Modeling Line Pattern Collapse Using Finite Element Methods

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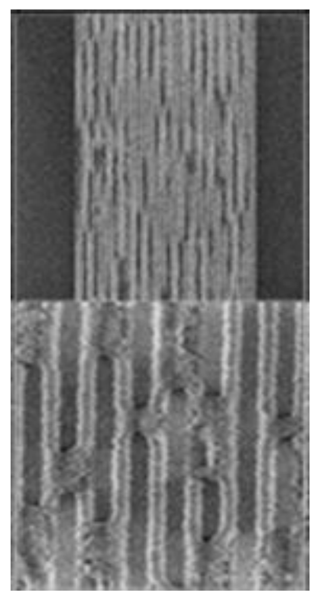
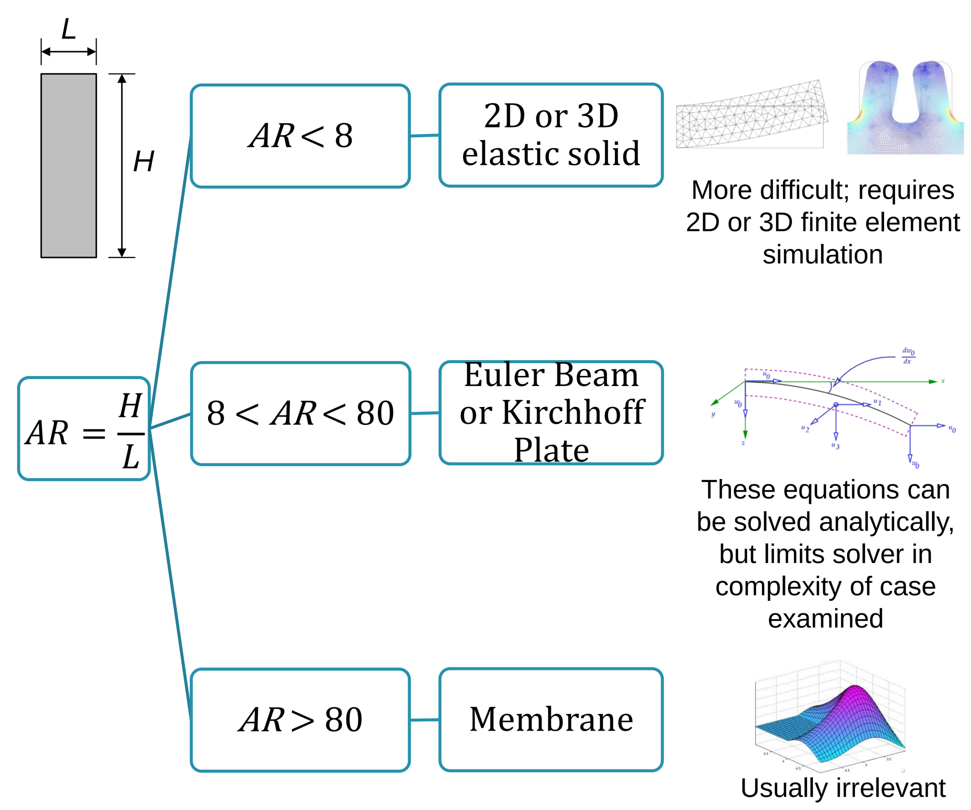
Problem Statement



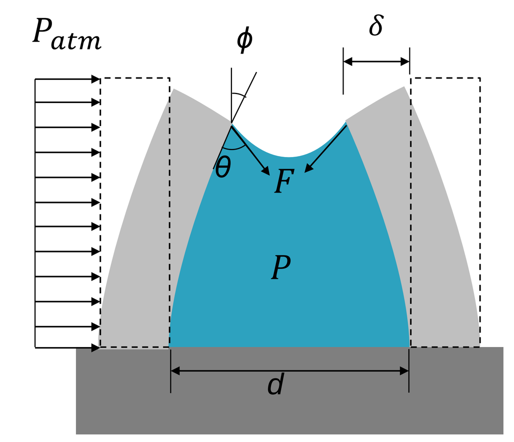
DIW, 75nm Height, ~28nm L/S

- Line pattern collapse (LPC) is a critical concern as IC fabrication advances towards 22nm node and below.
- The ability to explore LPC mitigation techniques is experimentally limited by the cost and availability of EUV exposures.
- Models based on Euler beam are limited in their profile and material assumption complexity, as well as being used outside of their intended aspect ratio regime[1]

Bending Models



Main Physics Involved



Two separate effects from surface tension:

- Laplace pressure, ΔP
- Surface Tension Force at the contact line

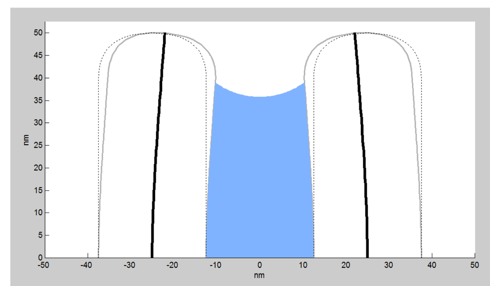
$$\Delta P = P_{atm} - P = \frac{2\gamma\cos(\theta-\phi)}{d-2\delta}$$

$$F_x = \gamma\sin(\theta-\phi)$$

$$F_y = \gamma\cos(\theta-\phi)$$

F_y is force applied along feature surface and assumed to be non-factor in analytical models

Euler Beam Simulations

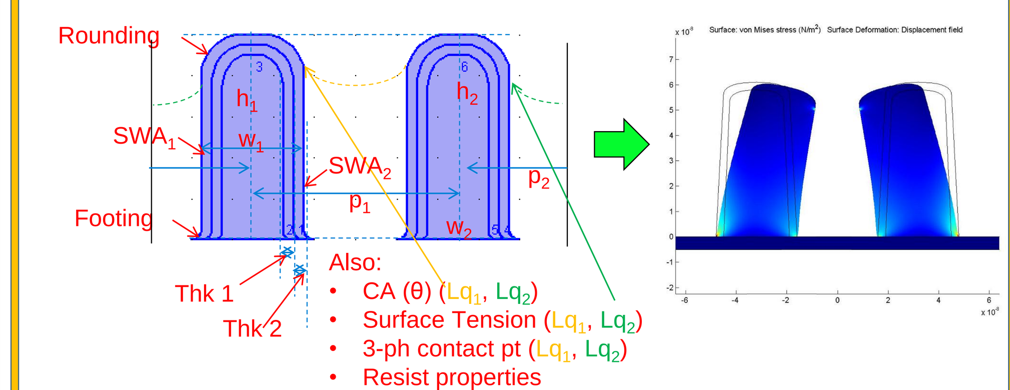


Parameters:

- Height
- Width
- Spacing
- Surface Tension
- Contact angle
- Stiffness

- An analytical solution to the bending and collapse of a feature can be derived using the Euler beam or Kirchhoff plate theory.
- It is a fourth-order equation that enables the calculation of the bending displacement of the feature as a function of external forces and flexural rigidity of the feature.
- If the flexural rigidity is constant, then an analytical solution to the equation can be found.

Finite Element Simulations



Simulations performed with a finite element commercial package making use of:

- Linear elastic model, assuming geometric nonlinearity
- Moving mesh (arbitrary Lagrangian-Eulerian, ALE)
- Surface tension applied with both F_x and F_y terms
- Surface tension force distributed over an area comparable to molecular scale[2]
  - Falls off with distance
- Material properties, including Young's modulus, can be applied as uniform distributions or can be varied in 2 (bi-layer) or 3 (tri-layer) steps
  - This is something not easily solved in Euler beam method, usually treated as effective modulus

Finite Element Verification

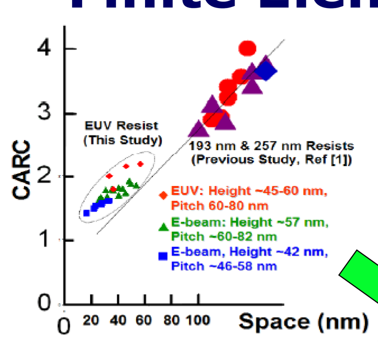
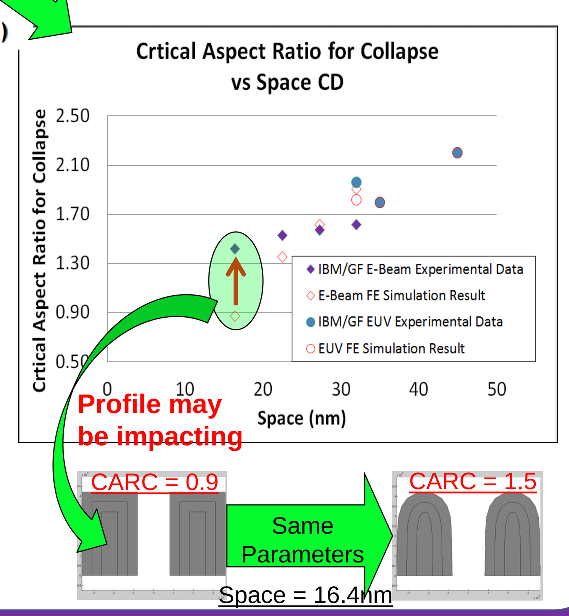


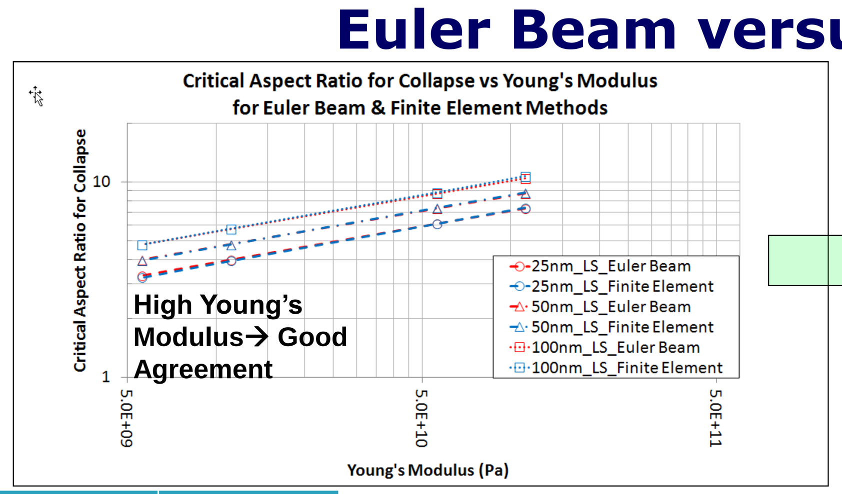
Figure from Yoshimoto, et. al., *"Revisit Pattern Collapse for 14nm node and Beyond"*. Proc. SPIE (2011)

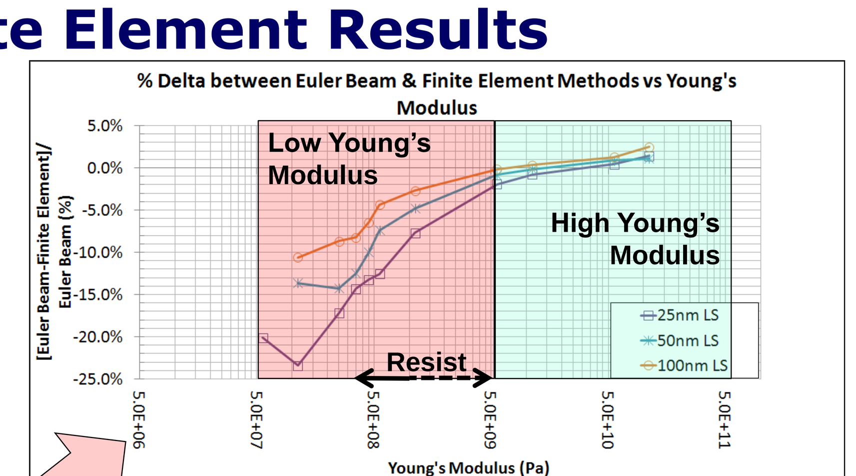
- Made use of IBM/GF/CNSE/Toshiba historical LPC CARC[7] vs. feature size, to judge whether model predicts similar AR/feature size trends
- Good agreement found



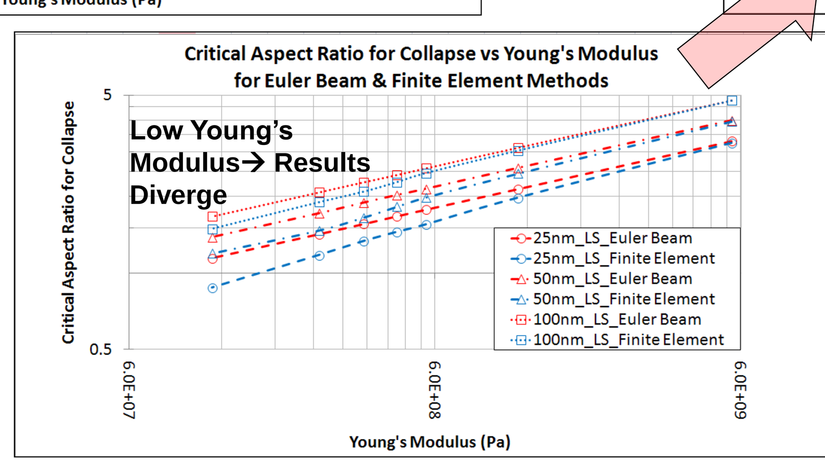
Parameter	Value
SWA (deg)	90
Top Round	No
CA (deg)	70
Gamma (N/m)	0.072
CL Position	99% of Height
Young's Modulus (Pa)	3.4E8
Modulus Distribution	Uniform
Poisson	0.4

Euler Beam versus Finite Element Results



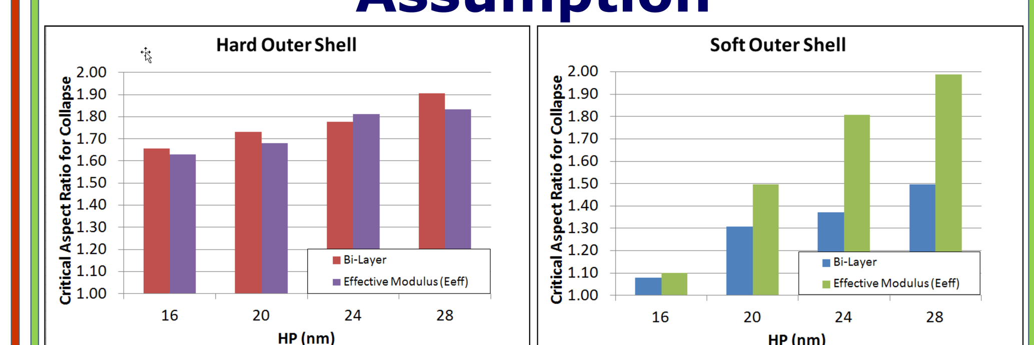


Parameter	Value
CD (nm)	25, 50, 100
Duty Cycle	1:1
SWA (deg)	90
Top Round	No
CA (deg)	55
Gamma (N/m)	0.072
CL Position	99% of Height
Modulus Distribution	Uniform
Poisson	0.35



- As space CD shrinks, CARC decreases
- As material becomes more elastic, the % difference between Euler beam and finite element method grows
- The % difference between Euler beam and finite element method scales with space CD
- Local deformation from surface tension force observed for finite element method at high elasticity

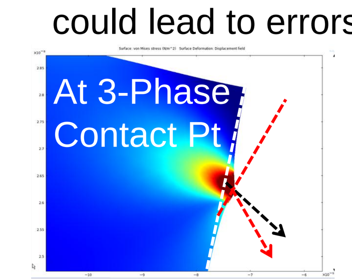
Bi-Layer vs. Effective Modulus Assumption



Node (nm)	Inner E (Pa)	Outer E (Pa)	Distance (nm)
Soft Shell	1.50E9	3.00E8	7.5
Hard Shell	4.00E8	9.00E8	7.5

Node (nm)	Soft E_{eff} (Pa)	Hard E_{eff} (Pa)
16	3.75E8	8.69E8
20	6.00E8	7.75E8
24	7.50E8	7.13E8
28	8.57E8	6.68E8

- Local deformation from surface tension means effective modulus assumption could lead to errors



Why Bi(Tri)-Layer was added to Finite Element Model?

The work of University of Wisconsin[3,4] (Dr. Bohme, Dr. de Pablo, Dr. Yoshimoto, et. al.), NIST[5] (Dr. Stafford, et. al.), and most recently at GT[6] (Wei-Ming Yeh, et. al) have all pointed to a free surface effect at the polymer / air interface. This free surface effect is beginning to dominate because of the ratio of surface to total volume

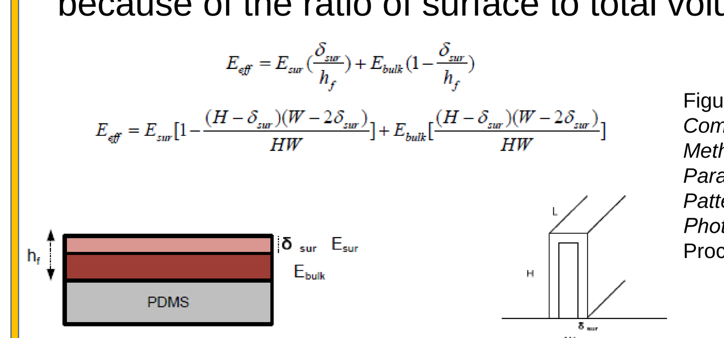


Figure from Yeh, et. al., *"A Comprehensive Model and Method for Model Parameterization for Predicting Pattern Collapse Behavior in Photoresist Nanostructures"*. Proc. SPIE (2011)

Finite Element Parametric Simulation Study

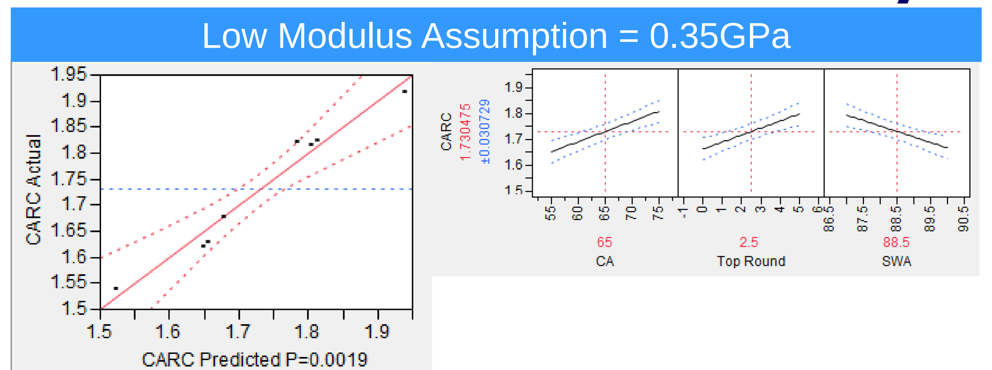
Simulated Iso-Line Pair			Feature		Rinse	Resist
Space/ node (nm)	Surface Tension (mN/m)	Aspect Ratio (Height) (to find CARC)	SWA (deg)	Top Round (0 = Square Profile, 5 = Rounded Profile)	CA (deg)	Young Moduli (Gpa)
32	72	Parametrically based on feature width	87, 90	5, 0	55,75	0.35, 0.65
22	72		87, 90	5, 0	55,75	0.245, 0.455
16	72		87, 90	5, 0	55,75	0.172, 0.32
11	72		87, 90	5, 0	55,75	0.12, 0.225

Parameter	Value
CL Position	95% of Height
Modulus Distribution	Uniform
Poisson	0.4

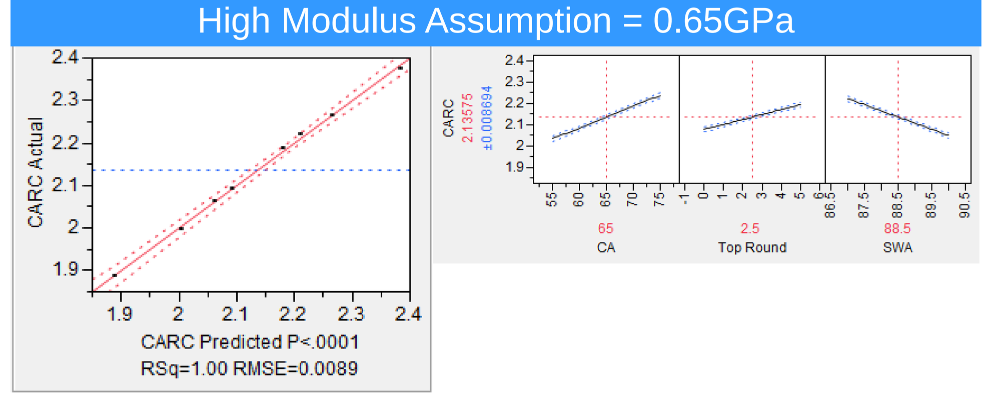
- A parametric finite element study of DI Water drying was explored in order to understand the extendibility of simple rinse drying, as well as the relative parameter sensitivities to collapse

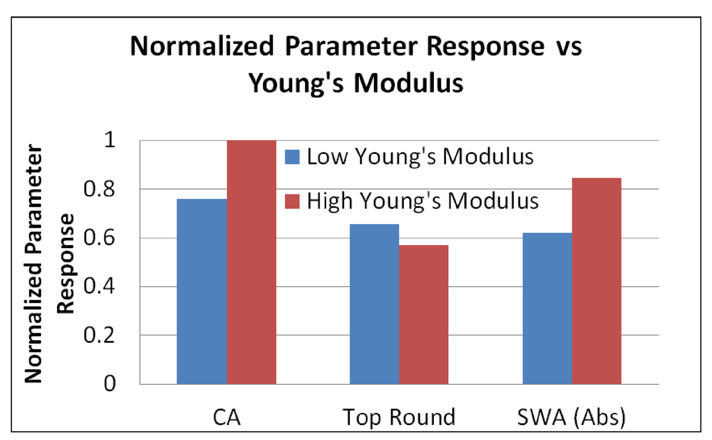
Parametric Simulation Study Parameter Analysis (32nm Case)

Low Modulus Assumption = 0.35GPa



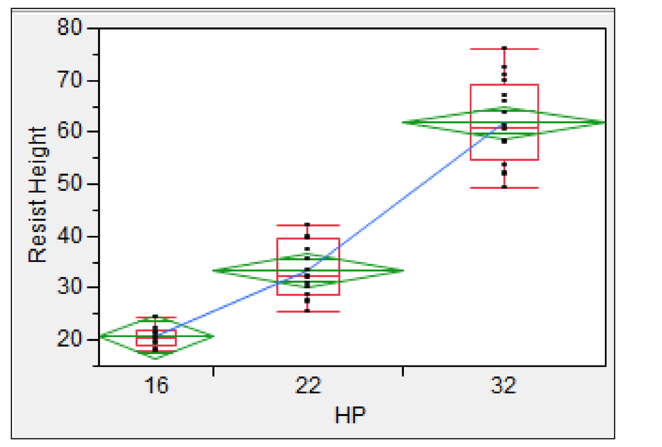
High Modulus Assumption = 0.65GPa





- Material properties (Young's modulus) and rinse properties (CA, surface tension) obviously play big role
- Nature of feature shape (SWA, amount of top rounding) also plays an important role

Parametric Simulation Study DIW Space Mapping



For Iso-Line Pair

- This study found that softer resist materials result in a CARC that may be unreasonable for spin-coater materials and subsequent etch processing
- For example, at 16nm HP, a film thickness below 25nm was commonly required

Conclusions

- A finite element based and Euler beam based simulation was compared.
- For an effective modulus below 6GPa, analytical solutions are no longer valid, especially at small feature sizes.
- Good agreement found with finite element simulations and historical CARC published results; smallest feature agreement found when including top rounding profile.
- Local deformation from surface tension force observed for finite element method at high elasticity; this effect is not captured in Euler beam method
- Film thicknesses to avoid LPC at small feature sizes may need to be considered against etch-selectivity requirements.

Future Work

- Tokyo Electron is focused on providing the industry with a LPC mitigation strategy and we will continue to use experiment and simulation to guide us to the most cost effective solution.

Acknowledgements

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Citations

[1] Ventsel, E., and Krauthammer, T. , *"Thin Plates and Shells: Theory, Analysis, and Applications"*, (2001).
[2] Bonn, D., et. al., *"Wetting and Spreading"*, Reviews of Modern Physics, Vol 81, Iss 2, 739-805 (2009)
[3] Bohme, TR, de Pablo, JJ., J Chem Phys, 116:9939-51 (2002).
[4] Yoshimoto, K., Jain, T.S., Nealey, P.F., de Pablo, J.J., J Chem Phys, 122:144712 (2005).
[5] Stafford, C. M.; Vogt, B. D.; Harrison, C.; Julthongpiput, D.; and Hunag, R., *"Elastic moduli of ultrathin amorphous polymer film"*, Macromolecules, 39, 5095-5099 (2006).
[6] Yeh, W., et. al., *"A Comprehensive Model and Method for Model Parameterization for Predicting Pattern Collapse Behavior in Photoresist Nanostructures"*. Proc. SPIE (2011)
[7] Yoshimoto, K., et. al., *"Revisit Pattern Collapse for 14nm Node and Beyond"*. Proc. SPIE (2011)