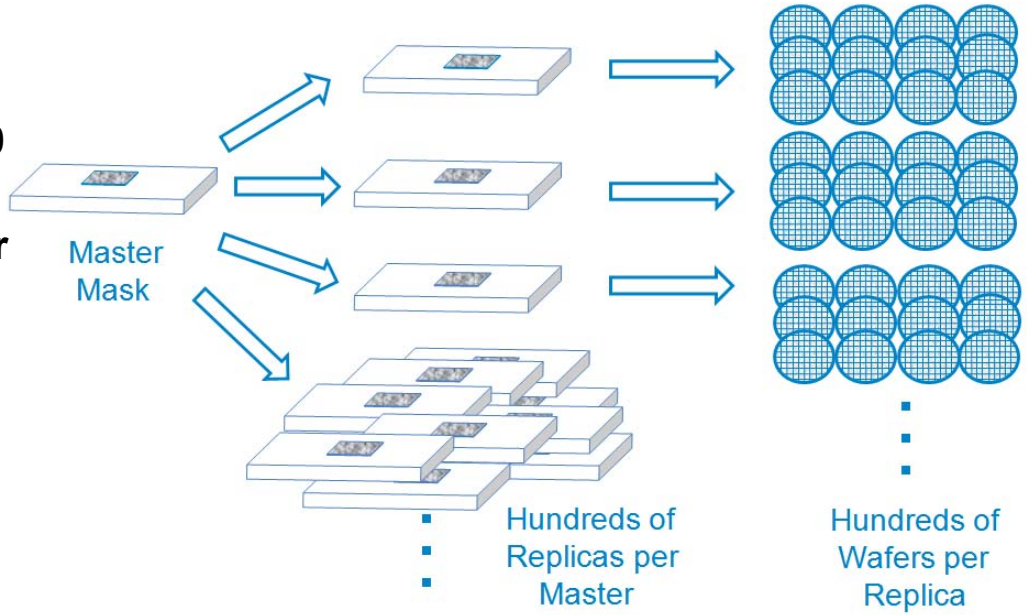
Mask Replication

- **The lifetime of a mask is anticipated to be ~ 50,000 – 100,000 imprints**
- **An e-beam written master mask will cost ~ $500K**
- **If you wanted to print 1M wafers, you would spend ~ $500M on masks**
- **Go share that strategy with a fab manager!!!**



- The solution: create a Master Template that can easily be replicated
- Master ⟶ Daughter approach
- Good news! You can use an imprinter to make the Daughter Templates

Do Mask Replication Tools Exist?

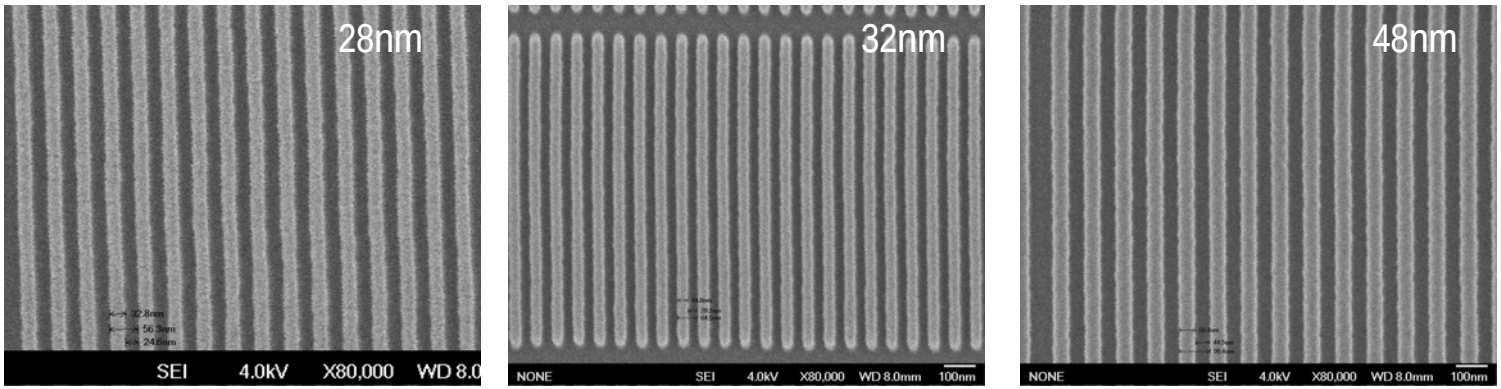
Canon is also supplying mask replication tools to the industry

FPA-1100 NR2
Mask Replication Tool

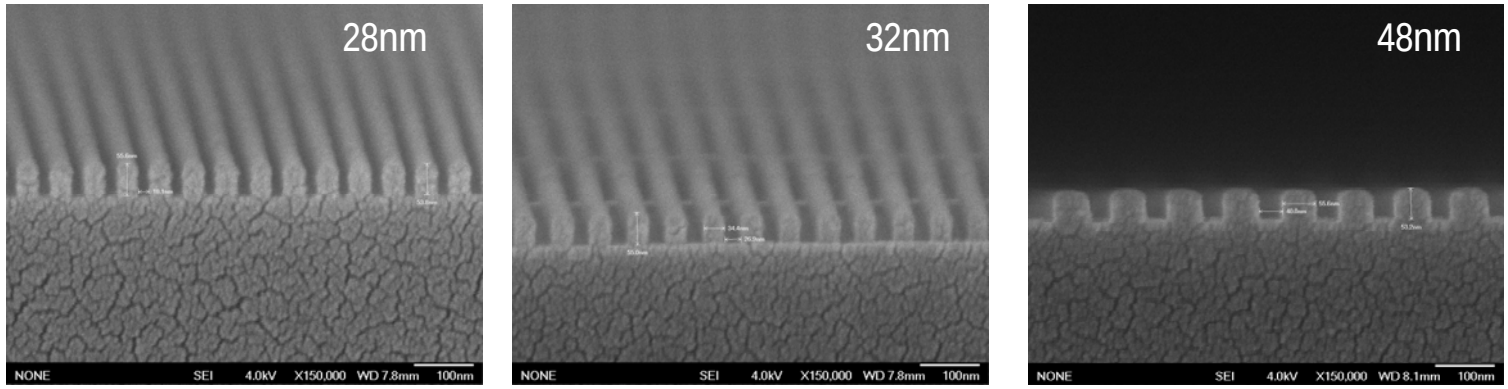
Target specifications		
Throughput	shots/hour	4
CD Uniformity	nm	0.8
Image Placement Accuracy	nm	1.0
Particle	pcs/replica	0.002

- *NR2 shipped in early 2017*

Replication Example: Semiconductor



a) Master Imprint



b) Replica Mask

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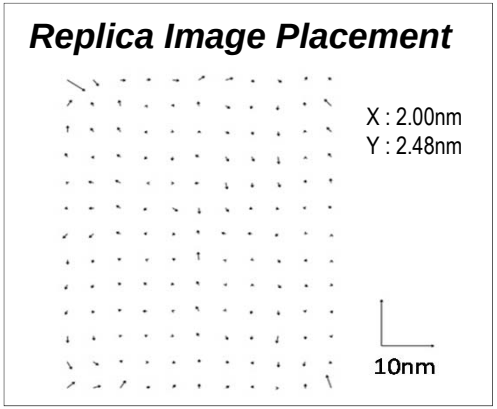
Replication and Image Placement

Courtesy DNP

- During replication, all the usual parameters need to be controlled, in addition to just feature resolution
  - Defectivity
  - Critical dimension uniformity
  - Image placement
- The data below indicates that final image placement can be as low as 2.5nm

Master/Replica @ 2x nm	Target	2015
Defectivity (pcs/cm^2)	1.0	0.6
CD Uniformity (3σ, nm)	2.2	1.5
Image Placement (nm, 3s)	2.5	2.5



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What's Left?

- I can write the mask
- I can etch the mask
- I can replicate the mask
- And I've satisfied requirements for CDU, IP and defectivity
- I'm done, right???

- NO!! Masks must be perfect. No defects can exist in a critical area of the mask. As a result, the mask must be
- Inspected
- Repaired

Imprint lithography is challenged by the fact that it is a 1x technology. This makes inspection and repair more difficult

Inspection Methods

Year of Production	*2008 **	*2009*	*2010*	*2011*	*2012*	*2013*	*2014*	*2015*
DRAM ½ pitch (nm) (contacted)	*59*	*52*	*45*	*40*	*36*	*32*	*28*	*25*
Flash ½ pitch (nm) (un-contacted poly)	*45*	*40*	*36*	*32*	*28*	*25*	*22*	*20*
Defect size, patterned template (nm) [V]	**35**	**30**	**30**	**20**	**20**	**20**	**20**	**10**

- Optical Inspection - Mask
  - KLA-Tencor: 6xx
  - Reflection/Transmission Mode

- Electron Beam Inspection - Wafer
  - Die-to-Die
    - KLA-Tencor eS35
    - HMI eScan315
  - Die-to-Database
    - NGR2100

eS35

eScan315

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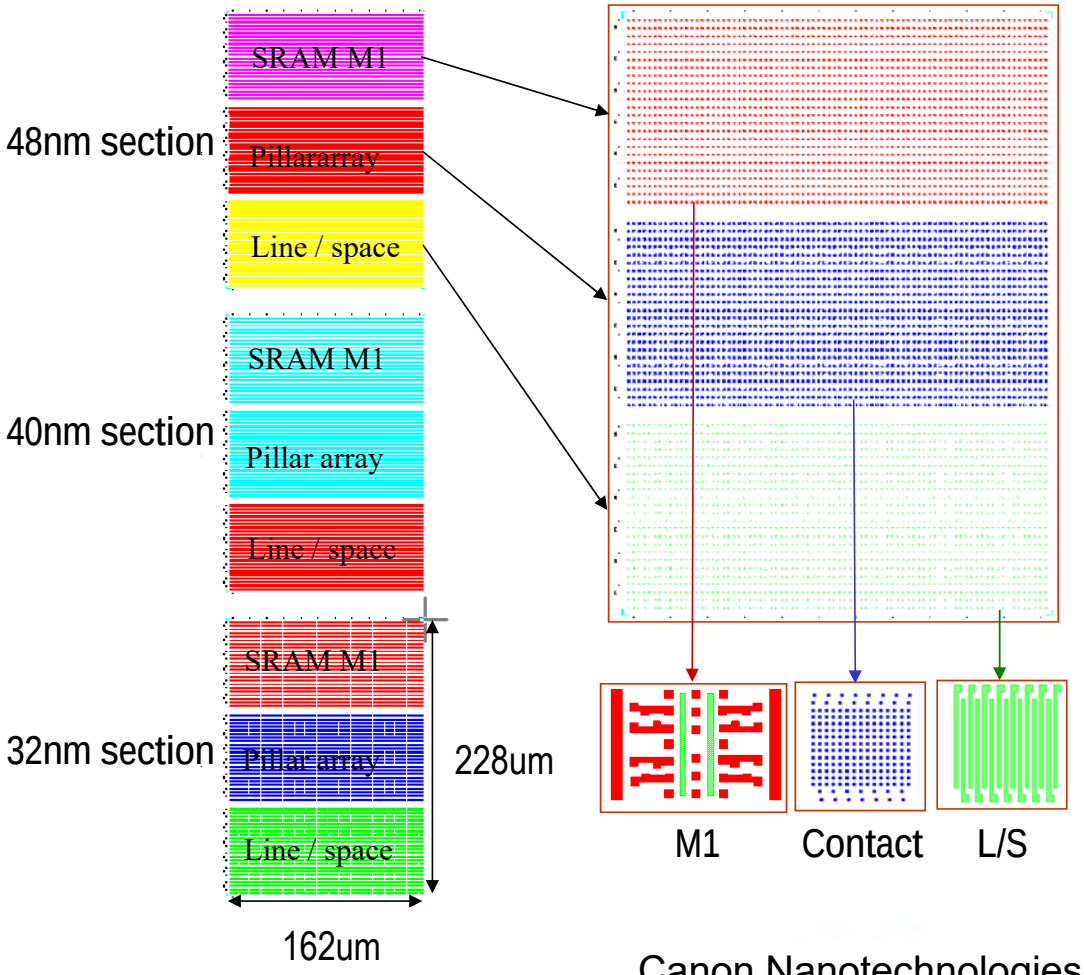
Claymore: 32nm Programmed defect layout

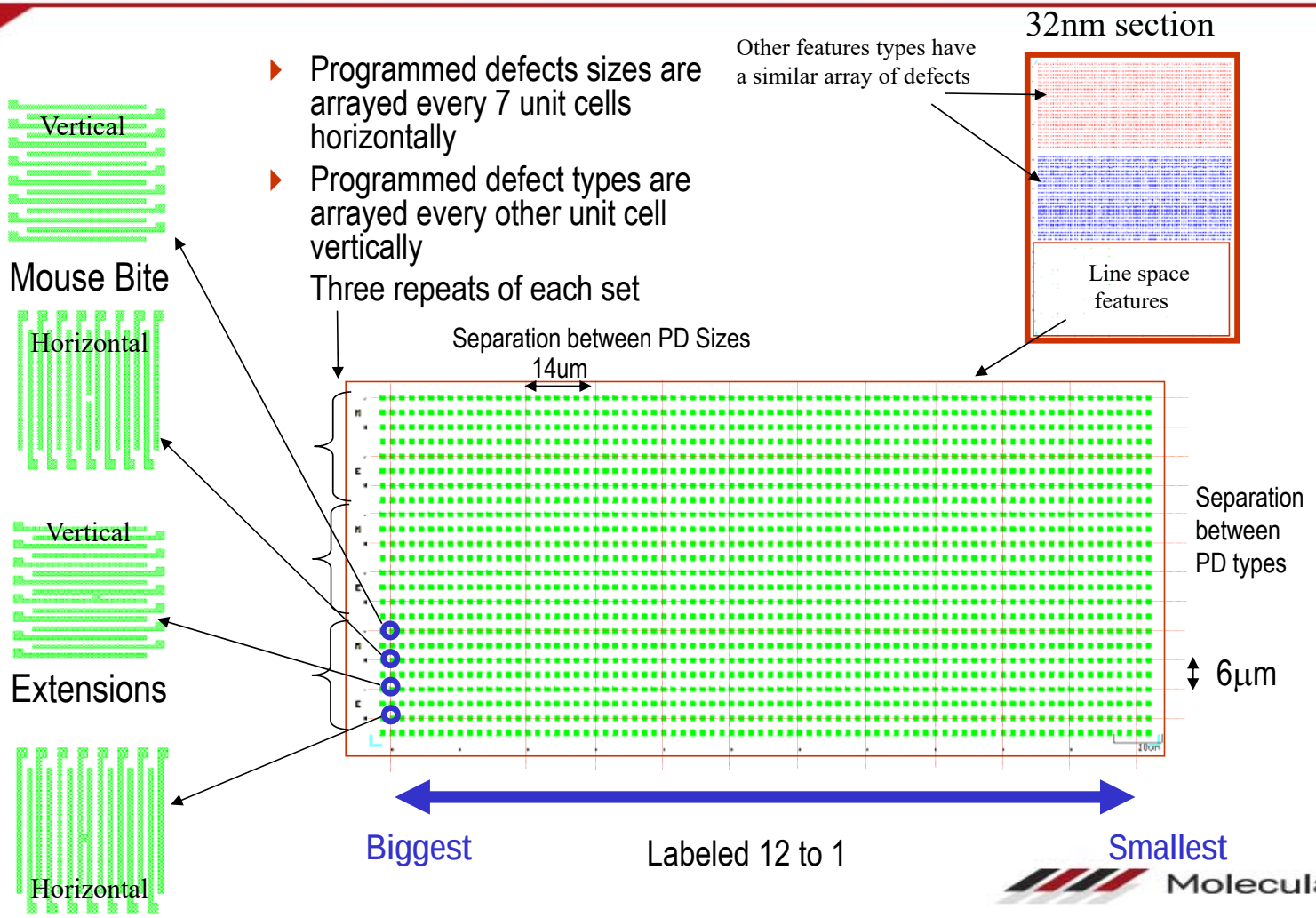
- All sections (32nm, 40nm, and 48nm) have the same corner marks and unit cell step distances
  - X = 2um, Y = 3um
- 32 nm 40nm and 48nm feature types are the same design with different dummy shrinks.



Defect locations

- Programmed defects sizes are arrayed every 7 unit cells horizontally
- Programmed defect types are arrayed every other unit cell vertically

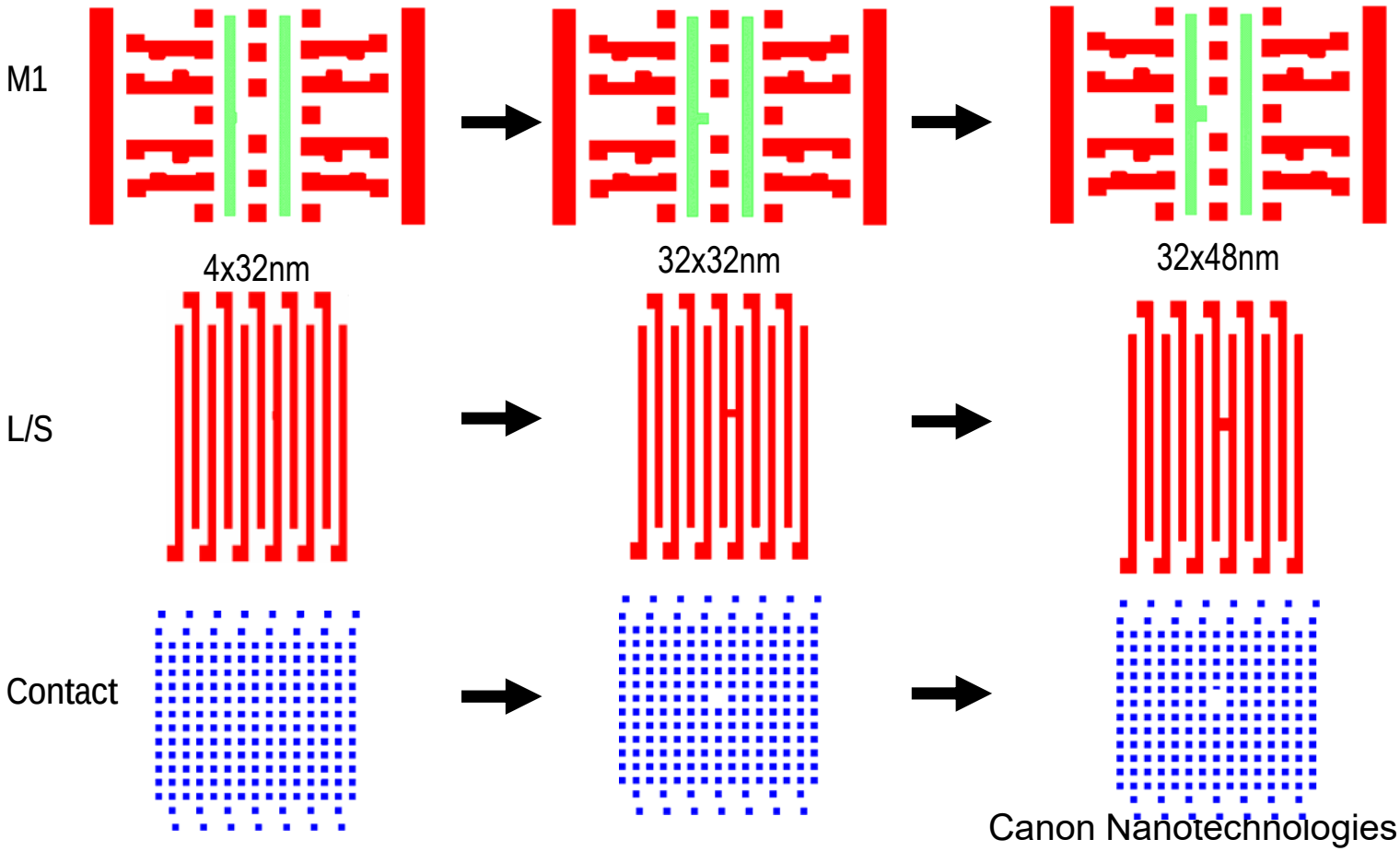
Three repeats of each set



Molecular Imprints

Programmed Defects for 32nm Patterns

Programmed defects start at 4nm and increase in increments of 4nm up to 48nm



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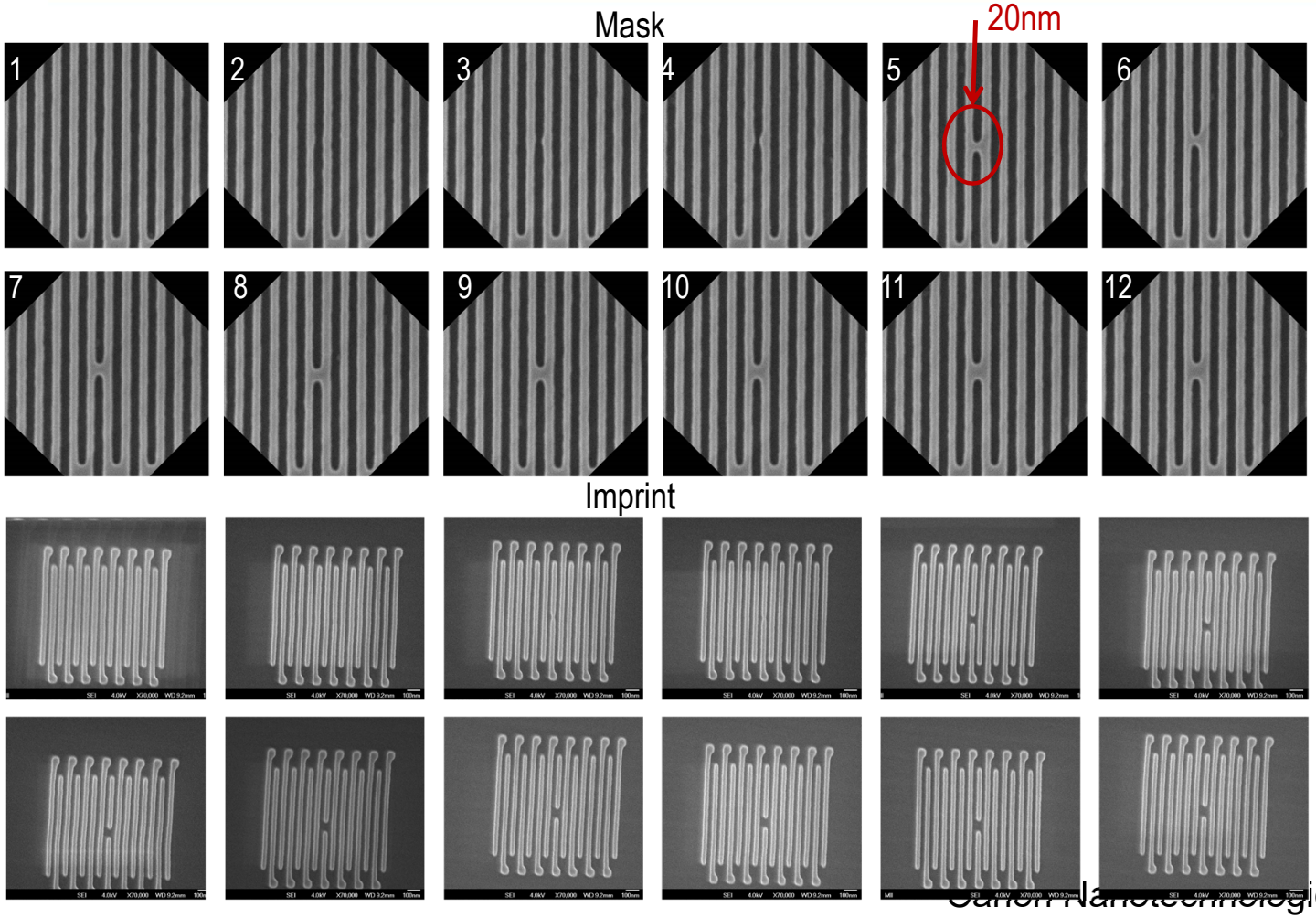
Mask and Imprint Analysis

- SEMs of the Mask were captured with a Holon EMU-270A SEM
  - 1.5 nm resolution at 1.0 kV when applying aberration correction.
  - Low vacuum and charge control enable high quality imaging on fused silica masks.
- Images of the imprints taken with a JEOL JSM-6340F field emission cold cathode SEM
  - 1.2 nm resolution capability at 15 kV and 2.5nm at 1 kV.

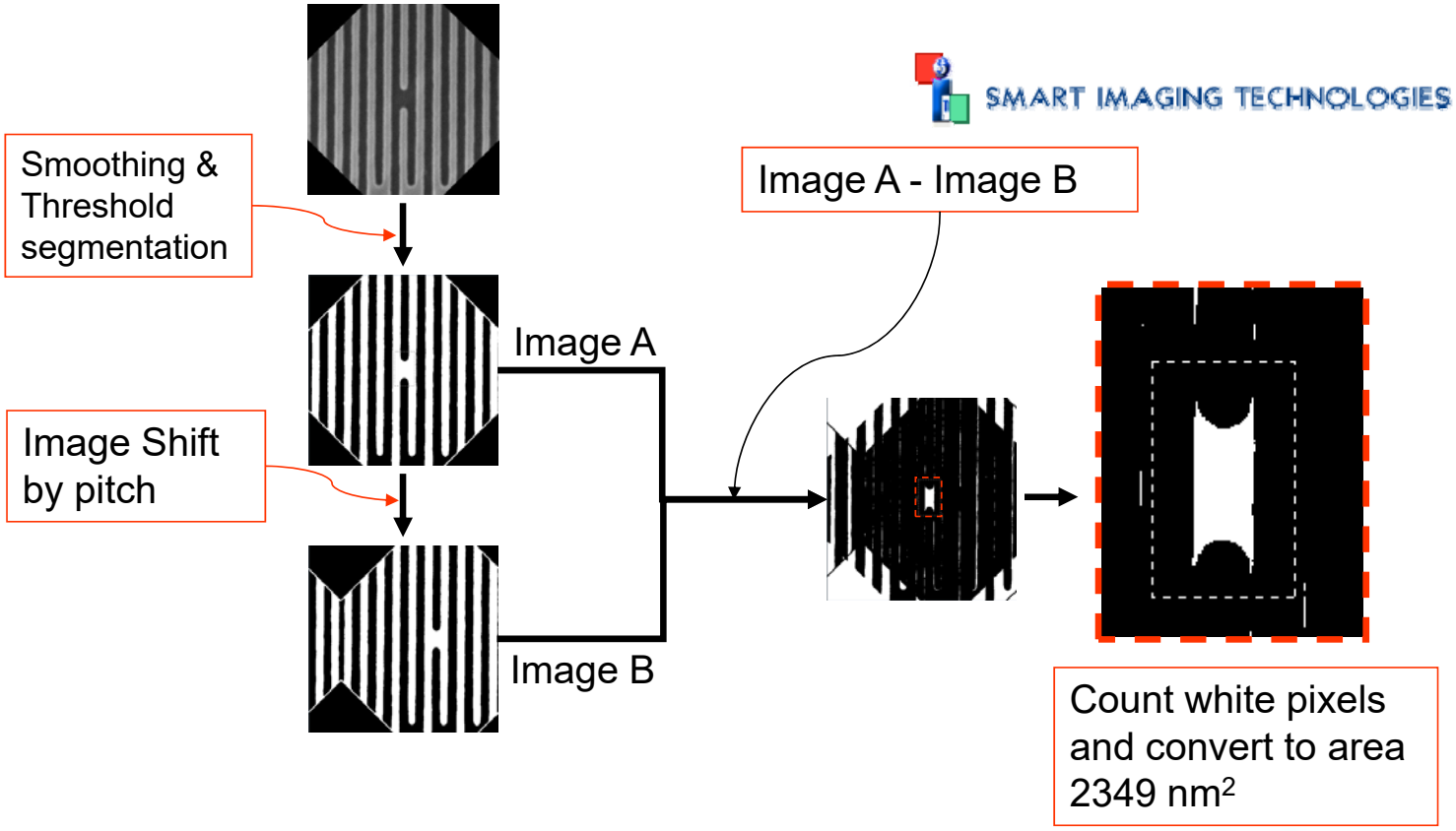
HOLON

32 nm Half Pitch Lines

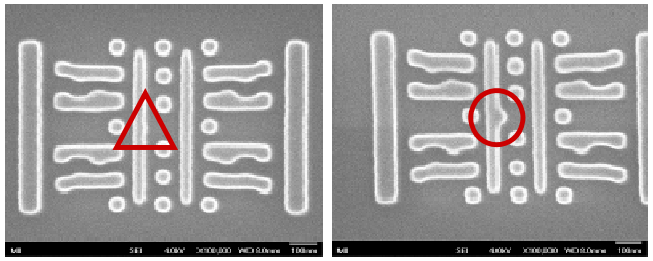


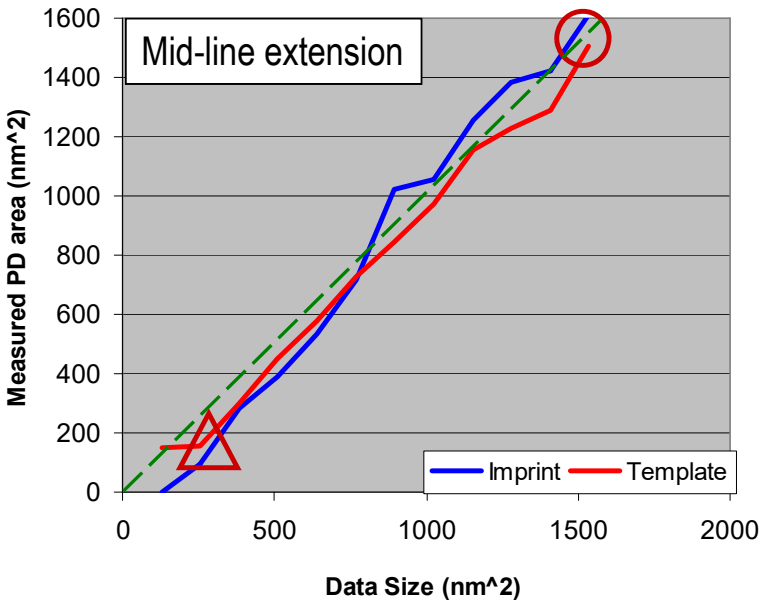
PD measured area evaluation process

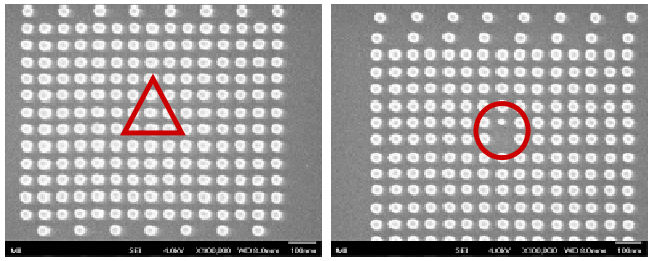
DAFC – Defect Analysis for the Financially Challenged

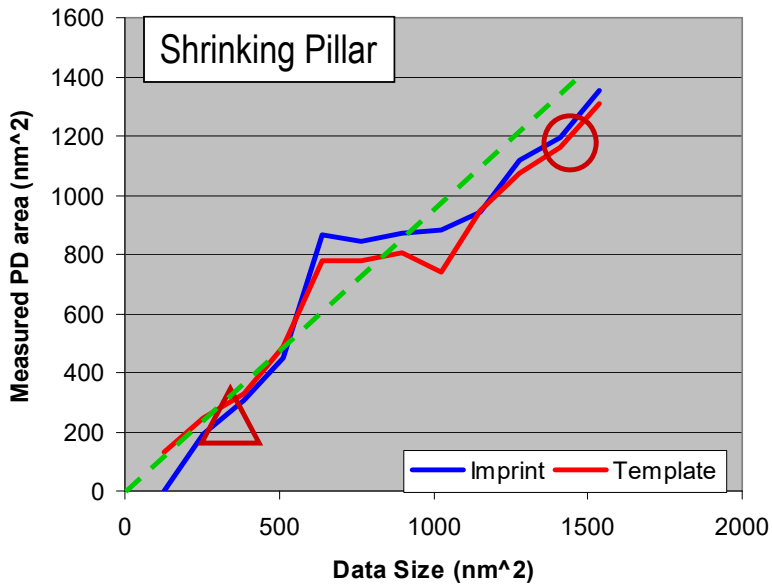


Measured area compared to data size





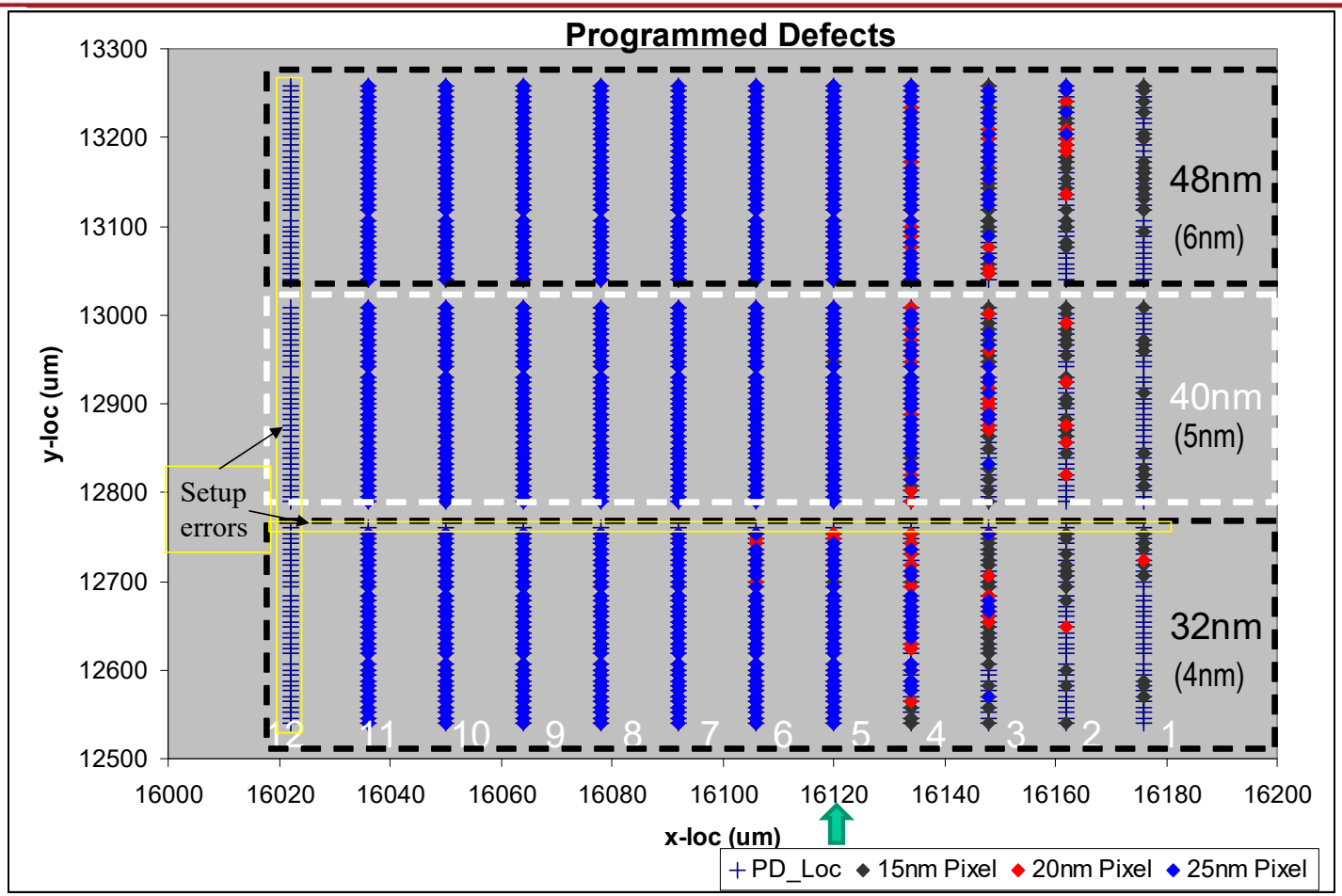




Electron beam inspection systems

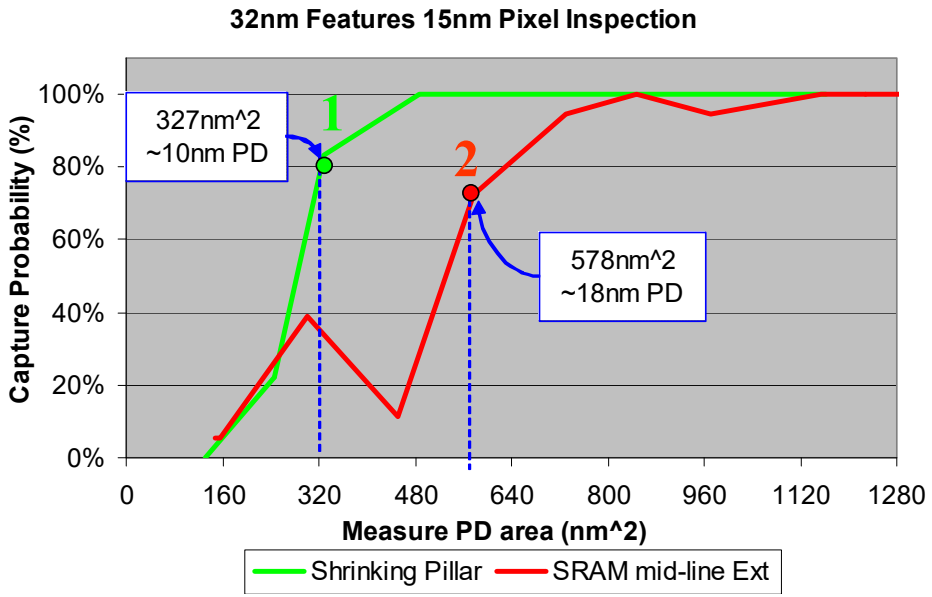
- KLA-Tencor eS35
  - Die-to-die
  - Image contrast inspection
  - Pixel size: 15, 20, 25nm
  - Landing energy 1750V
  - Data rate 50mpps
- Hermes Microvision eScan 315
  - Die-to-die
  - Image contrast inspection
  - Pixel size: 10, 15nm
  - Landing energy: 2000V
  - Data rate 100mpps
- NGR 2100
  - Die-to-database
  - Fast CD inspection
  - Pixel size: 3nm
  - Landing energy 2600V
  - Data rate 50mpps

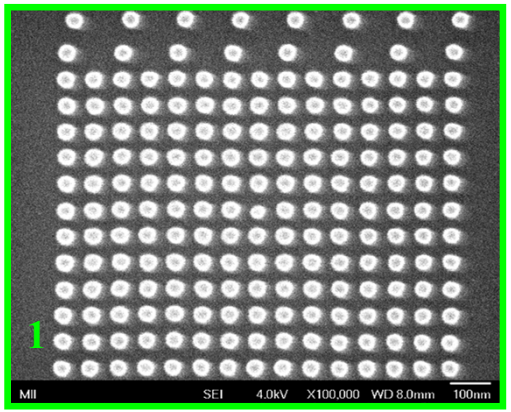
Programmed defect pixel progression

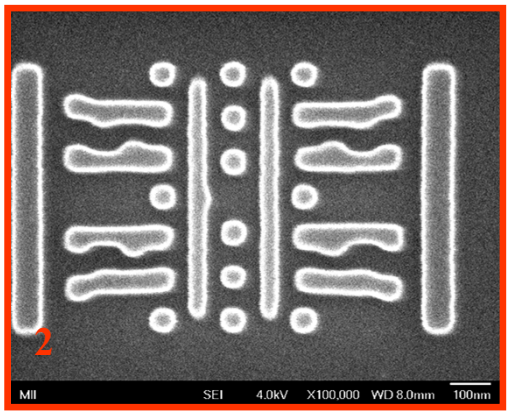


80% capture rate examples

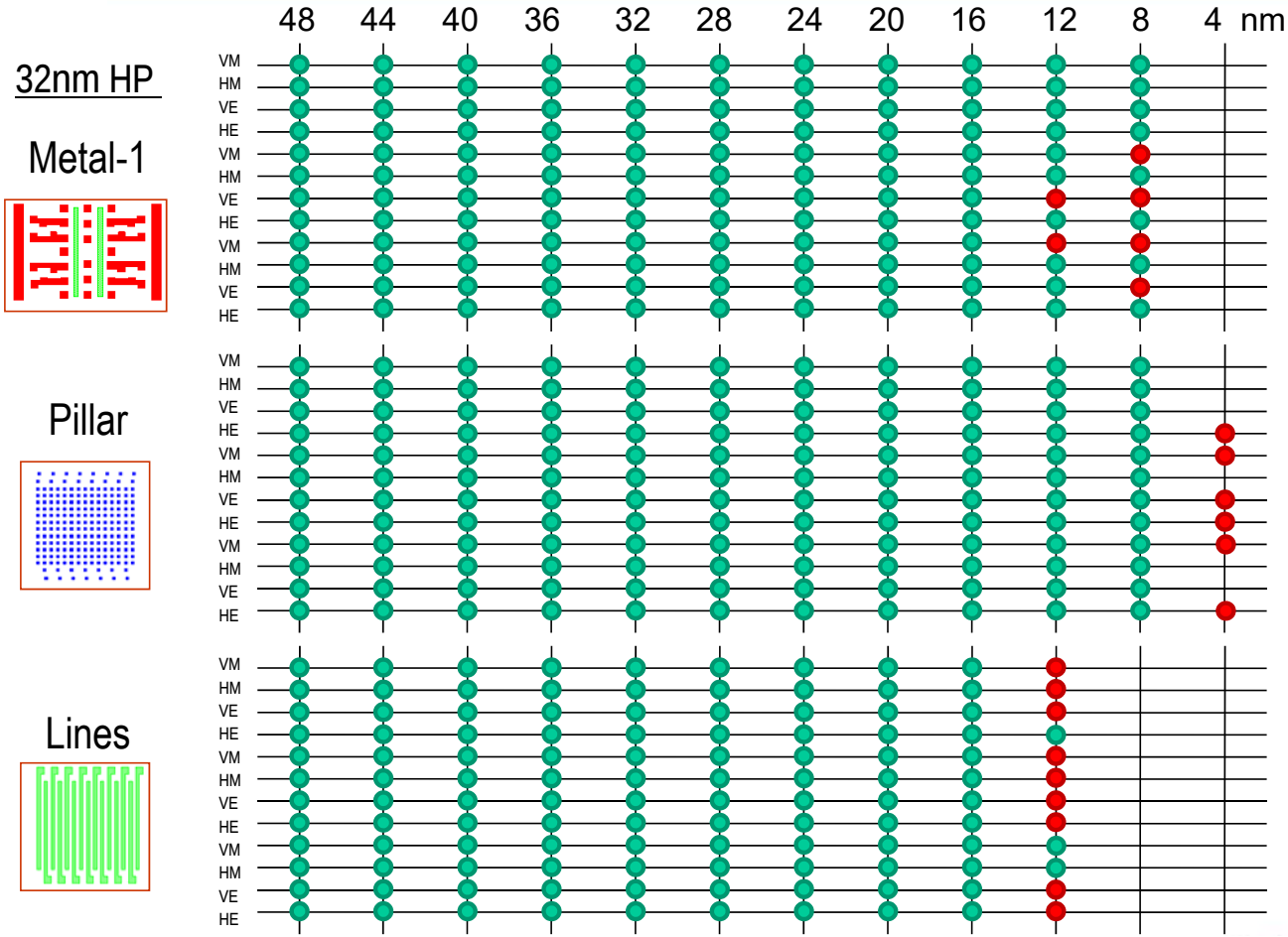
- The sensitivity range is 10 to 18nm for an 80% capture rate







eScan 315: e-beam wafer inspection



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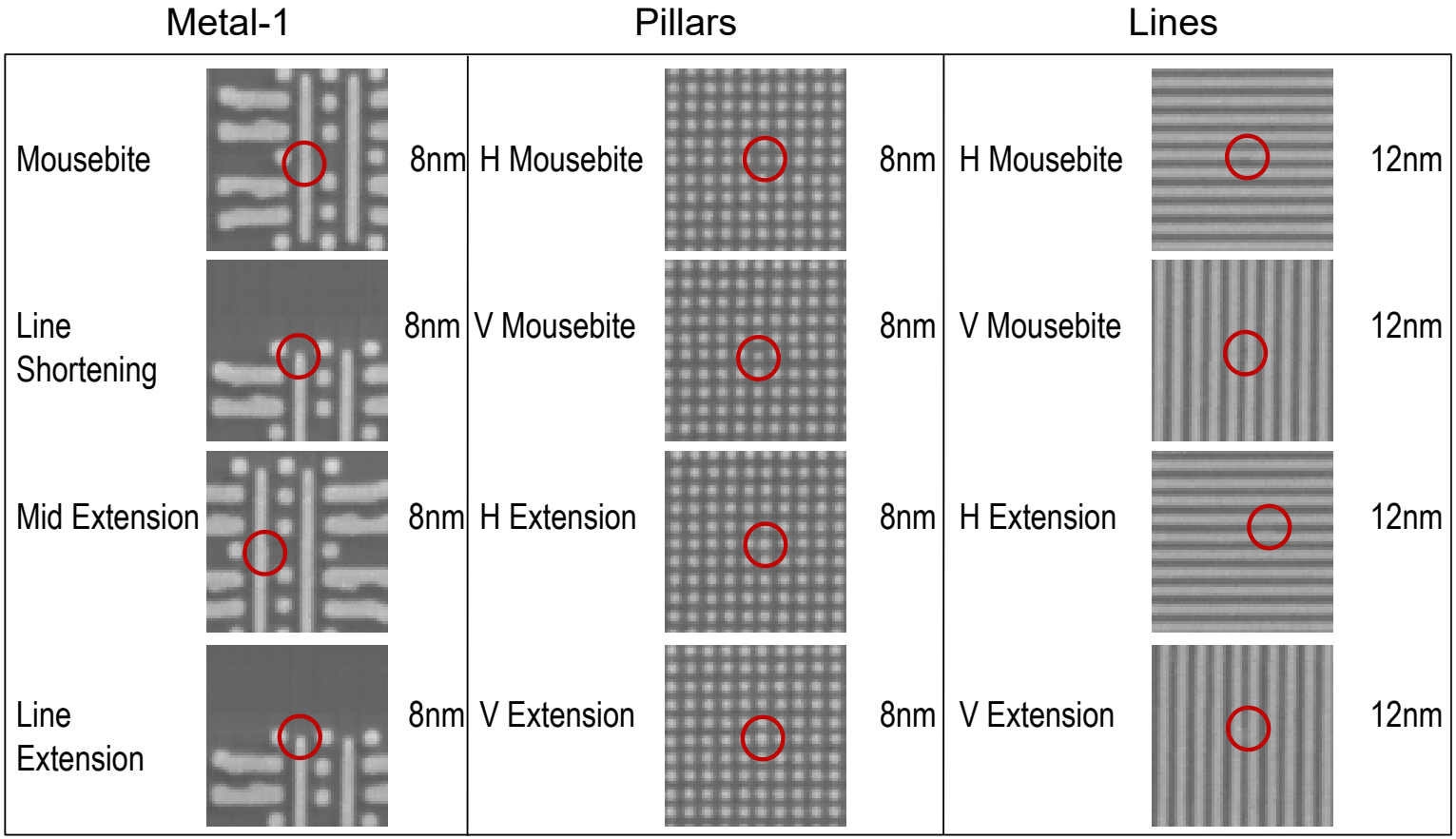
Captured Programmed Defects: 10nm Pixel

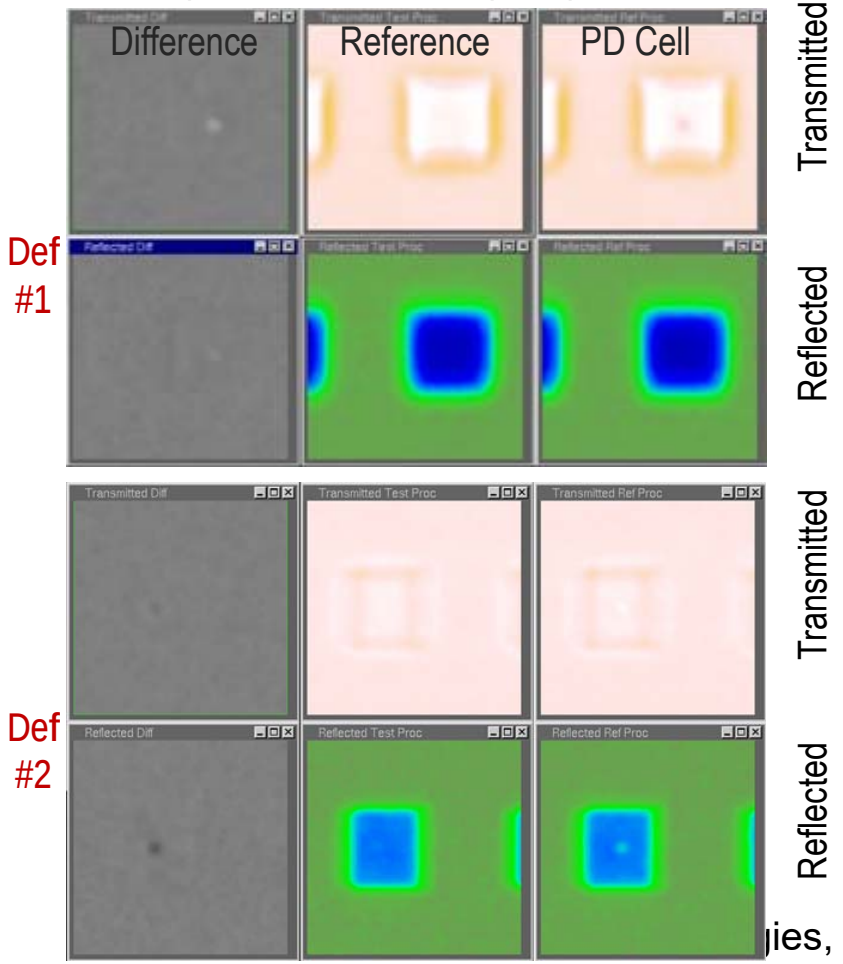
Programmed defects: 8nm – 12nm



KLA-T 6xx Optical Inspection Results

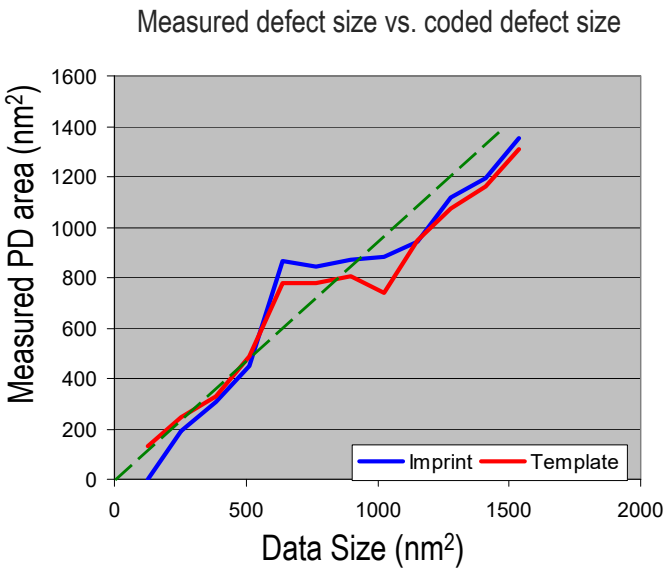
- Because the background noise is low, it is possible to discern the defect without resolving the 32nm pattern.
- The KLA-T 6xx platform works in both Transmitted and Reflected light modes.
- Transmitted and Reflected Light capture different types of defects. Having both modes essential for capturing critical defects.
- In these examples, one defect in the 32nm half pitch pattern has signal in transmitted and one in reflected mode.

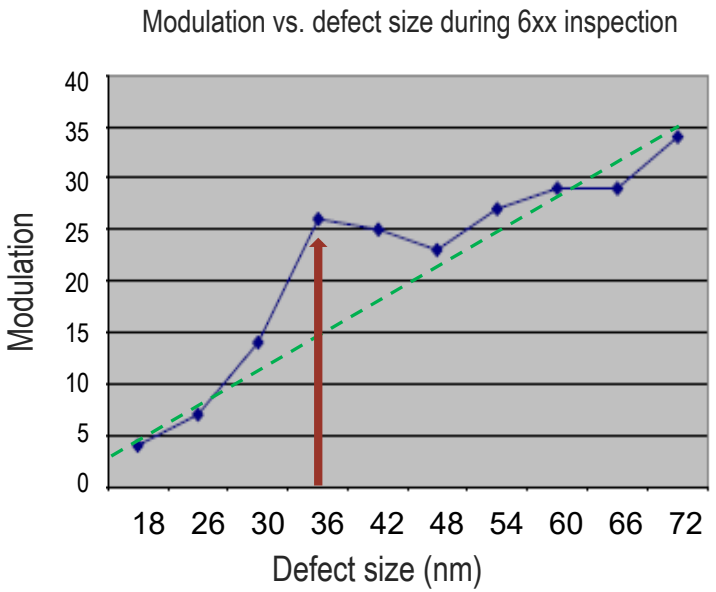
Inspection of 32nm half pitch patterns



Modulation vs. Programmed defect size

- Modulation tracks well with the measured defect size in the mask
- Sensitivity is on the order of 32nm
- Thresholds can be optimized to increase sensitivity





Infrastructure: Template Repair

RaveLLC

Nanomachining system

Nawotec

E-beam Deposition/Etch

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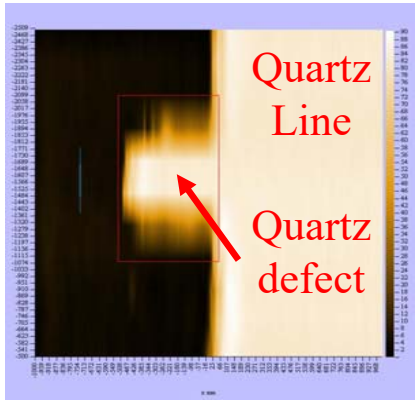
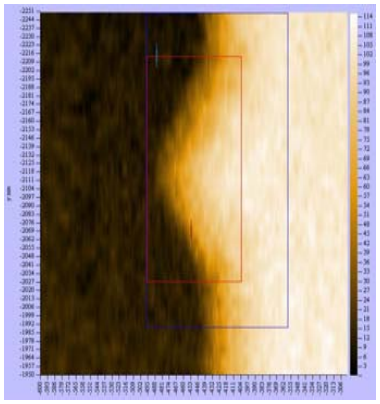
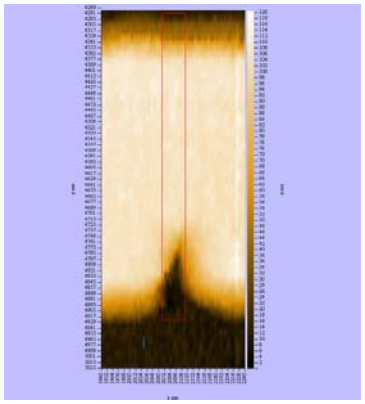
Repair Examples

After repair on a RaveLLC 650nm system

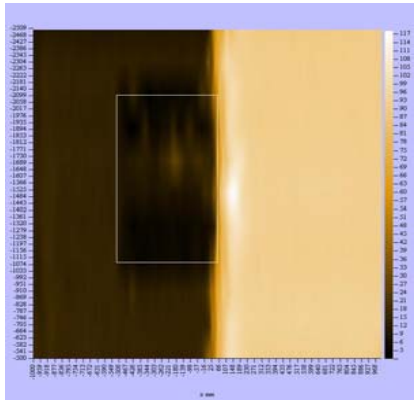
Before repair



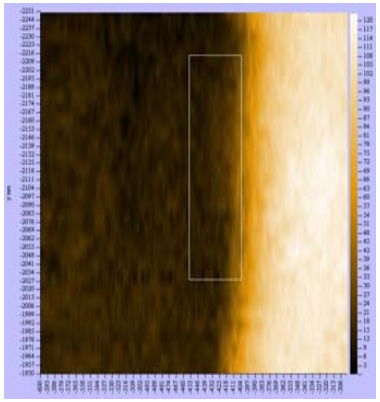




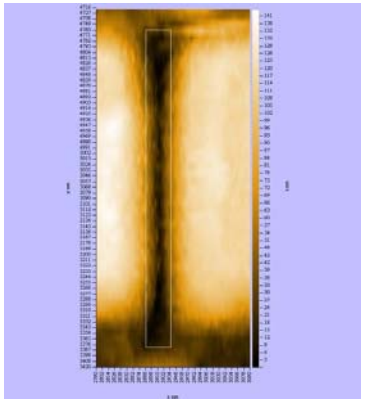
After AFM repair



300 nm defect



50 nm defect



50 nm trench

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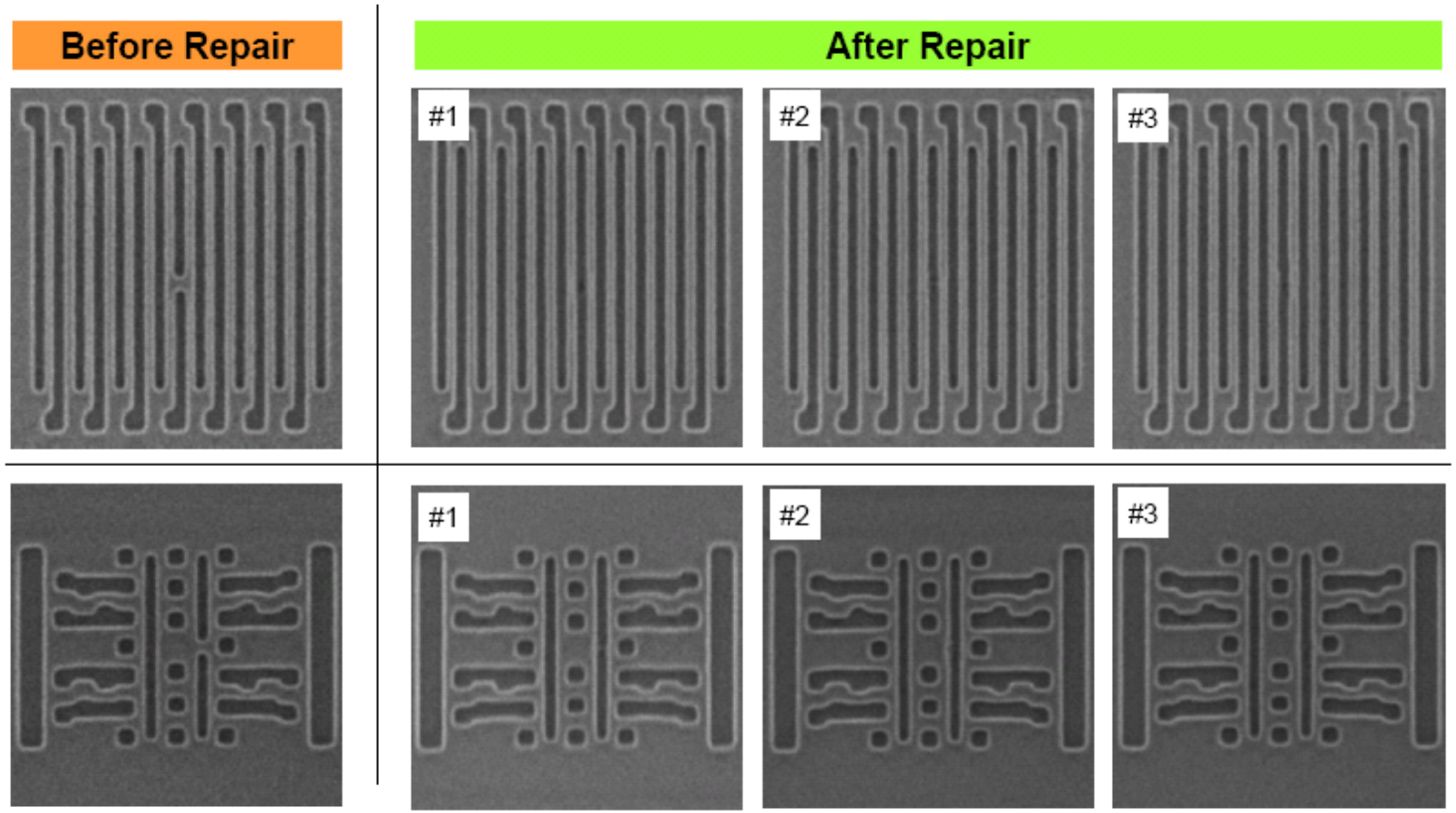
Zeiss: MeRiT MG E-beam Mask Repair



ims chips

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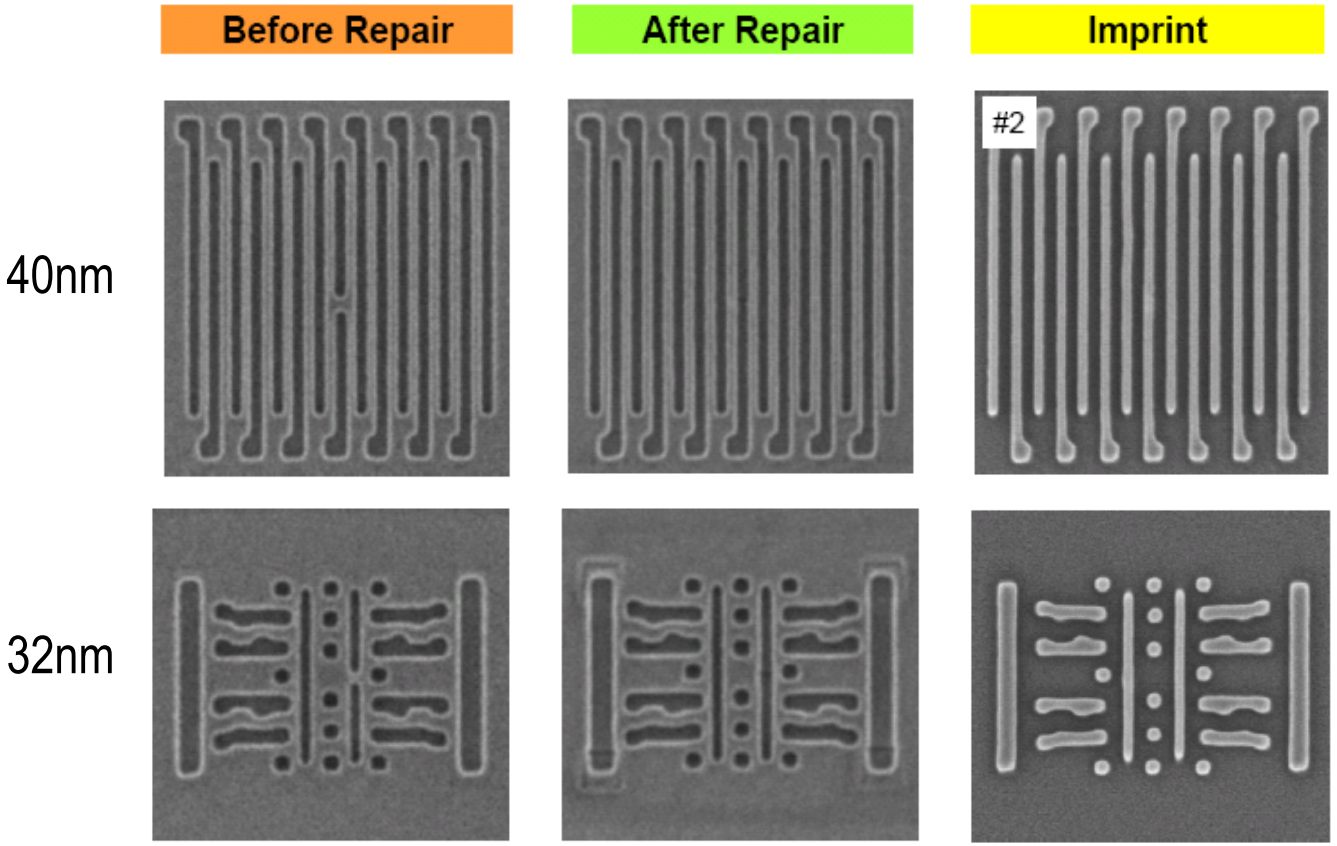
nprints

Repairs: After Imprint



So is this this technology really going to work?

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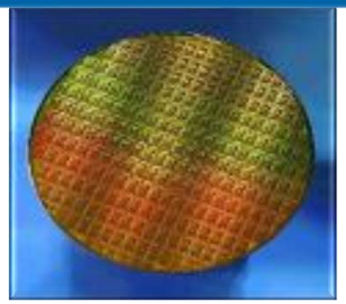
Emerging Market Applications

J-FIL™ nanopatterning advantages can serve a variety of markets

Semiconductor ICs



Hard Disk Drives

J-FIL's low cost, high resolution patterning enables increase memory capacity at lower cost per bit

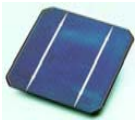
Drives resolution and cost of ownership for both CMOS and magnetic memory

Emerging Applications

Displays

Efficiency
Cost
Brightness

Solar

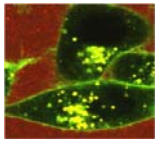


Efficiency

Batteries

Capacity
Faster Recharge

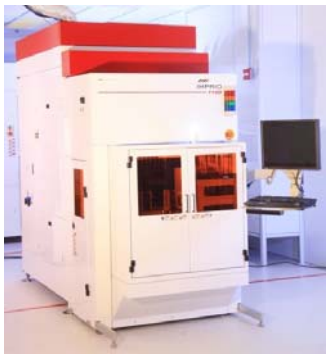
Nano-Bio



Drug Delivery Targeting
And Efficacy

J-FIL enables a broad range of other market opportunities with low cost, high resolution, and large substrate area patterning

Full Wafer/Disk Imprint Process



Molecular Imprints™

Imprio 1100 (Photonic Crystals)

Imprio HD7000 (Patterned Media)

Thin Template

150mm Diameter Patterned Media Template

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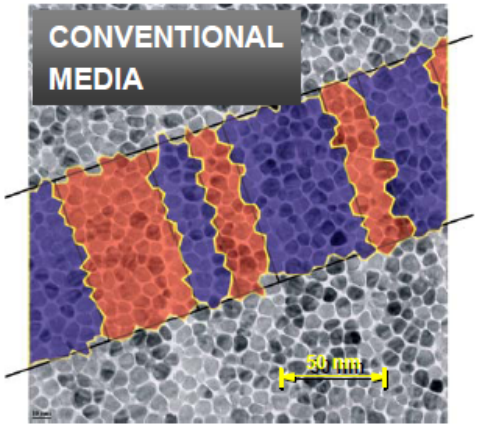
Hard Drives

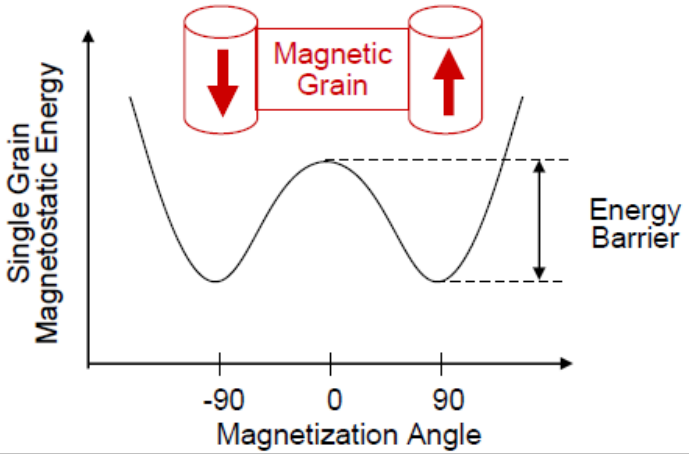
- Hard disk drives operate by storing bits of information on a disk coated with a magnetically influenced film
  - Magnetic media

- These things have been working for years. What's the problem?

The problem: thermal stability, write-ability, and density

HITACHI
Inspire the Next





Magnetic Stability: $\dfrac{\text{energy barrier}}{\text{thermal energy}} \propto \dfrac{\text{anisotropy x volume}}{k_B \text{ x temperature}} = \dfrac{K_u V}{k_B T} > 70$

PROBLEM:

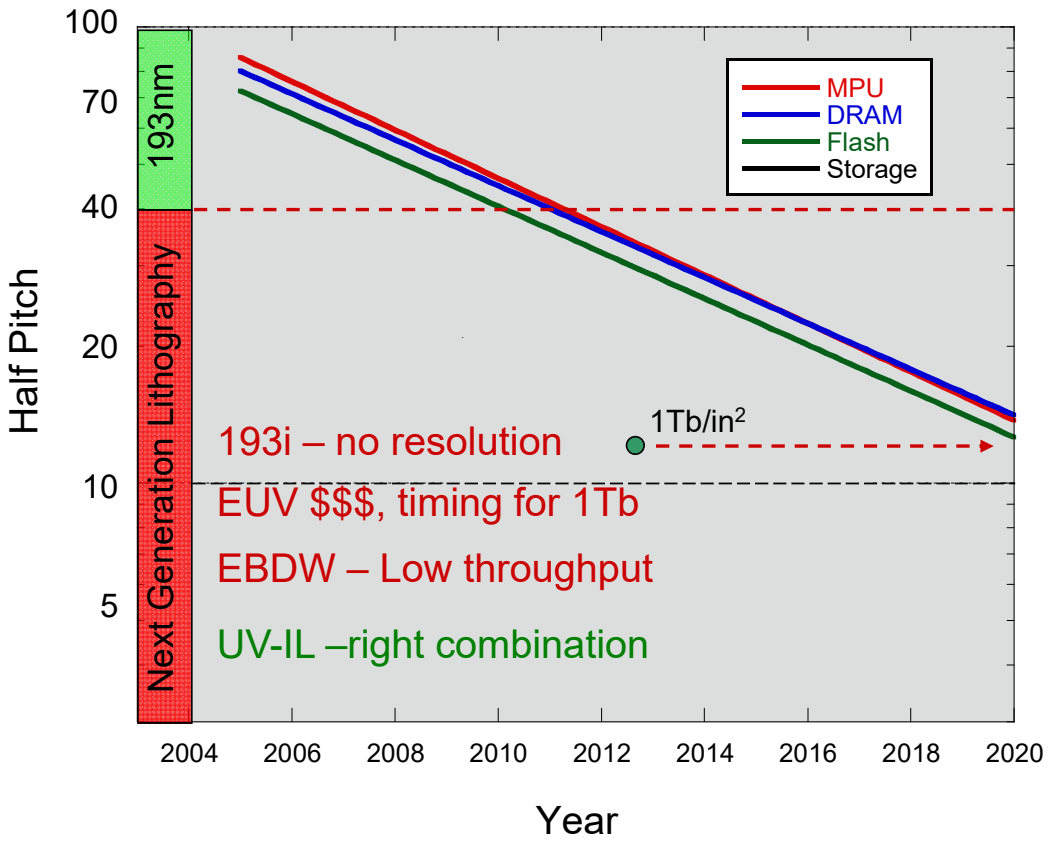
- To increase density, need smaller grains
- Smaller grains are thermally unstable
- To avoid thermal instability, increase grain anisotropy Ku
- This increases the medium coercivity and makes the medium more difficult to write

SOLUTIONS:

- Work with higher anisotropy:
  - Capped and exchange spring media
  - Thermally assisted recording (TAR)
- **Work with larger 'grains': patterned media**

Why Imprint Lithography for Patterned Media?

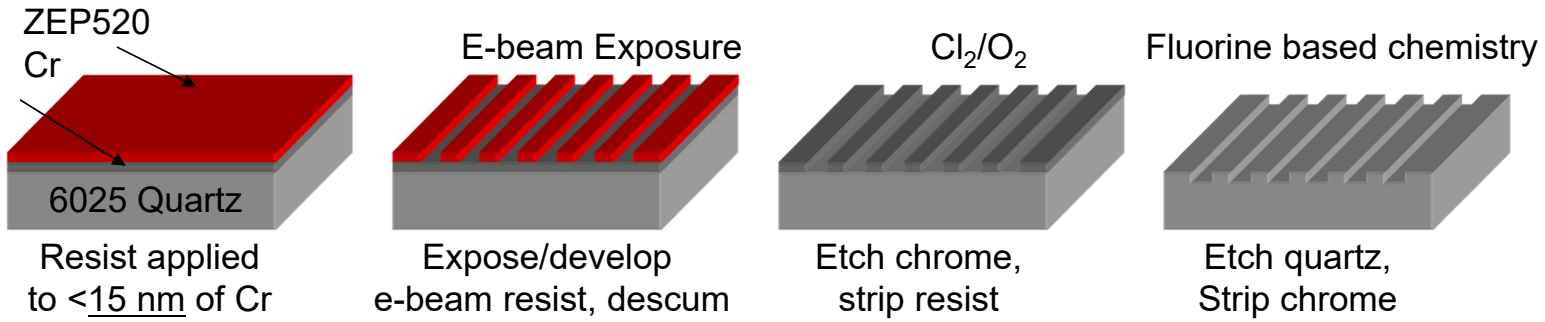
- Let's compare the Information storage roadmap against the well established ITRS Roadmap for integrated circuits



- The Storage Roadmap is much more aggressive than the ITRS Roadmap
- High volume optical tools will not be available in time
- The price of an EUV printing tool is prohibitive
  ~~($50-75M)~~ ~~$90-100M~~ $100-150M
- Electron beam writers have the resolution, but not the throughput
- Imprint offers the best combination of cost, throughput and resolution

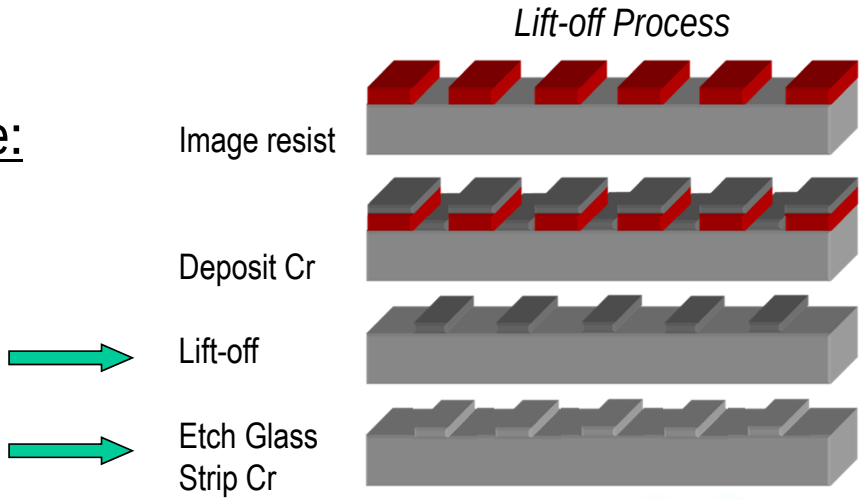
High Density Template Fabrication for PM

- Conventional Method for defining small features



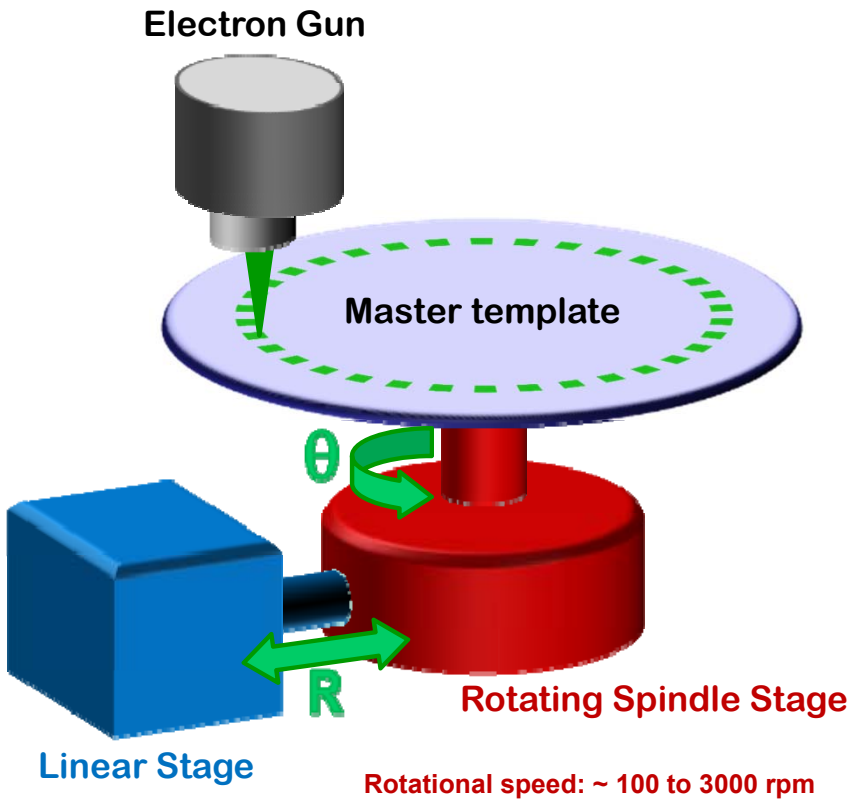
Alternative methods include:

- PMMA or ZEP520A lift-off
- High Resolution HSQ resist
- Ion beam Lithography



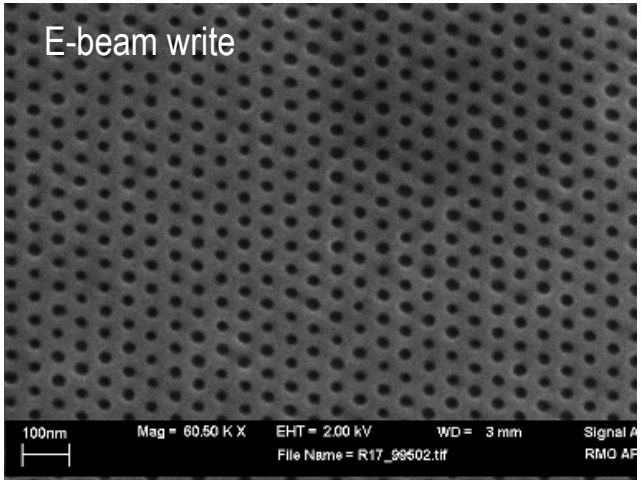
Template Mastering with Rotary E-beam

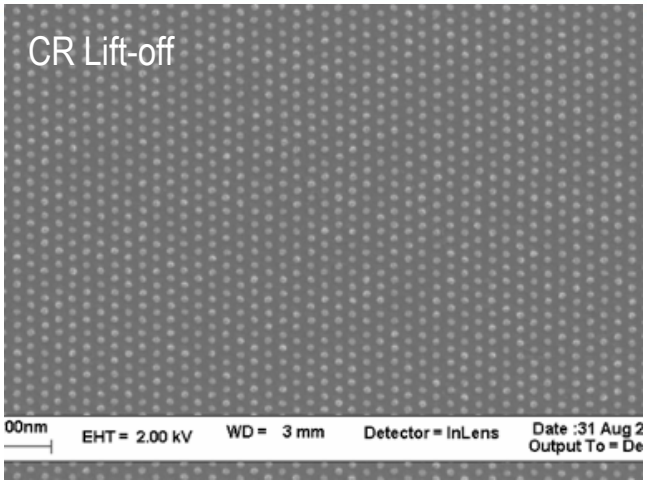
- Fabrication of Master Templates for Patterned Media requires high resolution patterning over large areas
  - Sub-50 nm resolution
  - Very low pattern distortion
- Patterns are concentric lines, arcs, and dot arrays

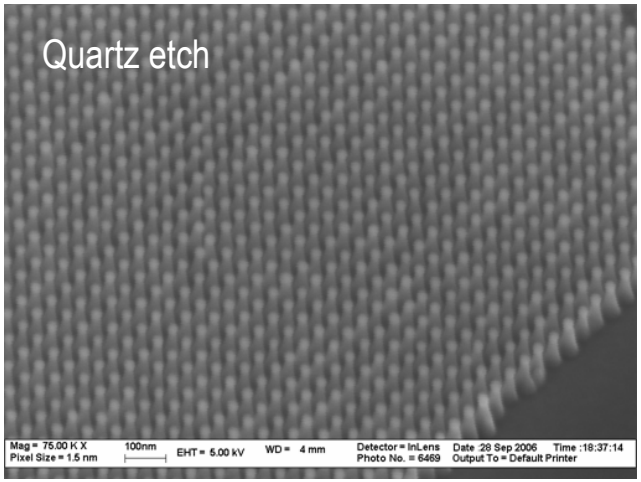


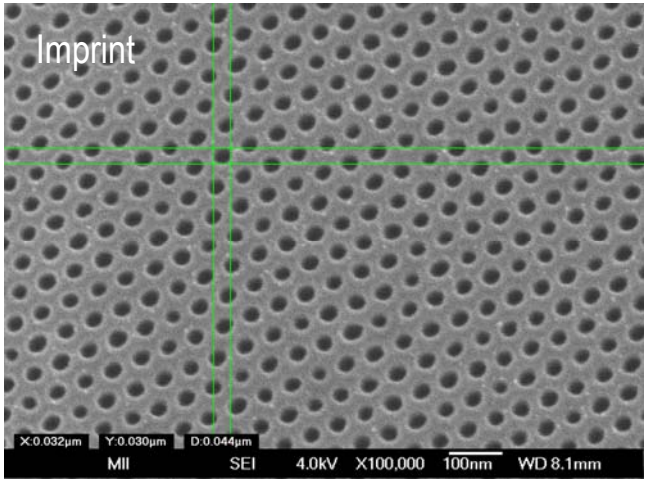
Rotational speed: ~ 100 to 3000 rpm
Direction: CW or CCW
Linear translation in one radial direction

Example: BPM – 25nm Half Pitch









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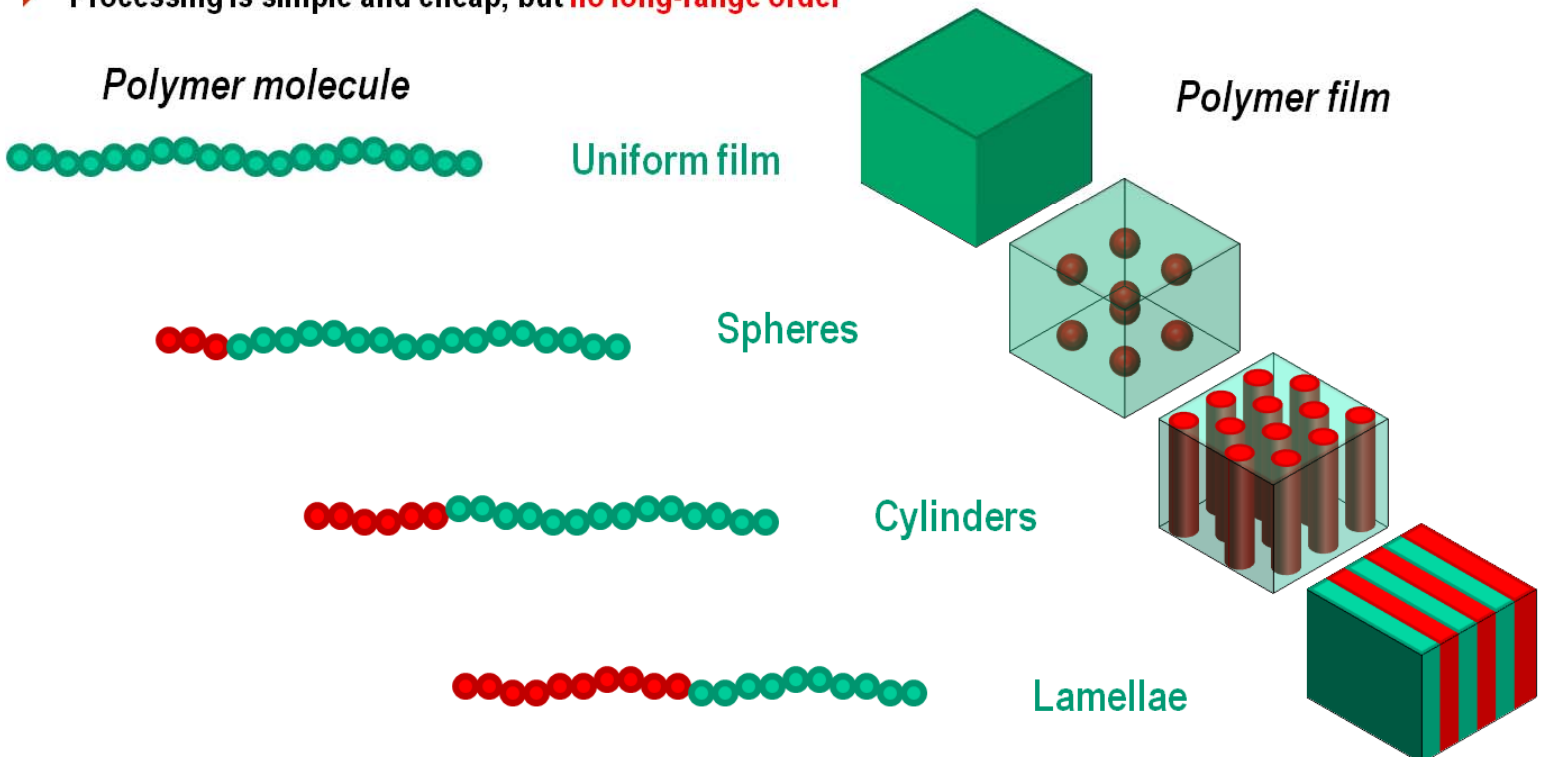
Master Template Fabrication for 1Tb and beyond

- **For Bit Patterned Media (BPM), a 1Tb Master requires a half pitch of 12.5 – 13.5nm!**
- **While it may be possible to resolve these feature types with a Gaussian beam pattern generator, there are several problems that you will need to overcome**
  - Pattern placement of the individual bits and write errors
  - Write time! (7 days at a minimum)
- **An alternative approach is to combine the best attributes of e-beam writing and self assembly**
  - Directed Self Assembly

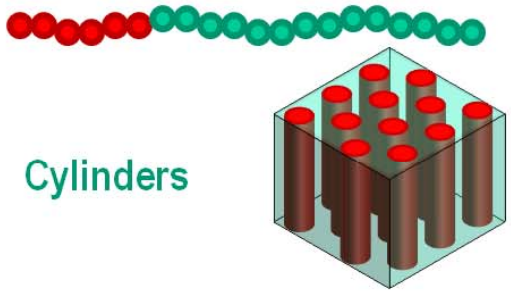
Diblock Copolymer Self-Assembly

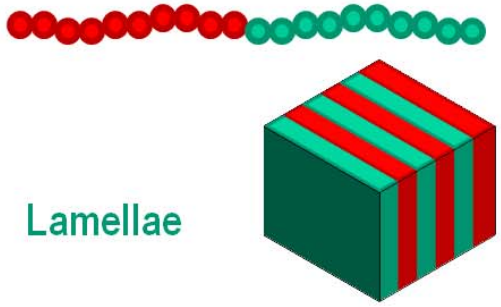
- Diblock copolymer materials undergo phase separation to form morphologies with short-range order
- The morphology and phase dimensions are controlled by the chemical composition
- Processing is simple and cheap, but no long-range order



Exa Examples: Short-range order

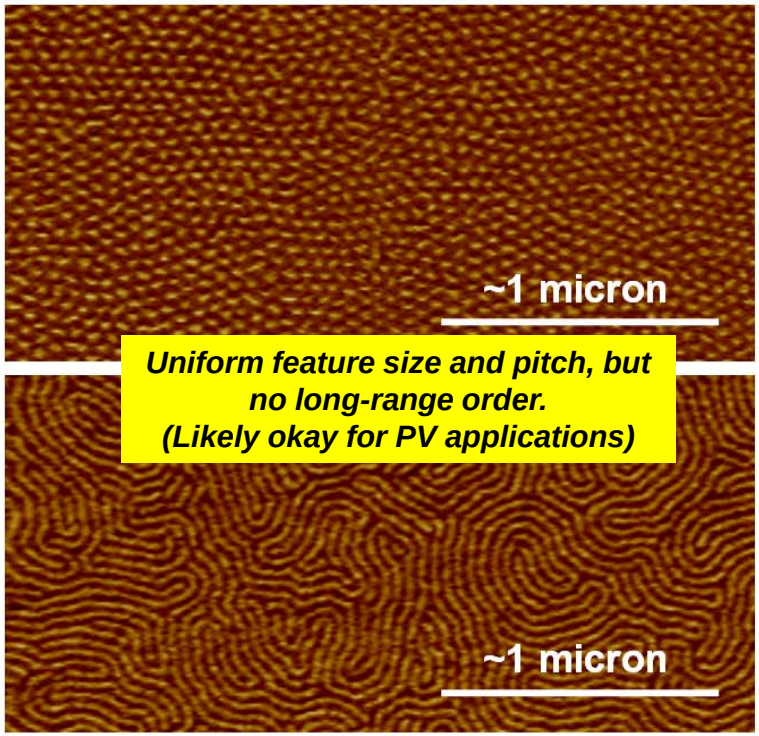
- From Joy Cheng, IBM Almaden





Polymer solution is spincoated on an unpatterned substrate and then annealed for several minutes.

PS-b-PMMA



Uniform feature size and pitch, but no long-range order. (Likely okay for PV applications)

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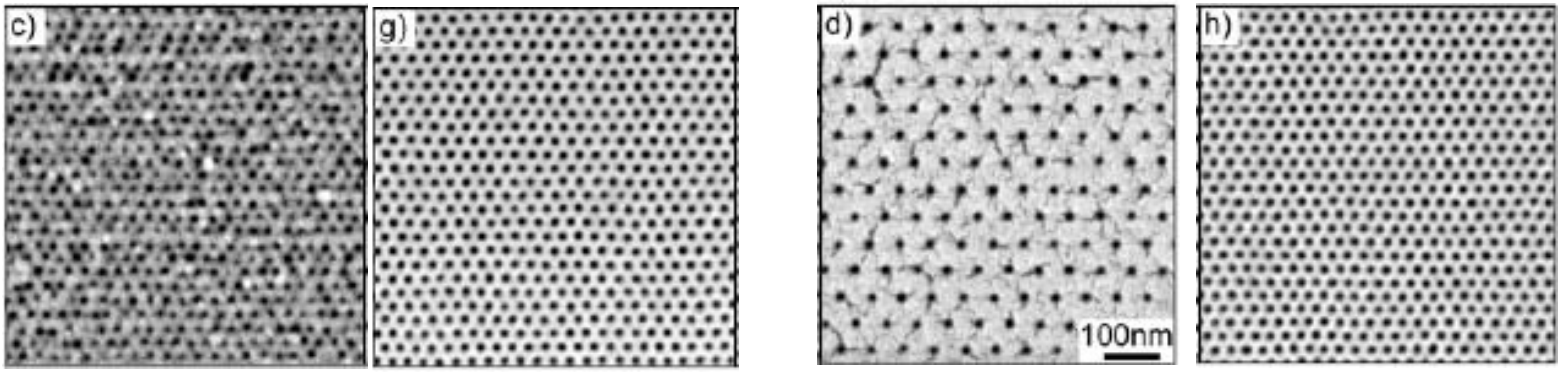
Directed Self Assembly

- To achieve long range order, we can use the e-beam writer to "guide" the placement of the block copolymer

Pattern Rectification

Density Multiplication



Half pitch = 13.5nm

R. Ruiz, H. Kang, F. A. Detcheverry, E. Dobisz, D. S. Kercher, T. R. Albrecht, J. J. de Pablo, P. F. Nealey, **Science 2008**, 321, 936.

HITACHI
Inspire the Next

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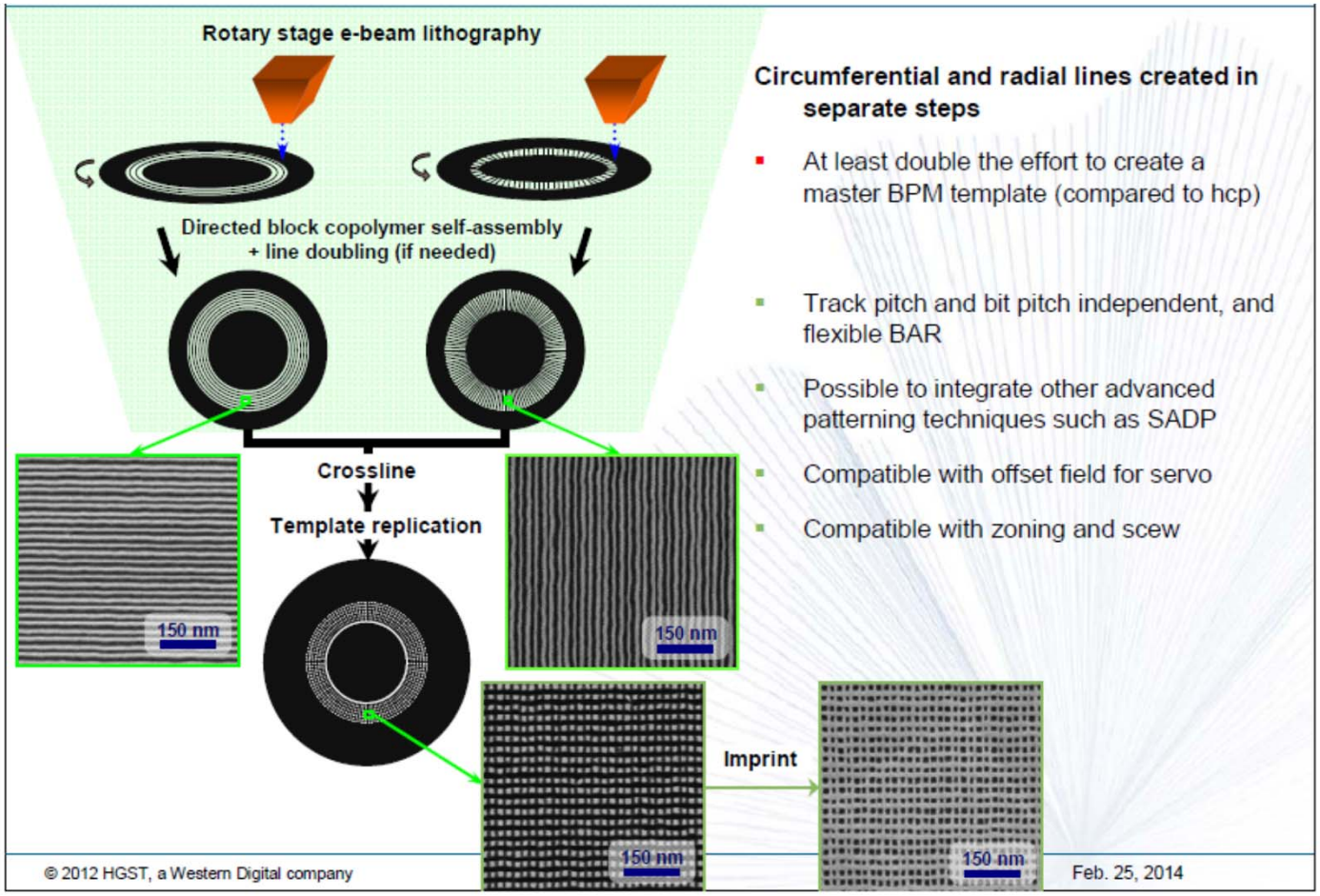
Another DSA Example



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Template Inspection

Candela X-Beam™ Optical Surface Analyzer

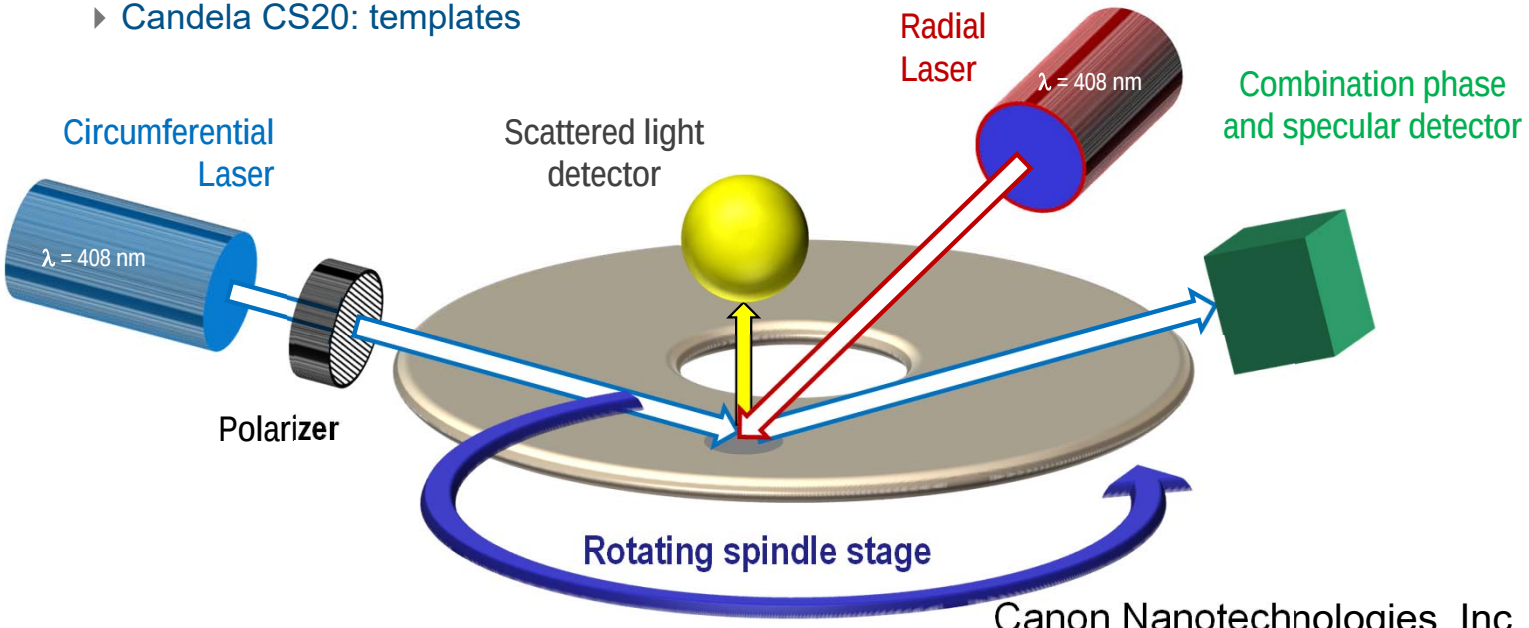
KLA-Tencor
Accelerating Yield

Multi-channel inspection of optical properties

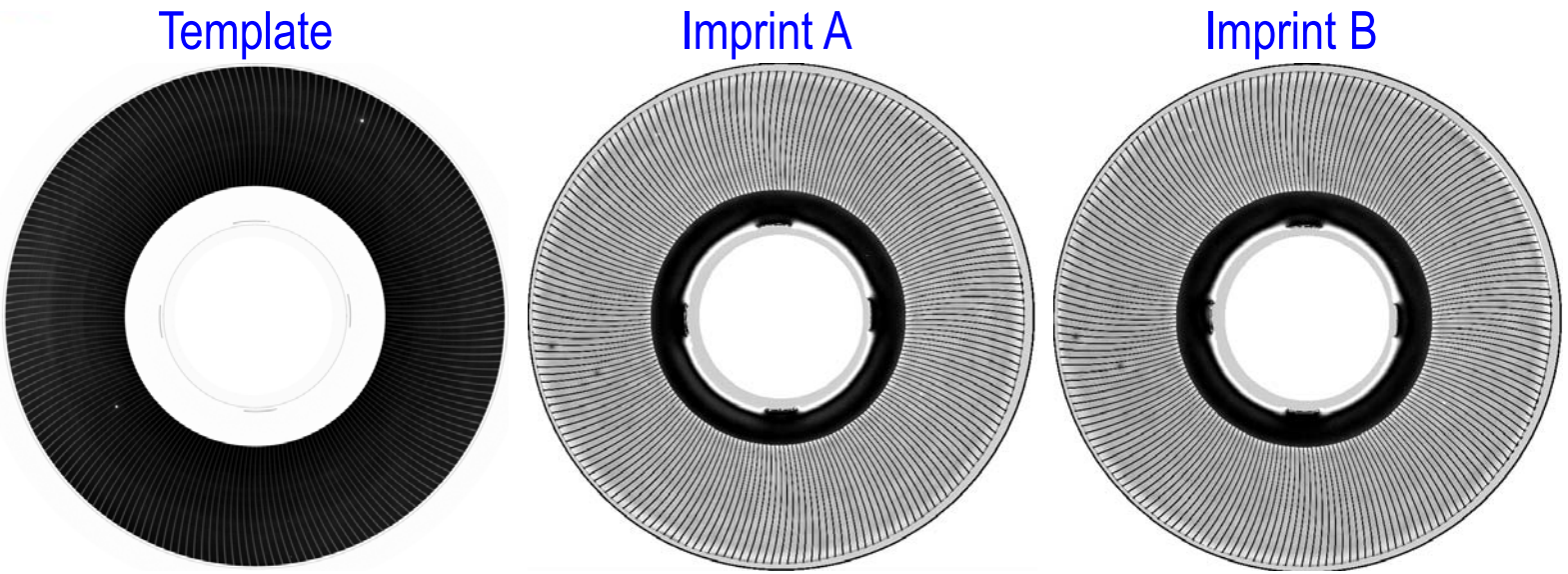
- Scattered light → dark field
- Reflected light → bright field, reflectometry
- Phase shift → thin film measurements

This work:

- Candela 6120: disk substrates
- Candela CS20: templates



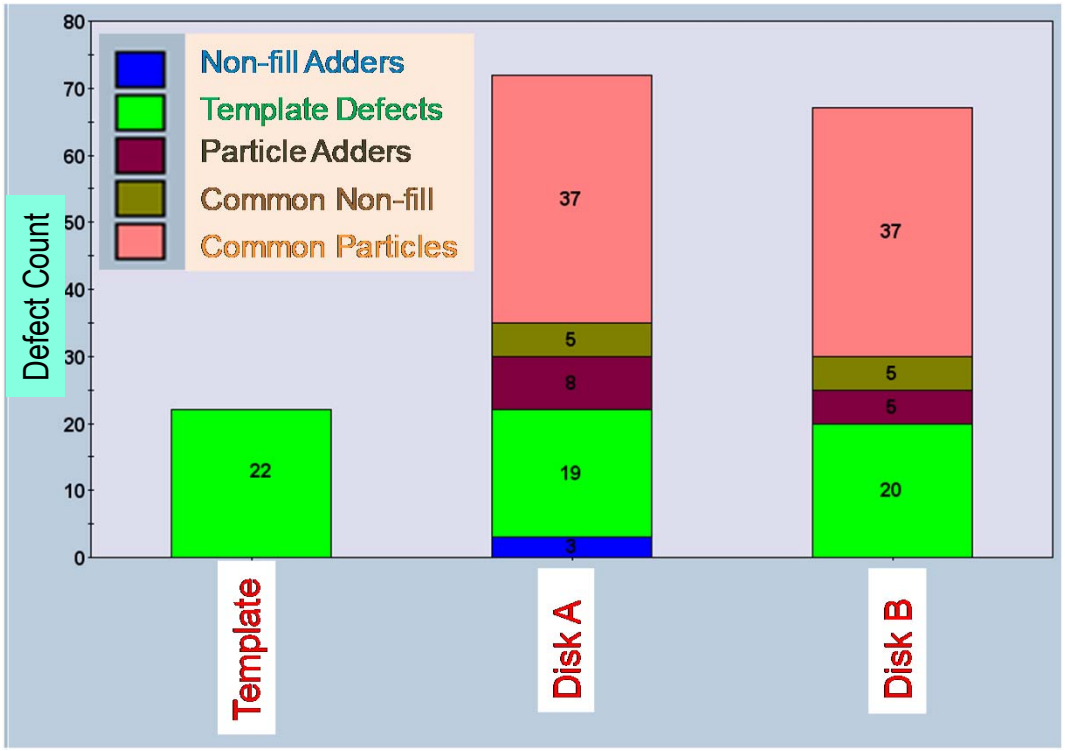
Identifying Defects on Templates and Disks



Specular Inspection

- There are 3 critical defects that need to be tracked: template, particle, non-fill
- How do we identify each defect type (defect classification)?
- How do we track defectivity?
  - From template to disk
  - From disk to disk

Defect Source Analysis

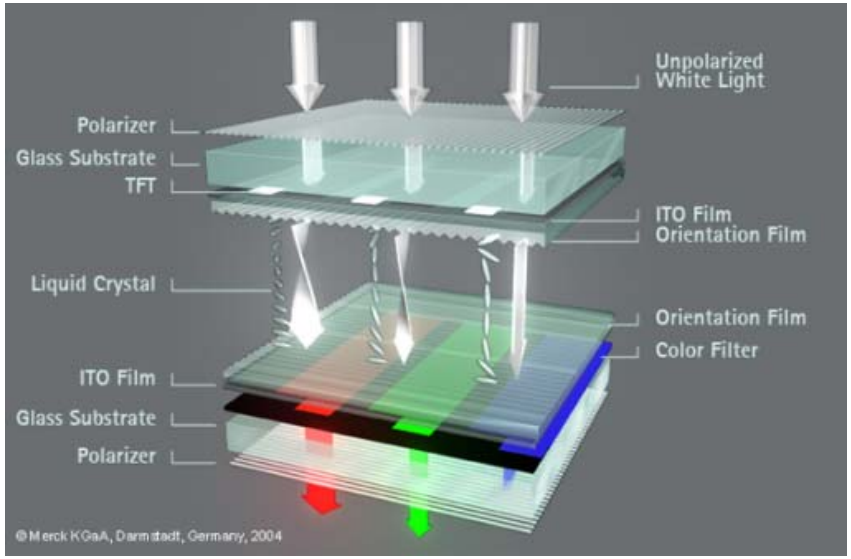


- Total inspected area: ~ 29 cm^2
- Total defectivity: ~ 2.4 def/cm^2

Liquid Crystal Display Panel Fabrication

- LCD displays are ubiquitous:

LCD Panel Components



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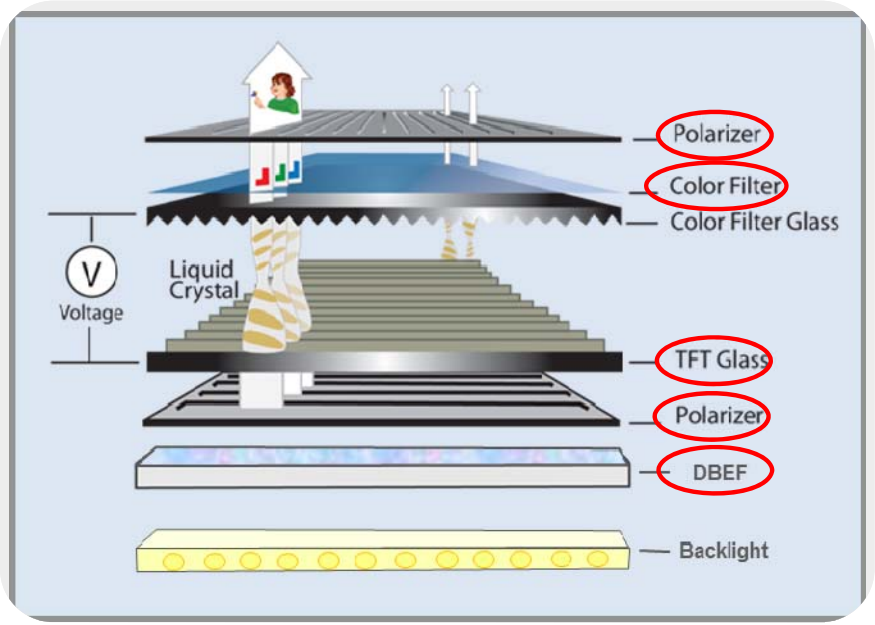
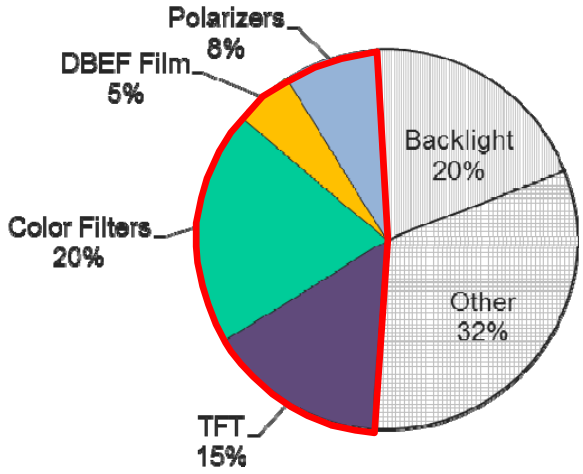
Nanoscale Patterning Can Improve Many Critical Components in Displays

J-FIL™ can offer improved technologies at lower cost that impacts approximately 50% of liquid crystal display Bill of Materials (BoM).





LithoFlex 350™

Molecular Imprints

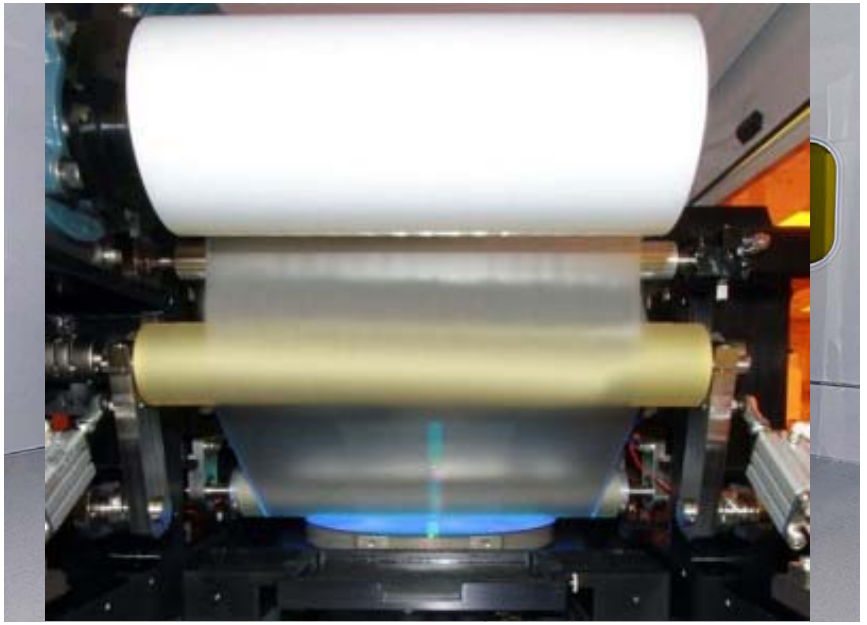
LithoFlex 350

SYSTEM CONFIGURATION

- Plate-to-Roll (P2R) or Roll-to-Plate (R2P) Template Substrates:
  - P2R ≤ 300mm glass or silicon wafer
  - R2P ≤ 350mm width web
- Automated or manual template loading
- Automatic protective film particle control
- UV cure (365nm) light source

PERFORMANCE

- Sub-50 nanometer feature resolution
- Throughput >1 meter per minute
- Position accuracy of 600 microns (3σ)
  - Alignment Option Available
- Print width: 300mm maximum



TECHNOLOGY

- Jet and Flash™ imprint technology
- IntelliJet™ resist jetting dispensing system

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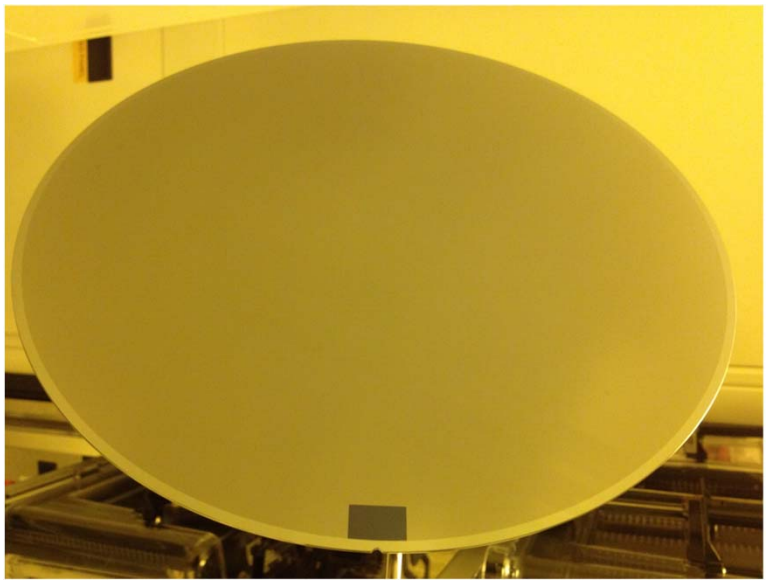
Plate to Roll (P2R) imprinting

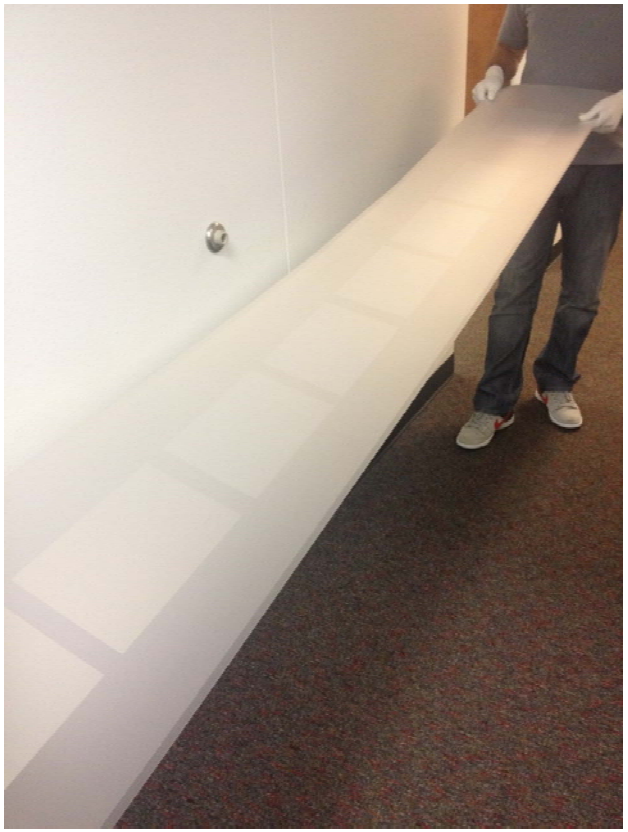
- P2R imprinting uses patterned rigid substrates:
  - As an example, a 300mm wafer can be used as the working template



- Can be patterned several different ways:
  - Photolithography
  - Imprint Lithography
  - Electron beam Lithography
  - Photo or E-beam/DSA

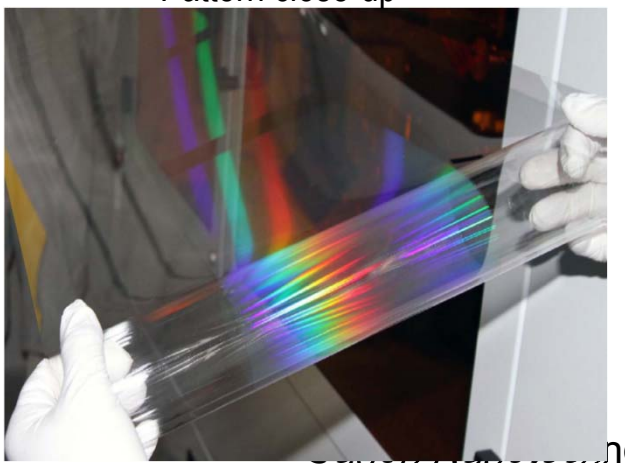
J-FIL Results

350mm web with protective film



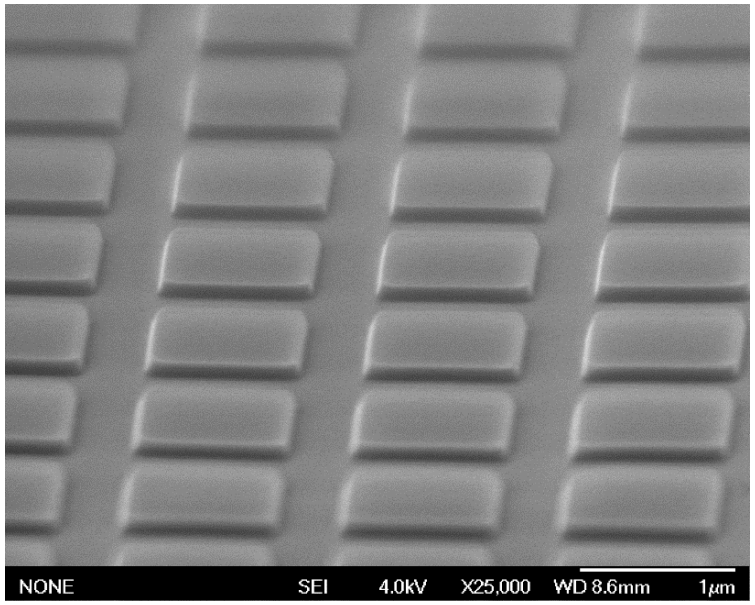
Protective film removed

Pattern close-up

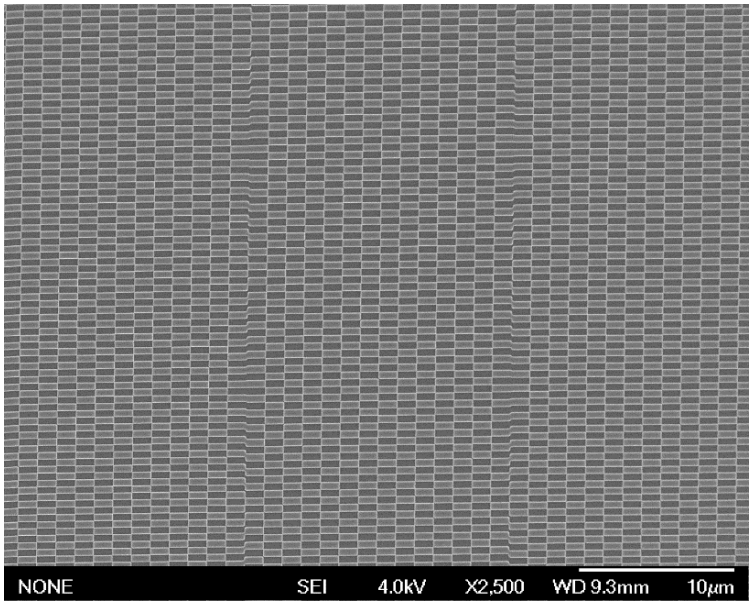


Test Pattern SEM images

- Both micron size and nanoscale patterns can be imprinted within the same field

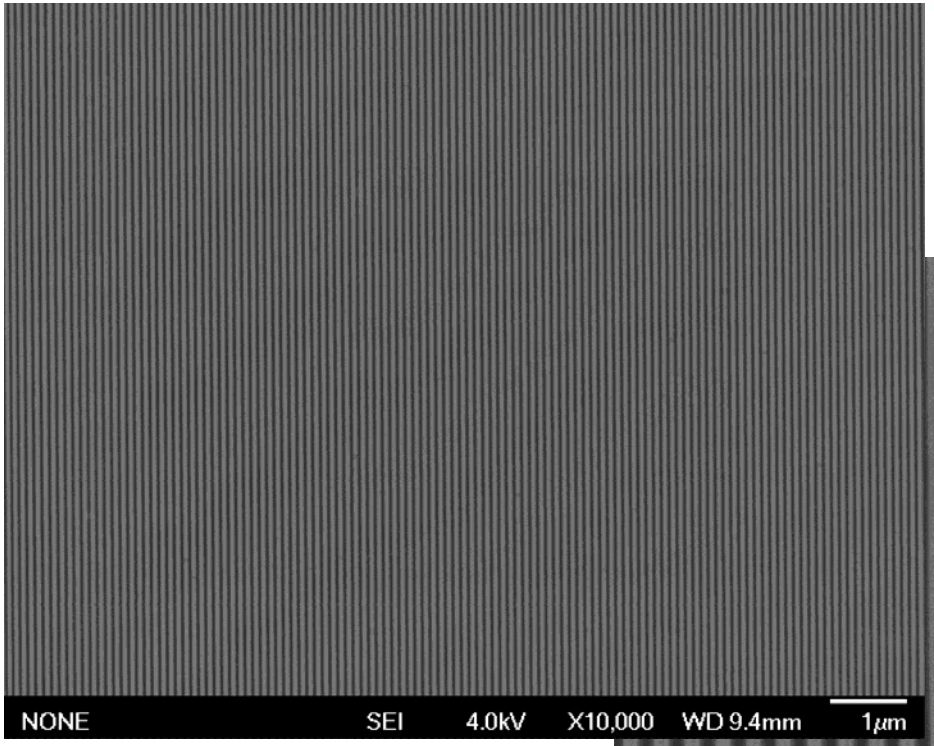


Micron scale pattern

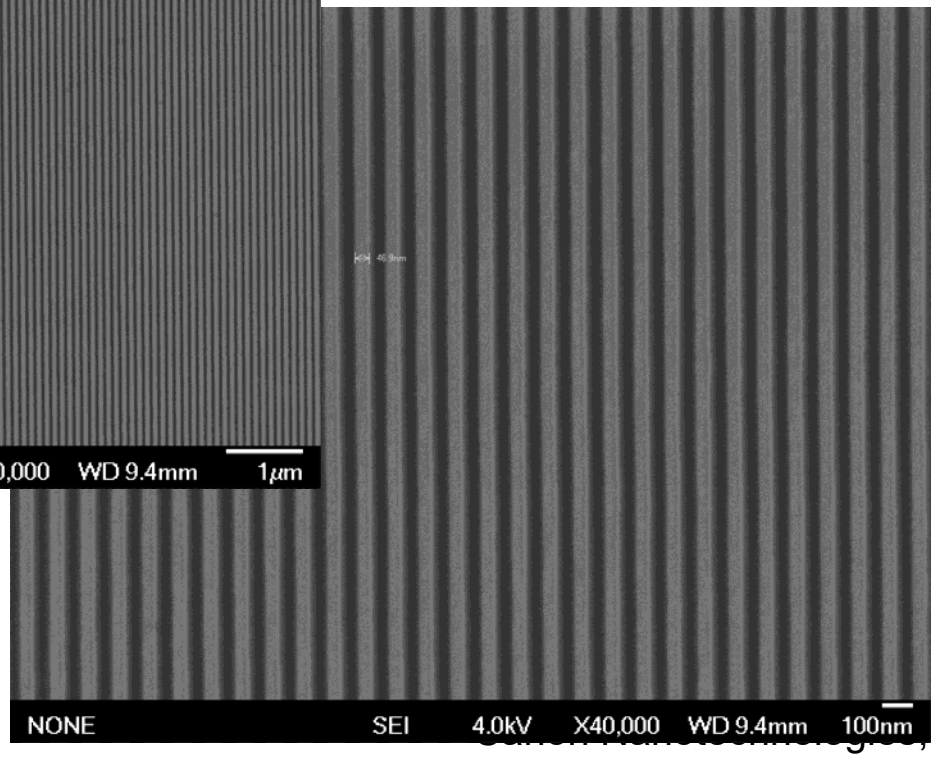


450nm test pattern

Nanoscale imprinting



50nm half pitch grating

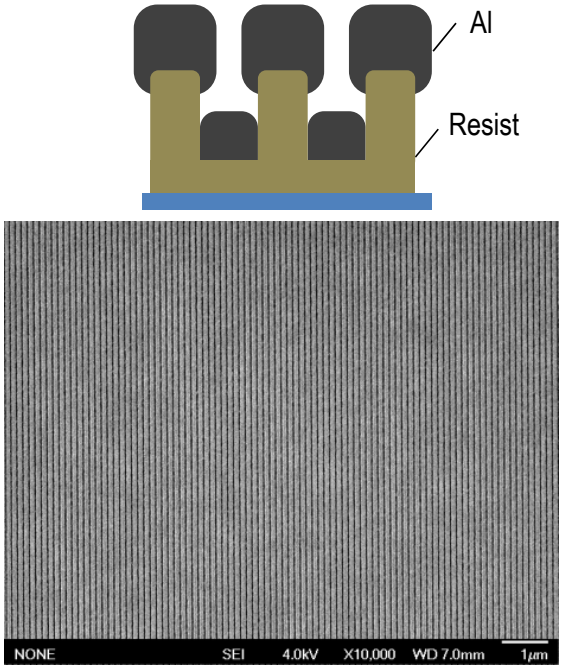


Inc.

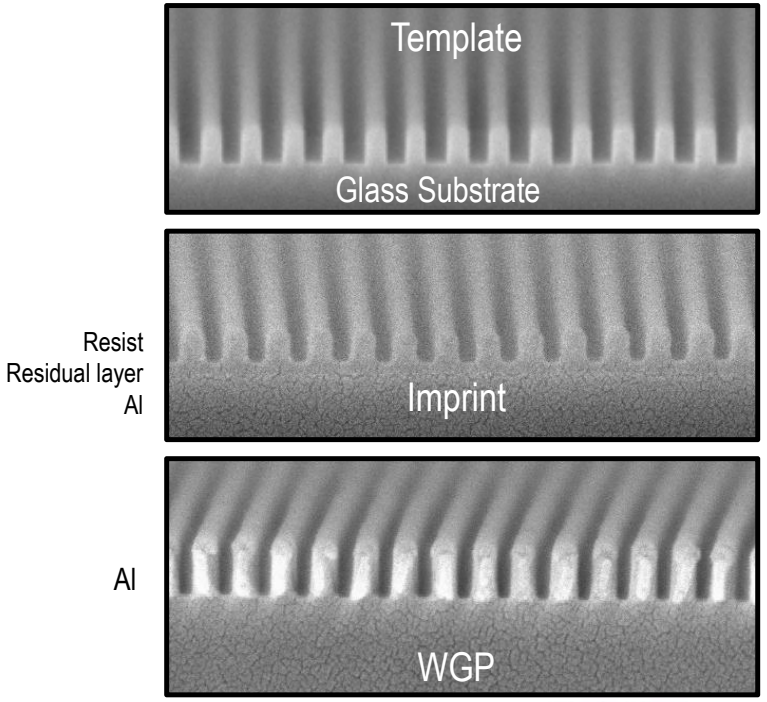
Wire Grid Polarizers

Two methods for fabricating Wire Grid Polarizers(WGPs):

Very low cost



Very High Performance



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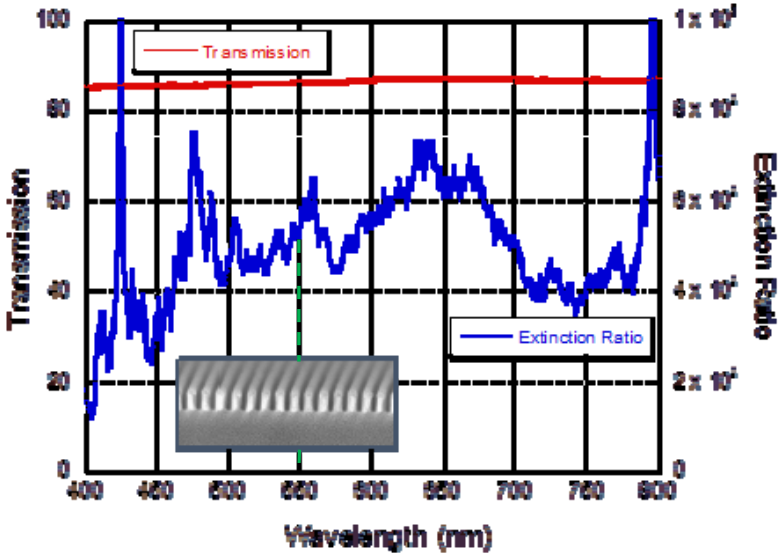
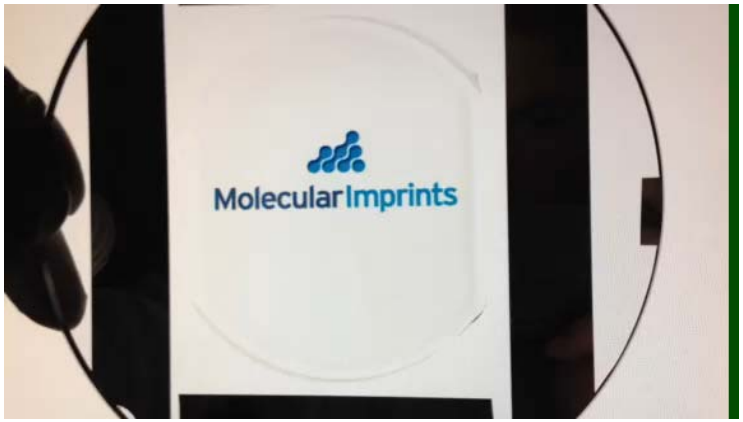
Etched WGP Results

- Performance is driven by many factors
  - Defectivity
  - Pitch
  - Duty Cycle
  - Aspect Ratio
  - Al quality





Integrated Transmittance : ~44%
Extinction ratio at 550nm: ~50K

Final Thoughts

X-ray Lithography
1X proximity-based technology using
a membrane-based mask

Ion Beam Lithography
1X and projection technology using
a stencil-based mask

SCALPEL
Projection electron lithography using
a thin membrane mask

1. I worked on all three mask technologies

2. From a manufacturing perspective, all three are now dead

3. All three died, in part, from a lack of mask infrastructure

Acknowledgments

CNT and Molecular Imprints

Ecron Thompson, Gerard Schmid, Mike Miller, Kosta Selinidis, Ian McMackin, Cindy Brooks, Gary Doyle, Gaddi Haase, Kang Luo, Lovejeet Singh, David Curran

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Motorola

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KLA-Tencor

Mark McCord

Vistec-Semiconductor

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LBNL, RaveLLC, Zeiss, NuFlare, Mentor Graphics, HMI

This work was partially funded by:
DARPA (N66001-02-C-8011, N66001-01-1-8964) and NIST-ATP

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References

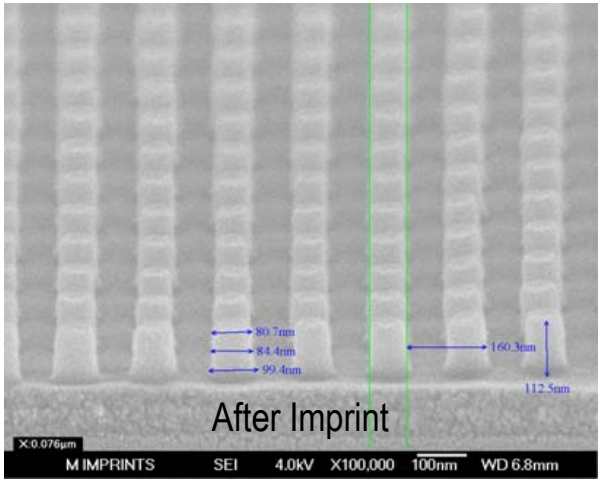
- To learn more about Jet and Flash Imprint Lithography, go to:
  - http://www.molecularimprints.com/news-and-publications
  - http://cnt.canon.com/technical-library/

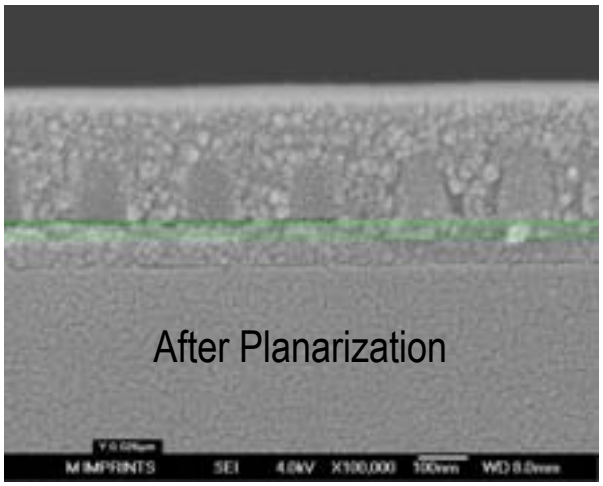
Appendix

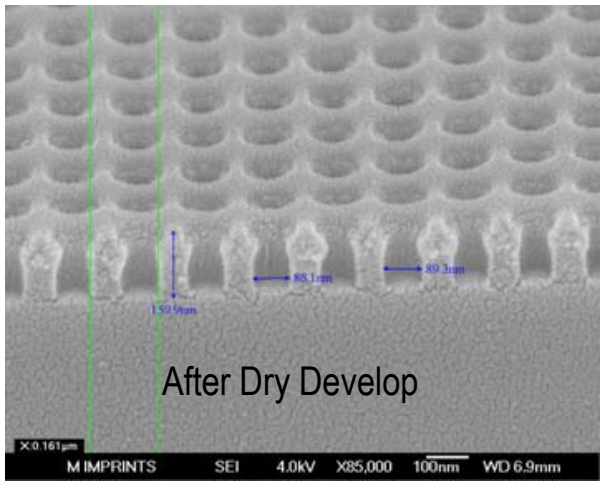
- Applications
  - Photonic Crystals
  - Contacts
  - Memory
  - Dual Damascene
  - Micro Lens Arrays
  - SAW Devices

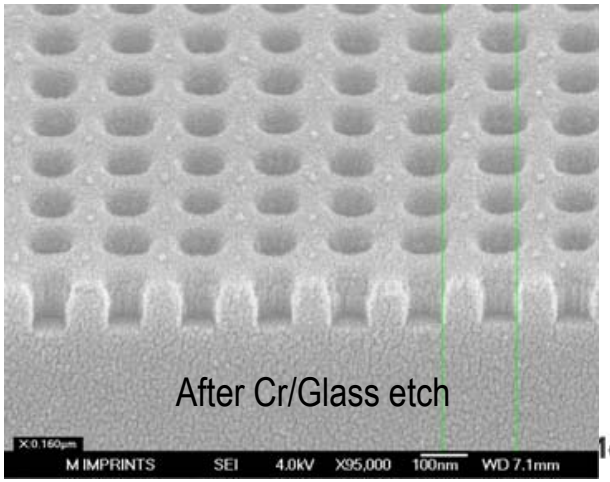
An Example: Photonic Crystal – 80nm HP

Example: Photonic Crystal Array – Pattern Transfer



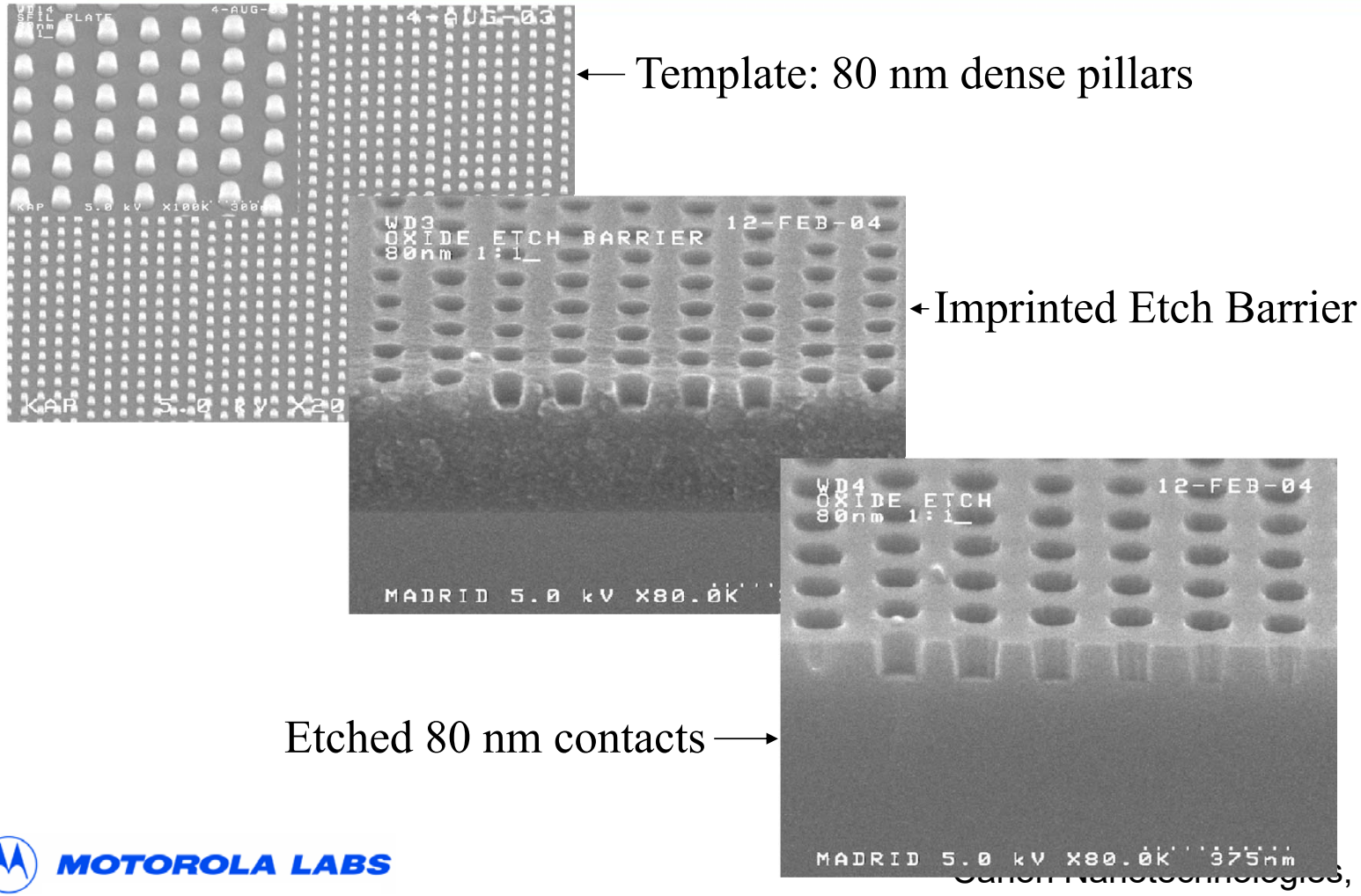






olecular Imprints

The Complete S-FIL Process: Contacts



← Template: 80 nm dense pillars

← Imprinted Etch Barrier

Etched 80 nm contacts →

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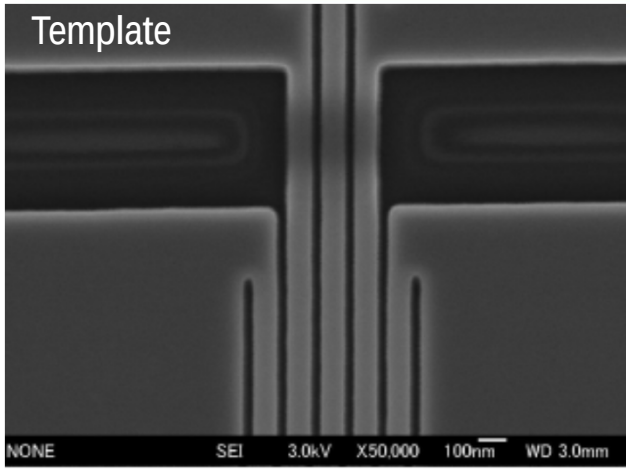
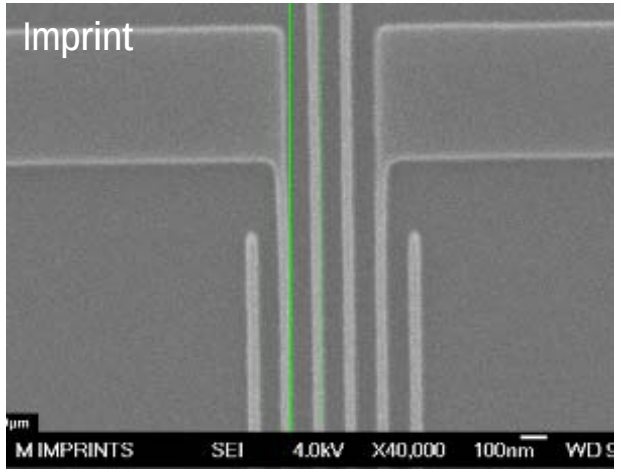
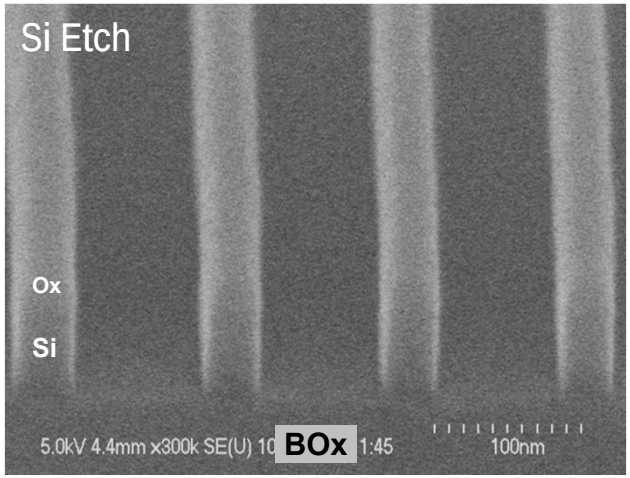
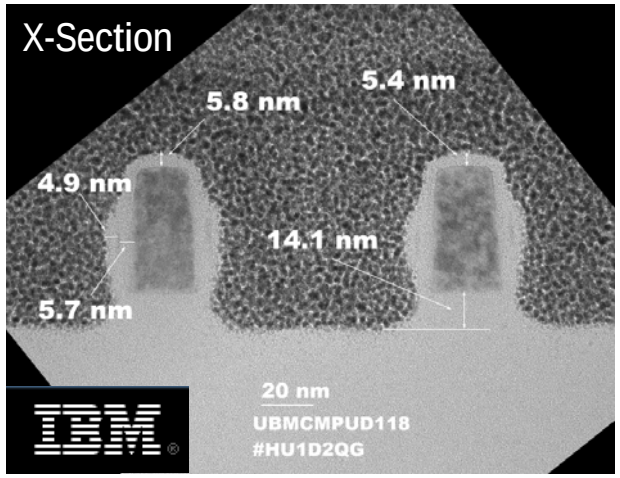
Hoya: 30nm IBM Memory

HOYA









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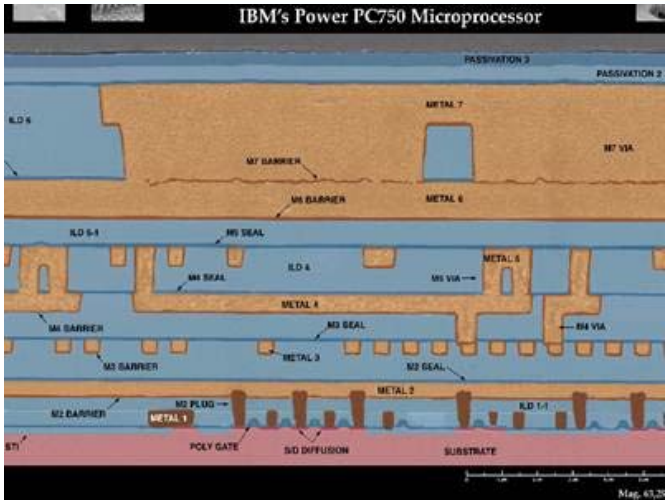
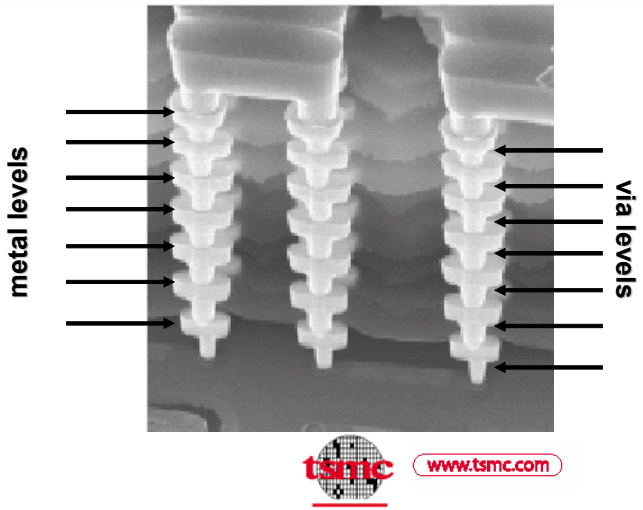
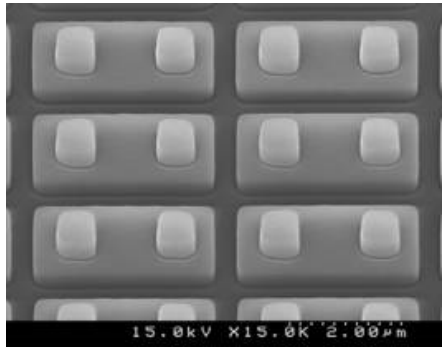
Dual Damascene

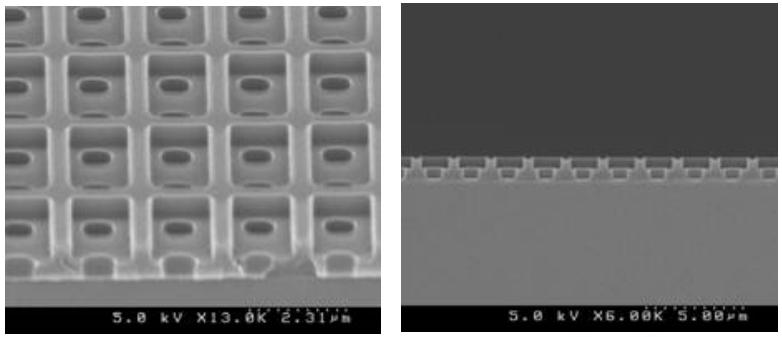




Template by Toppan



Replication on Imprio™ 55, **Willson et al. at UT.**



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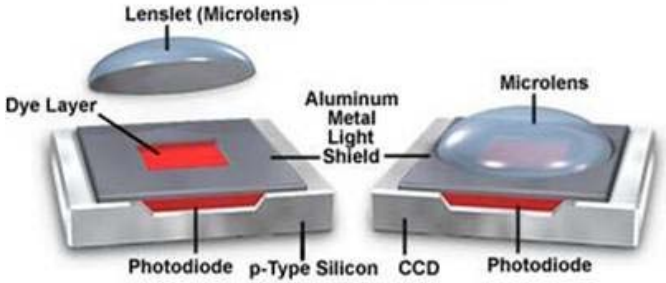
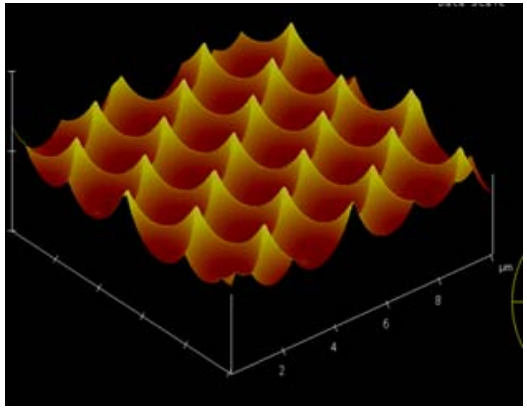
Micro Lens Arrays

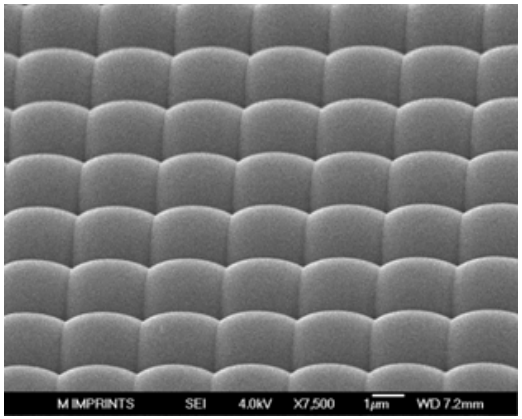
Background: Added to a digital camera's CMOS/CCD image chip to improve optical collection efficiency

Challenge: Patterning of high packing density aspheric lens arrays requiring no etching





Template



Imprinted Lens Array

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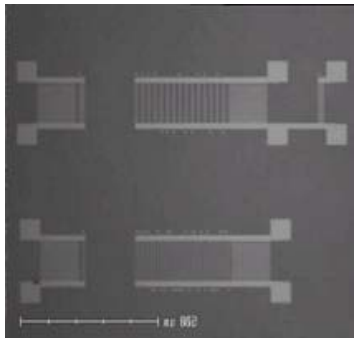
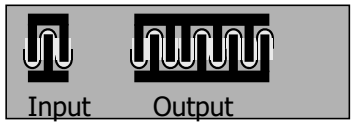
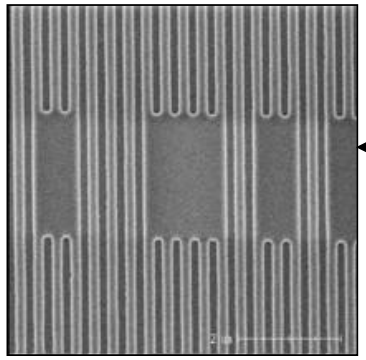
SAW Device Fabrication

Step 1. Create Template

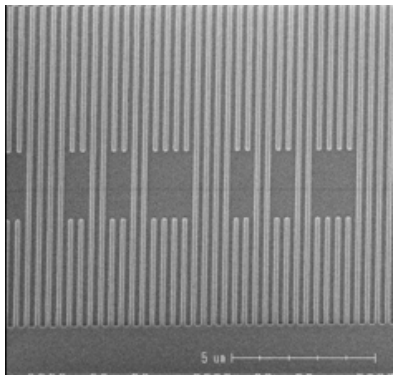


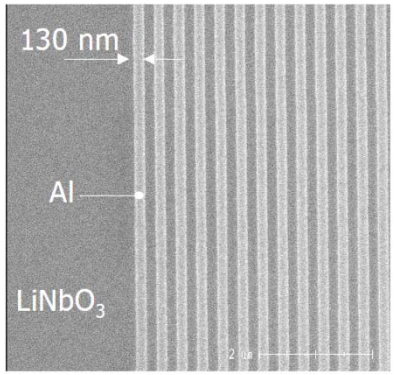




←Template

Step 2. Imprint, etch the aluminum IDT, and remove the resist





The patterned aluminum (light grey) is 40 nm thick X 130 nm wide, and the substrate material (dark grey) is $LiNbO_3$.

Note the line uniformity and the absence of line edge roughness in the final pattern.

Sandia National Laboratories

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