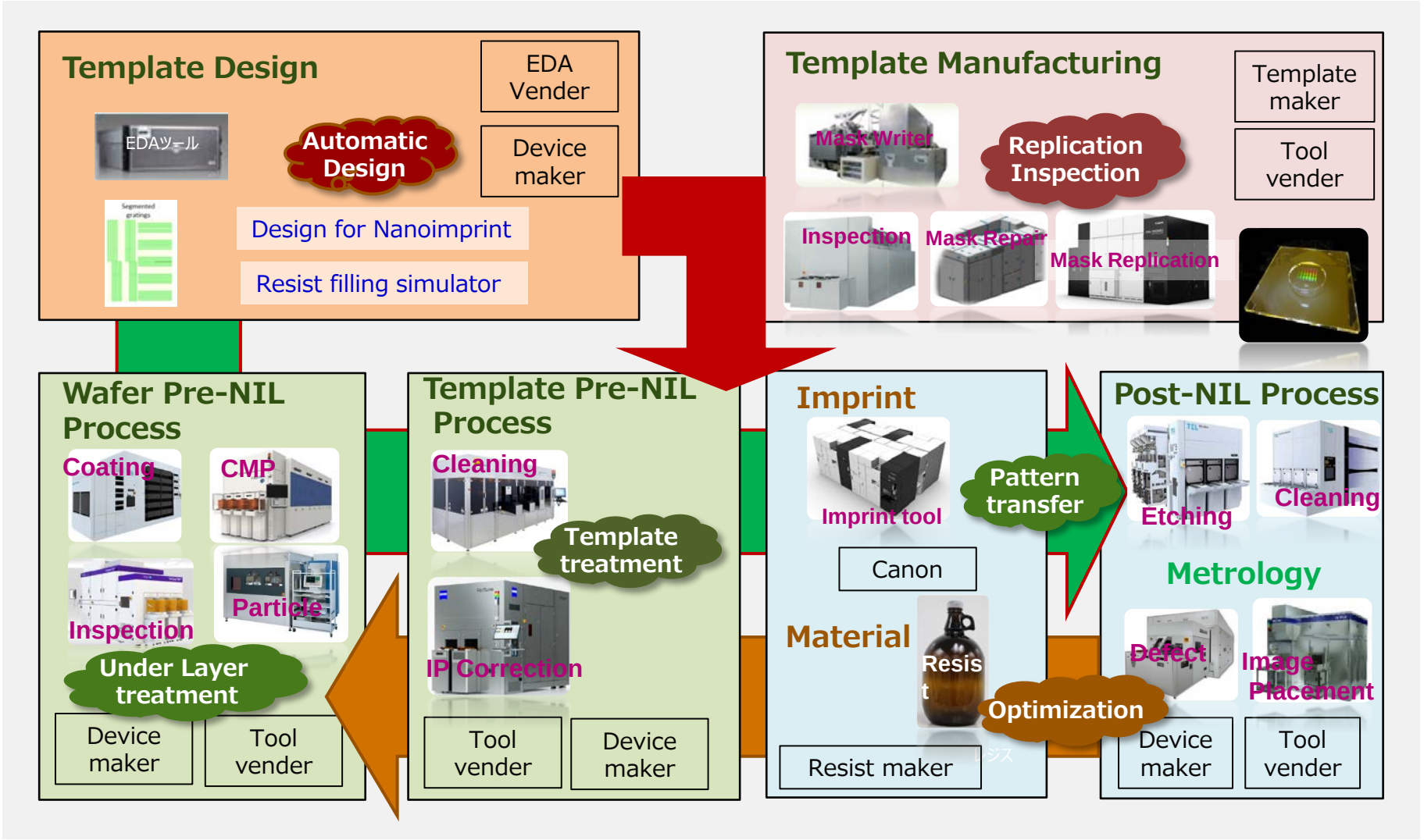


Cut layer demonstration

Metalens

NIL Metrology Requirements

Nanoimprint Ecosystem



Yield

- ***Overlay***
- ***Pattern Transfer***
- ***Defect***

Productivity

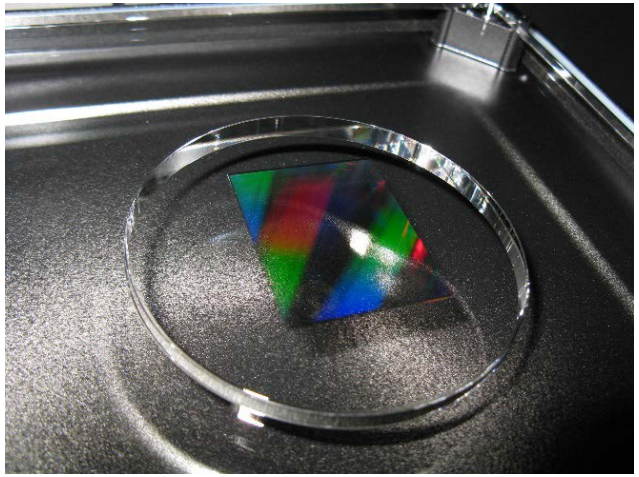
- ***Throughput***
- ***TAT***

Sustainability

Many ecosystem requirements are connected with the imprint mask (template)

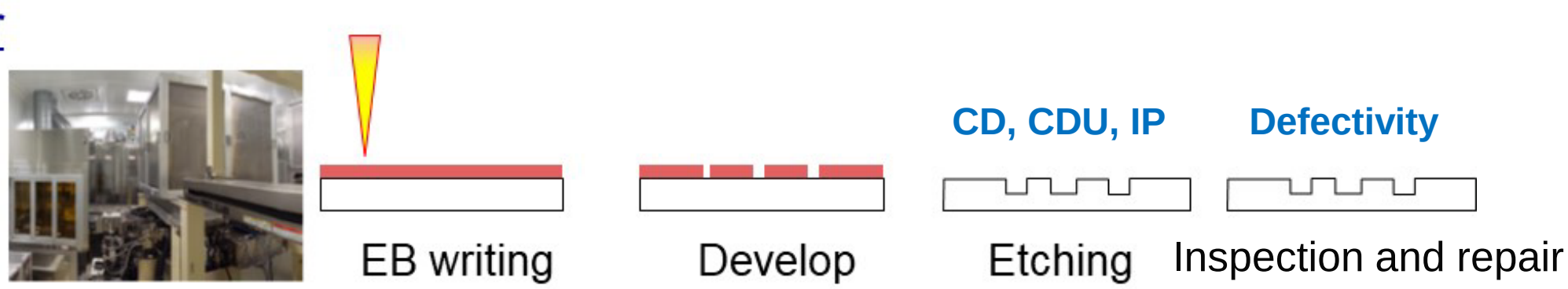
The NIL Mask

- One clear advantage of NIL is that the pattern formed on the mask is what is printed on the wafer – no complex computational lithography
- But everything we need to measure must be done on a 1x pattern
  - There is no 4x reduction
- In addition, replica masks are required since the lifetime of the mask is limited by defects induced during the imprint process
- Key metrics to be measured include
  - Critical dimension (CD), CDU and linewidth roughness (LWR)
  - Image placement
  - Defect inspection
  - Defect repair



Master Mask Fabrication

- The basic mask pattern is defined using a very typical process sequence



- For best resolution and lowest linewidth roughness, non-chemically amplified resists are used
  - These resists require higher doses, but the higher dose creates more secondary electrons, which reduce LWR
  - Non-chemically amplified resists also minimize the stochastics introduced from acid diffusion that occurs during the post exposure bake process
  - Years ago, the e-beam resist of choice was ZEP520A
    - Best performance was achieved by biasing the features in the GDS (smaller), increasing exposure dose and using diluted developers to enhance resist contrast
    - Newer materials, including chemically amplified resists and metal oxide resists with even better performance may be available

Master Mask CDU and Image Placement

- 1nm image placement has been demonstrated using an MBMW-101*

2x nm LS

		Master
Defects	pcs/cm^2	-
CDU (3σ)	nm	0.44
IP (3σ)	nm	1.52/0.91

2x nm pillar

		Master
Defects	pcs/cm^2	-
CDU (3σ)	nm	0.65
IP (3σ)	nm	0.97/1.02

*MBMW-101 is an 8-year-old tool with a global registration spec of 2nm

Source: SPIE 2023

Mask Replication Tool

- Canon makes an FPA-1100NR2 for the purpose of fabricating replica masks
- NR2 is located at a DNP manufacturing site and at Utsunomiya
  - An older legacy tool is also located at DNP
- Tool specifications are shown in the table to the right
  - Replica mask costs are low (compared to a master mask), and driven by the throughput of the mask replication tool

FPA-1100 NR2
Mask Replication Tool

Target Specifications		
Throughput	4	Mask/hour
CD Uniformity (3σ)	0.8	nm
Image Placement Accuracy (3σ)	1.0	nm
Particle	0.002	pcs/Mask

Mask CDU and Etch Depth

CDU

- Mask CDU for lines typically < 1nm*

Mask Type	Typical pattern	Feature size	CD* [nm]	
			Ave.	3σ
Master	L/S	19nm	20.12	0.34
		32nm	38.86	0.49
		54nm	65.59	0.66
Replica	L/S	26nm	33.61	1.07
Replica	Hole	17nm	18.04	1.70
		18nm	19.91	1.45
		20nm	22.68	1.27

* Imprinted measurements

Etch Depth

- Mask Feature Etch Depth is very well controlled.
- Shown is a run of six replica masks with a targeted etch depth of either 40nm or 50nm

Mask ID	1	2	3	4	5	6	7
Target (nm)	40.0	40.0	40.0	40.0	40.0	50.0	50.0
Mean	40.2	40.6	40.3	40.0	39.5	52.2	51.6
STDEV	0.17	0.25	0.22	0.21	0.20	0.20	0.25
Max	40.5	41.0	40.8	40.3	39.8	52.5	51.9
Min	40.0	40.3	40.1	39.5	39.3	51.8	51.3
Range	0.52	0.68	0.68	0.77	0.52	0.67	0.66

Replica Imprint Mask Results: Image Placement

- This slide demonstrates Image placement mapping across three replica masks.
- Image placement is ~ 1nm and the results are repeatable, replica to replica

Template Matching Example

- 3 replica masks were generated from a single master mask
- 322 measured locations per field

Replica 1

	X	Y	unit
3σ	1.17	1.11	nm
max	1.12	1.29	nm
min	-1.17	-1.10	nm

Replica 2

	X	Y	unit
3σ	1.16	0.91	nm
max	0.99	1.11	nm
min	-1.25	-0.78	nm

Replica 3

	X	Y	unit
3σ	1.17	0.81	nm
max	1.09	0.86	nm
min	-1.22	-0.74	nm

IP difference = (2) - (1)

	X	Y	
3σ	0.38	0.34	nm

IP difference = (3) - (1)

	X	Y	
3σ	0.33	0.40	nm

IP difference = (3) - (2)

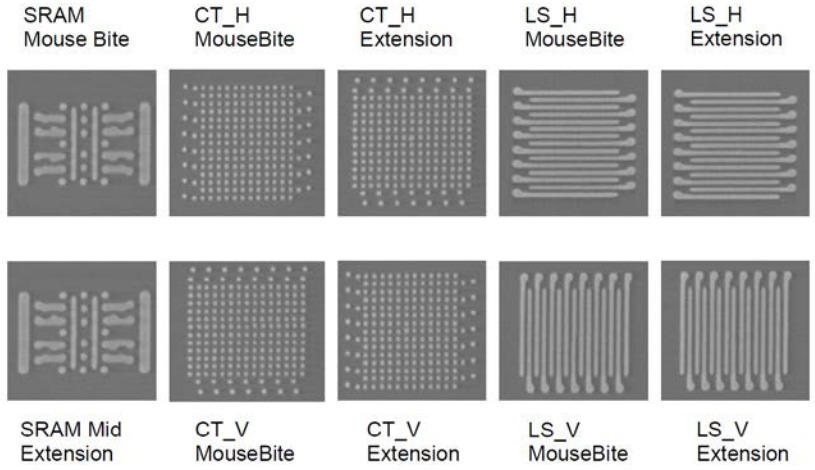
	X	Y	
3σ	0.35	0.37	nm

Mask Inspection

- NIL direct mask inspection has been done with both e-beam and optical systems

E-beam Inspection

- Hermes Microvision eScan 315xp



Bacus 2009

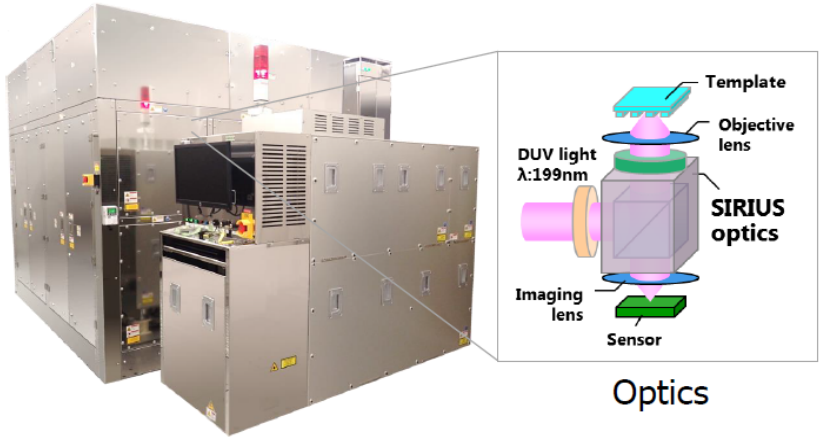
		48nm	44nm	40nm	36nm	32nm	28nm	24nm	20nm	16nm	12nm	8nm	4nm
SRAM	Mousebite	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%
	Shorten	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%
	Mid Extension	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	0%
	Extension	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	93%	0%
CT	H_Mousebite	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	40%
	V_Mousebite	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	40%
	H_Extension	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	13%
	V_Extension	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	20%
L/S	H_Mousebite	100%	100%	100%	100%	100%	100%	100%	100%	100%	93%	20%	0%
	V_Mousebite	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	27%	0%
	H_Extension	100%	100%	100%	100%	100%	100%	100%	100%	100%	87%	7%	0%
	V_Extension	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	27%	0%

Optical Inspection

- NuFlare

✓ **New inspection tool NX-8000 was developed by NFT which specialized for the nano-imprint pattern inspection featuring**

- **199nm inspection wavelength**
- **High inspection throughput : 60min@26x33mm**
- **3 inspection modes for NIL inspection**



NIL template inspection tool NX-8000

Inspection mode

Mode	Defect Sensitivity*	Through put
RIGEL	24-28nm	20min
VEGA	24nm	40min
SIRIUS	15nm	60min

*Detectable defect size on L/S pattern

SPIE 2017

E-beam has acceptable resolution but is too slow. Optical inspection has reasonable throughput, but resolution is lacking

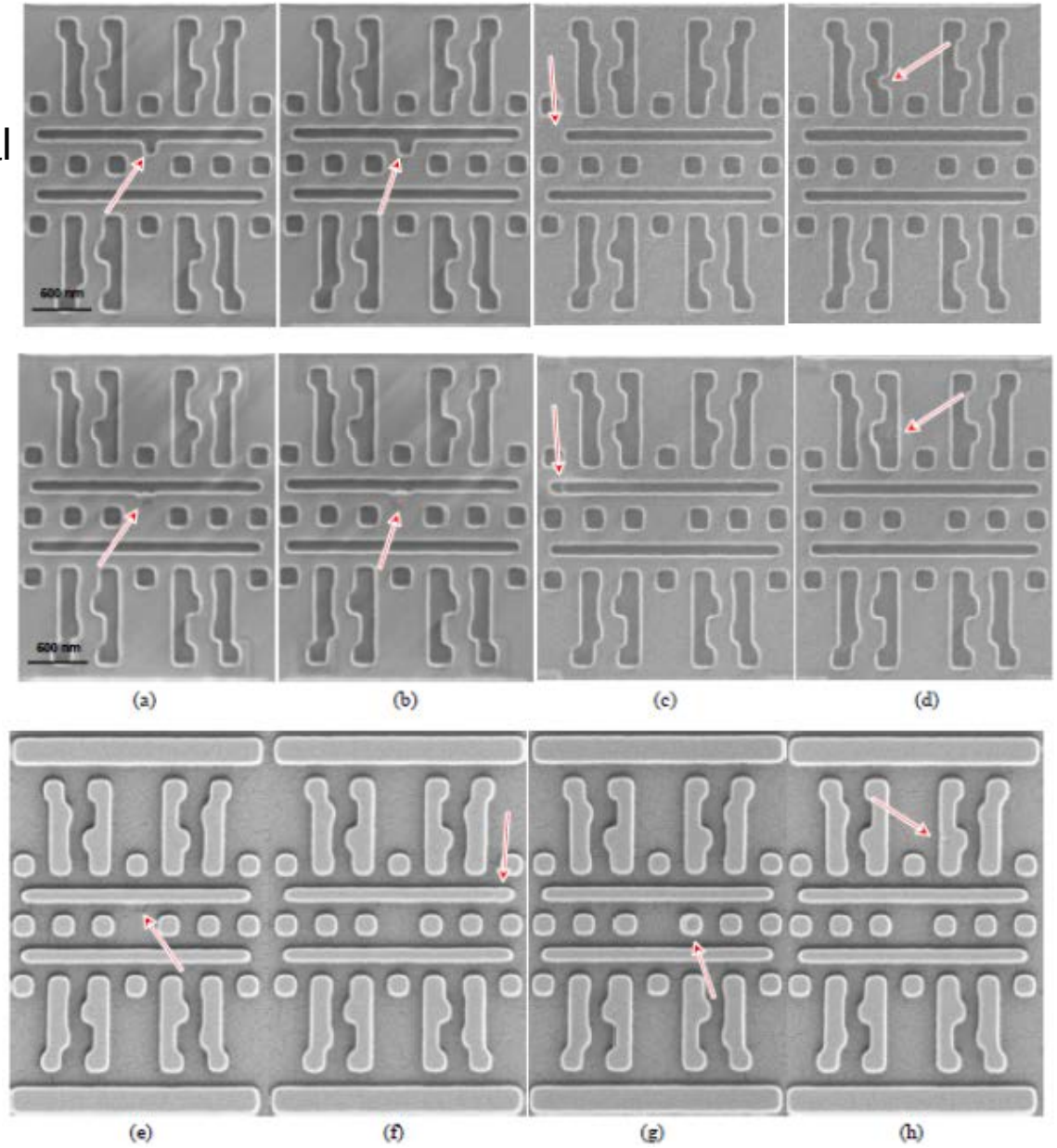
Mask Repair

- The most advanced repair work has been done using an e-beam repair system from Nawotec (now Zeiss)
  - 32nm pattern
  - SPIE 2008
  - Nawotec was later acquired by Zeiss (tool name is MeRiT)
  - Both subtractive (glass etching) and additive (deposition of an oxide) repairs are possible

Original mask

After repair

After imprint



Repair of smaller pitch features is largely untested

Want more mask metrology?

https://spie-org.zoom.us/webinar/register/9617563205851/WN_cczRJVM1S6SFSOek9hWCKg#/registration

zoom

Support English

Mask Metrology for Advanced Nodes

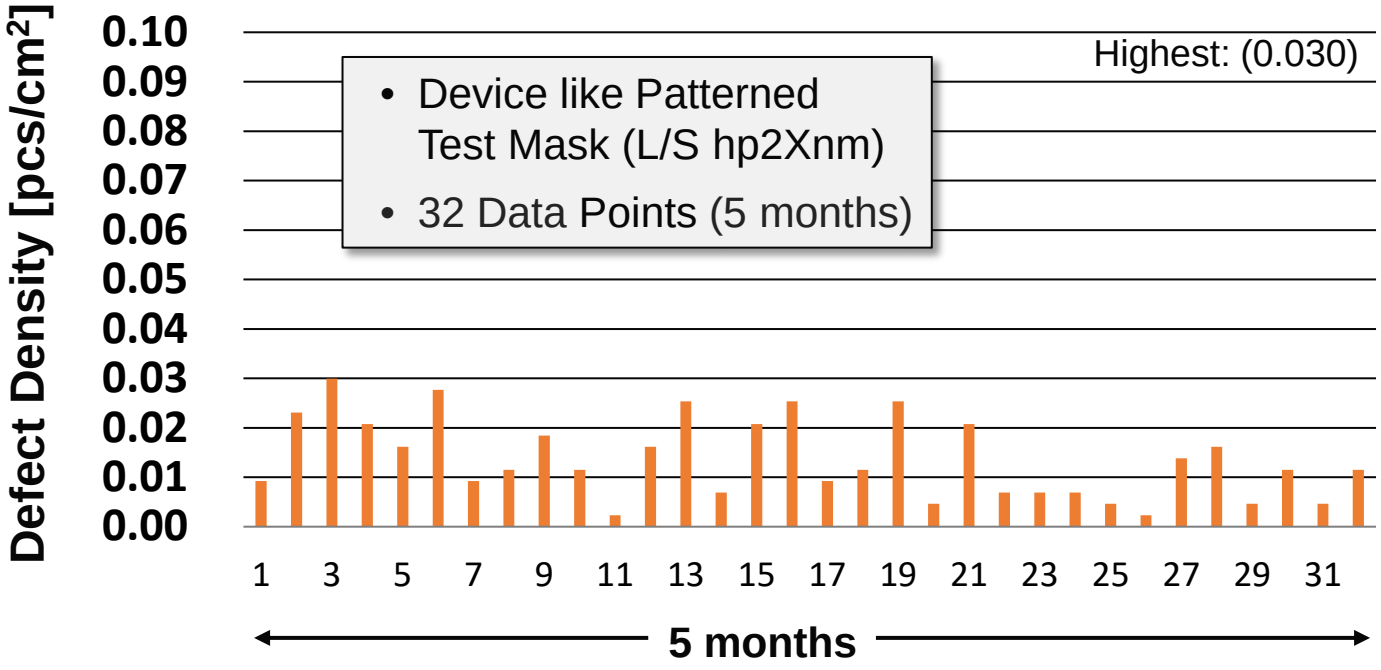
Date & Time	Mar 20, 2026 08:00 AM in Arizona
Description	Photomasks are an essential component of the lithography process. With increasingly tighter requirements on edge placement error (EPE), controlling crucial mask parameters —such as pattern placement, critical dimension (CD), and induced phase changes by absorbers—is necessary to ensure optimal chip production yields.

NIL Defectivity

There are two defect modes that need to be tracked: Random and Repeating

Random Defects

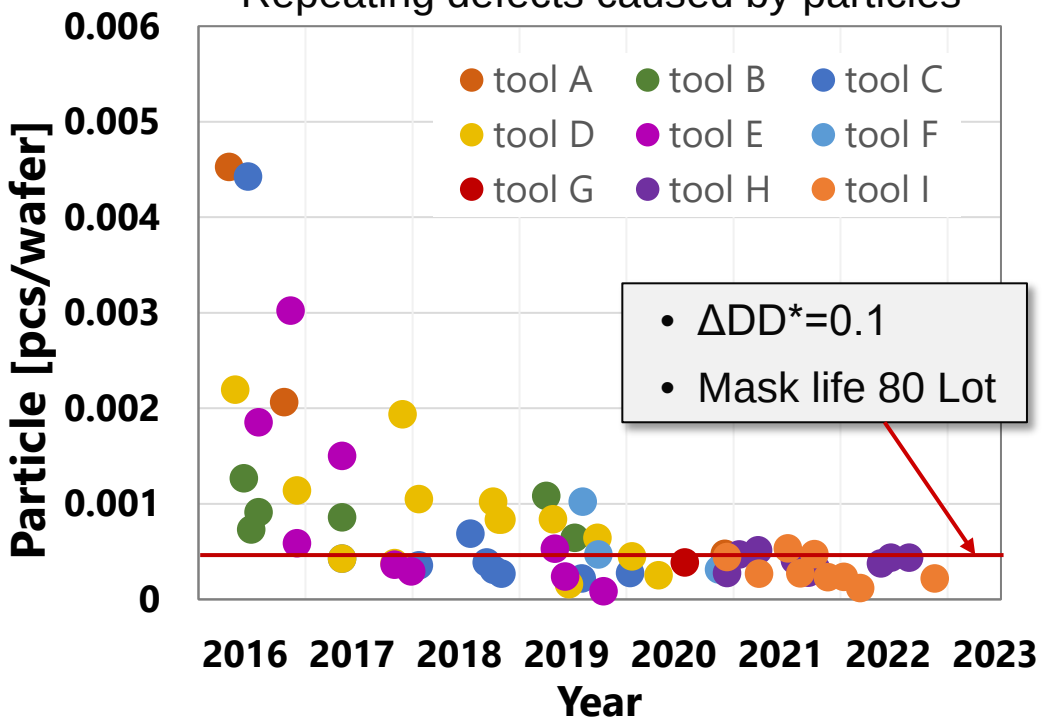
Main source of random defectivity: non-fill and feature collapse



Day-to-day Defect stability meets 3D NAND mass production level.

Repeater Defects

Repeating defects caused by particles



Particle adder target is one defect every 2,500 wafers and is now being achieved in multiple stations

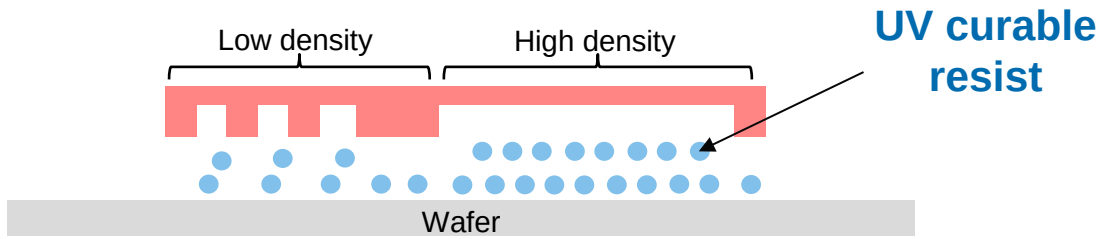
Introduction to Inkjet-based Adaptive Planarization (IAP)

NIL vs IAP

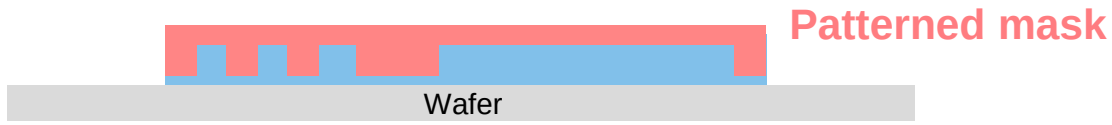
- Inkjet-based technology can be used both to create patterns and to remove topography from a wafer surface

Nanoimprint Lithography

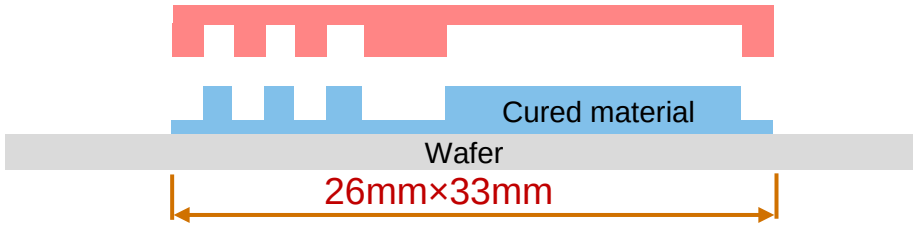
Step 1. Jetting of droplets onto a wafer



Step 2. Mask contacts a liquid resist

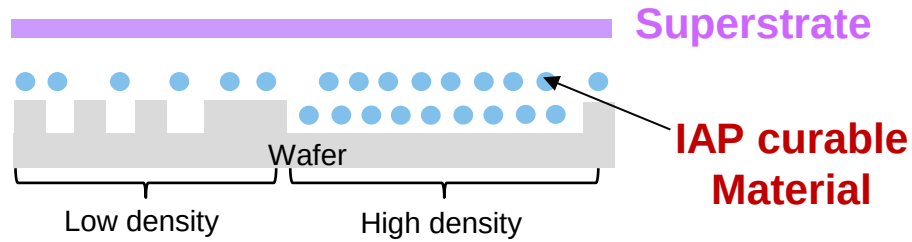


Step 3. UV Cure and Separation



Inkjet-based Adaptive Planarization

Step 1. Jetting of droplets onto a wafer



Step 2. Glass superstrate contact to an IAP Material

Step 3. UV Cure and Separation

Why take a full wafer approach?

There are three primary reasons:

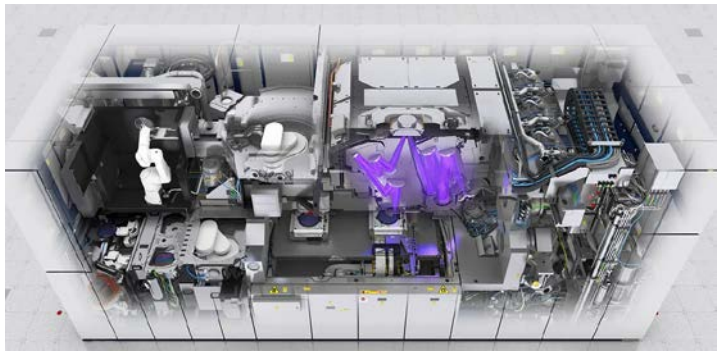
- **Throughput**: We can process a wafer faster with a single print than we can having to do it in a step and repeat fashion ~ 100 times
- **Field stitching**: A whole wafer process avoids the field stitching problem and allows easy printing of a contiguous film across the entire wafer
- **Minimize Defectivity**: If I pick up a repeater defect in a 26mm x 33mm field, I now repeat that defect in every printed field. With a full wafer approach, that defect gets repeated only once on a wafer

Why does topography matter?

- Advanced lithographic technologies and all device types are all impacted by topography
  - For ArF immersion, topography affect depth of focus (DOF)
    - Reduced DOF impacts CDU and therefore device performance
  - For EUV, topography affects both DOF and overlay
    - EUV masks have a 3D component. Topography shifts pattern placement, which again impacts yield
  - For NIL, topography affects residual layer thickness uniformity, overlay and resist fill time
    - Impacting CDU, throughput and yield
- Topography generally takes on two forms:
  - Topography induced from the 300mm wafer
  - Pattern topography
- The industry routinely uses CMP to remove topography, but there are many device levels where this does not work

ArFi

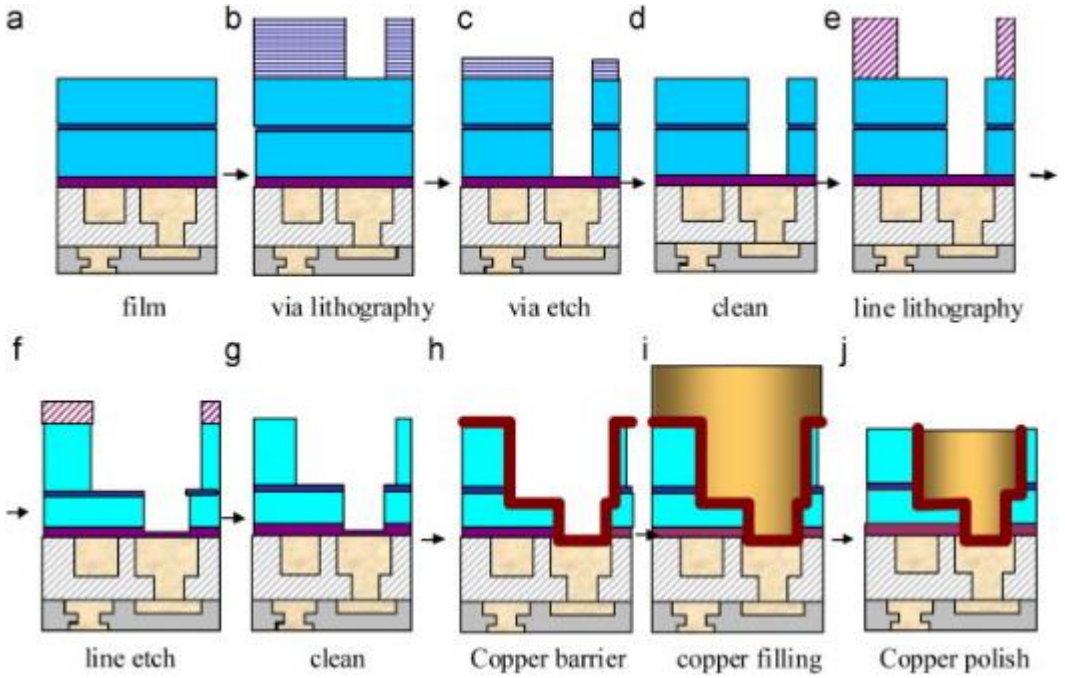
EUV

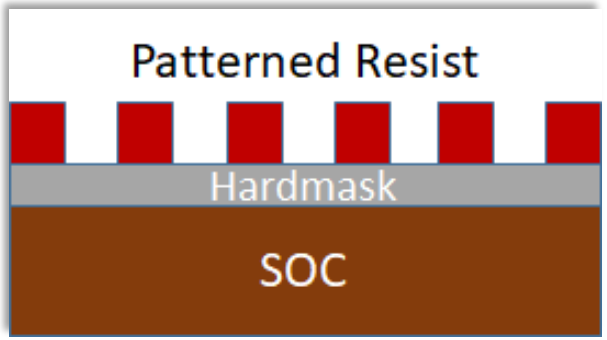


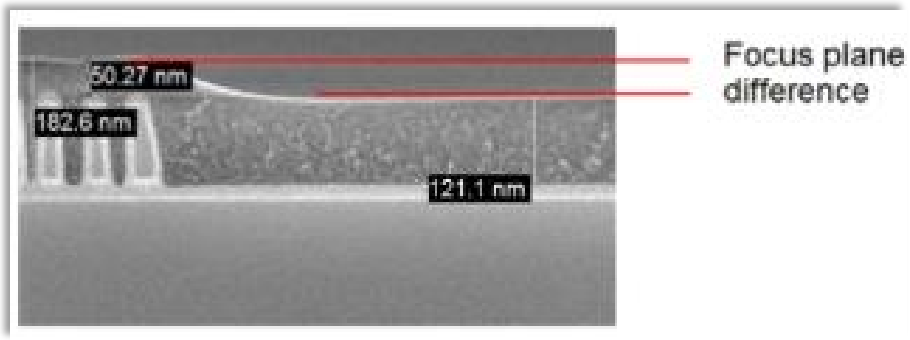
NIL

Dual-damascene illustrates challenges

- Back-end metal levels use a dual damascene process
- This introduces pattern topography







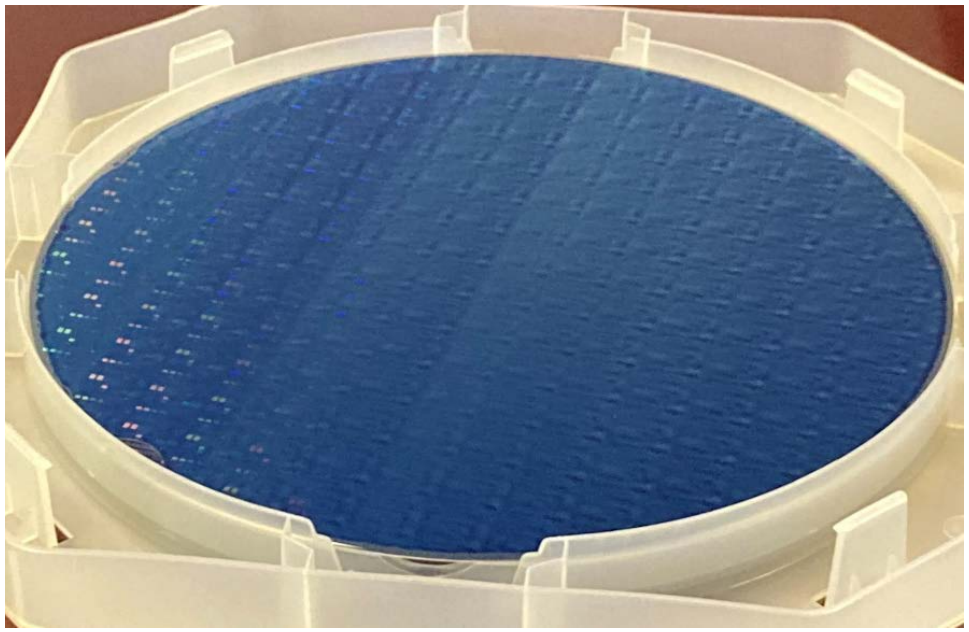
- So, what do device manufacturers do?
  - Apply multi-level resist stacks, e.g., SOC, to minimize the pattern topography
    - SOC does not correctly planarize larger features
    - Sometimes, multiple step processes are needed
  - Restrict design layouts
    - Smaller features, dummy patterns
    - Adversely affects device performance and adds cost

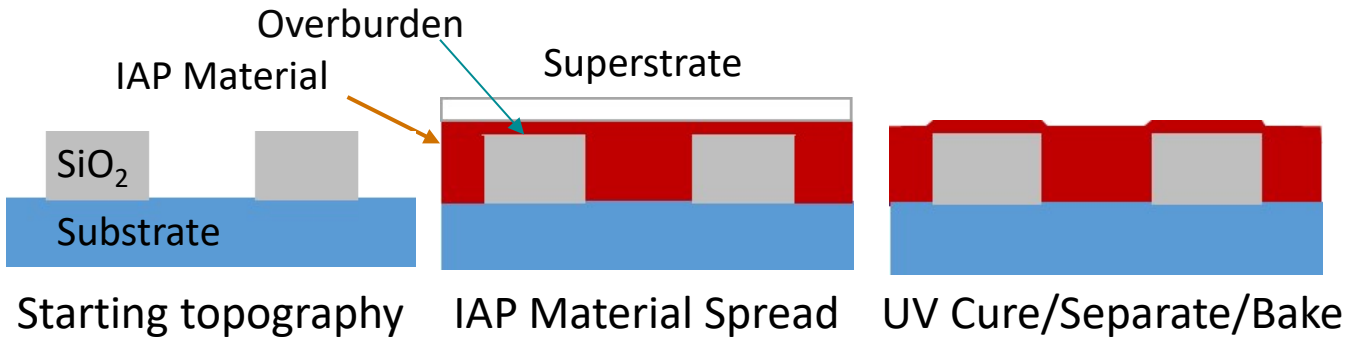
What does the industry require?

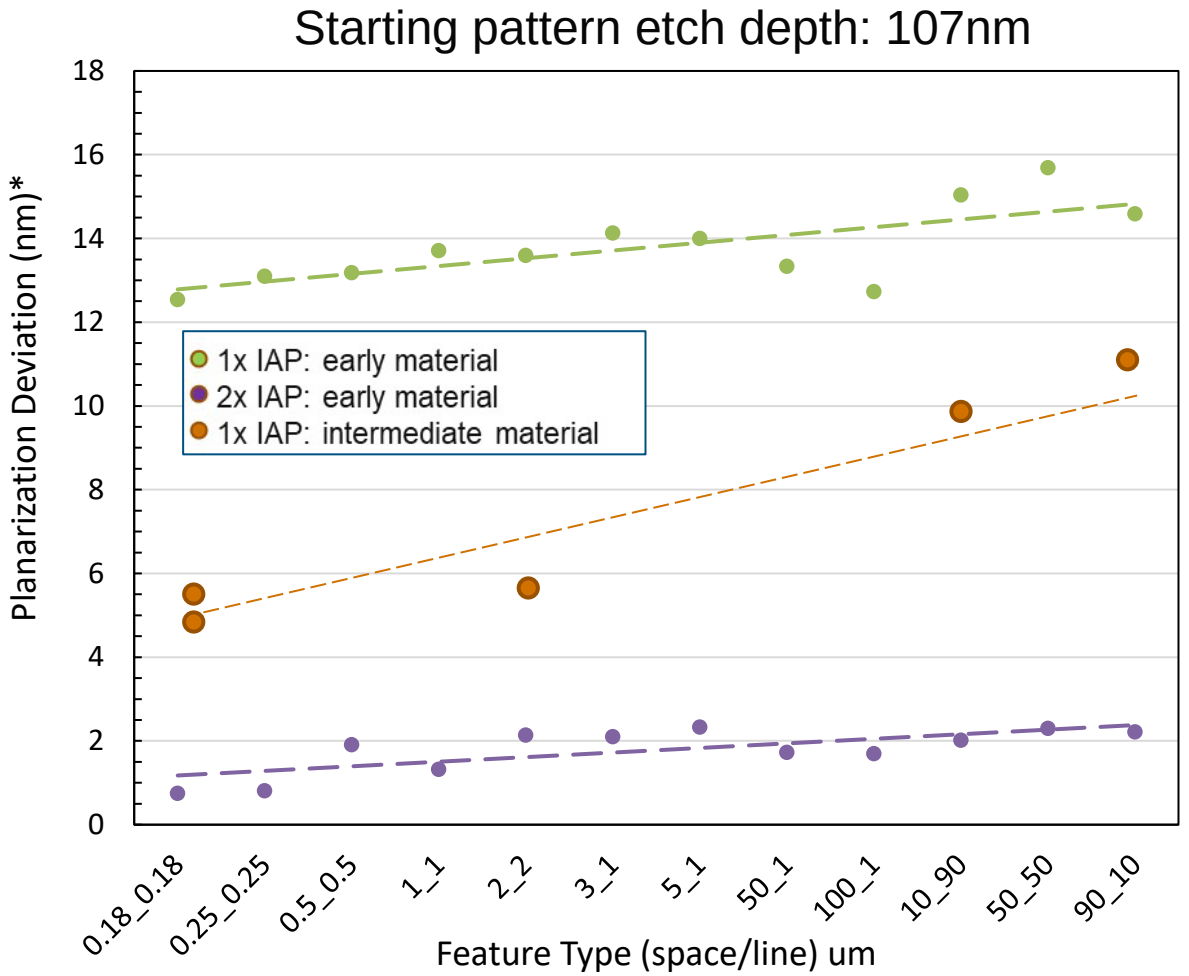
- Planarization technology that:
  - Reduces topography, allows more design freedom, improves performance
  - Is lithography agnostic
- Planarizes existing pattern topography ***and*** conforms to wafer topography
  - ***With excellent gap-fill***
  - ***Producing a uniform overburden needed for downstream processes***
  - ***With materials that allow robust post-processing***
- Cost-effective
  - One tool that puts down the required planarization layer and readies that layer for all the required downstream processes

IAP Results

Local Planarization: Initial Results*





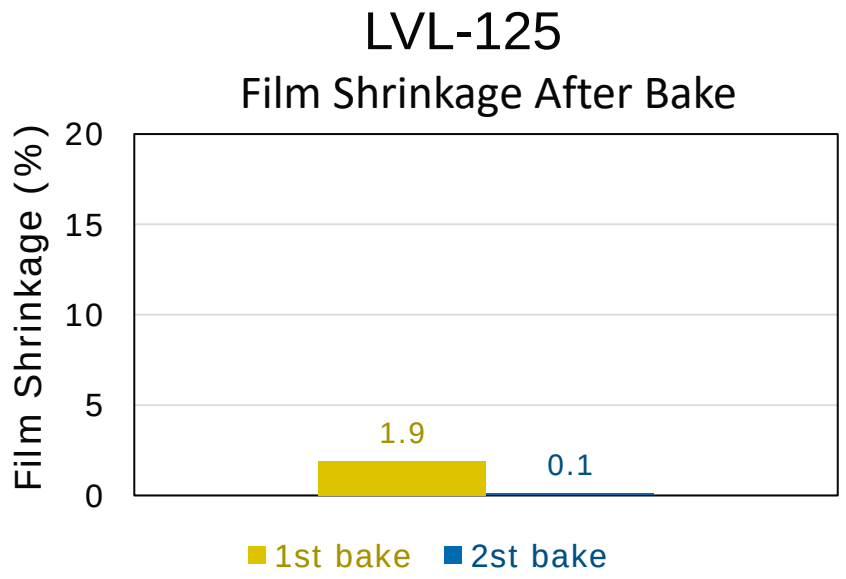


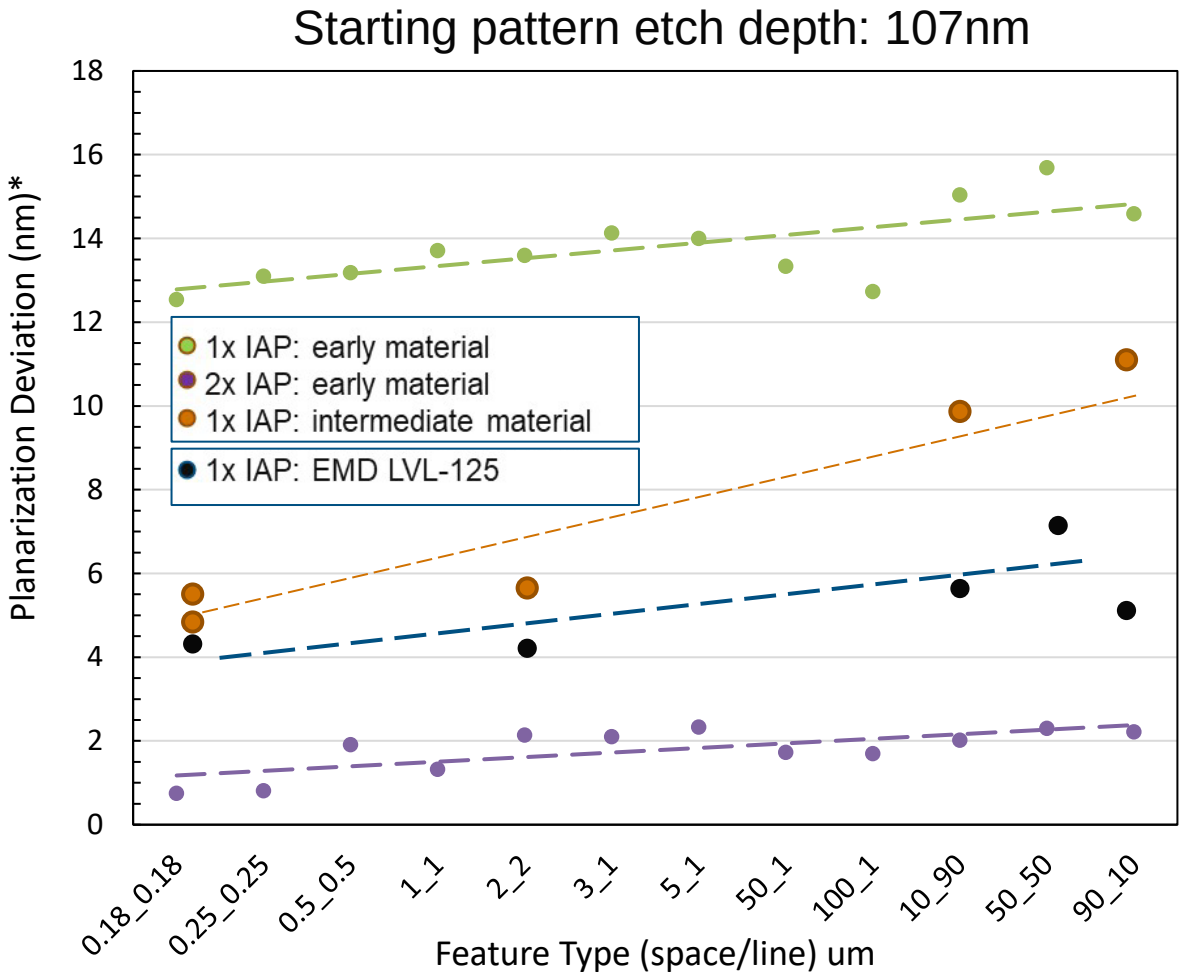
- NIL resists and early IAP formulations were subject to shrinkage during UV cure and bake

* Measured using a Bruker Insight tool in AFM mode

Local planarization: Recent Results

- By developing new IAP materials with reduced shrinkage after UV cure and bake, it is possible to significantly improve IAP performance after a 1X IAP process*





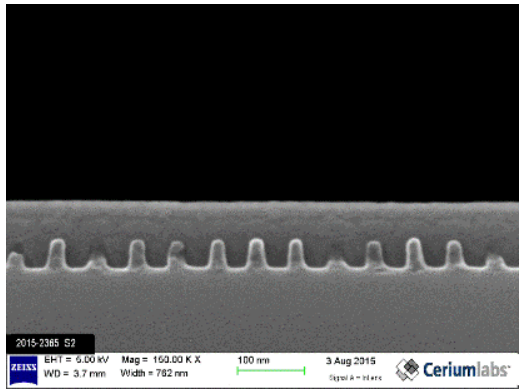
- 1x IAP results better than 7nm for all features
- 2x IAP results better than 3nm for all features

*See paper by Sekito-san for more details

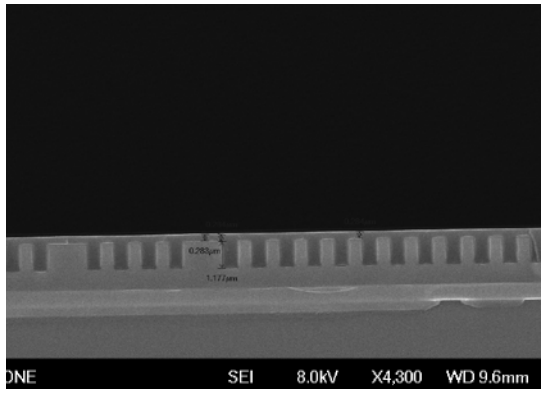
* Measured using a Bruker Insight tool in AFM mode

Local Planarization Results

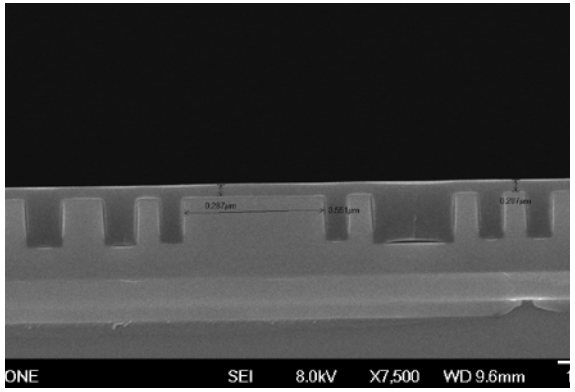
Excellent planarization across small and large pitch features



30nm HP lines



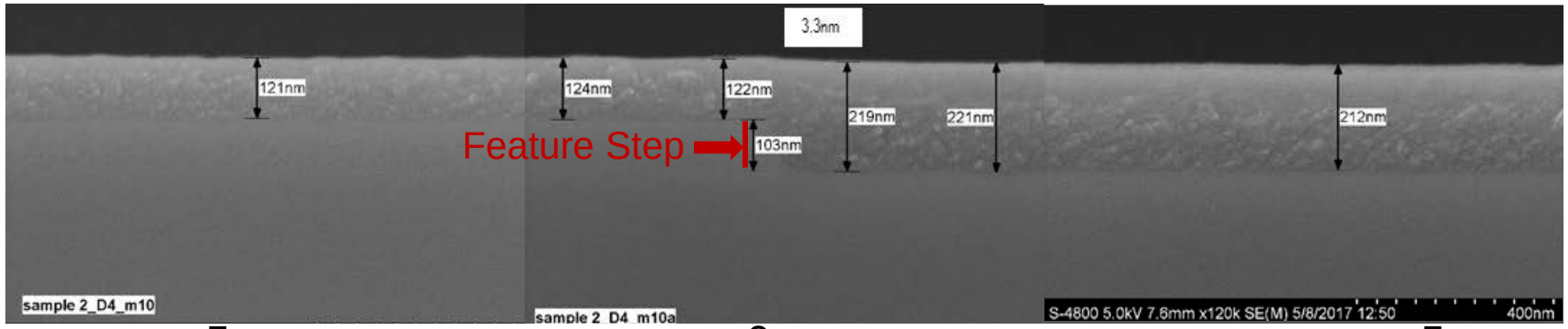
750nm HP lines



Dense and semi-dense lines

10 um line

90 um space



-5 um

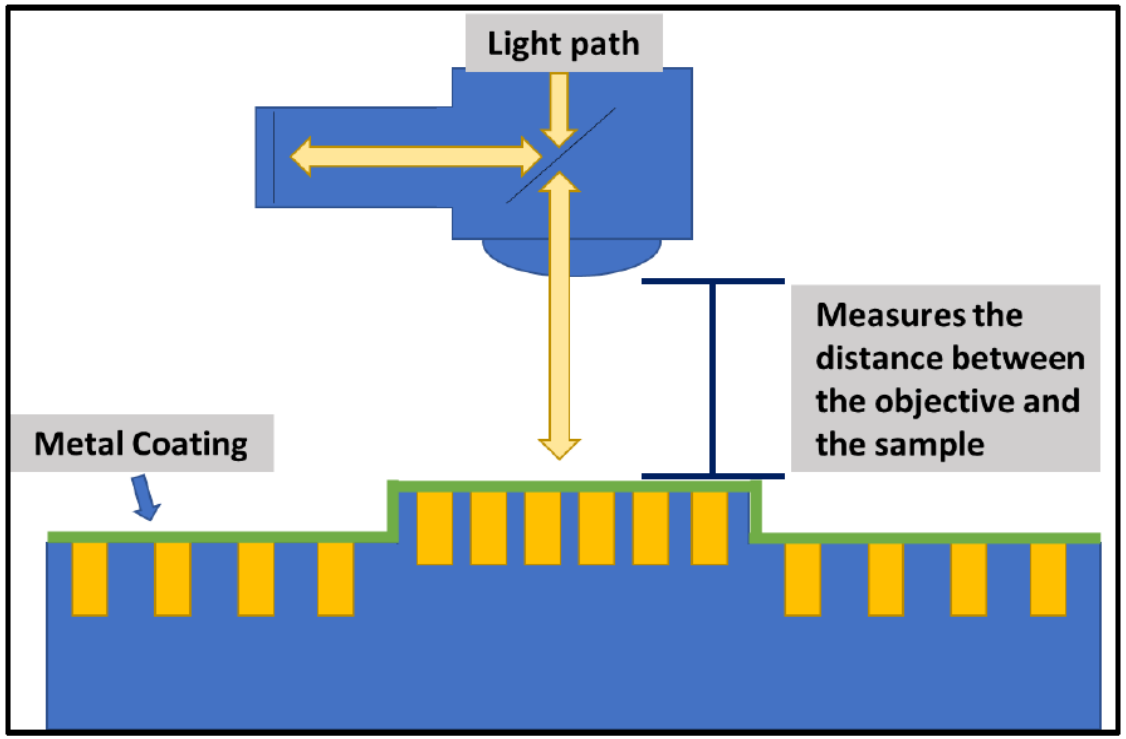
0

+5 um

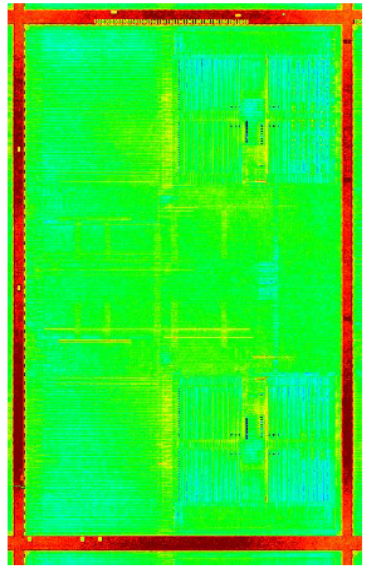
Large Area Planarization

- Measuring pattern topography requires methods other than AFM or SEM x-section.
- White light interferometers, are used for high-precision, non-contact 3D surface mapping, measuring surface topography, roughness, and finish.

Interferometry Measurement



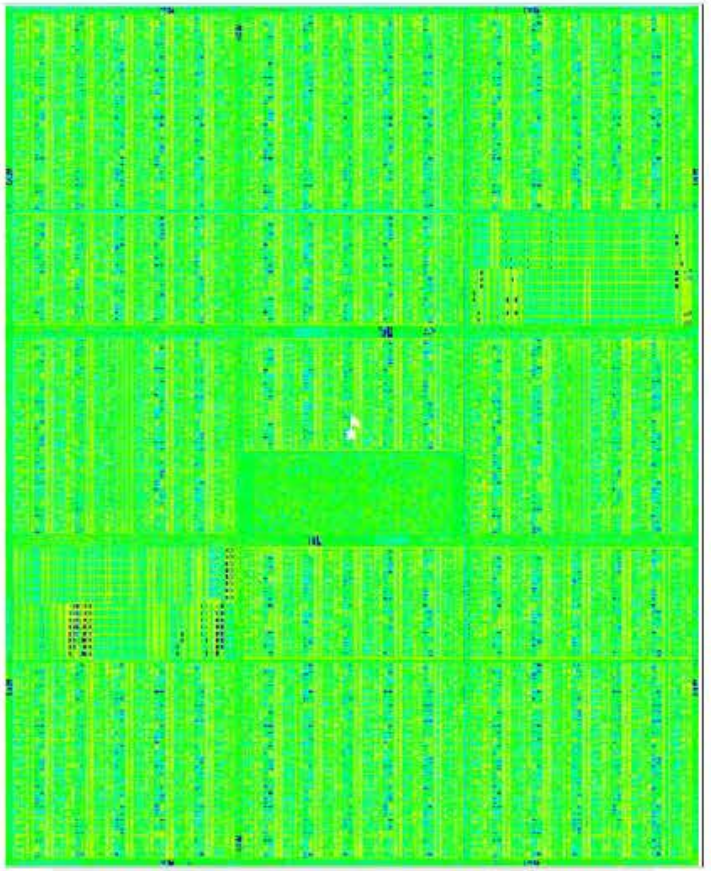
Images the entire reticle

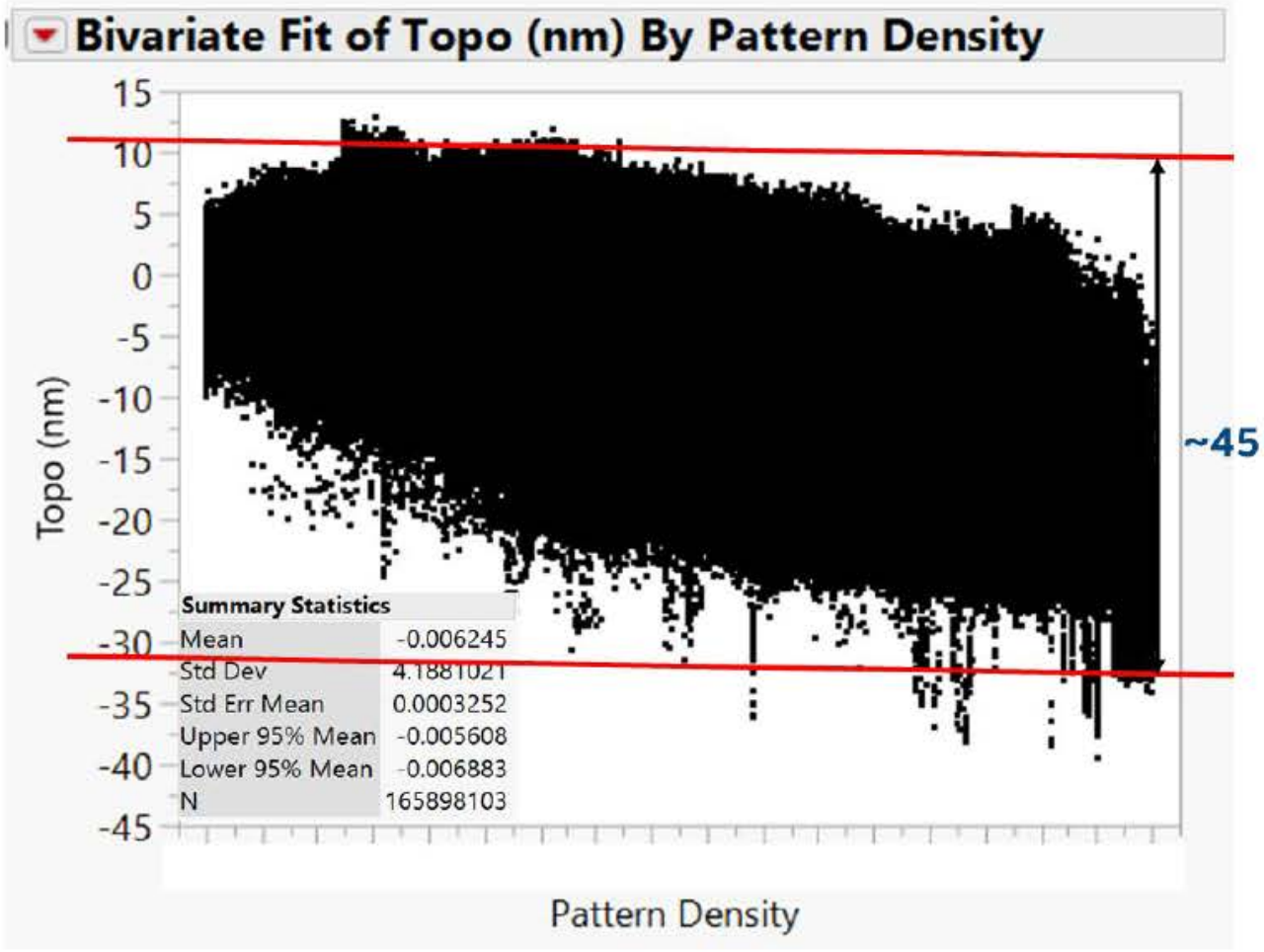


Pixel size is ~2.5x2.5um

Good for understanding overburden uniformity trends, but numbers reported within a single pixel are averages

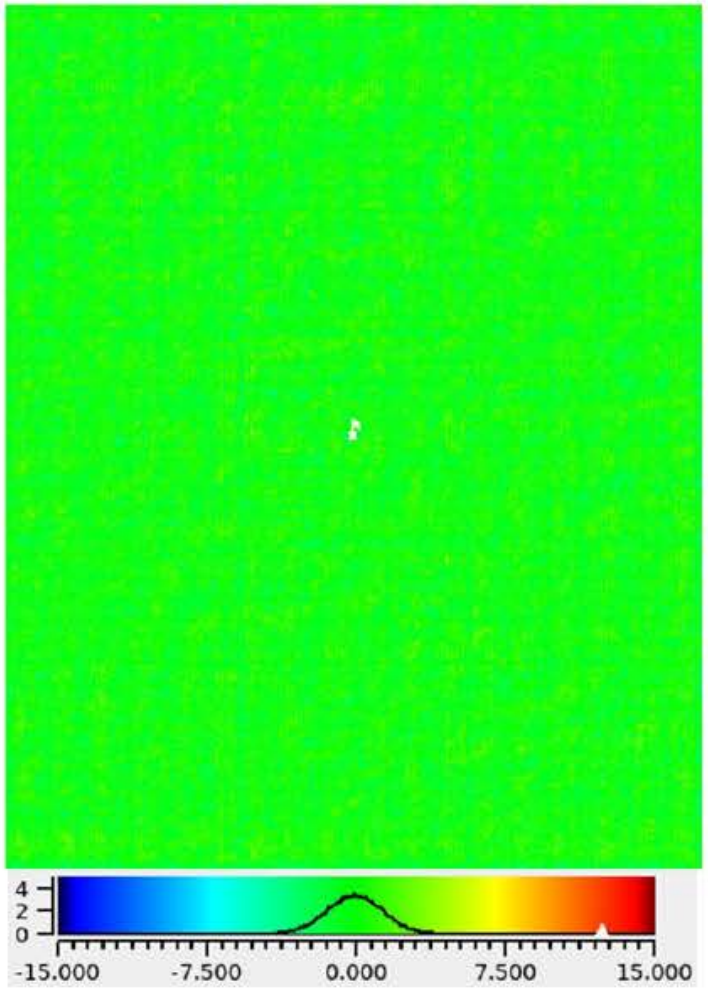
Full Field Topo with SOC

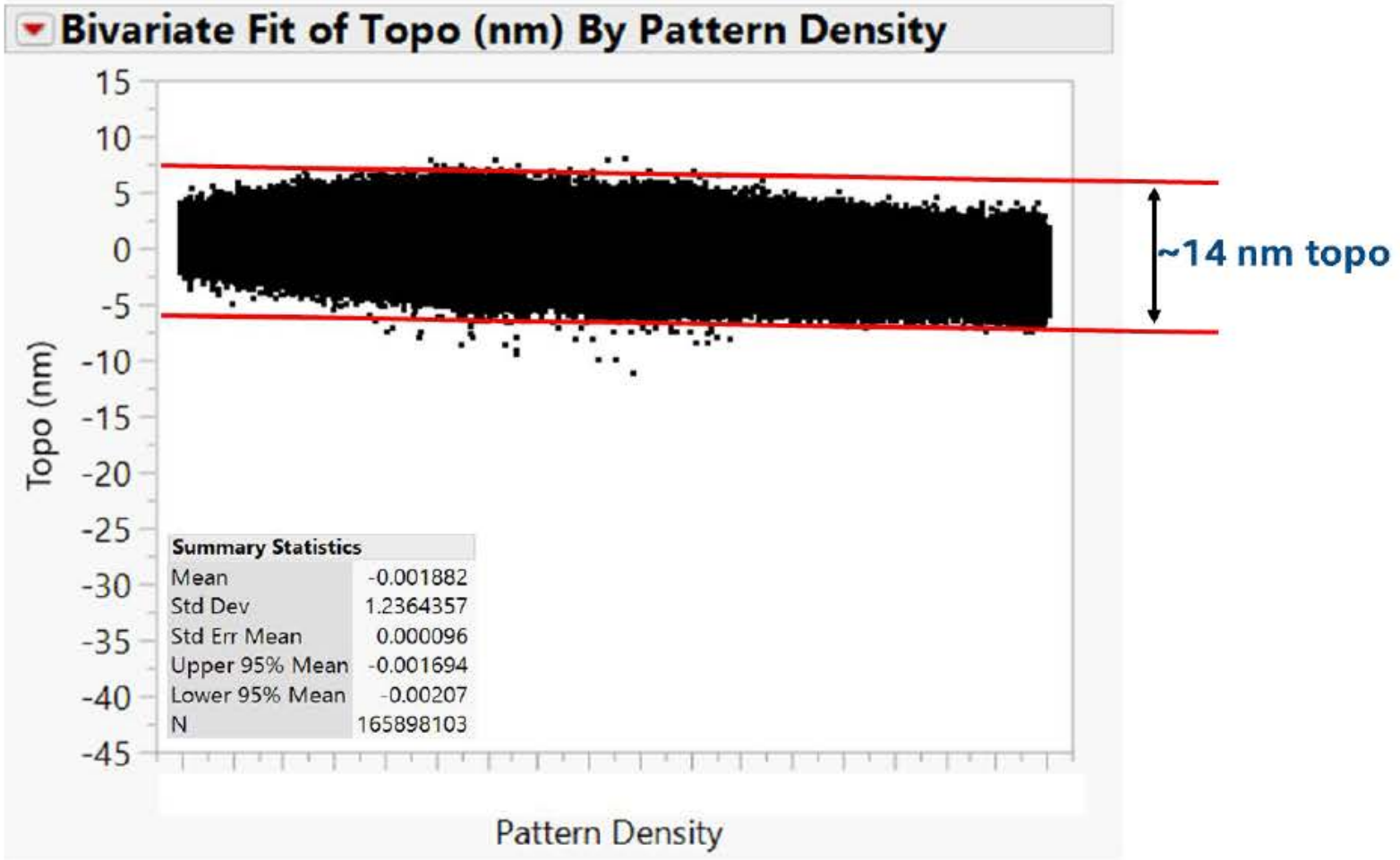




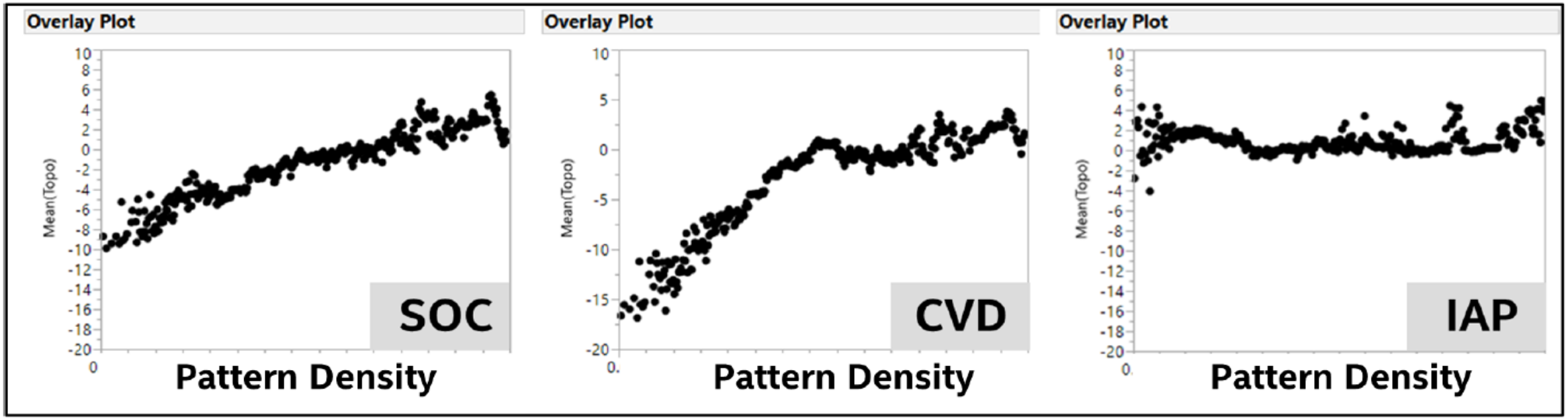
~45 nm topo

Full Field Topo with IAP – Rev 0 Recipe





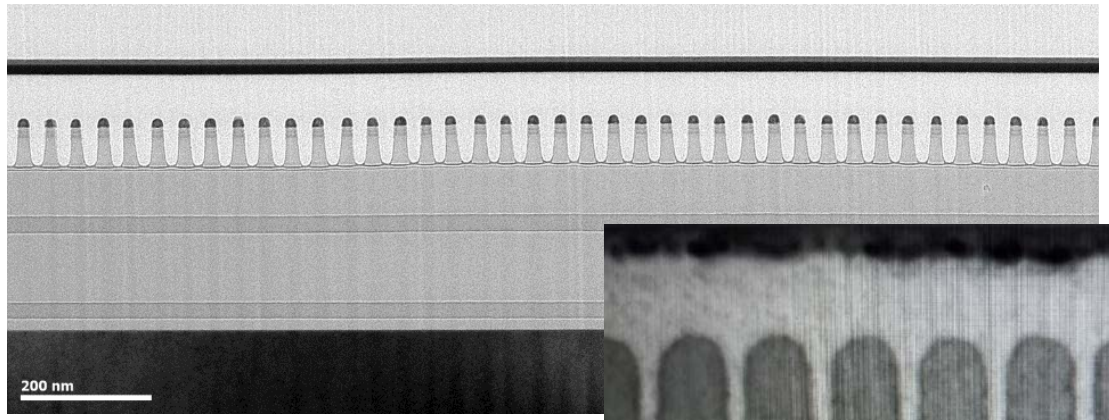
Topo vs Pattern Density



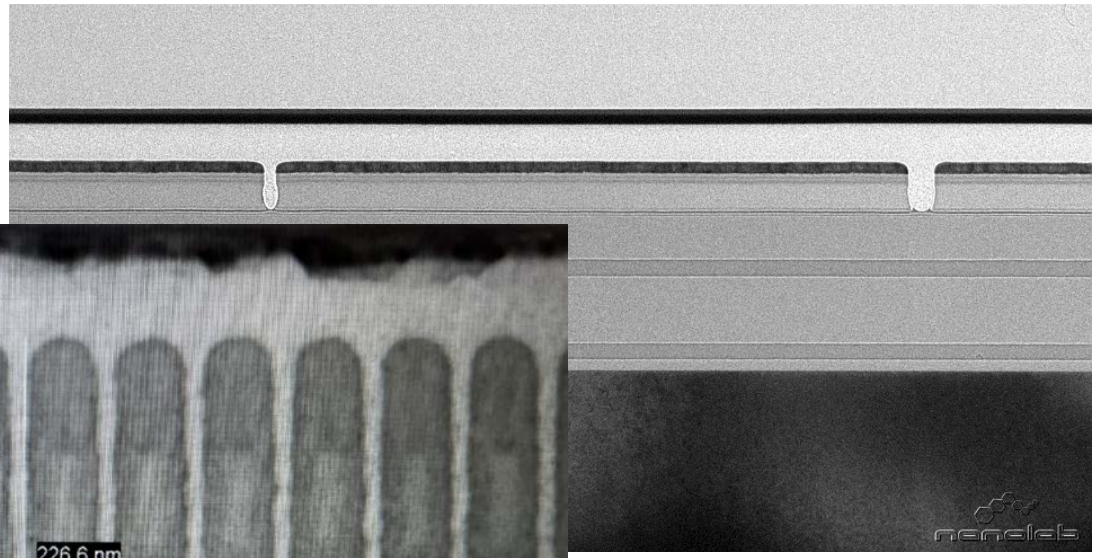
- SOCs show almost linear dependence on pattern density
- CVDs can have additional tunability for targeted pattern densities and structures but are still conformal over a larger range
- IAP shows little to no variation with pattern density

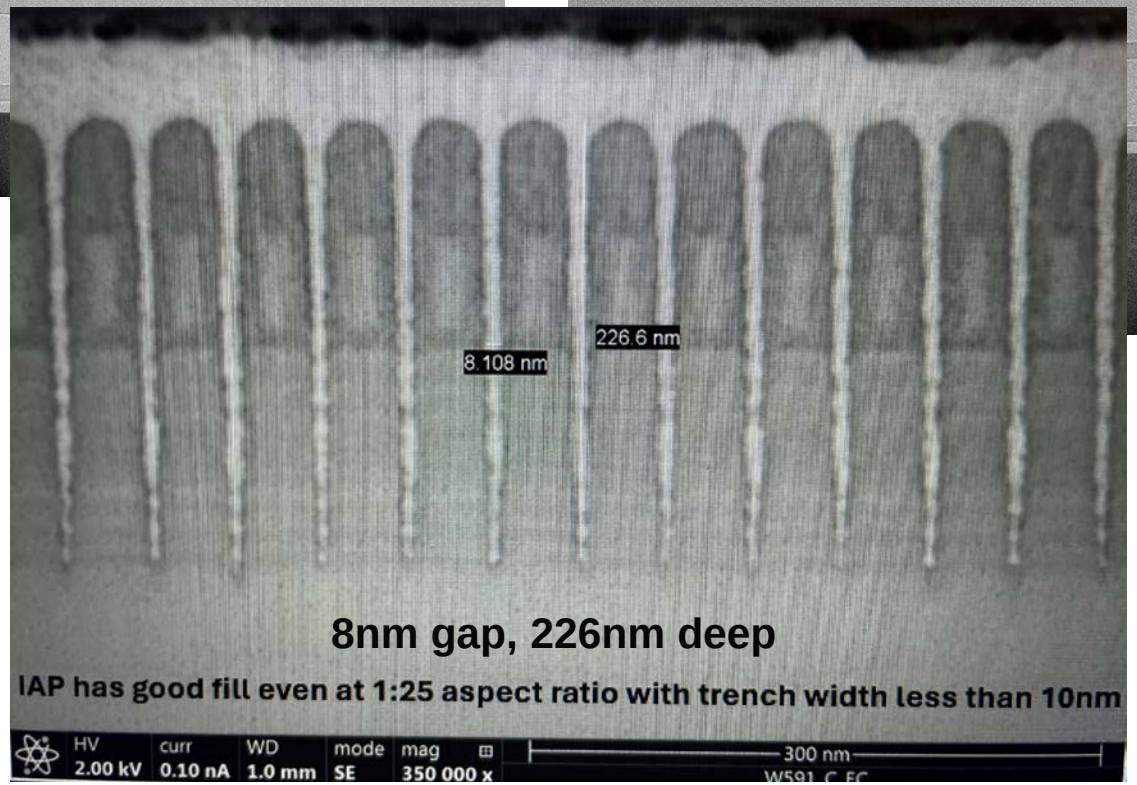
Gap Fill

20nm HP Aspect ratio~5:1



20nm and 40nm isolated lines

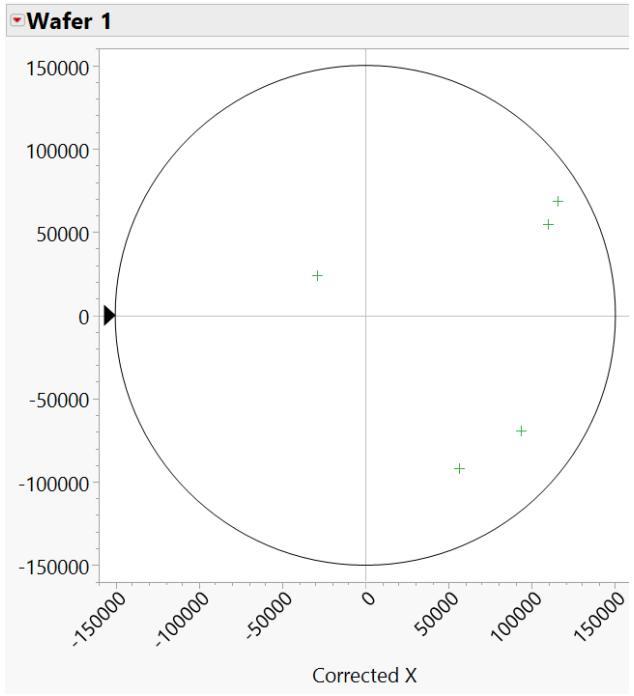




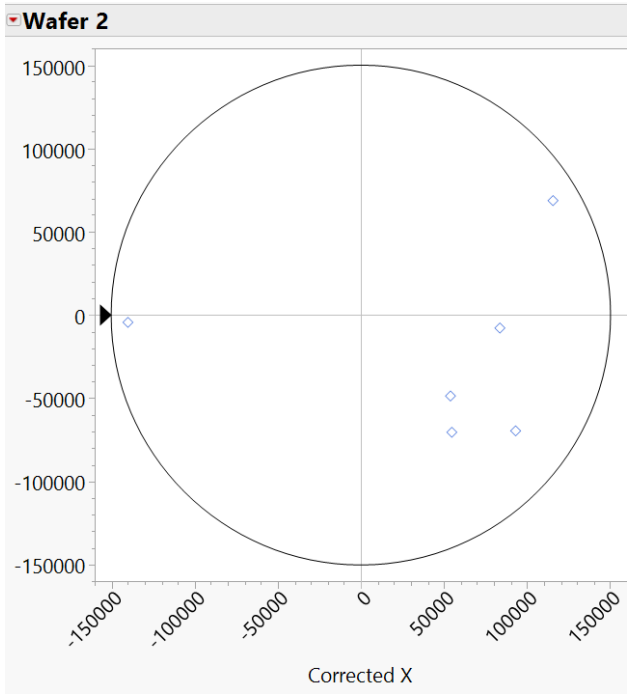
Gap fill performance is driven by the capillary force induced with thin overburden

Defectivity after IAP

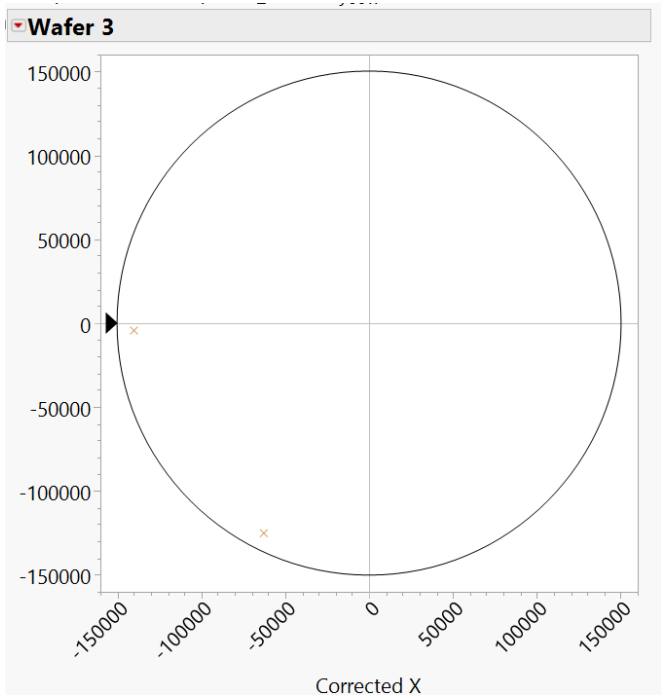
- Defectivity was also studied by applying a uniform film using IAP and using an SP7* to measure the number of defects after the process
- The defect target was <0.01/cm^2, meaning < 7 defects/wafer



Defect count: 5



Defect count: 6



Defect count: 2

*Resolution ~ 20nm

Conclusions

Conclusions

- Two Inkjet-based technologies, were discussed
  - Nanoimprint Lithography (NIL)
  - Inkjet-based Adaptive planarization (IAP)
- NIL is challenged, from a metrology point a view, since all mask features are “1x” patterns
- Defectivity is a key metric that will decide how NIL gets used in production
- IAP is promising new technology that works with all advanced lithographic methods
- What can be done to better understand local planarization and overburden uniformity across large areas?

Many thanks to DNP and Intel for providing some of the data used in this presentation

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