October 4th, 2012

Extending Patterning Capability Using Directed Self-Assembly

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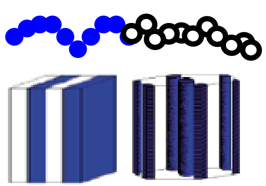
Directed Self-assembly

Directed self-assembly (DSA) is a material-based method to extend the patterning capability of 193i, EUV, & e-beam direct write lithography

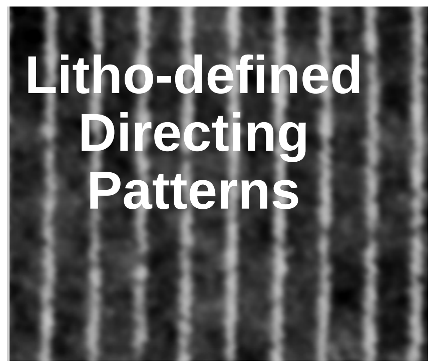
Overcome resolution, pattern fidelity, or throughput issues

block copolymer



Self-forming
Chemical contrast
5-30 nm feature size

+

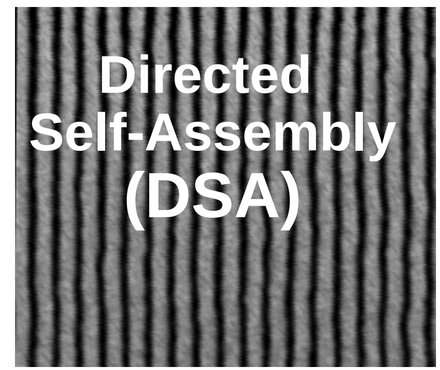


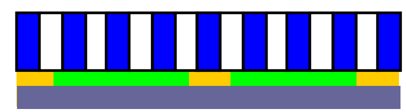
Chemical prepattern

Topographical prepattern

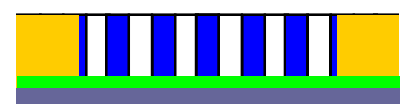
Topographical &
Chemical Patterns

=





Chemical Epitaxy



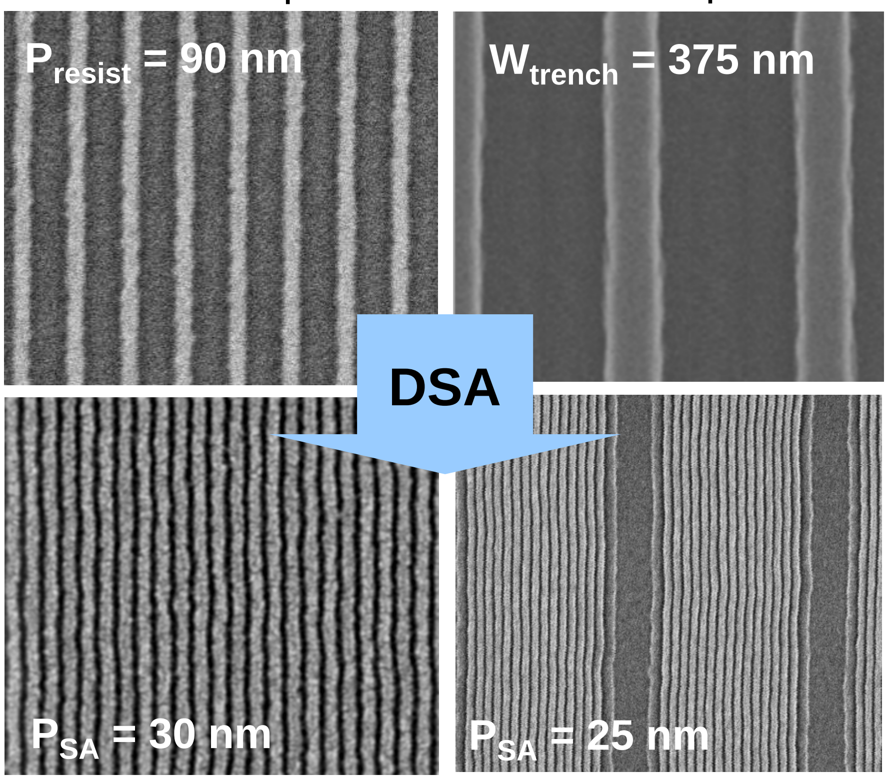
Graphoepitaxy

Smaller & Denser
Patterns

Track Compatible DSA (2010 SPIE)

Line-space patterning

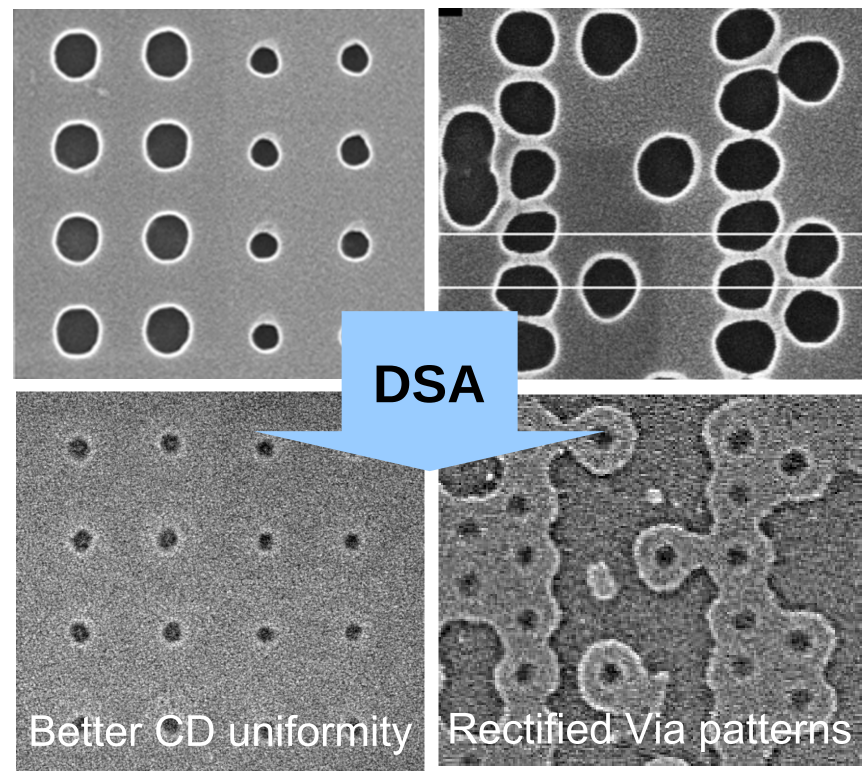
Chemical Prepattern | Trench Prepattern



Frequency multiplication (2X to >10X)

Contact/via patterning

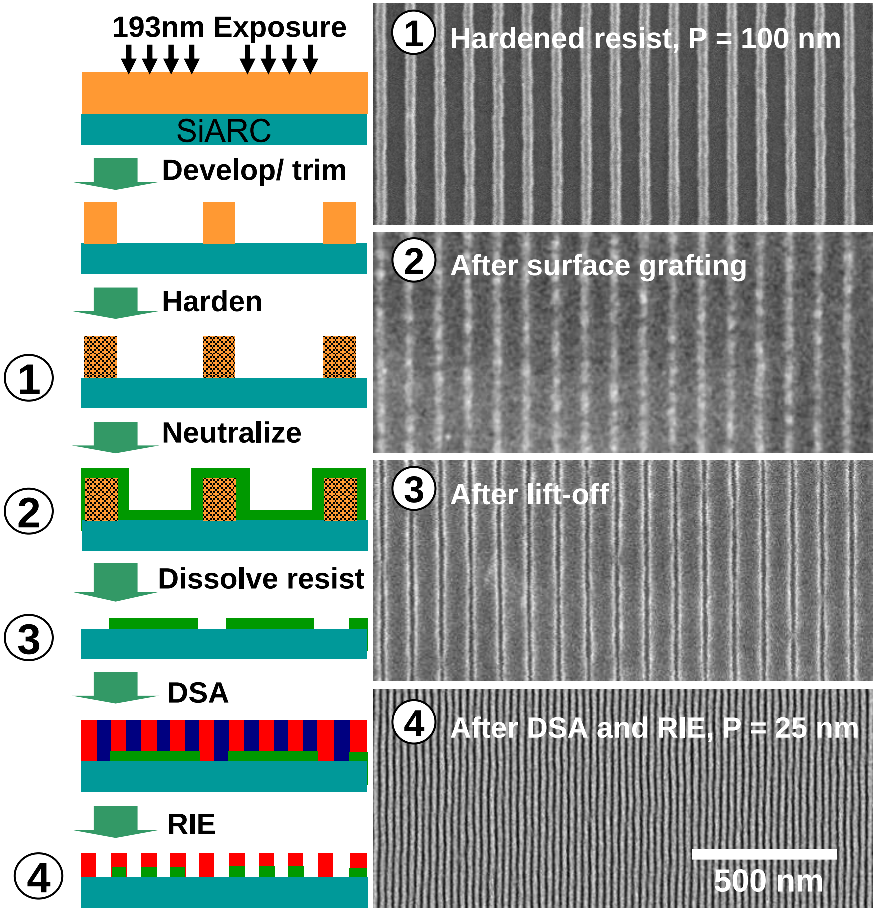
Poor CD uniformity | Arbitrary patterns



Via shrink and Rectification

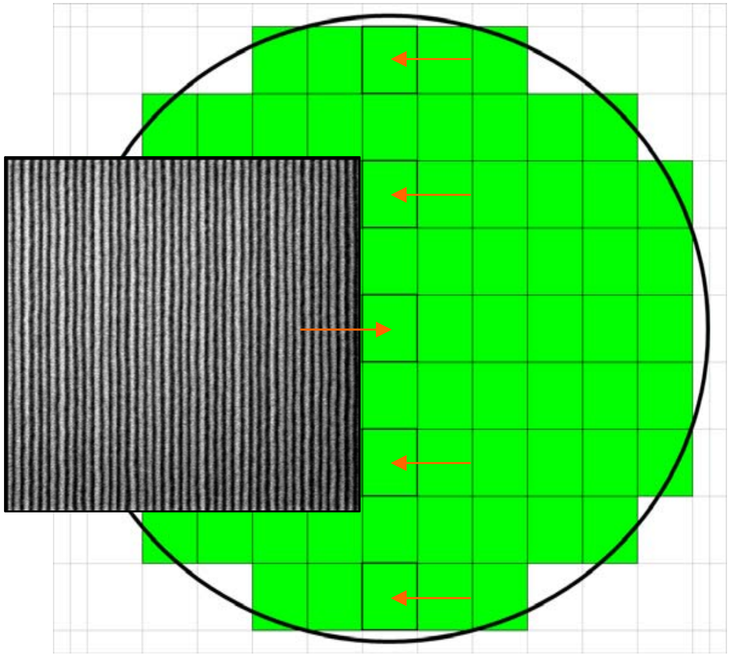
Transition from Lab to Fab (2011 SPIE)

193i + DSA for Quadrupling



Cheng, ACS Nano, 2010

300 mm DSA LS wafer



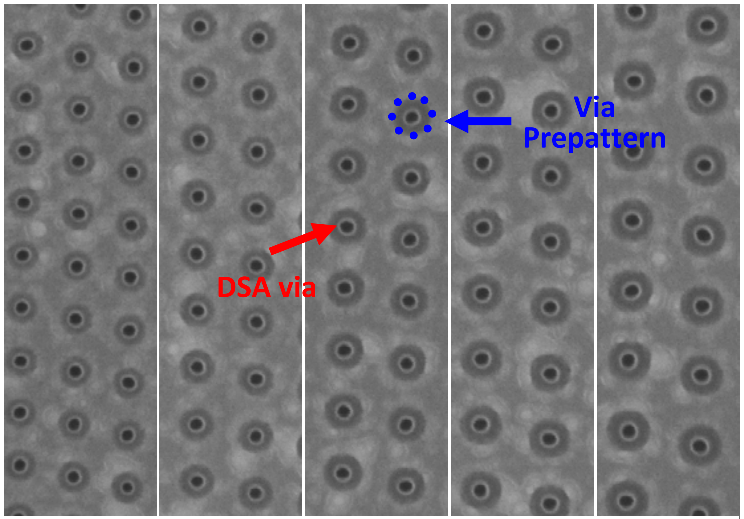
- 193i litho (ANT) + DSA (ARC,AMAT)
- 4x multiplication
- 12.5nm half-pitch DSA gratings
- Preliminary defect ~25/cm^2

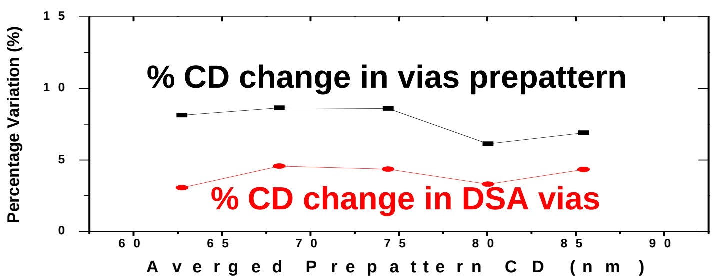
Bencher, SPIE Proc. 2011

IBM

Via Rectification (2011 Litho Extension, 2012 SPIE)

DSA Via Rectification

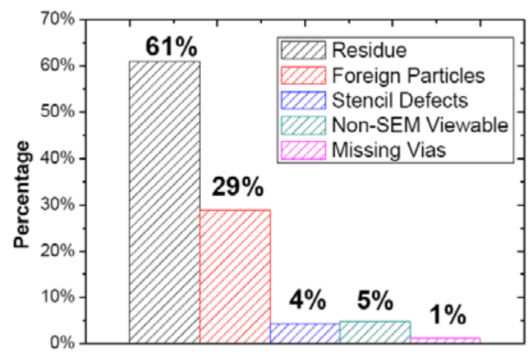


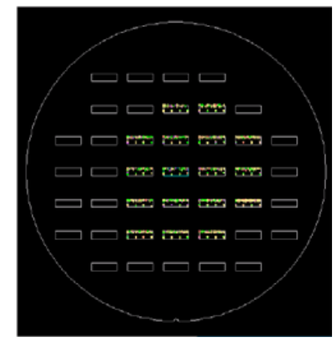


DSA provides via shrink & rectifications: %CDU of DSA vias are 50% smaller than the % CDU of via prepattern. J Cheng, 2011 LithoExtension

DSA via Defectivity Measurement

Inspection Tool	Uvision 3
# of Dies Scanned	17
Total Area Scanned	16million μm²
Total # of Vias Within	**~ 550,000,000**
# of Defects	2643





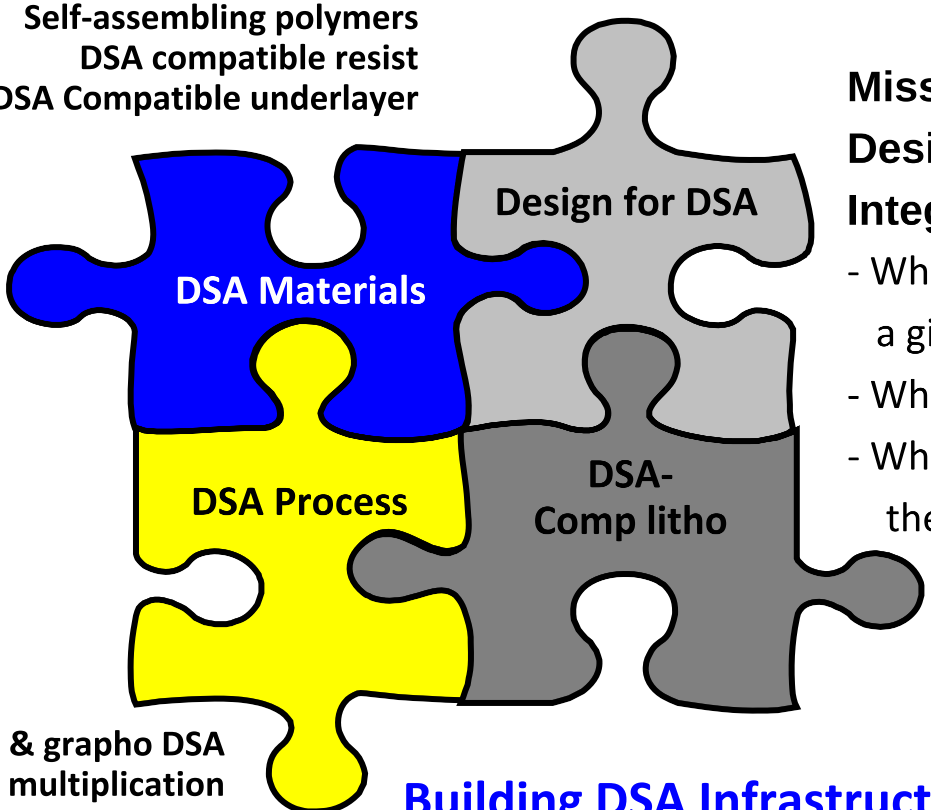
- **DSA provides robust via shrink.**
- **DSA shrinks 65-85nm holes into ~25nm holes**
- **DSA related defects ~ 1 per 25 million vias**
- **Promising initial DSA defect value.**

C. Bencher, SPIE Proc. 2012

APPLIED MATERIALS

Directed Self-Assembly (DSA) as a Resolution Enhancement Technology?

Self-assembling polymers
DSA compatible resist
DSA Compatible underlayer



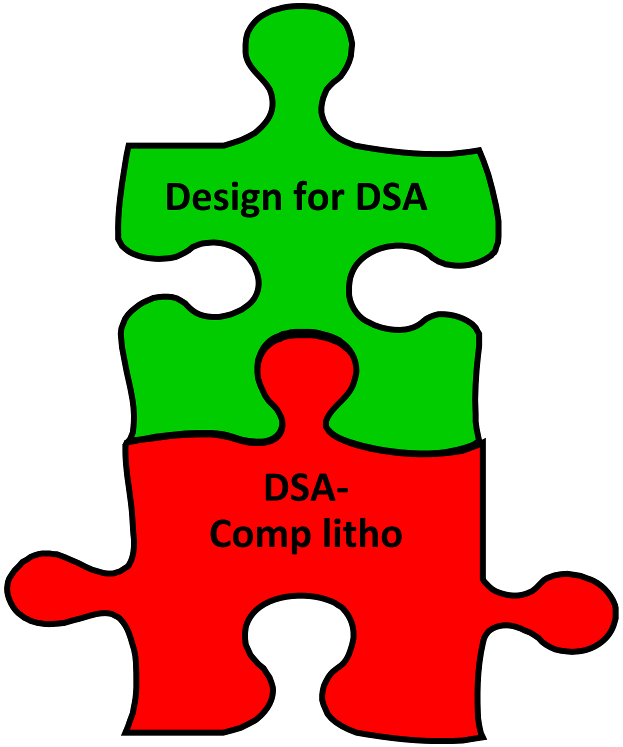
Missing pieces in the puzzle:
Design for DSA
Integration of DSA into comp litho

- What is the optimal guiding prepattern for a given target pattern?
- What is the error in DSA feature?
- What is the error processing window of the guiding prepattern?

Chemo & grapho DSA
Pattern multiplication
Via shrink & rectification
300mm DSA demo

Building DSA Infrastructures for design and integration is important to enable DSA as a resolution enhance technology.

Steps towards DSA as a Resolution Enhancement Technology:



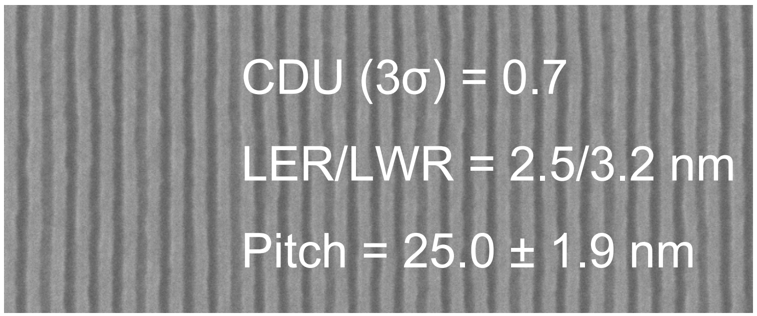
Design for DSA relies on understanding the relationship between guiding pre-patterns & resulting DSA patterns:

- **Rule-base design:**
  1D Guiding prepatterns + 1D Self-assembly
  ex: line-space multiplication using chemical-epitaxy of lamellae-forming block copolymers (Doerk, SPIE 2102)

- **Model-base design:**
  2D Guiding prepatterns + 2D Self-assembly
  ex: Via shrink and rectification using 2D grapho-epitaxy of cylinder-forming block copolymers (Liu, SPIE 2102)

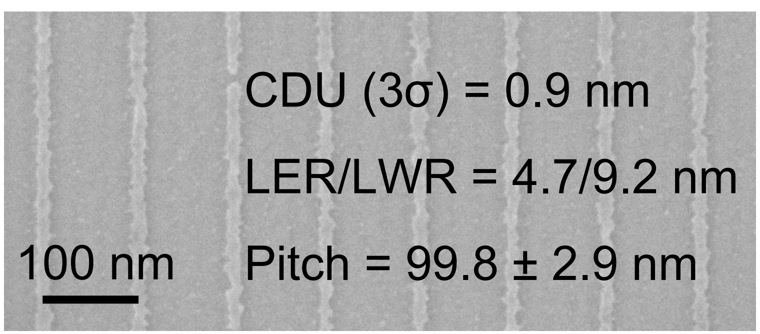
Behind Simple 1D-DSA:

DSA and RIE

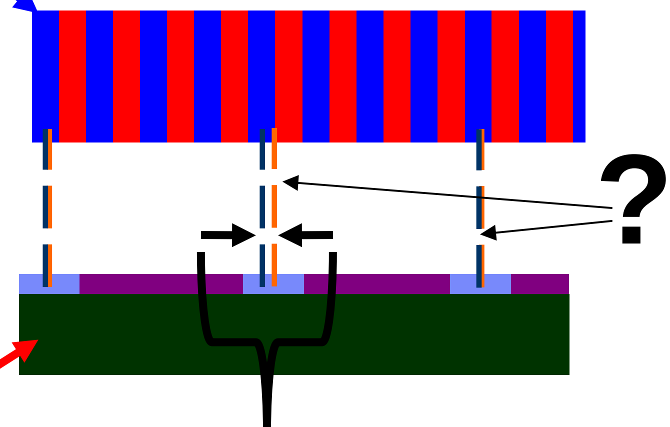


- 4X multiplication

Chemical prepattern



two distinct images



Pattern placement error (Δ)

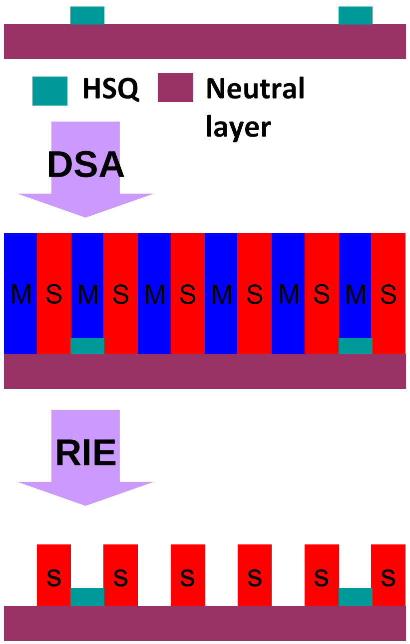
What is the correlation between chemical prepattern and DSA?

How does the error in the prepattern transfer into the error DSA?

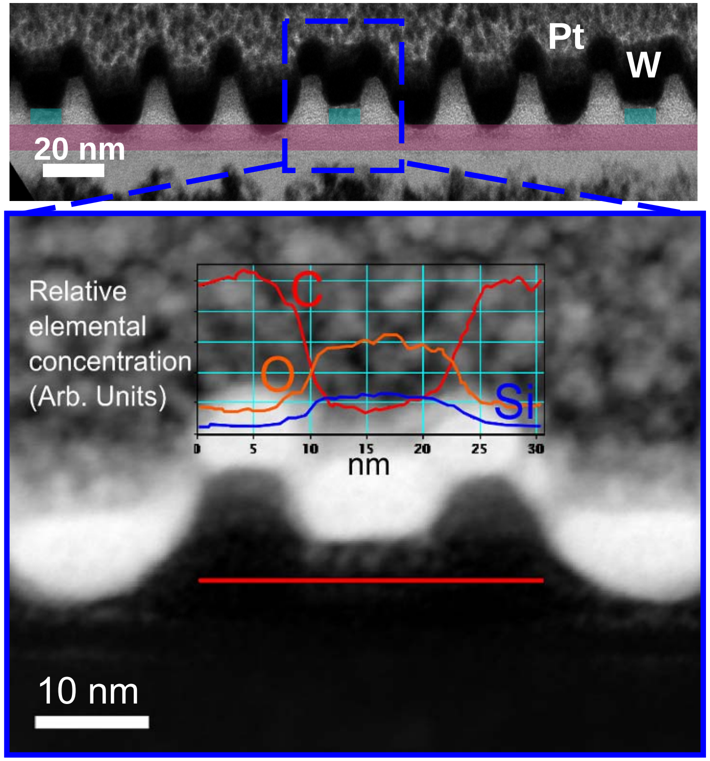
Doerk et. al. SPIE 2012 Proceeding

Characterization of Registration Using TEM

Chemical Prepattern:



Cheng, *et al*. Adv. Mater. (2008).

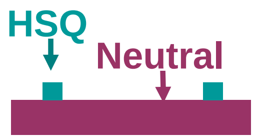


Doerk et. al. ACS Nano Submitted

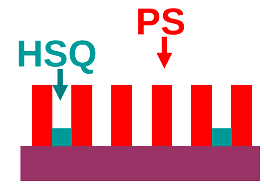
- Inorganic pinning lines gives contrast in TEM /EELS.
- TEM image confirms HSQ pins PMMA domains.
- However, TEM is time consuming and generates limited amounts of data.

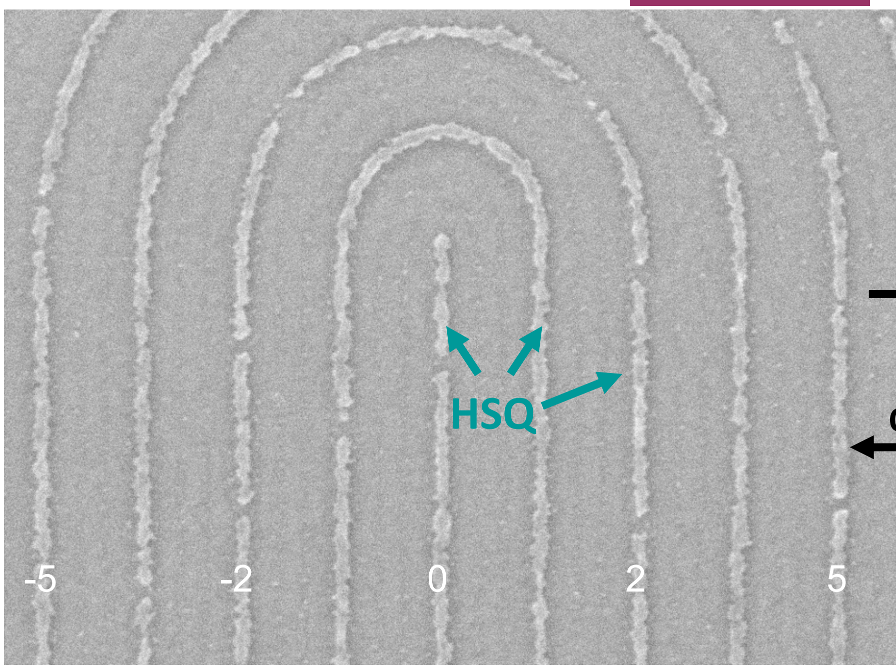
Characterization of DSA Pattern Placement Using In-situ Registration Marks

In-situ registration marks
Chemical prepattern
(HSQ on neutral layer)



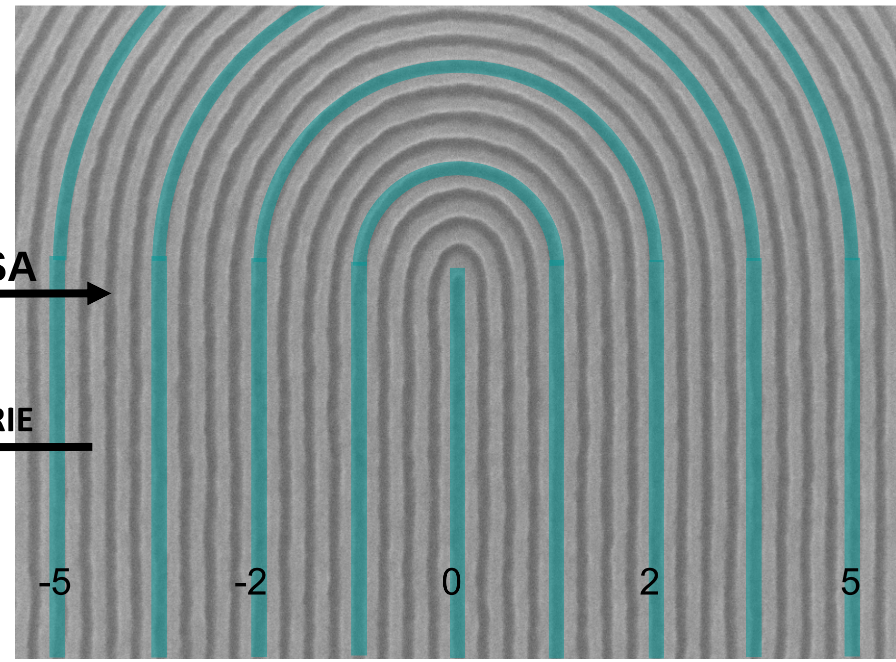
DSA structures on
In-situ registration marks





DSA →

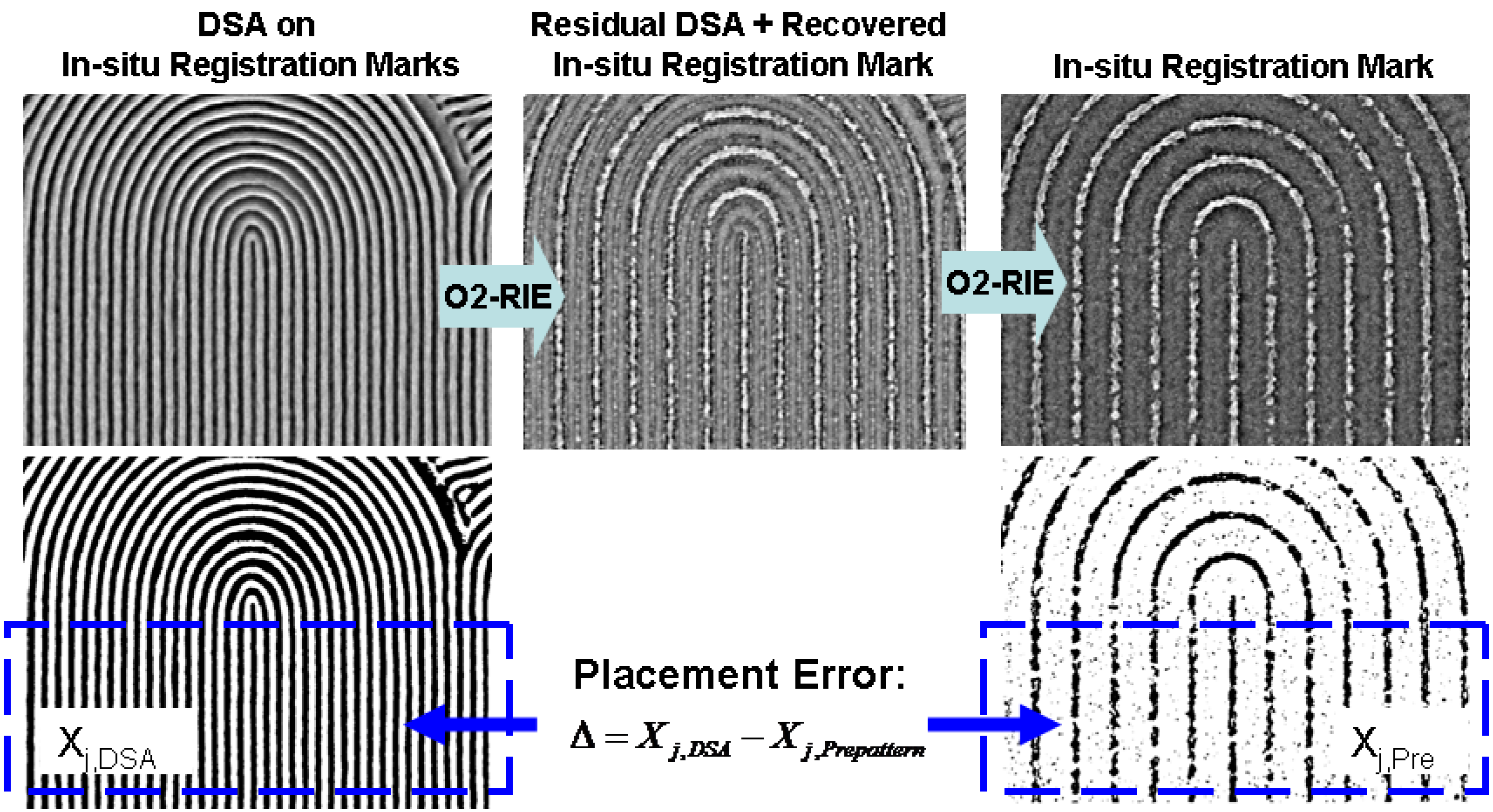
← O_2 RIE



Doerk et. al. ACS Nano Submitted

- In-situ alignment marks → Avoids extra sample preparation, does not perturb DSA
- Inorganic pinning lines → Allow recovery of prepattern after DSA
- Concentric, symmetry → Enables image registration and identification of center line

DSA Placement Error for Chemical Epitaxy
Characterization Using In-situ Registration Marks



Placement Error:

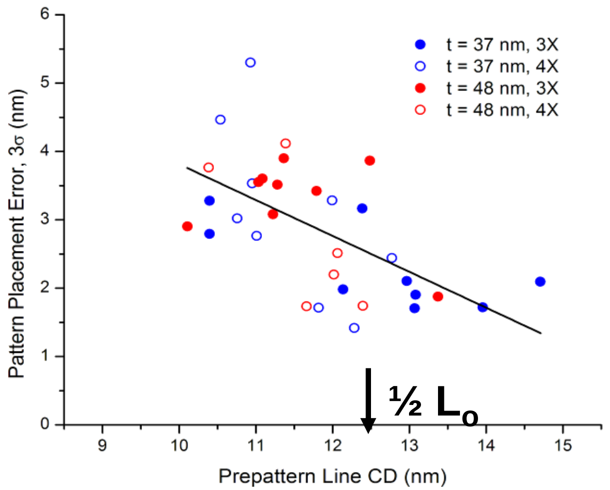
$$\Delta = X_{j,DSA} - X_{j,Prepattern}$$

Doerk et. al. ACS Nano Submitted

- Placement error based on guiding chemical prepattern: (mean + 3σ) = 2-3nm for pinned domains, (mean + 3σ) = 1-2nm for unpinned domains
- Placement error is insensitive to multiplication factor and lamellae thickness.

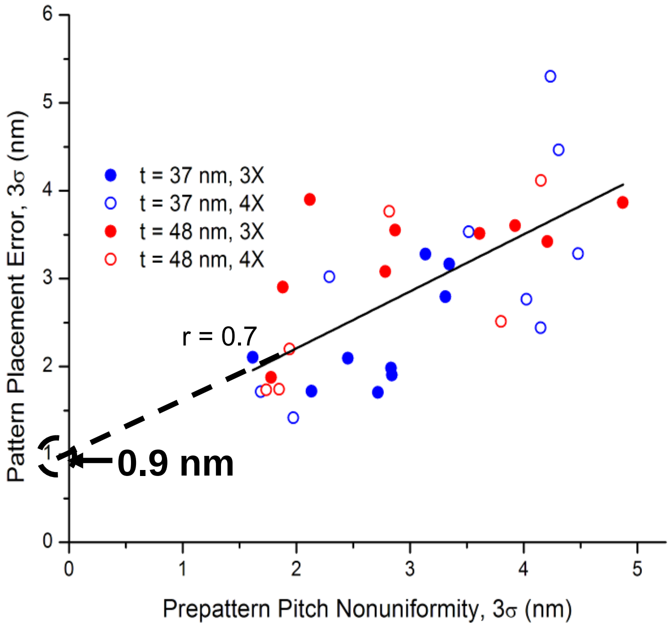
Root Causes of DSA Placement Error in Chemical Epitaxy

Pinning Line CD



- **Lower free energy ~ 0.5 Lo reduces the fluctuation of domain locations**
- **Pinning CD ~ 0.5 Lo gives minimum DSA placement error.**

Placement Error in Prepatterns



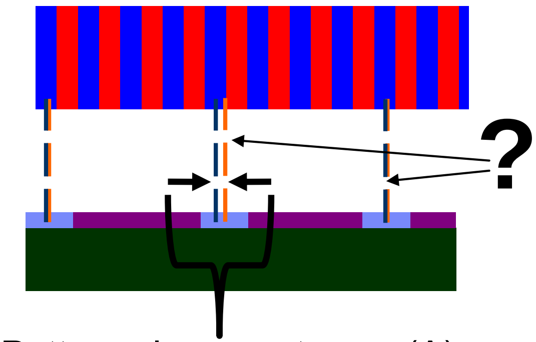
Placement error correlated with prepattern residuals through self-healing behavior

- **Placement error between DSA feature and good chemical prepattern is very low.**
- **With uniform prepattern pitch, DSA placement error (3σ) < 2nm (99.7% confidence level)**

Doerk et. al. ACS Nano Submitted

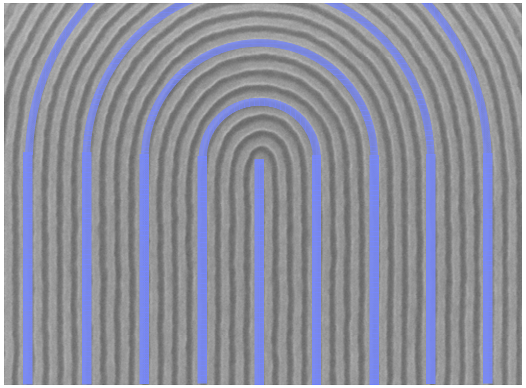
Defining Rules for Simple 1D-DSA

DSA Chemical Epitaxy

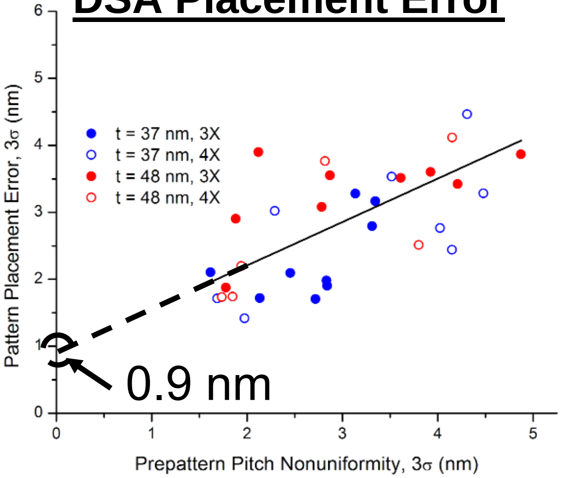


Pattern placement error (Δ)

In-situ Registration Marks

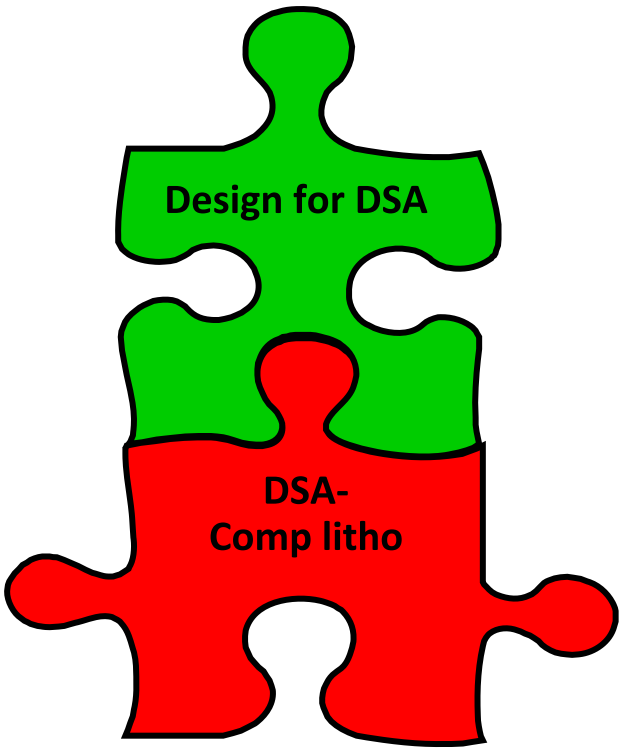


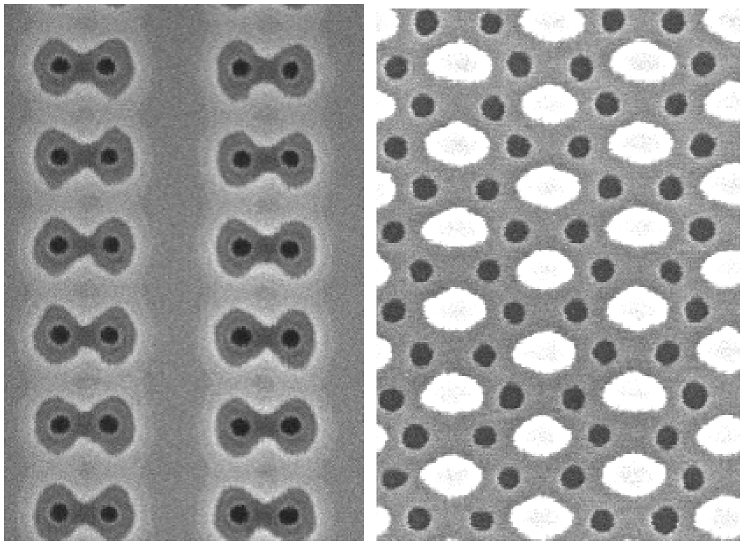
DSA Placement Error



- Relationship between DSA and its chemical preatterns was characterized using in-situ registration marks. Error sources on chemical prepatterns are identified.
- **Very good self-alignment** (mean+3σ < 2nm) at good chemical prepattern
- **Simple design rules** for 1D DSA based on the correlations between chemical prepatterns and DSA structures are made possible through detail direct measurement of position corresponding DSA and its guiding prepattern.

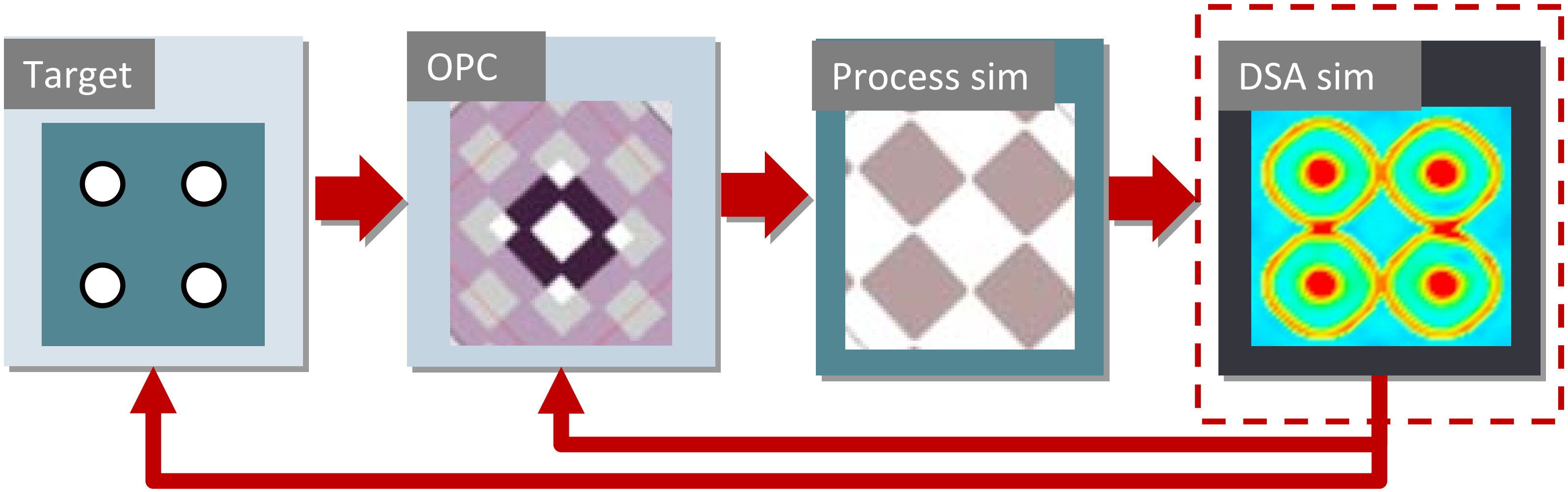
How about 2D DSA?





How to design topographical guiding Prepattern to generate desired DSA vias?

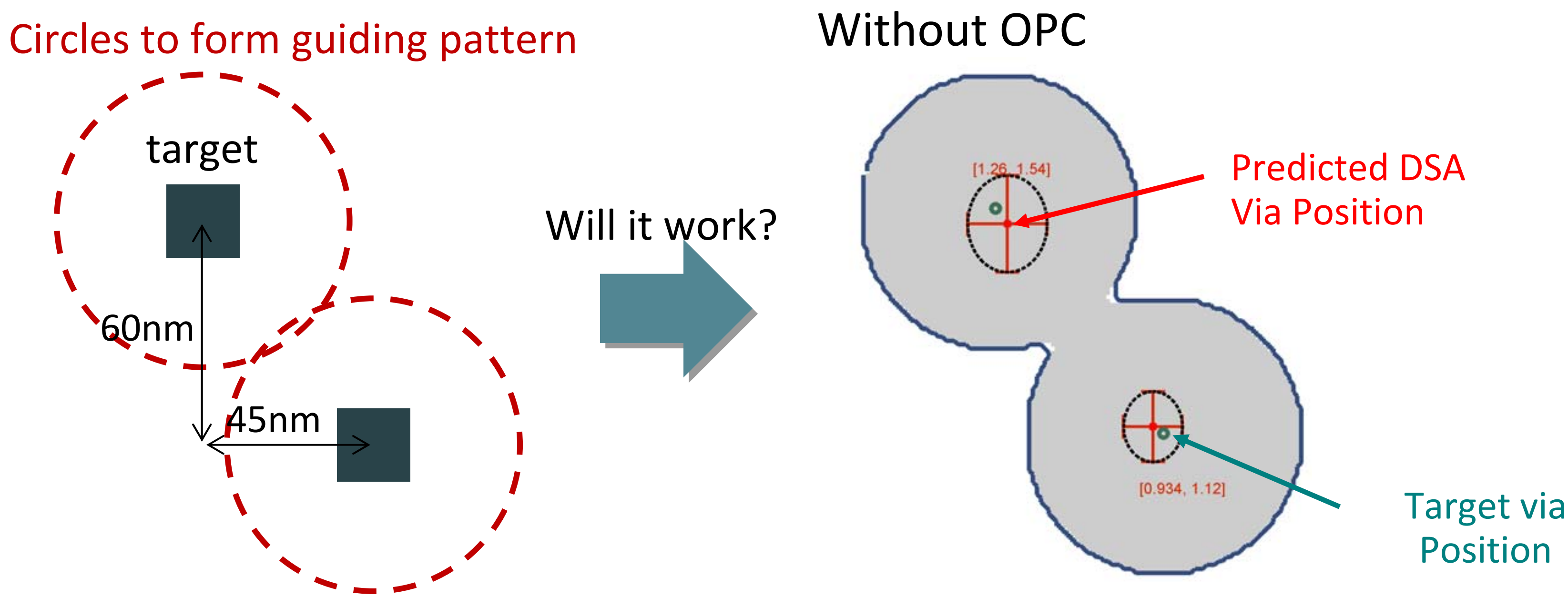
How to Integrate DSA with Computational Litho?



Why is a fast DSA model needed?

- ~10^9 transistors on a modern processor. ~5*105 unique designs
- Our current Monte Carlo codes take ~100 CPU-h/transistor
- A typical mid-size computer system has 10^3 -10^4 cores (threads), so even if perfectly parallel, ~10^4 h = 416.7 days will be needed.
- **A fast DSA model is needed for full-chip DSA/OPC verification.**

Issues with Rule-Base Design



	"Placing circle" method
Average displacement from target	4.3nm
Predicted X-positional variation (1 sigma)	1.1nm
Predicted Y-positional variation (1 sigma)	1.3nm

Design DSA via through rules is fast, but may not be precise in the via placement.

Liu et. al. SPIE 2012 Proceeding

Calibrate the fast DSA model with Monte Carlo

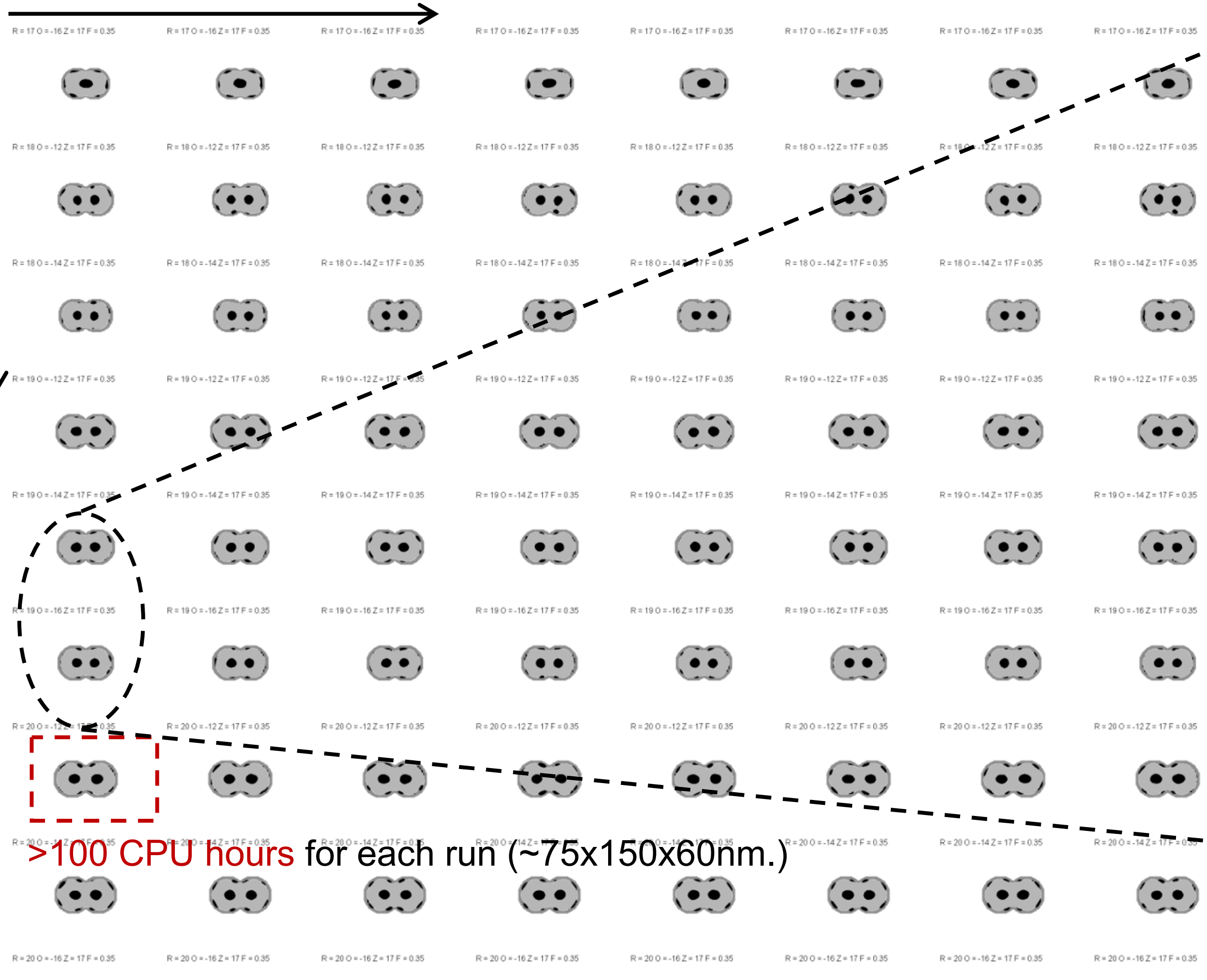
3D Monte Carlo DSA Model

Image resolution = 1 nm/pixel.

fast DSA Model

different MC simulation

different GP design

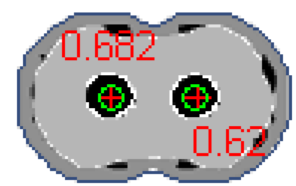


>100 CPU hours for each run (~75x150x60nm.)

+ predicted by fast model

O predicted by MC

#.## distance between the predictions



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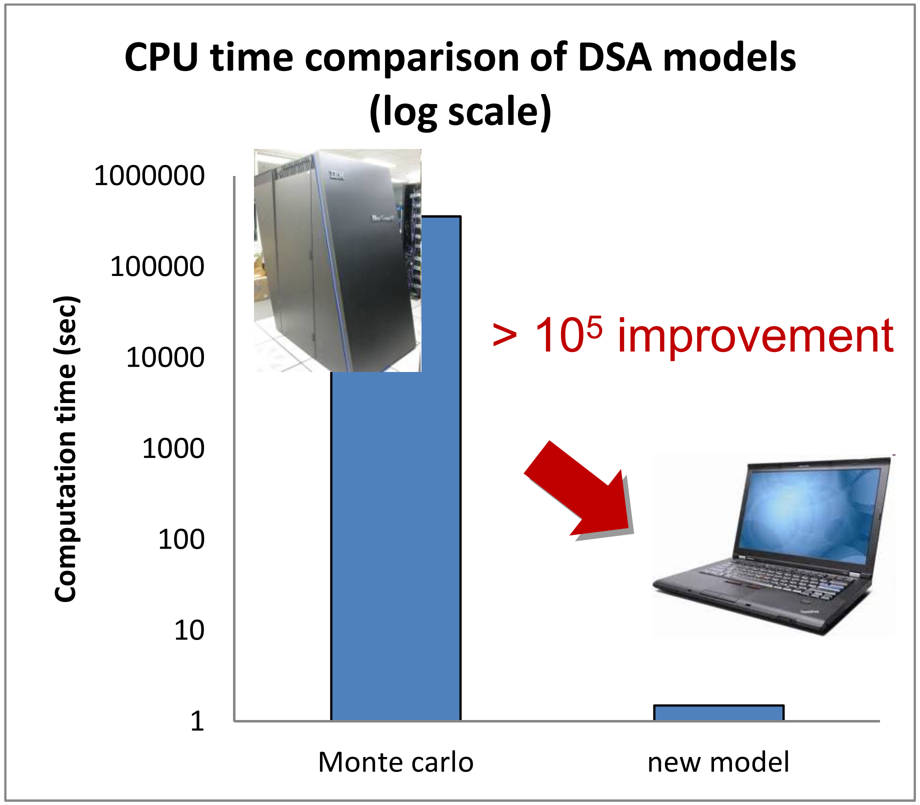
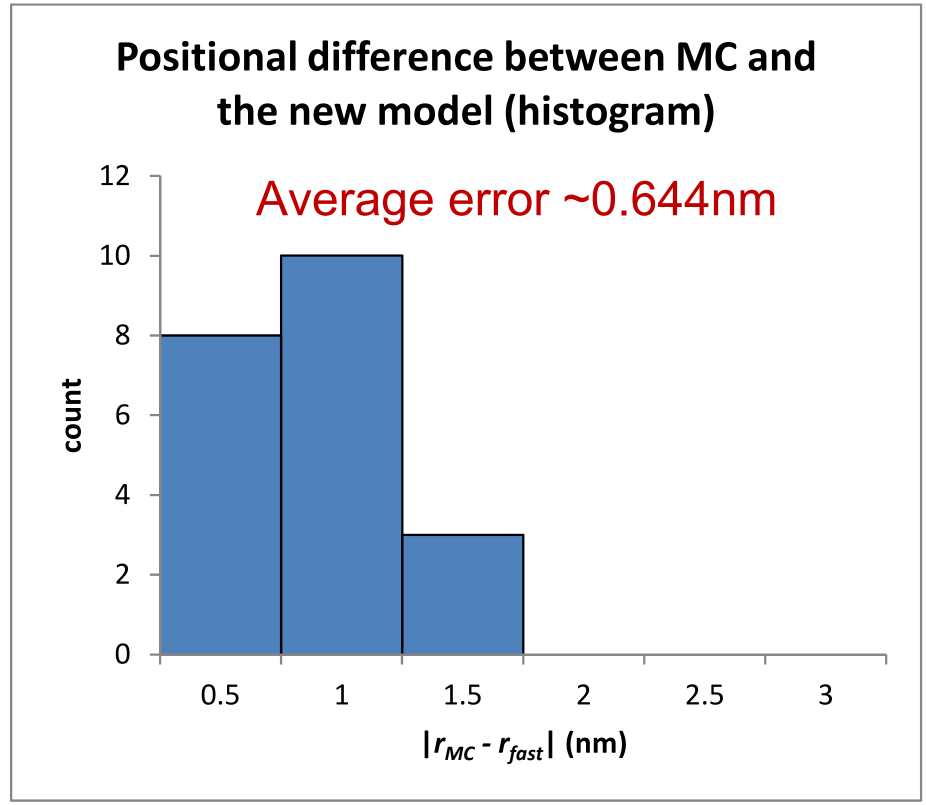
Computational Efficiency





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- The fast DSA model is 10^5 x faster
- The predictions from both models are highly consistent.

=> Dramatic improvement with minimal accuracy penalty

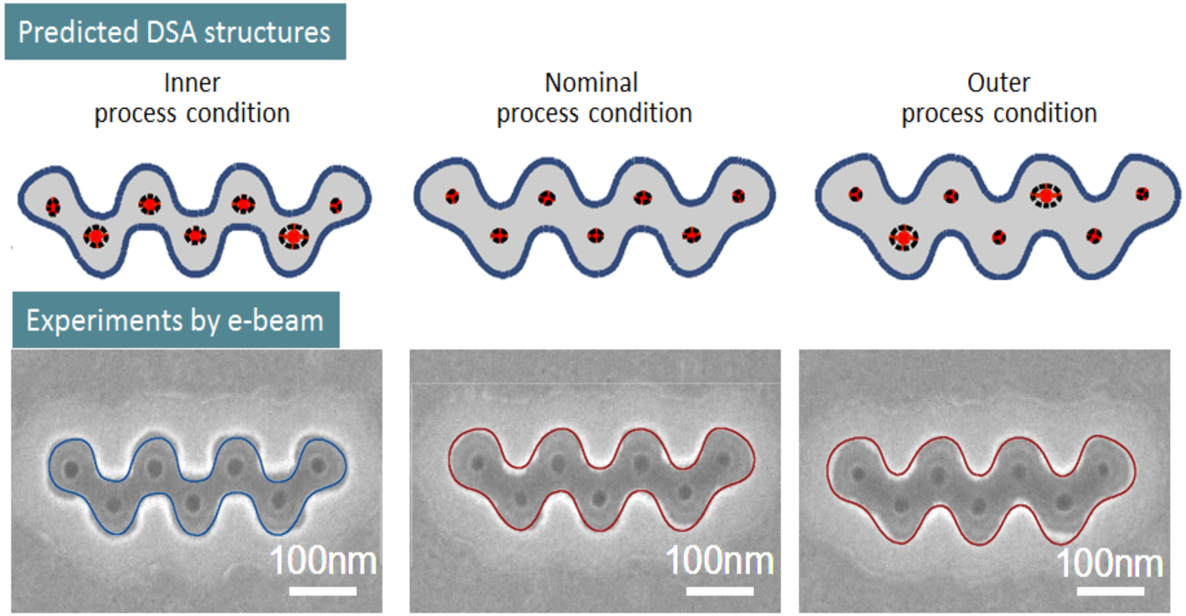
Process Window Verification for 7-via chain

Predicted DSA Structure

Resist Guiding Prepatterns
Generated from an OPC tool
→
Predicted DSA Structures

Physical DSA Experiments

Physical Guiding Prepatterns
Generated by E-beam lithography and pattern transfer
→
Experimental DSA Structures



- **Demonstrated the formation of DSA minority domains from various guiding prepattern generated from an OPC tool.**
- **Physical DSA experiments where resist contours show good agreement between experimental results and simulated results.**

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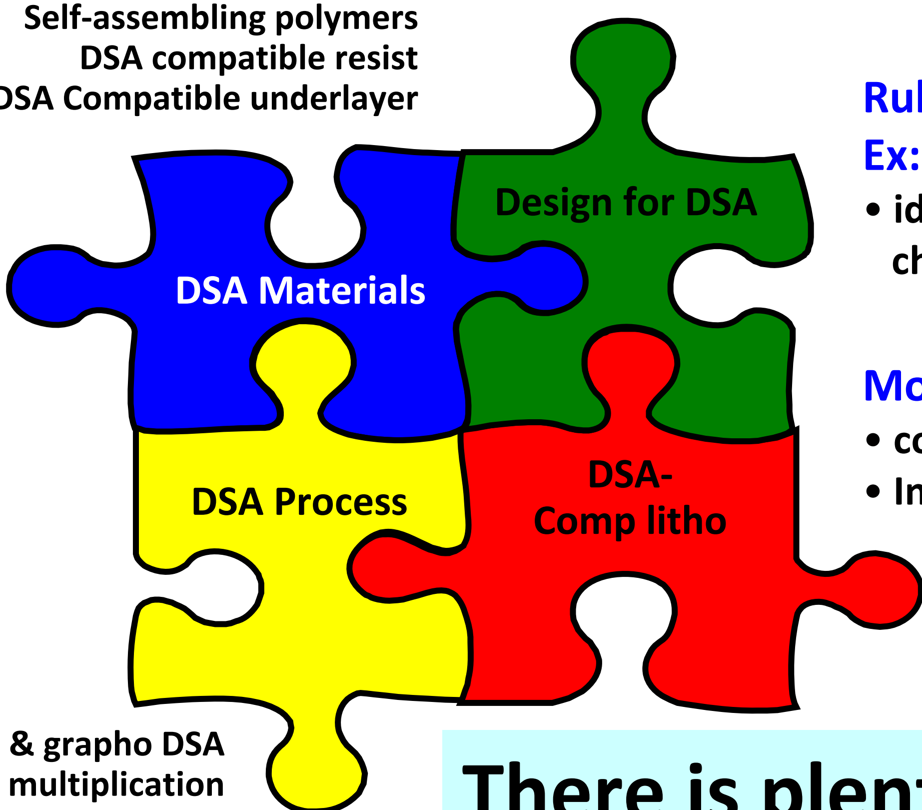
Steps Toward Directed Self-Assembly (DSA) as a Resolution Enhancement Technology

Self-assembling polymers
DSA compatible resist
DSA Compatible underlayer



Rule-base design simpe DSA
Ex: 1D DSA on chemical prepattern
- identify the correlation between chemical prepattern and DSA

Model-base design complex DSA
- compact DSA model
- Integration of DSA model + OPC

Chemo & grapho DSA
Pattern multiplication
Via shrink & rectification
300mm DSA demo

There is plenty of room at bottom.

Richard Feynman, 1959

Acknowledgements


Dan Sanders


Joy Cheng


Jed Pitera


Melia Tjio


Hoa Truong

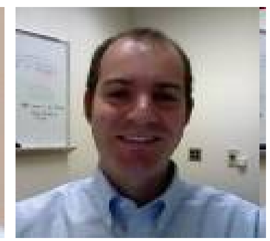

Noel Arellano


Gregory Doerk


Chi-chun Liu


Charles Rettner


Kafai Lai


Neal Lafferty


Srini Balakrishnan

Steven Holmes, Matthew Colburn, Bill Hinsberg, Ho-Cheol Kim, Stefan Harrer, Anuja De Silva, Alex Friz, Young-hye Na, Wai-kin Li, Da Yang (IBM) Su-mi Hur, Glen Frederickson (UC Santa Barbara) Chris Bencher and team (AMAT)