SAND2010-7037C

Evolution of Line Edge Roughness during Block-Copolymer Nano-Patterning

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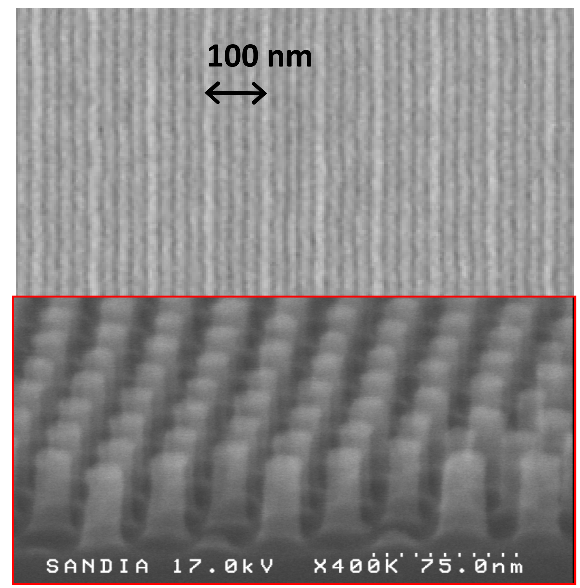
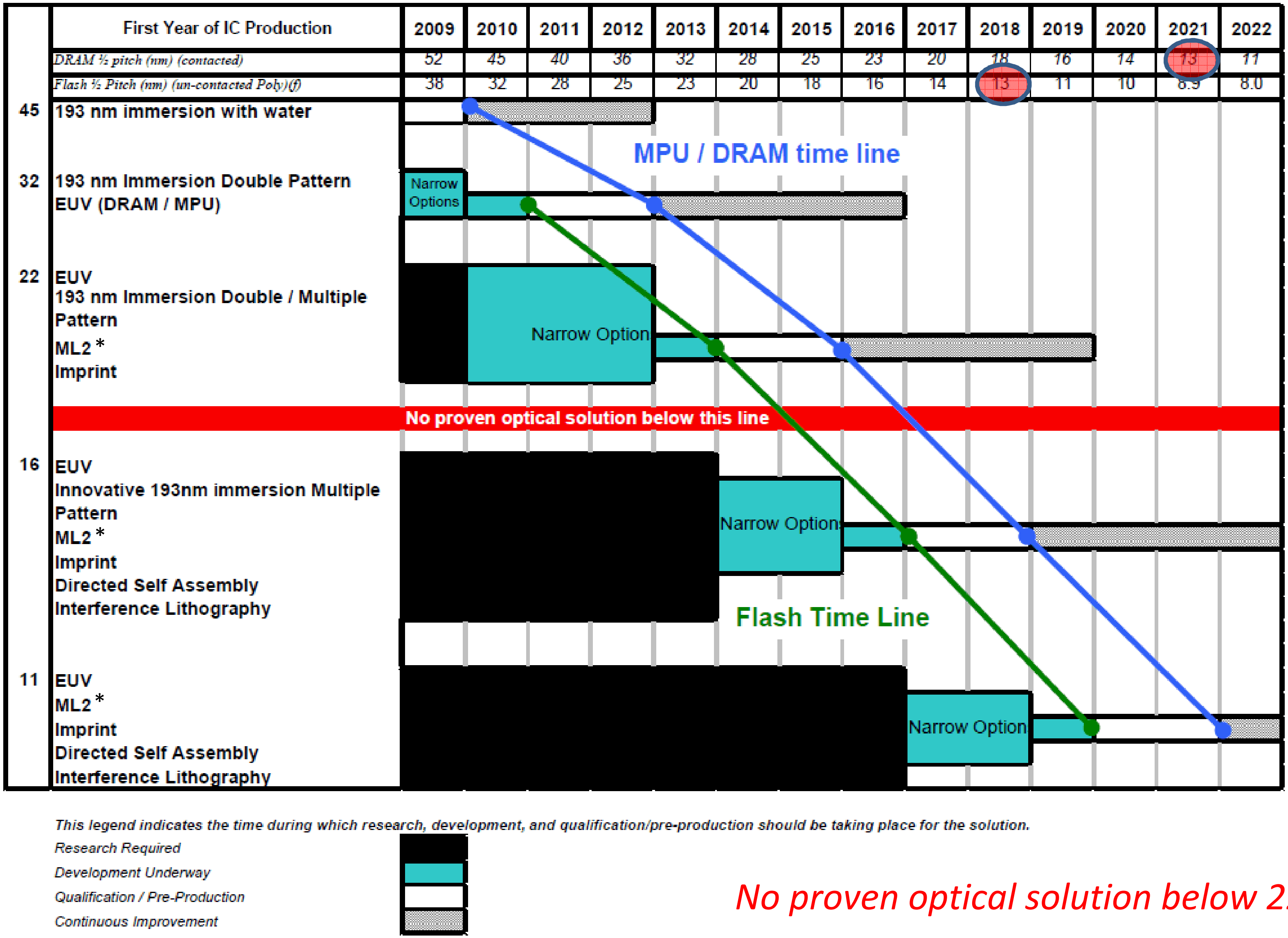
National Institute for Nano Engineering (NINE)



A portion of this work was supported by the Laboratory Directed Research and Development program at Sandia National Laboratories. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under Contract DE-AC04-94AL85000.

2009 International Technology Roadmap for Semiconductors

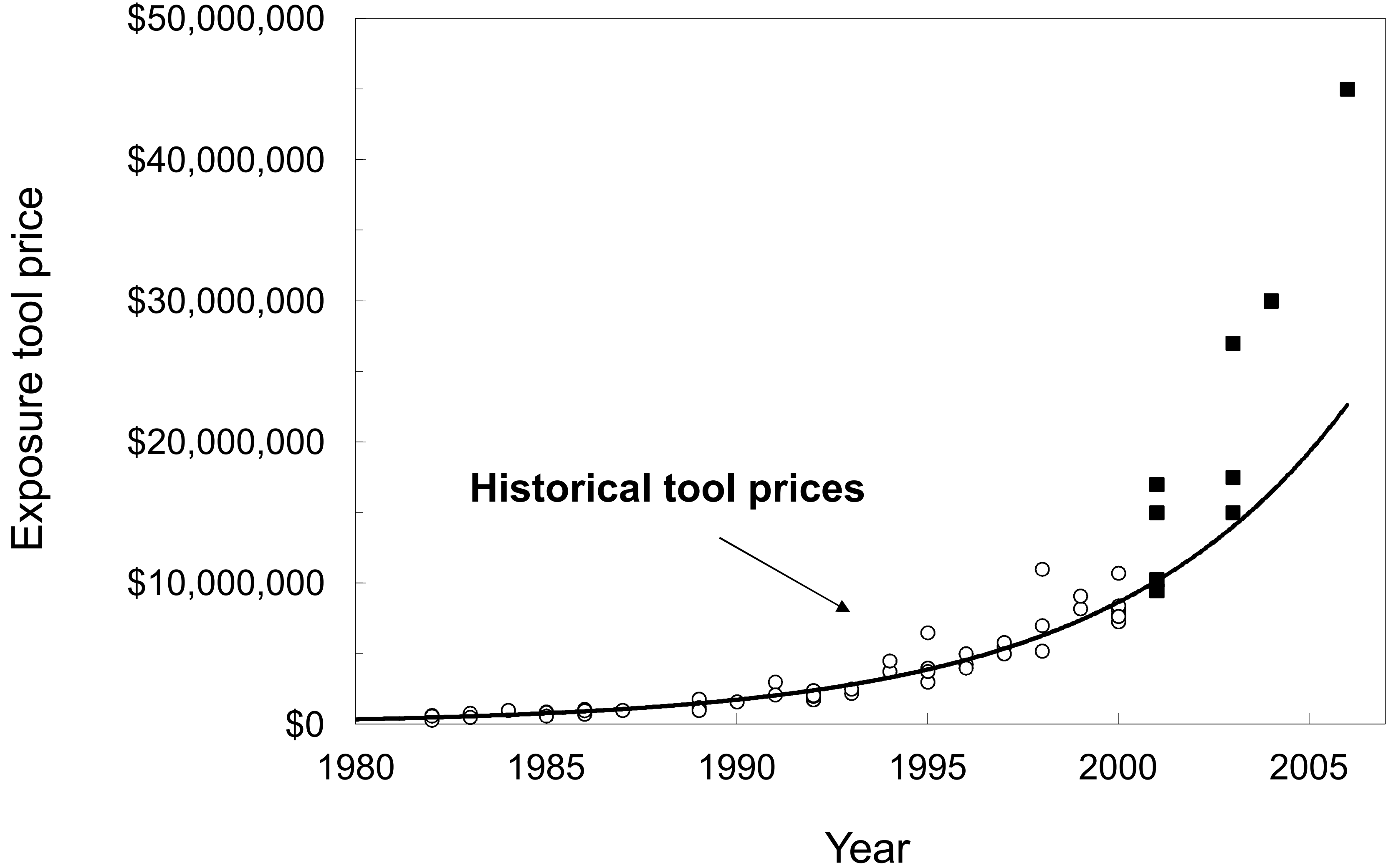
Lithography Exposure Tool Potential Solutions:



No proven optical solution below 22nm node

* ML2 = Maskless (e.g. Electron-beam)

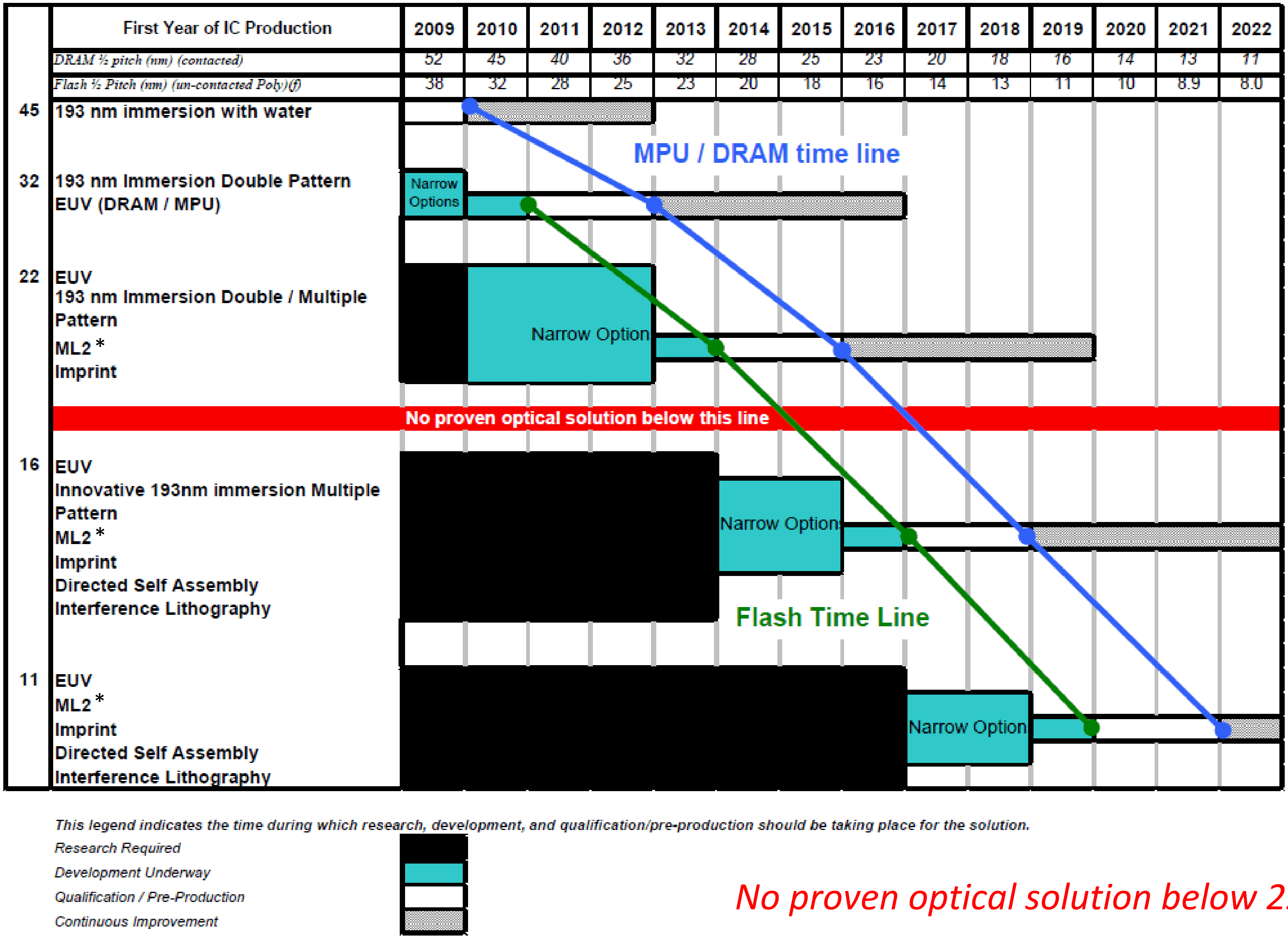
Soaring Lithography Costs



Lithography ITWG Report, ITRS Conference, November 29, 2001. Santa Clara, CA

2009 International Technology Roadmap for Semiconductors

Lithography Exposure Tool Potential Solutions:



No proven optical solution below 22nm node

* ML2 = Maskless lithography (e.g. Electron-beam)

Next Generation Lithography Candidates

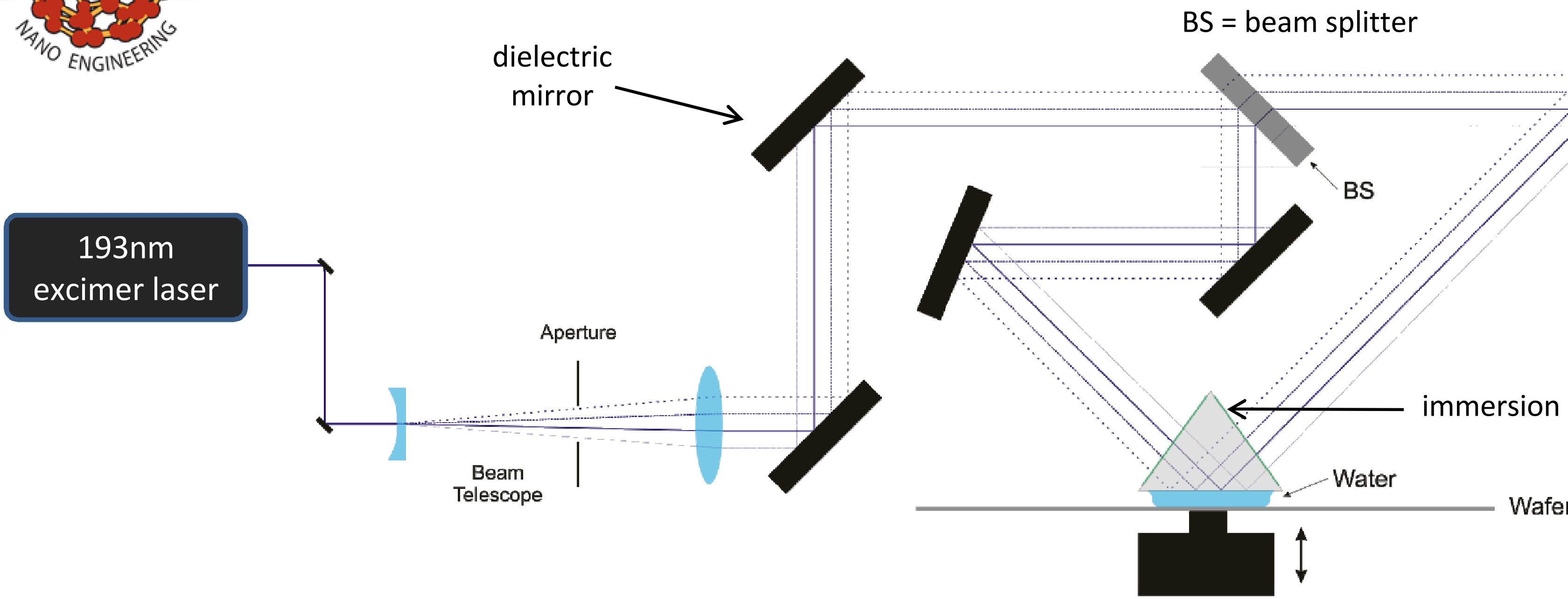
- Extreme Ultraviolet Lithography (EUVL)
  - 13.2 nm soft x-ray source power
  - (+) high-resolution resist development
  - (-) poor Line Edge Roughness (LER)
  - (-) complex, ***costly***
- Mask-less Lithography (ML2)
  - (+) high resolution electron-beam, ion-beam
  - (-) slow serial process, ***costly***
- Interference Lithography (IL)
  - (+) rapid, large area, parallel process
  - (+) **low cost** (rapid, large area, maskless)
  - (+) tunable symmetry, period, motif
  - (-) layer alignment & spatial pattern variation difficult
- Directed Self-assembly (DSA)
  - (+) alignment to pre-pattern gives long-range order
  - periodicity set by size of blocks
  - (+) pattern rectification and density multiplication
  - (-) slow process with many steps
- nano-Imprint Lithography (n-IL)
  - (+) long-range order set by master
  - (-) overlay can be difficult
  - (+) high resolution
  - (+) **low cost**

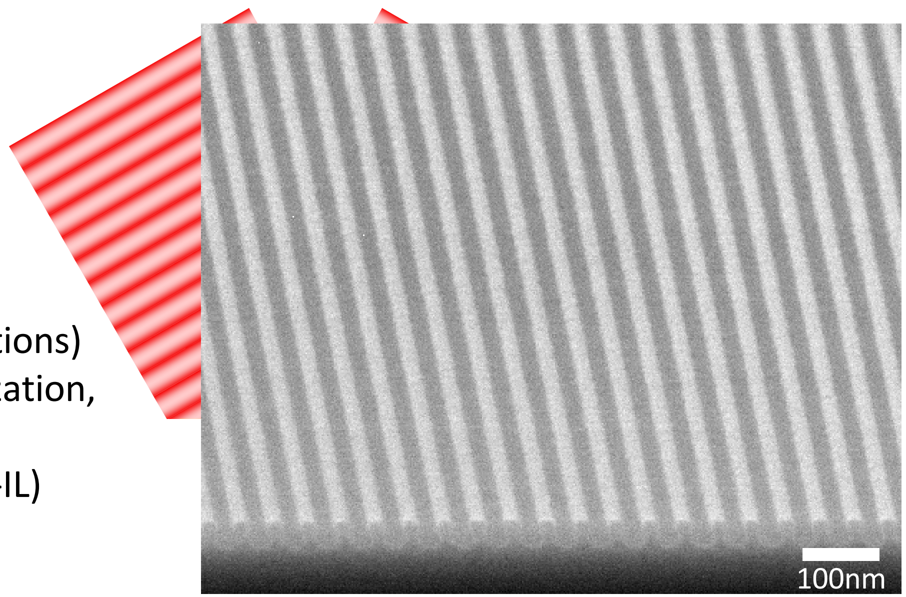
Use Integrated Lithographic Approach

- Leverage strength of one technique to cover weakness of another

Our charge: demonstrate integrated process and explore feasible limits for critical parameters (e.g., *CD*, *LER*, defect density, *uniformity*) especially as they relate to the relevant process parameters (e.g. DSA annealing time, *size and size distribution of directing features*, pattern transfer processes, etc.)

Immersion Interference Lithography





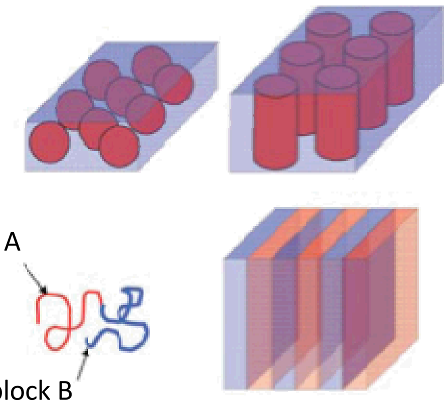
Benefits of Interference Lithography:

- large area, rapid, parallel processing
- low cost (maskless)
- 1D, 2D, or 3D periodic structures
- tunable period (vary beam angles)
- tunable duty cycle (vary exposure/development conditions)
- tunable motif (add beams, split exposures, vary polarization, vary relative beam strengths, etc.)
- proof of principle (coupling optical lithography, DSA, n-IL)
- NEED good Anti-Reflection (AR) coating

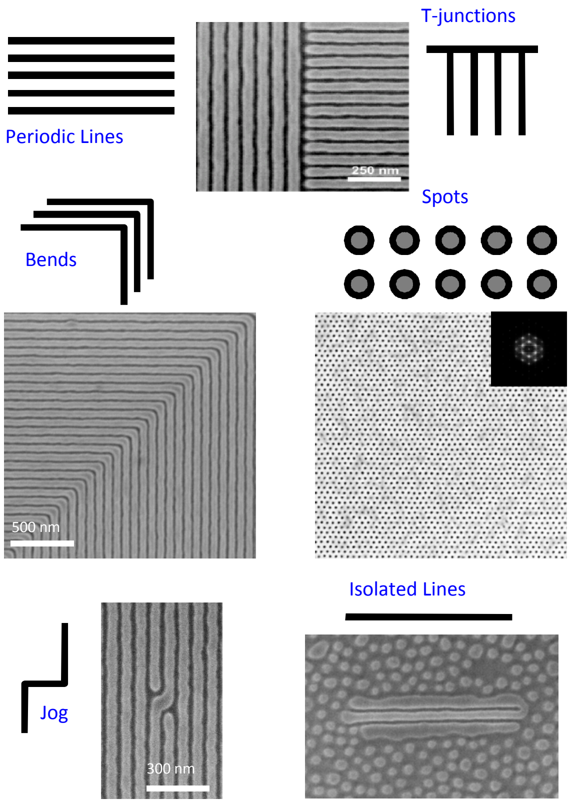
Directed Self-assembly of block copolymers

diblock copolymer: two immiscible polymer blocks covalently bonded together

- periodicity depends on the polymer molecule length and morphology depends on the volume fraction of each block
- equilibrium phases include periodic structures composed of lamellae, cylinders, spheres, and gyroids
- our block copolymer choice: polystyrene-b-PMMA



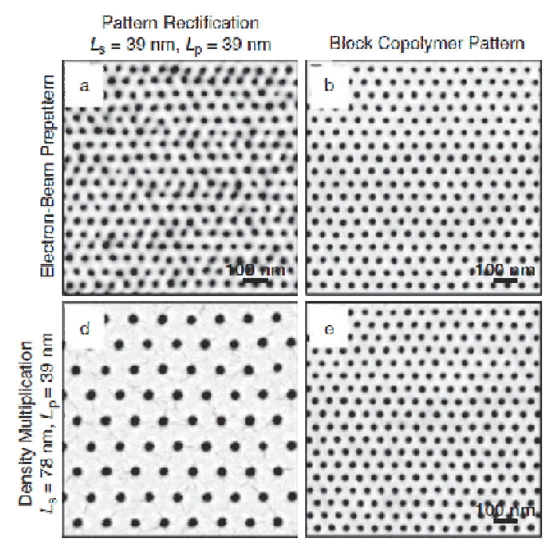
Ross *et al.*, MRSB 33 838 (2008)



Stoykovich et al. *ACS Nano*, 2007, *Science* 2005

Goals

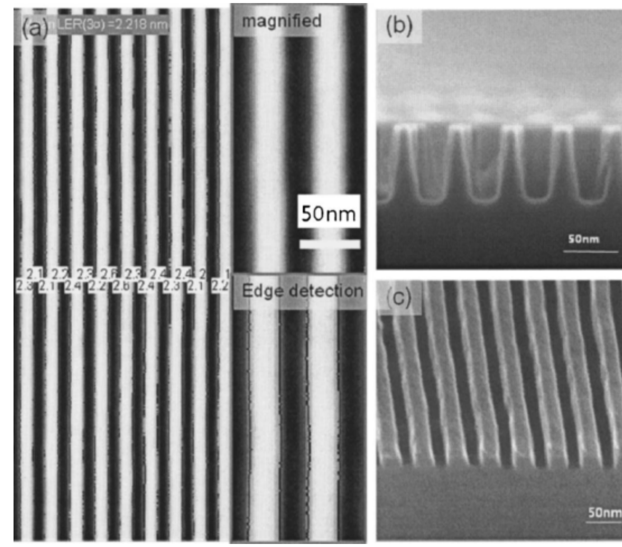
- anneal bcp films to drive self-assembly of lamellae or cylinders onto appropriate chemical patterns formed using IL
- leverage density multiplication to reduce critical dimensions well below 45 nm
- verify that thermodynamic equilibrium drives pattern rectification
- selectively remove one polymer block
- pattern transfer to substrate using plasma etching to generate masters with different patterns (lines/spaces or posts) and periodicities



Ruiz *et al.*, Science 321 936 (2008)

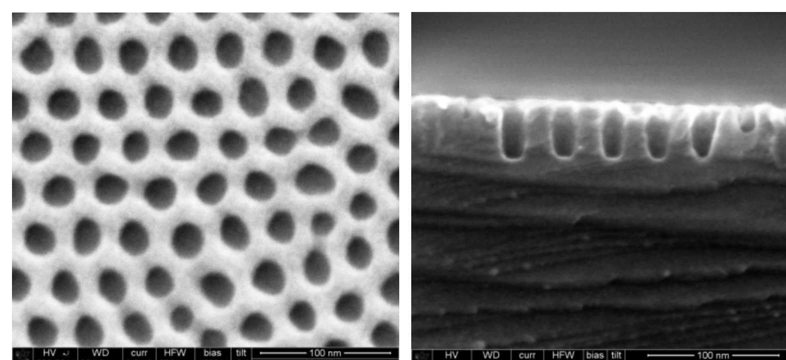
Pattern Transfer and Metrology

- IL/DSA-based patterns used as etch masks for pattern transfer into substrates using high-density plasma etching
  - Dry etching combines chemical reactivity with physical ion bombardment to selective remove desired materials at greater rates than the mask materials
  - Material removal is inherently anisotropic
  - High-density tools enable independent control of ion energy and density, providing more control over feature profiles, sidewall roughness, etching rates, selectivity
  - SOI-type substrates can finely control etch depth by providing an etch stop
- Patterned features non-destructively characterized after critical process steps using high resolution (sub-nm) SEM with electron deceleration capabilities
  - Characterize CDs, LER, defect densities before and after various etching and nano-imprint steps
  - Improve metrics by modifying process
  - Demonstrate reliable pattern transfer over large areas

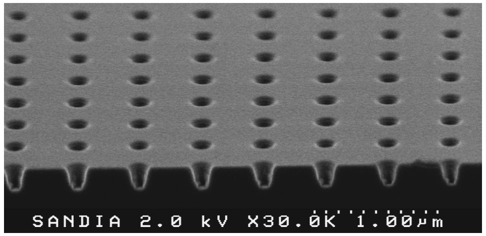


Liu *et al.*, JVSTB 25 1963 (2007)

block copolymer etching/imaging capability

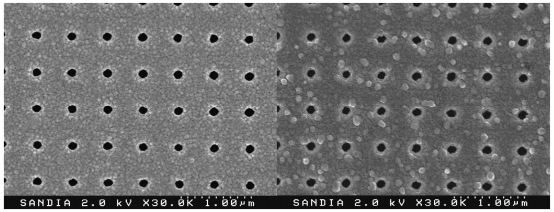


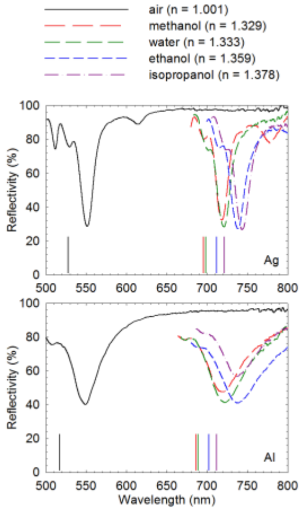
nano-Imprint Lithography (n-IL)



n-IL: uses a mold to transfer patterns into a thermally or UV cured resist

- n-IL can be used to fabricate large areas of features with sizes <10 nm
- unlike mask-less lithographic (ML2) techniques, n-IL can pattern entire wafer surfaces in minutes, which is important for high throughput
- n-IL is cost effective and shows great promise as an economical nanoscale manufacturing technology
- Sandia has used n-IL to create:
  - Plasmonic optical sensors for visible light →
  - Nanowire chemical sensors
  - Narrow band optical modulators

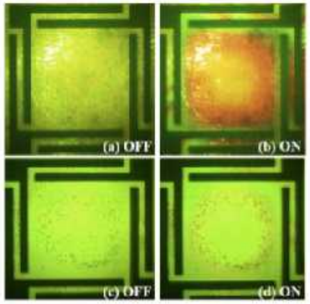




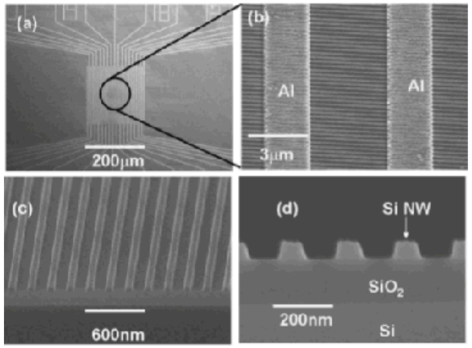
Skinner *et al.*, TNANO. 7 527 (2008)

Goals:

- fabricate and integrate multiple masters from IL/DSA onto a single stamp for n-IL
- fabricate prototype devices
- characterize devices



Skinner *et al.*, Opt. Express 16 3701 (2008)



Talin *et al.*, APL. 89 153102 (2006)

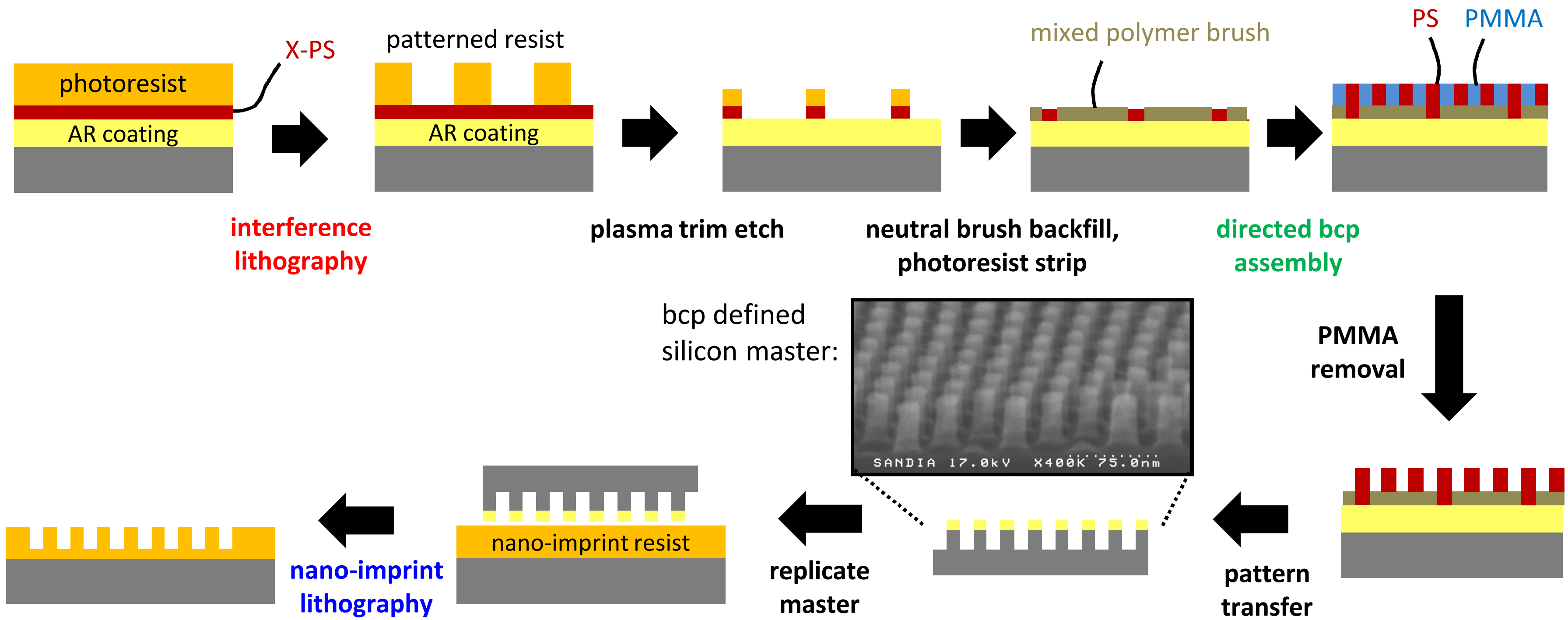
Integrated Lithographic Approach

1. Interference Lithography (IL) to define chemical pre-patterns
   - 70-90 nm pitch over ~4 cm^2 areas

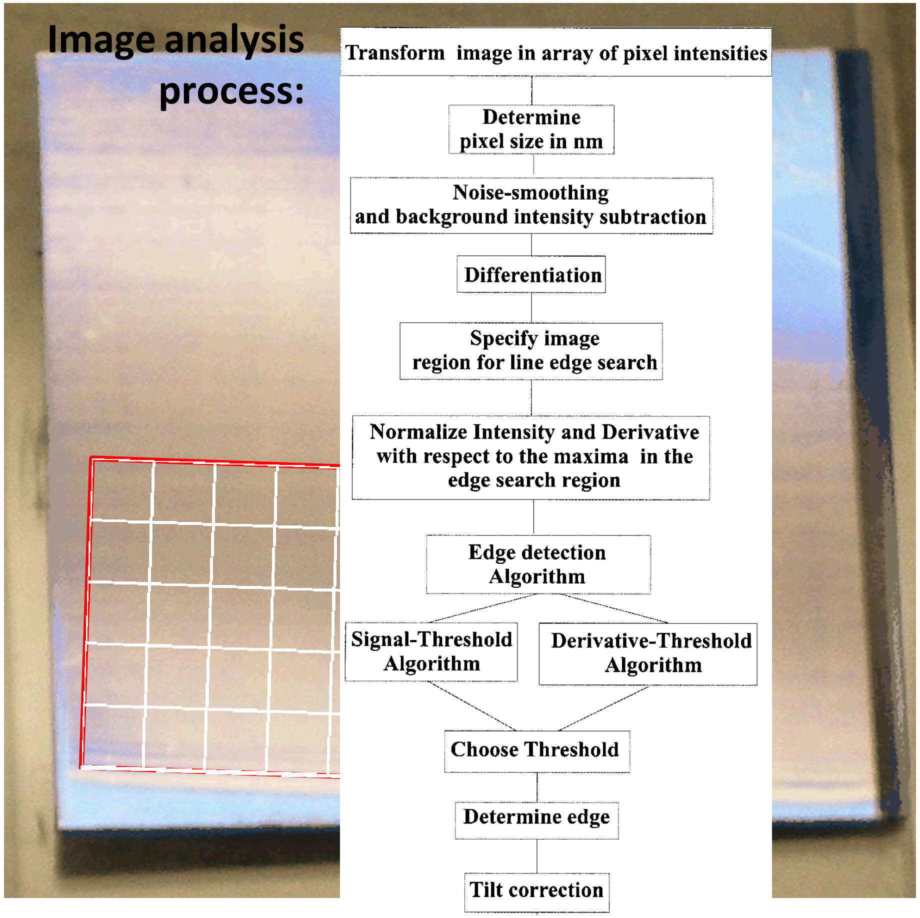
2. Directed Self-assembly (DSA) of block copolymers
   - 20-100 nm pitch (10-50nm CDs)
   - chemical pre-pattern ⇒ long-range order
   - density multiplication and pattern rectification over full IL exposure field

3. Pattern transfer and metrology
   - generate various masters, each with different patterns, from IL/DSA samples
   - non-destructive metrology at critical steps

4. nano-Imprint Lithography (n-IL)
   - make many stamps from masters (**save $**)
   - long-range order maintained
   - repeated molding into n-IL resist from different stamps ⇒ complex structures

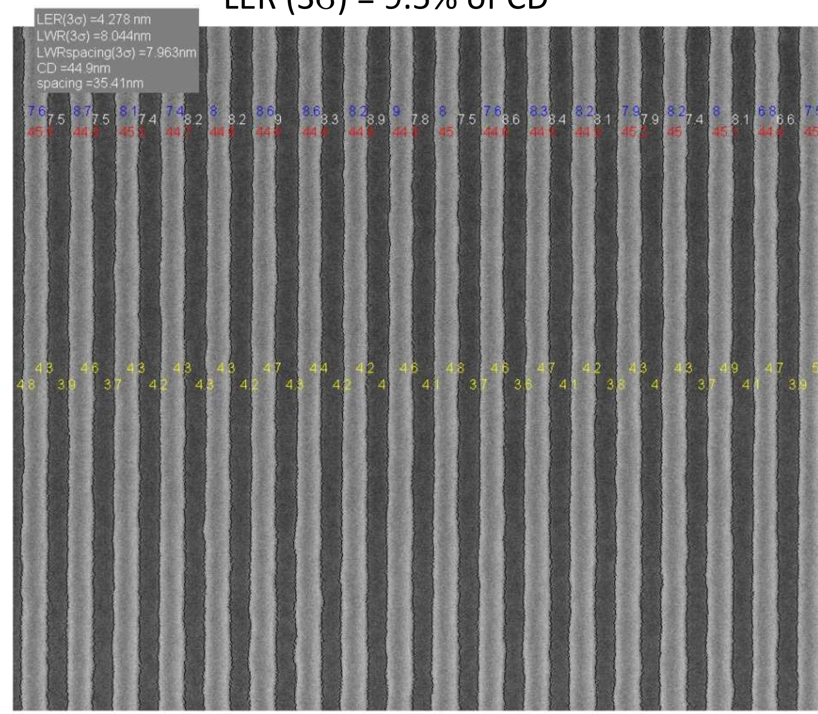


SEM Metrology of Lines/Spaces for CD and LER



Patsis et al., J. Vac. Sci. Technol. B, vol. 21.3, **2003**, pp. 1008-1018

LER (3σ) = 9.5% of CD



Basic process:

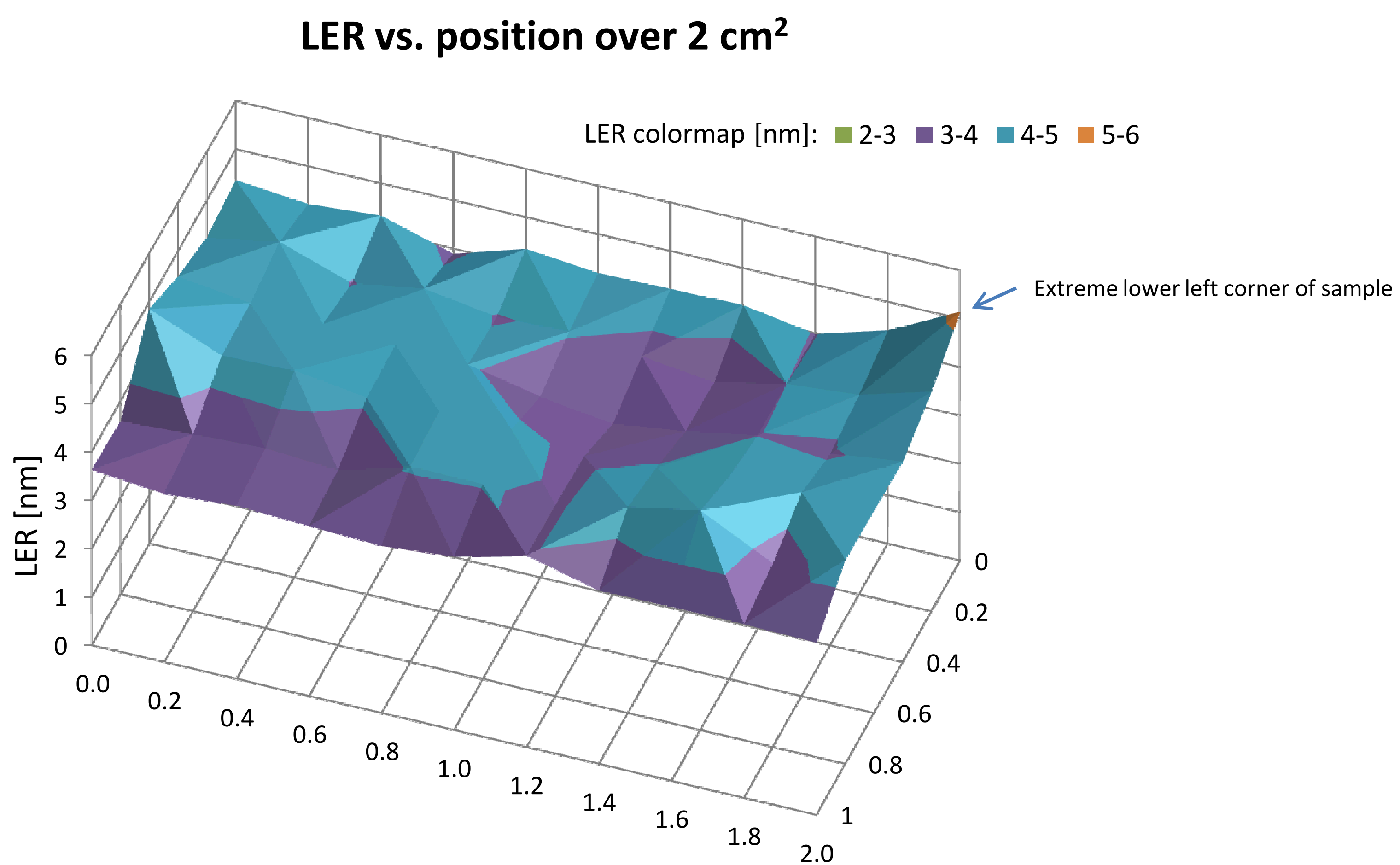
- determination of the edge pixel coordinates
- calculate average edge position
- calculate LER, CD, LWR, etc.

What is Line Edge Roughness (LER)?

- 3σ deviation of a line edge from best-fit straight line
- target LER – 5 %

$$\sigma_i = \sqrt{\sum_{j=1}^{P} \delta_i^{\,2}(j)/P}$$

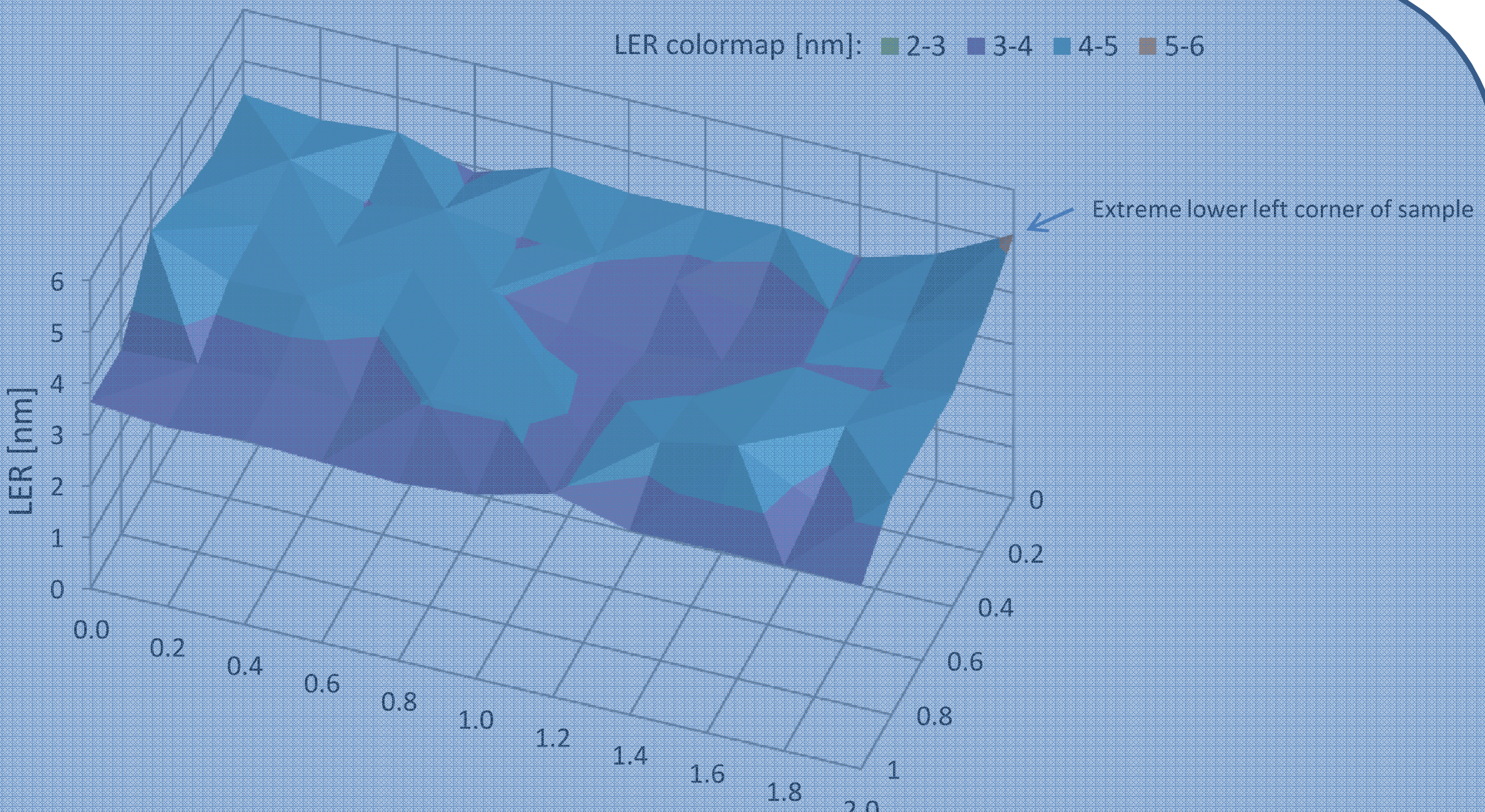
Metrology of Lines/Spaces



	LER [nm]	LER [% of CD]	CD [nm]	spacing [nm]	CD+spacing (pitch) [nm]	LWR [nm]	LWR spacing [nm]
average	4.03	9.4%	42.72	37.45	80.17	8.11	7.98
standard deviation	0.34	0.8%	2.26	2.42	0.31	2.48	1.73

Metrology of Lines/Spaces after plasma trim etch

Data coming



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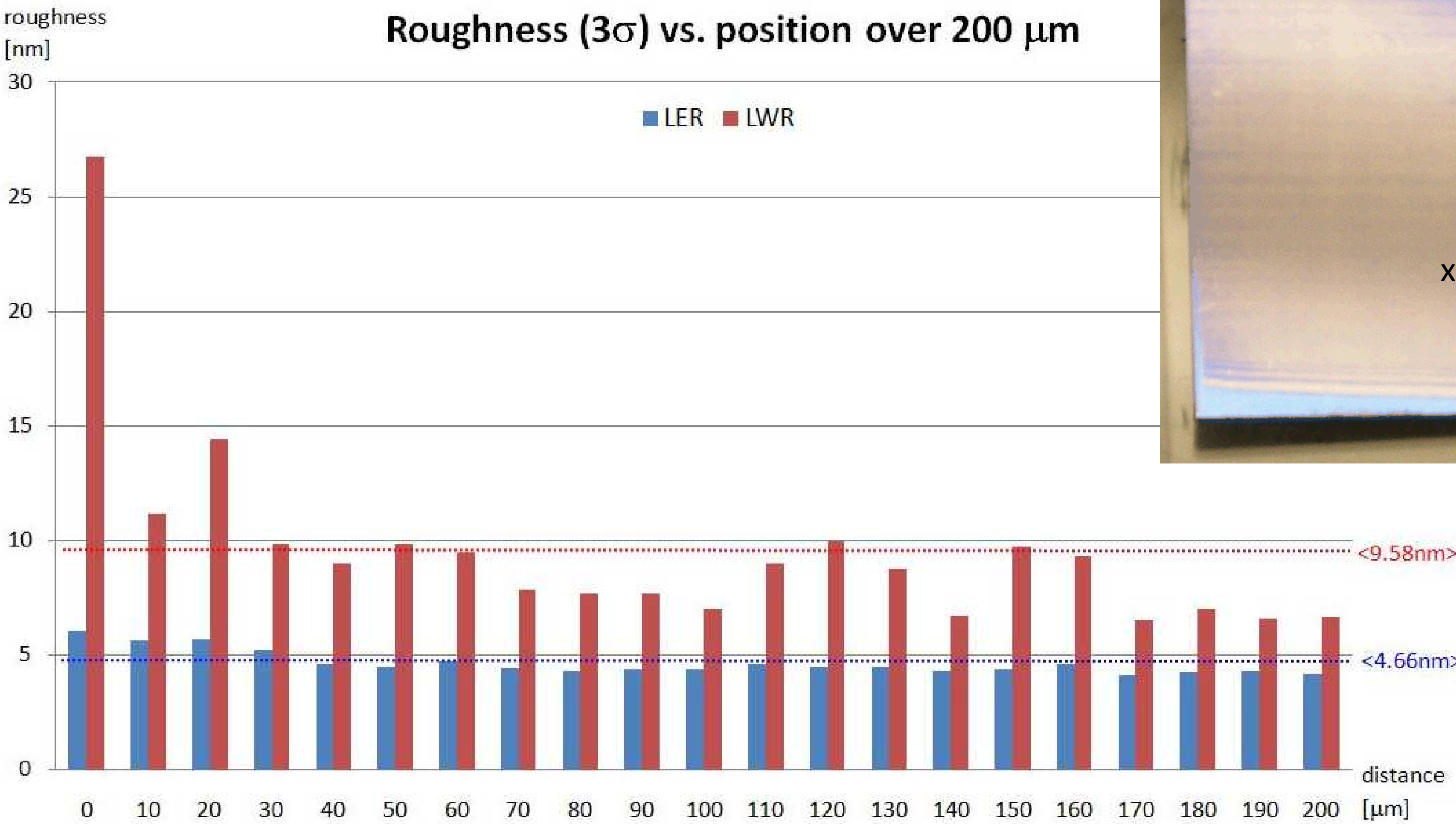
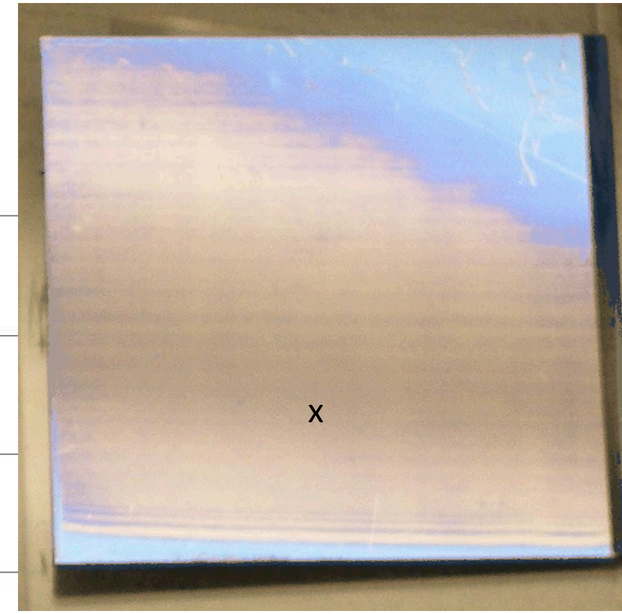
SEM Metrology – local variation study

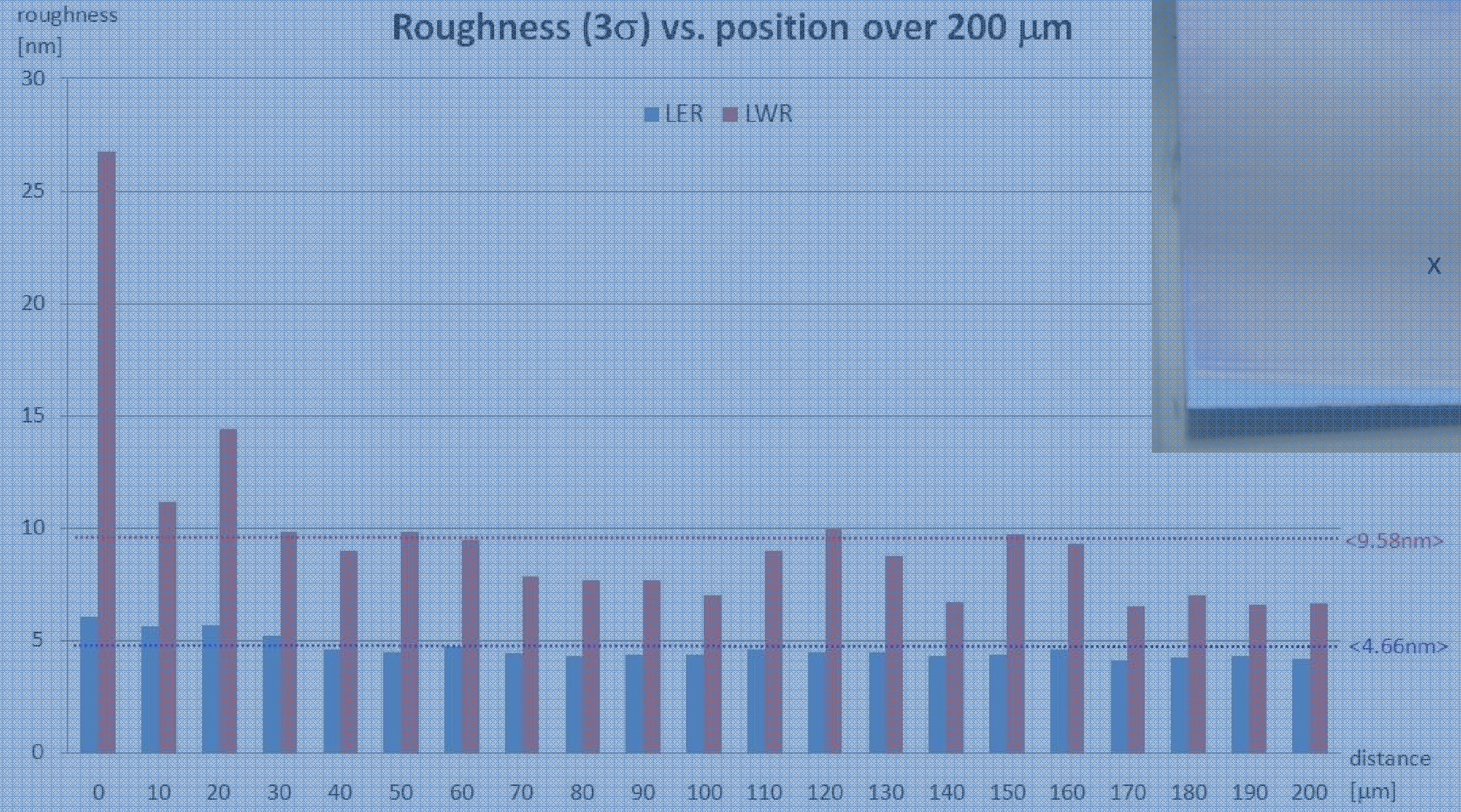


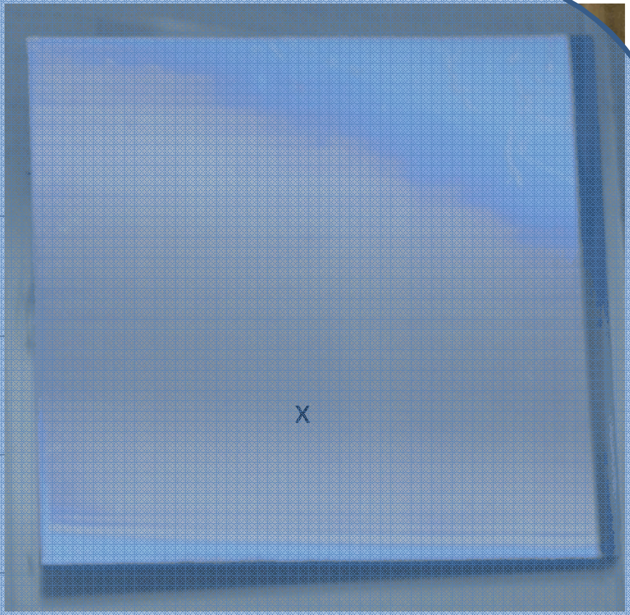


	LER [nm]	LER [% of CD]	CD [nm]	spacing [nm]	CD+spacing (pitch) [nm]	LWR [nm]	LWR spacing [nm]
average	4.66	10.7%	43.40	36.24	79.65	9.58	9.15
standard deviation	0.53	1.2%	0.98	1.19	0.53	4.36	3.48

SEM Metrology – after plasma trim etch

Data are coming





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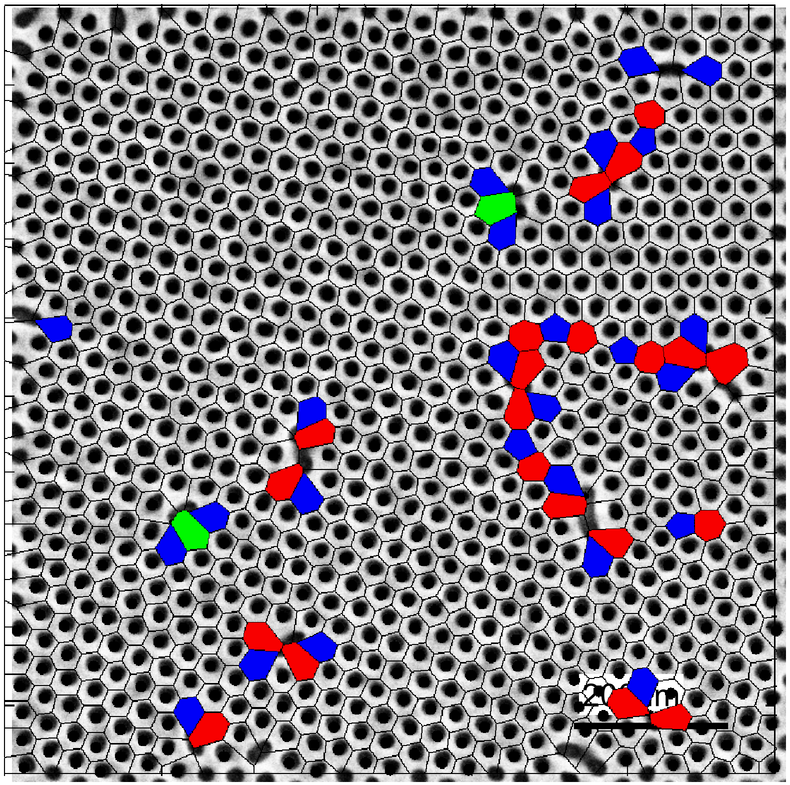
Future Work:

- Metrology after density multiplication by DSA (pattern rectification?), after RIE pattern transfer to master, after mold fabrication, and after n-IL.
- Scaling Analysis for Roughness Exponent and Correlation Length
- Metrology of hexagonal pores defined by IL double exposures, block-copolymer DSA, …



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Acknowledgements

SNL
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Alex Raub
Philip Hakeem

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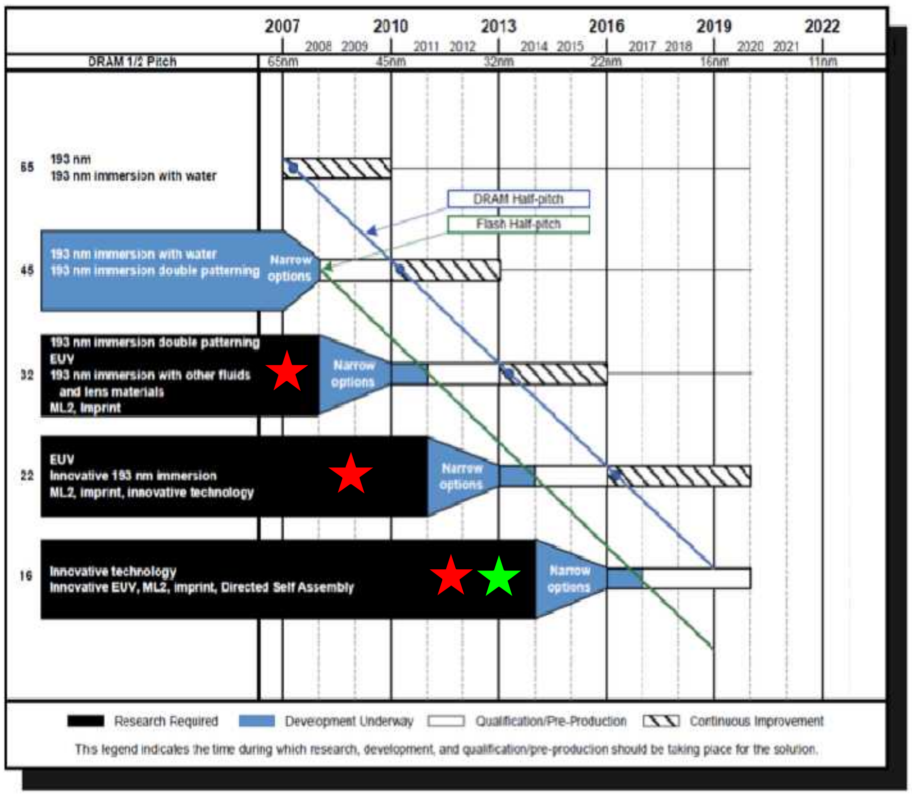
EXTRA SLIDES

International Technology Roadmap for Semiconductors (ITRS)

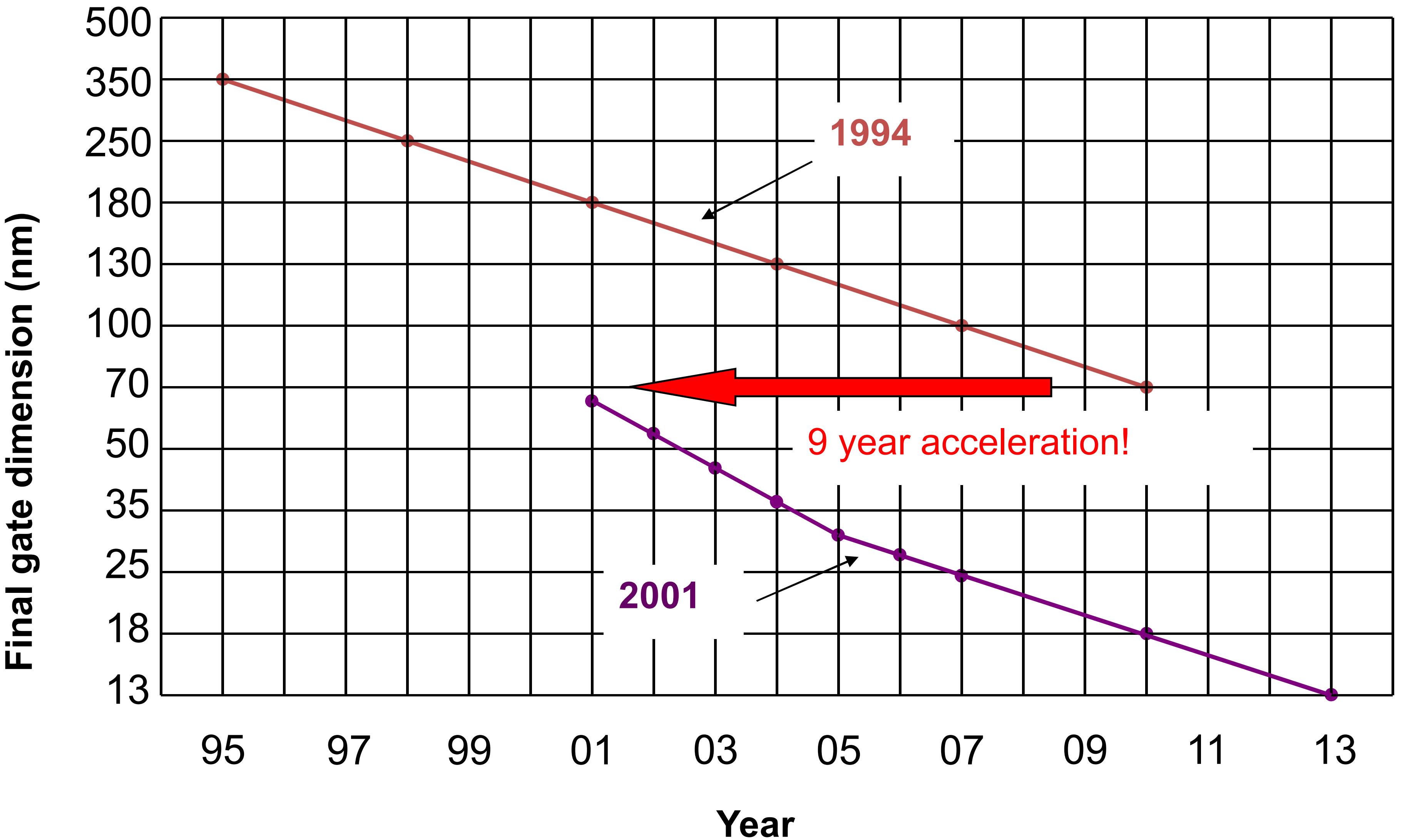
11 nm half-pitch for dense pattern, 4.5 nm CDs by 2022



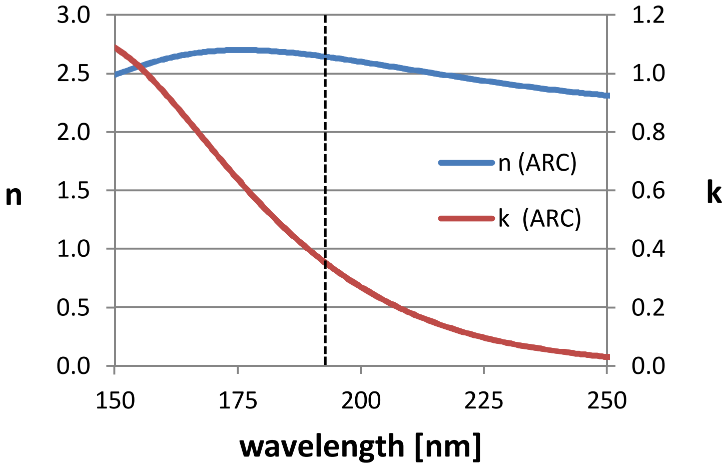
Our charge: explore the feasible limits for critical parameters (e.g., CD, defect densities, LRO, LER, etc.) especially as they relate to other relevant parameters (e.g. annealing time for assembly, size and size distribution of directing features, pattern transfer processes, etc.)

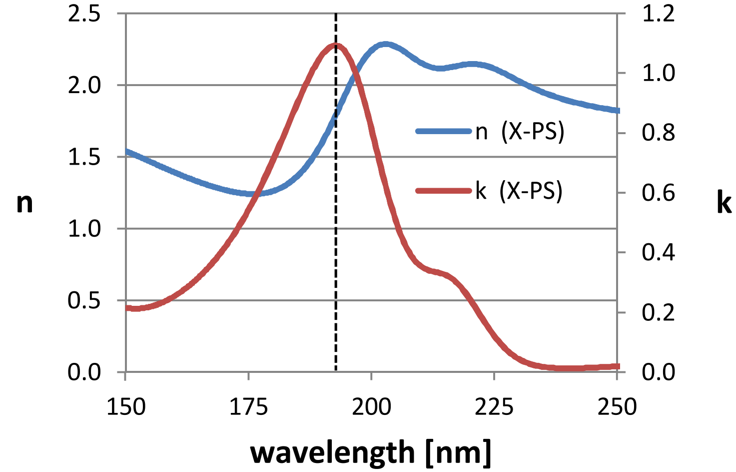
- Optical Lithography Limit:
  - 32 nm ½ pitch (193 nm, H_2O, double exposure)
- Next Generation Lithography (NGL)
  - Extreme Ultraviolet Lithography (EUVL)
    - 13.2 nm soft x-ray source power
    - High-resolution resist development
    - Low Line Edge Roughness (LER)
    - Complexity and cost
  - Maskless (ML2)
    - Electron-beam
    - Costly, slow
  - Imprint Lithography
    - Long-range order*
    - Overlay
    - Defect density
    - Low cost
  - Directed Self-assembly
    - Defect density
    - Alignment
    - Assemble various pattern densities/pitches
    - Long-range order

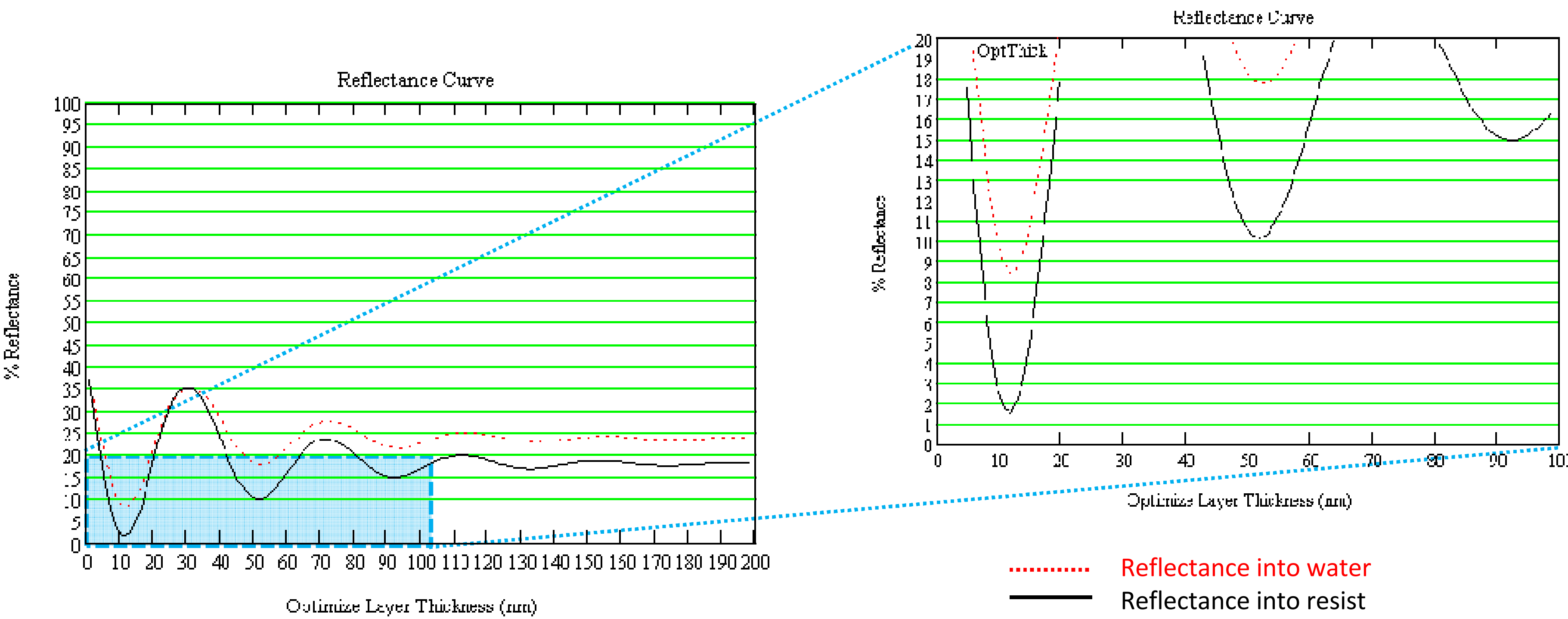
Microprocessor Gate CDs



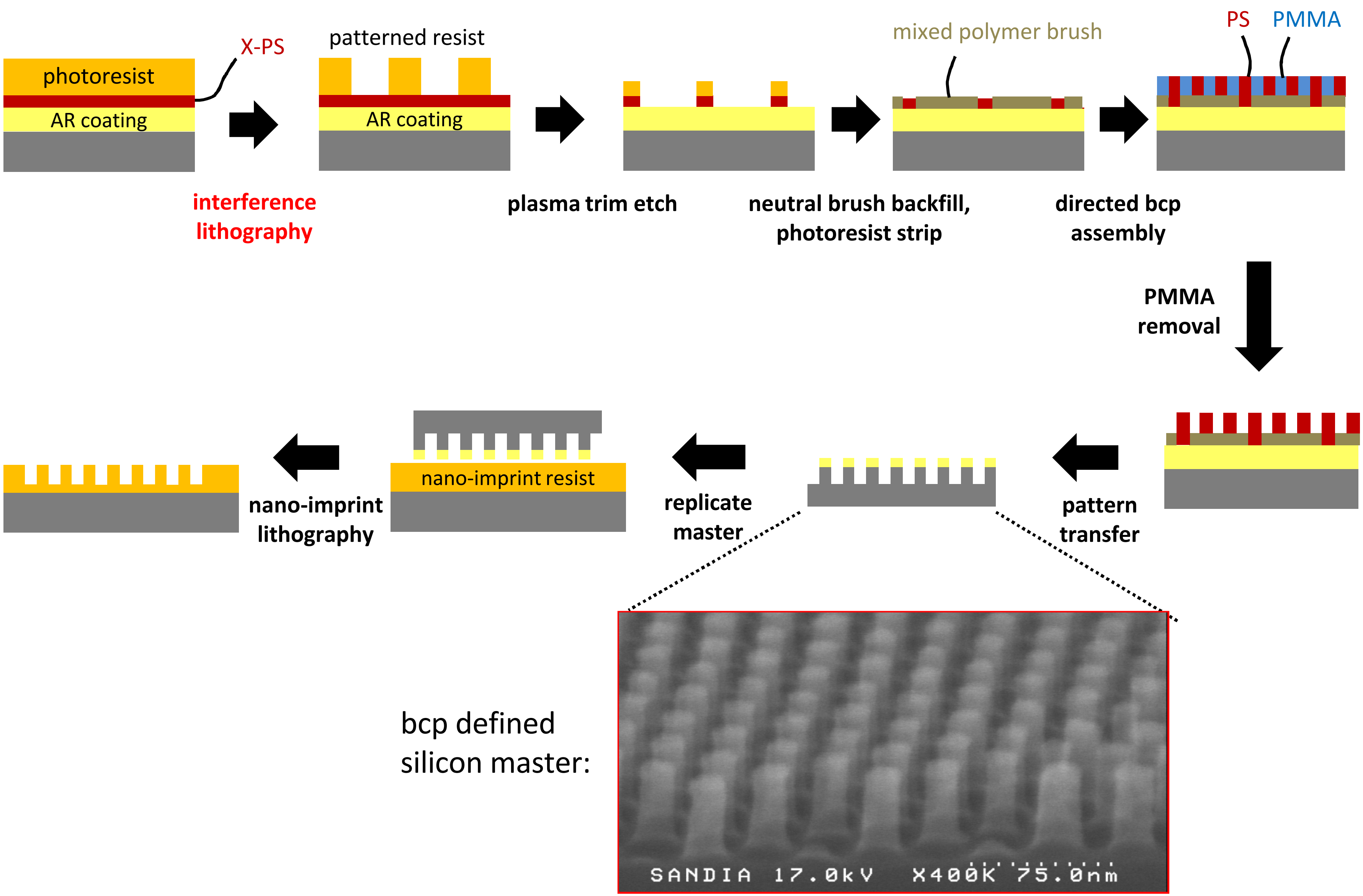
Optimized antireflection (AR) coating



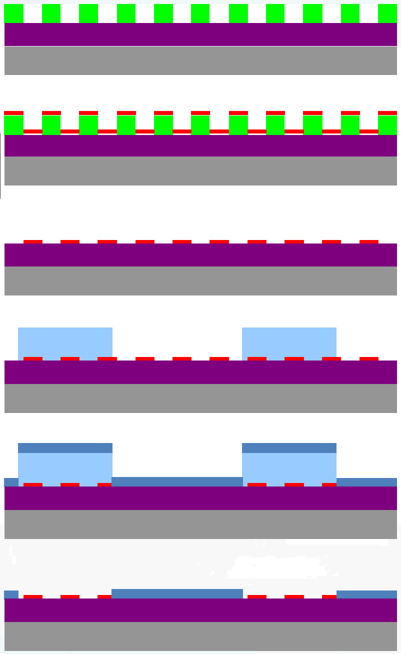




Process Flow for Density Multiplication



Demonstration Structures



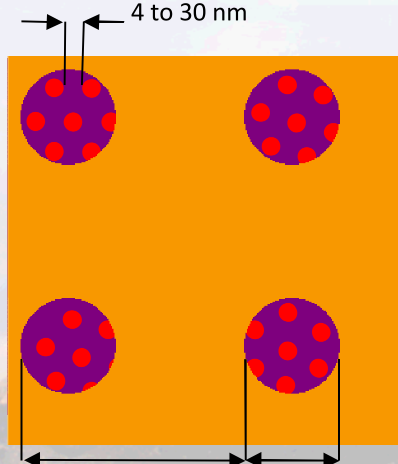
BCP shown after deposition, annealing, and removal of minority block

1D plasmonic structures after lift-off of majority block

PMMA cylinders shown after NIL

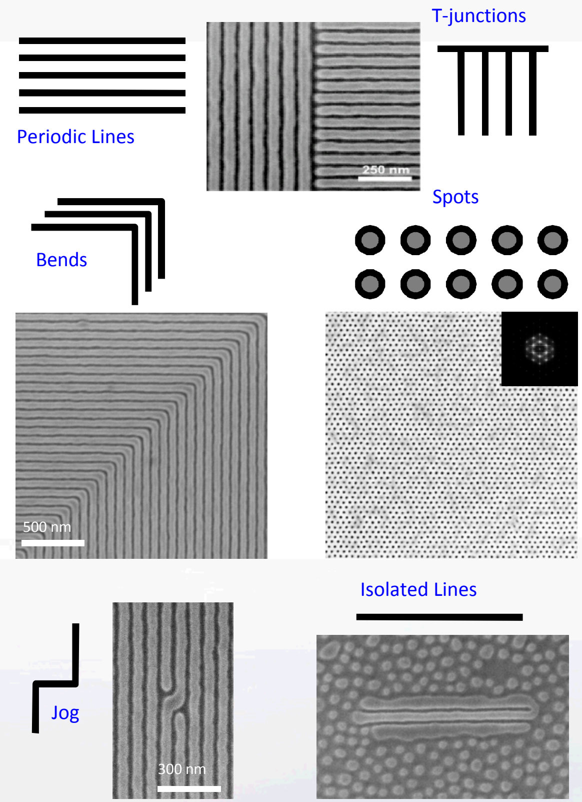
Second metal deposition with evaporation

Integrated 1D/2D plasmonic device shown after final lift-off



Top view of 1D/2D plasmonic device.

Start with straightforward plasmonic structure to establish proof of concept and initiate characterization; structure can also be fabricated with IL-directed self assembly (not shown).



Stoykovich et al. *ACS Nano*, 2007, *Science* 2005

Eventually demonstrate ability to fabricate wide variety of feature types, sizes, and pitches all on single die. Quantify defects at every stage, independent and compounding

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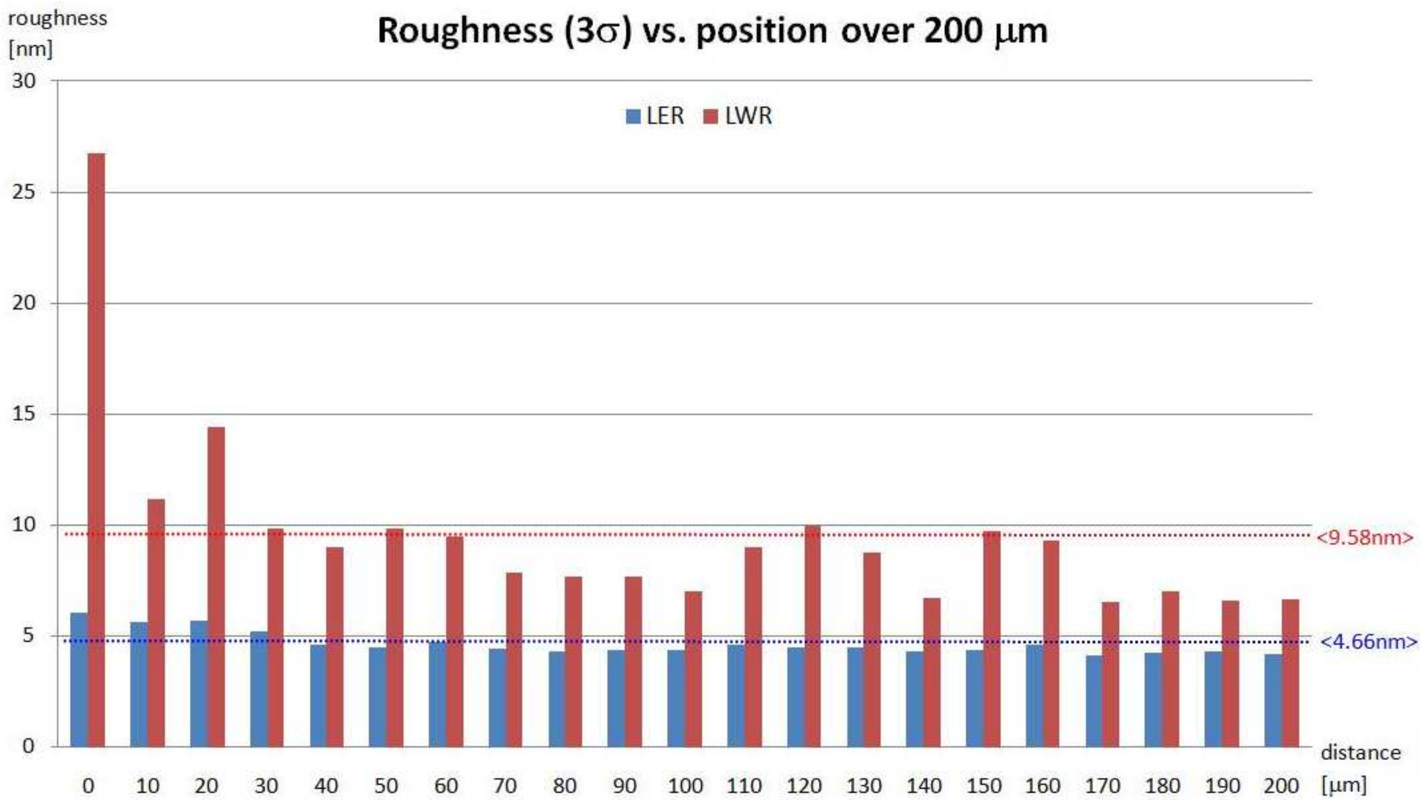
Metrology of Lines/Spaces, small area study



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average	4.59	10.6%	43.39	36.37	79.76	8.72	8.50
standard deviation	0.44	1.0%	1.01	1.07	0.14	1.94	1.83

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