SUNY POLYTECHNIC INSTITUTE

Investigating Printability of Native Defects on EUV Mask Blanks through Simulations and Experiments

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Outline

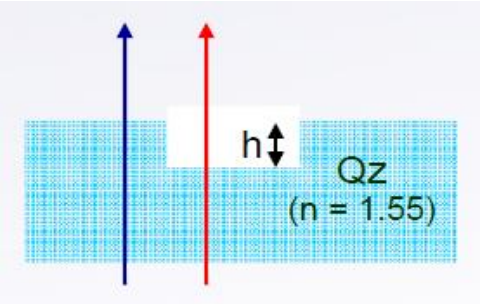
- Introduction and Roadmap
- Evaluating printability of native defects using the level-set multilayer growth model
- Experimental and simulation results
- Correlating printability performance between native, Gaussian and regular-shaped substrate defects
- Conclusions

193nm vs EUV Mask Defects

ArF Mask

$(2\pi / \lambda)(n - 1)h = \pi$ (out of phase)

$h = \lambda / [2(n - 1)] =$ **175 nm**

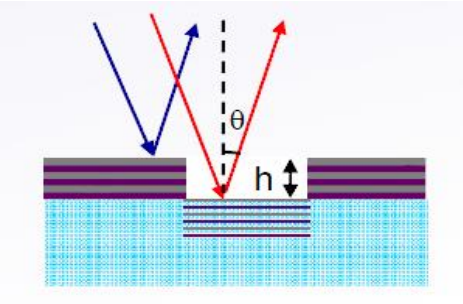


- Transmission
- Quartz to Air (n = 1.55 vs n = 1)

EUV Mask

$(2\pi / \lambda)n(2h / \cos\theta) = \pi$ (out of phase)

$h = \lambda\cos\theta / 4 =$ **3.4 nm**



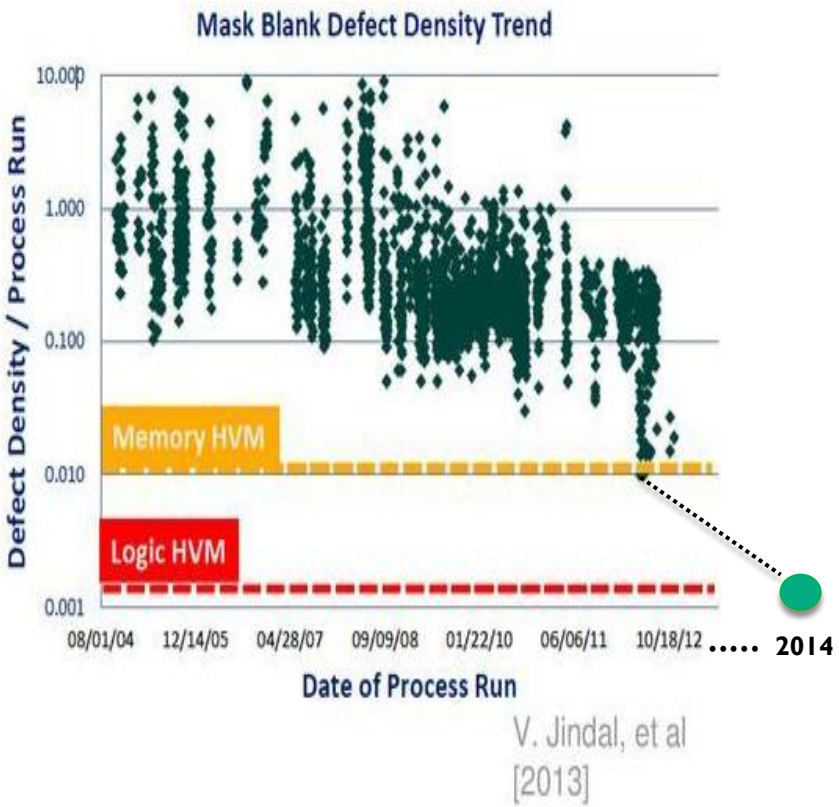
- Reflection (Δpath = $2h / \cos\theta$)
- Vacuum to Vacuum (n = 1 vs n = 1)

- Out of phase depth in EUV = 1/52 as that of ArF.
- Quantity and size of defects should be controlled more tightly in EUV mask.

Reference: H.S. Seo et al., International Symposium on EUVL, 18-21 October 2010.

EUV Mask Defect Progress

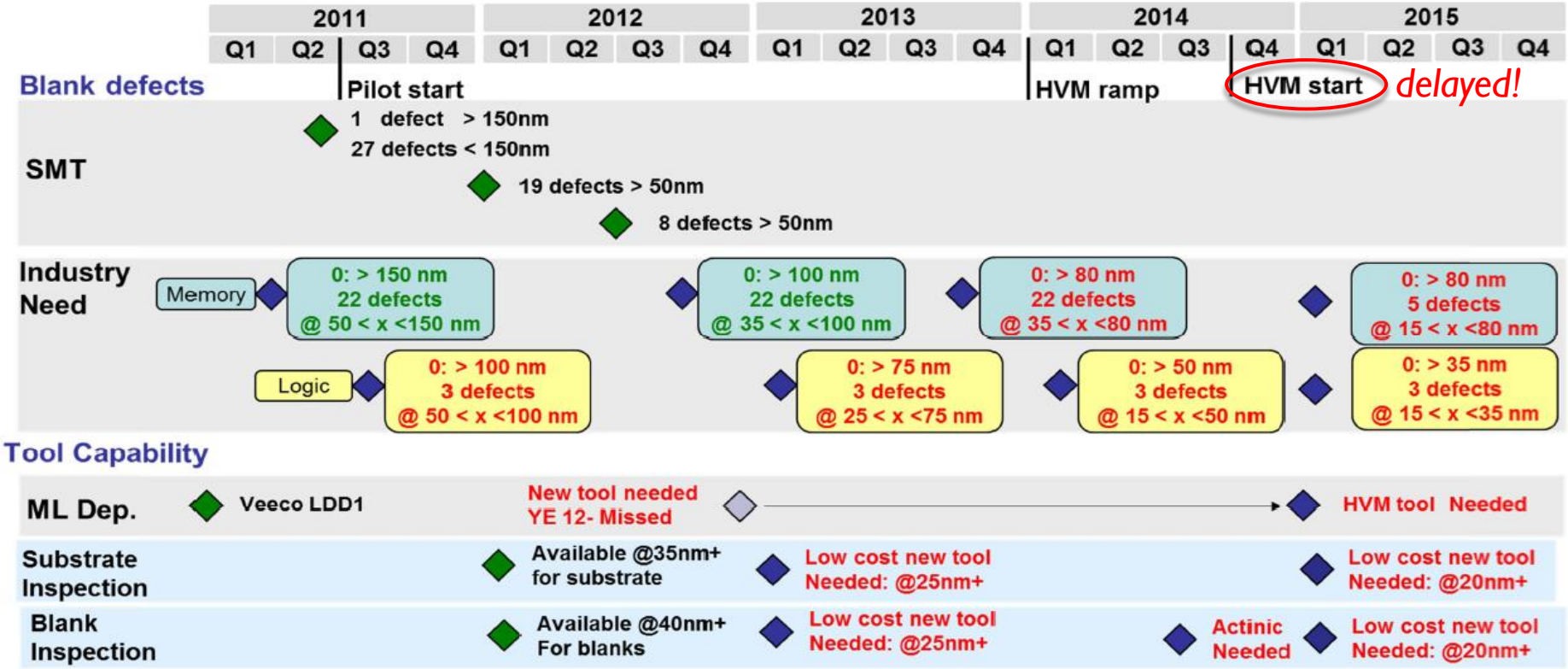
- Preparation of defect-free mask is one of the top 3 critical issues to launch EUVL into HVM.
- Mitigating EUV mask blank defects a serious challenge.
  - Embedded in multilayer structure.
  - These are non-repairable and can be challenging to compensate for.



High quality mask yield is low!

Reference: SEMATECH Press Release, May 6 (2014).

SEMATECH's EUV Mask Blank Defectivity Roadmap



- No more than 3 defects for logic larger than 15 nm.
- Actinic inspection a necessity. Simulation methods needed to predict printability of native EUV mask defects.

Reference: V. Jindal et al., Proc. SPIE, **8679**, 86791D (2013).

Evaluating Native Defects

PART I: Develop accurate multilayer growth model

1) Develop accurate multilayer growth model to simulate growth over native defects
2) Using modeled growth, perform defect printability simulation and compare to AIT

<u>Success criteria</u>: Obtain good match between AIT and simulated aerial images. It would imply accuracy of growth model as well as defect printability simulations.

PART II: Systematic study of native mask defects through simulation

1) Correlate multilayer growth over native defects to that over well-defined defect shapes having similar profiles
2) Compare printability results from native defects to those over the modeled defect geometries

<u>Success criteria</u>: Given an AFM profile of native defect at multilayer top, infer defect profile at substrate. Using our growth model over the substrate defect profile, perform accurate defect printability simulations, reducing dependence on as well as being an aid to actinic imaging tools.

Evaluating Native Defects: Process Flow

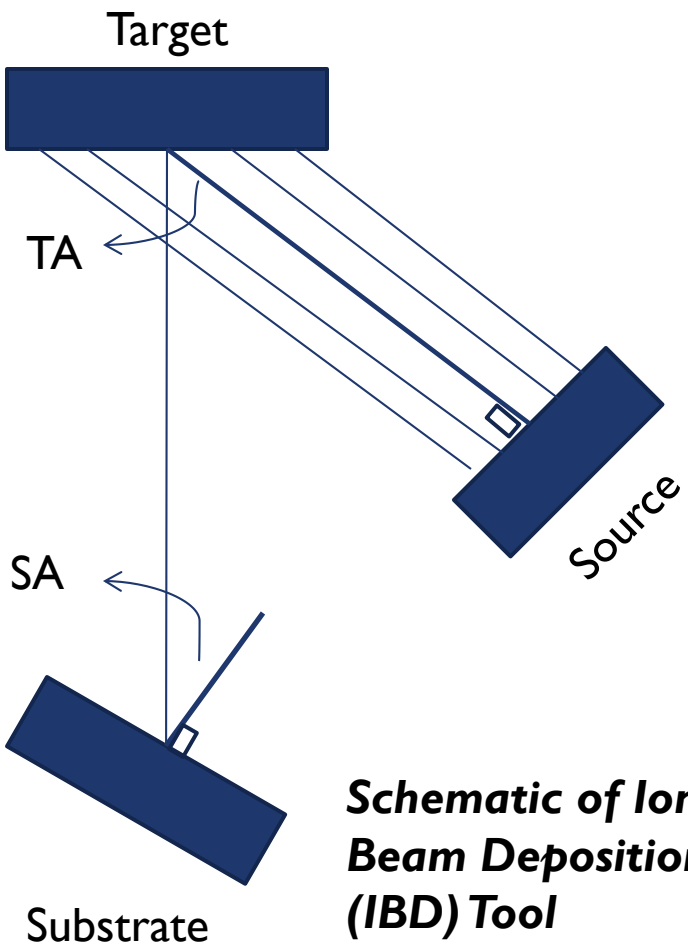
- Post multilayer deposition, the mask blanks were analyzed for defects (particles and pits) using Lasertec M7360 inspection tool.
- The defect locations were marked with the help of fiducials to easily locate the defects for AIT printability and AFM studies.
- The masks underwent AIT inspection at LBNL, Berkeley, CA. AFM was performed to look at the defect profile on top.
- TEM cross section was done on the defects to observe how the multilayer disruption over the defect evolved up the stack.

Reference: H.J. Kwon et al., Proc. SPIE, **8322**, 832209 (2012).

Modeling Defect Growth for Simulations

- A number of models exist to simulate the multilayer growth over defects:
  - Stearns Model: A non-linear continuum model to simulate the growth of defects in multilayer coatings due to particles on the substrate. Valid when the deposition and etch fluxes are near normal incidence to mask surface so the shadowing effects are negligible.
  - SSA (Single Surface Approximation): The defective multilayer structure is replaced by a single reflecting surface with the shape of the top surface of the multilayer. Valid for sufficiently low aspect ratio defects.
  - Conformal Multilayer Growth Model: This model assumes the defect to be uniformly propagated through the multilayer stack from the substrate. Again, this approximation only holds true for relatively small defects.

New Multilayer Growth Model developed at SEMATECH



Schematic of Ion Beam Deposition (IBD) Tool

- Parameters for modeling defect growth:
  - Geometry and profile of the defect.
  - Rotation speed of the substrate.
  - Flux and direction of atoms reaching the substrate surface. This will depend on the ion type, ion energy, ion beam direction on target, target tilt, and substrate tilt.
  - Scattering coefficients of atoms.
  - Diffusion coefficients of atoms on the substrate surface.
  - Sticking coefficients of atoms on the substrate surface.

Reference: M. Upadhyaya, V. Jindal et al., Proc. SPIE, **9048**, 90483L (2014).

Level-Set Method

- Growth model based on the level-set technique. It's used to study the evolution of surfaces .

$$\frac{d\varphi(r,t)}{dt} + \vec{V}.\nabla\varphi + a|\nabla\varphi| = b\kappa|\nabla\varphi|$$

$\varphi(r,t)$ is the definition of interface/surface initialized by pit or particle geometry, $\varphi(r,0)$

$\vec{V}$ is the external velocity vector of the deposition fluxes.

$\nabla\varphi$ defined as $\left(\frac{d\varphi}{dx}, \frac{d\varphi}{dy}, \frac{d\varphi}{dz}\right)$ is gradient of the interface/surface in three dimensions.

$\vec{V}.\nabla\varphi$ is deposition by the vector of direct line of sight.

$a|\nabla\varphi|$ is deposition due to the flux of atoms reaching the surface by scattering.

$b\kappa|\nabla\varphi|$ is deposition due to the curvature-driven force in the system.

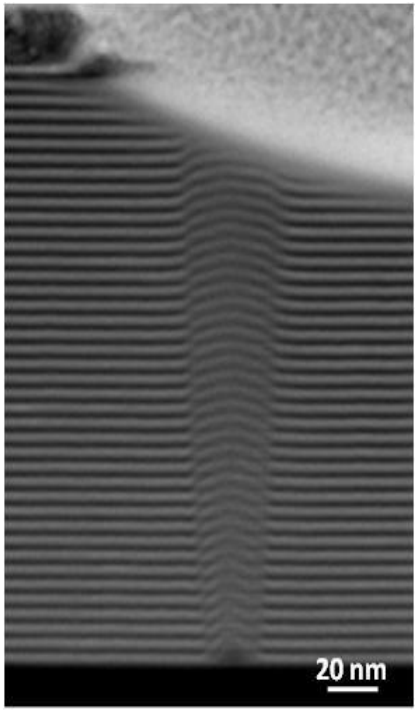
Reference: V. Jindal et al., Proc. SPIE, **7969**, 79691A (2011).

Defining Native Defect Geometry

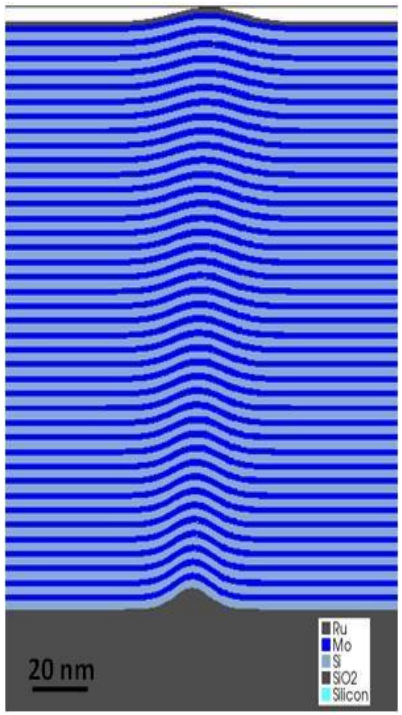
- The process to define initial defect geometry was an iterative one starting with TEM cross-section image of defects.
- The outline of the defect shape, as observed in the TEM images was traced and the function defining the traced shape was input into the growth model.
- Modeled FWHM and height at multilayer top surface compared with AFM measurements from multilayer top.
- Substrate defect profile was iteratively adapted until the modeled defect profile matched the AFM defect profile at the multilayer top, since top layers are most critical.

Multilayer Growth Native Defect – "A" bump type

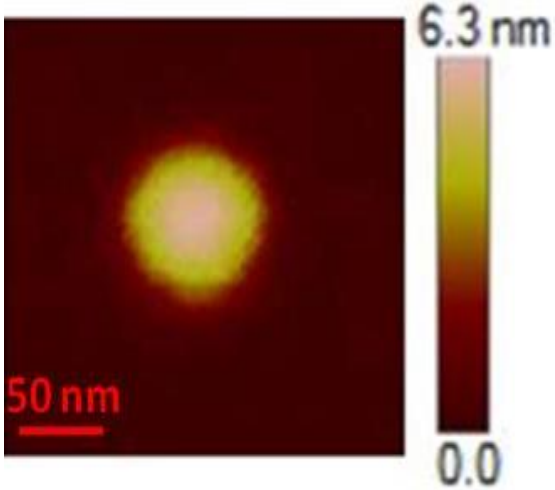
TEM Cross-section



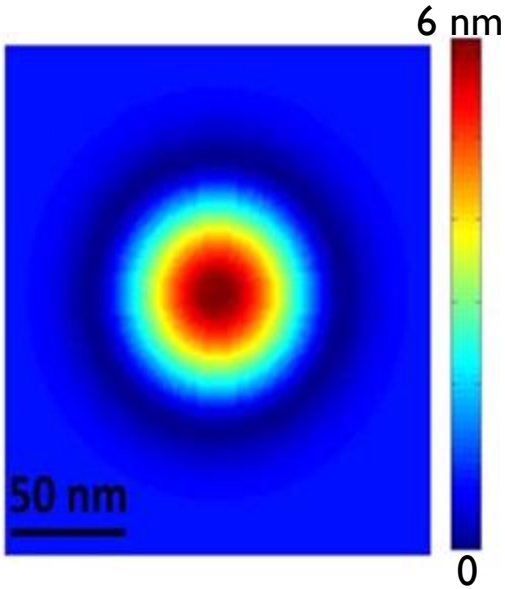
Modeled Cross-section



AFM at multilayer Top



Modeled Growth at multilayer top



- Top surface of modeled defect agrees with top surface AFM measurements within 1 nm for height and FWHM.

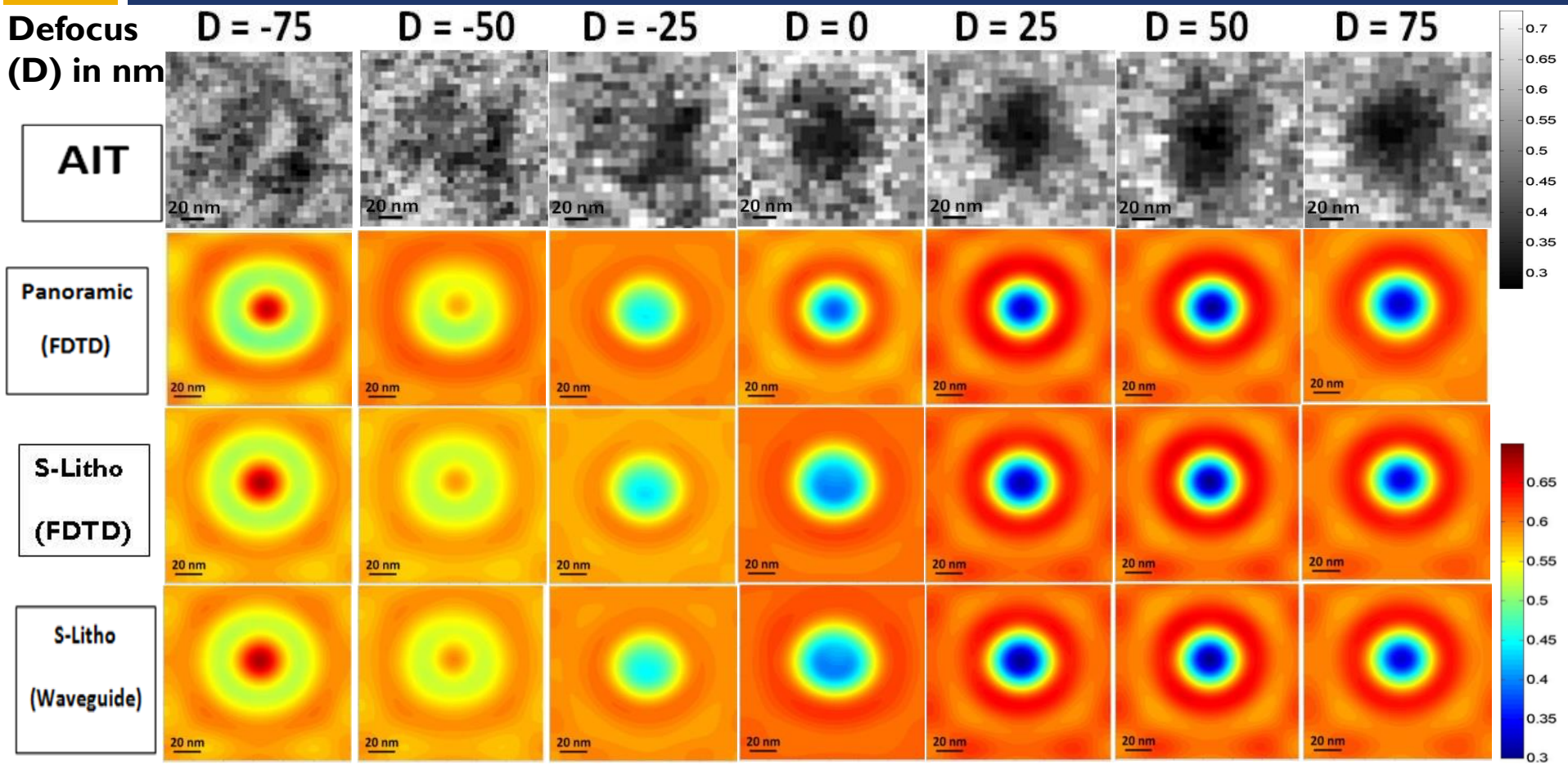
Simulation Packages/Algorithms

- Commercially available simulation software packages S-Litho from Synopsys and EM-Suite from Panoramic Technology Inc. were used for simulations.

- The Finite Difference Time Domain (FDTD) algorithm, and the Waveguide algorithm were used for the simulations.
  - FDTD is the most rigorous and is also widely identified as the most accurate algorithm. However, it is computationally expensive and more time consuming.
  - The waveguide algorithm requires lesser computational resources and is 100x – 1000x faster than FDTD. However, is the accuracy comparable to FDTD?

References: J. Frances et al., Proc. SPIE **8429**, 84291U (2012)
A. Erdmann et al., Proc. SPIE, **6283**, 628319 (2006).

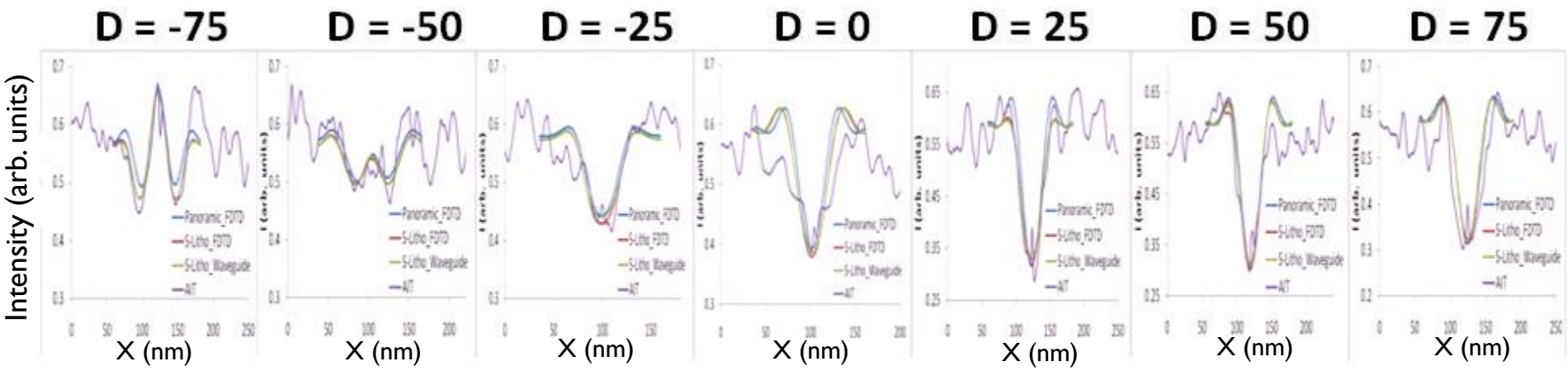
Multilayer Growth Native Defect – “A” bump type



- The average difference in contrast for the various focus conditions between AIT and simulated aerial image intensities is 5%.

Multilayer Growth Native Defect – "A" bump type

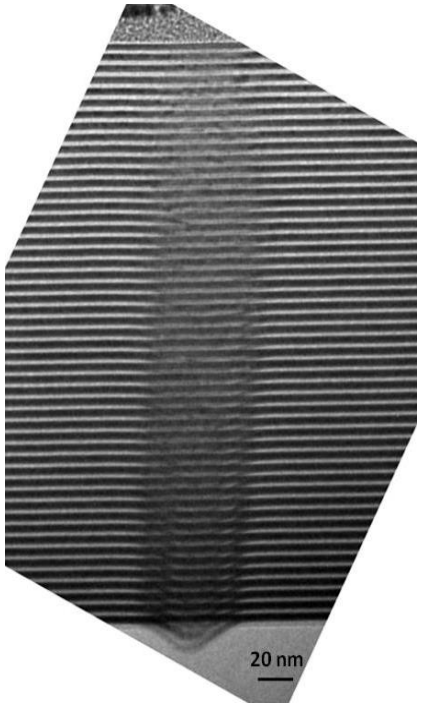
Defocus (D) in nm



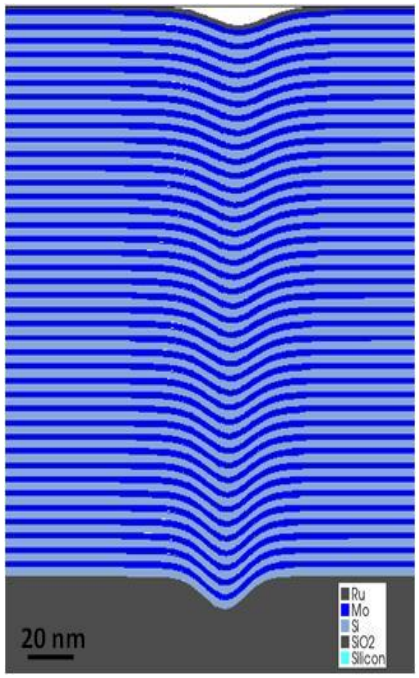
- Intensities normalized to the respective average intensities obtained from 2-D plots.
- 1-D cross section taken across an arbitrary axis as 2-D aerial image intensities are approximately symmetric.

Multilayer Growth Native Defect – “B” pit type

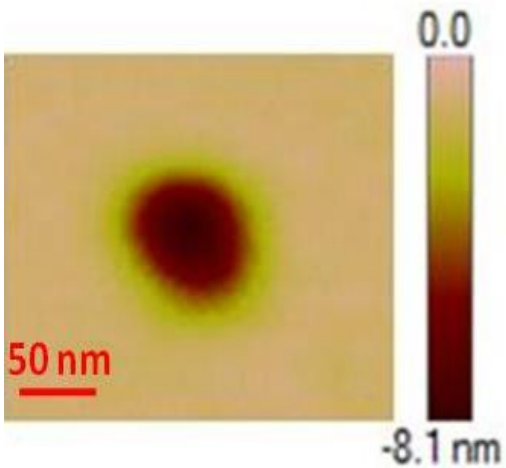
TEM Cross-section



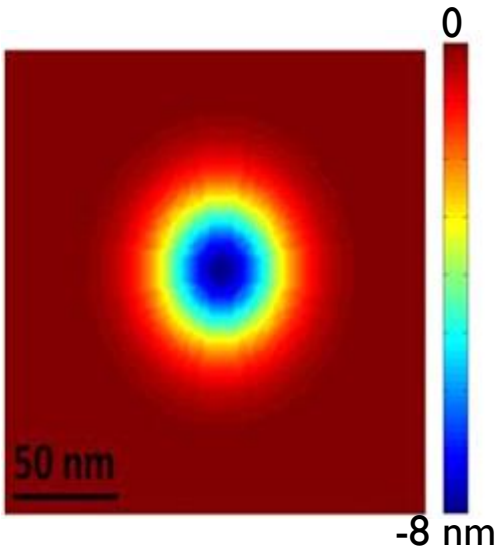
Modeled Cross-section



AFM at multilayer Top

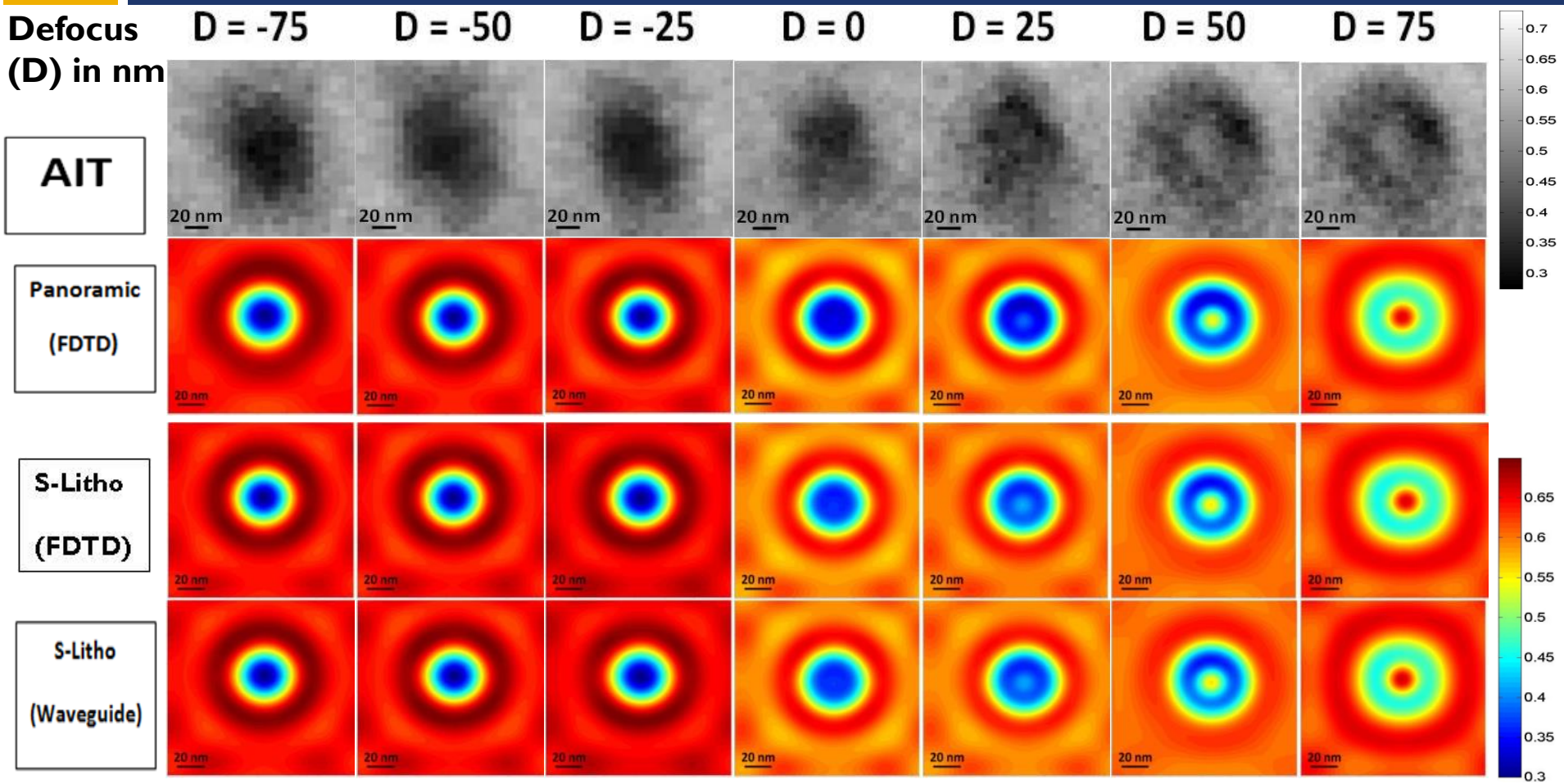


Modeled Growth at multilayer top



- Defect is measurably non-symmetric (15% longer in one axis).
- We modeled a rotationally symmetric defect to match the average FWHM and height to within 1 nm.

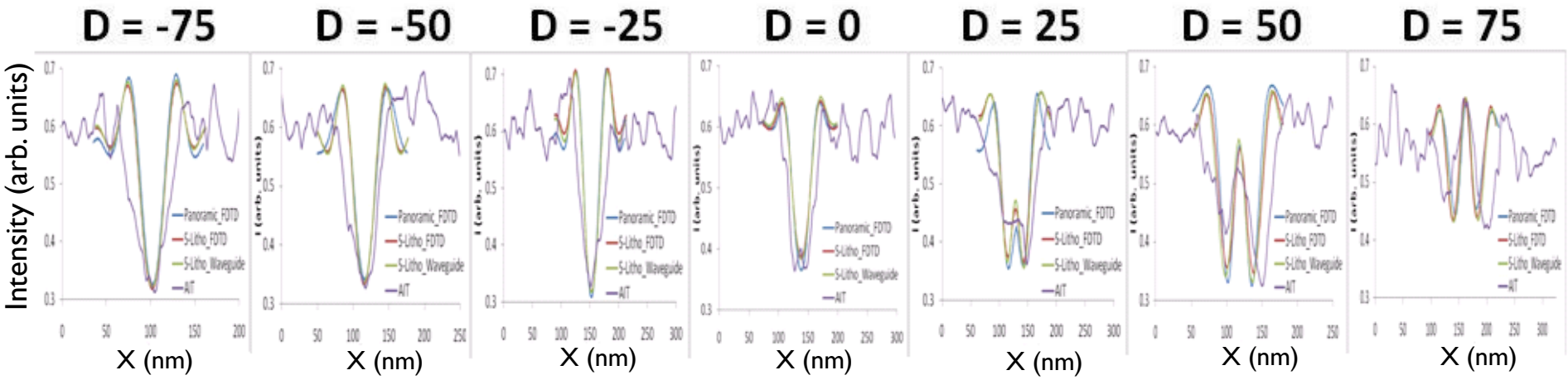
Multilayer Growth Native Defect – “B” pit type



- The average difference in contrast, for the various focus conditions, between AIT and simulated aerial image intensities is 3%.

Multilayer Growth Native Defect – "B" pit type

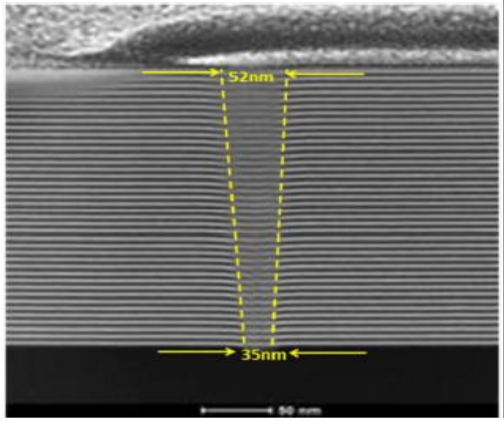
Defocus (D) in nm

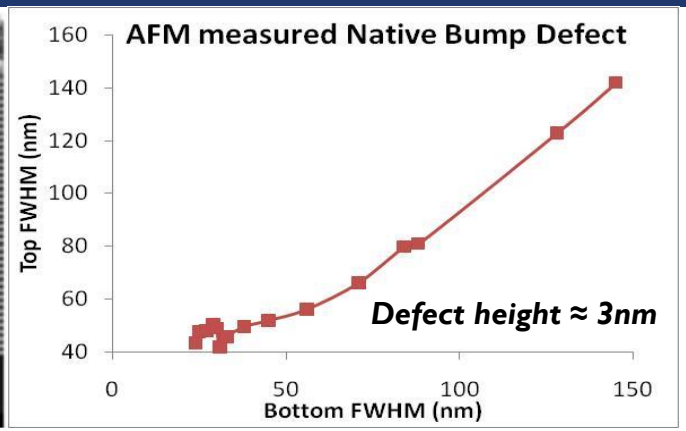


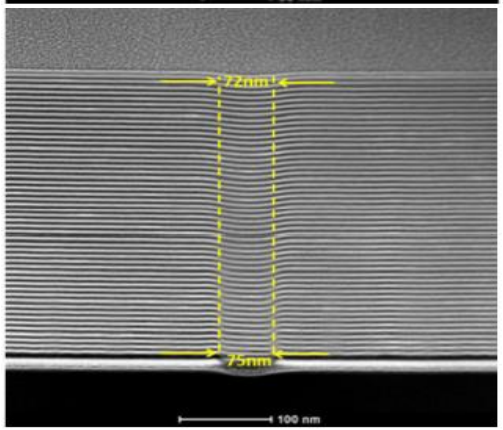
- Intensities normalized to the respective average intensities obtained from 2-D plots.
- 1-D cross section taken across an arbitrary axis as 2-D aerial image intensities approximately symmetric.

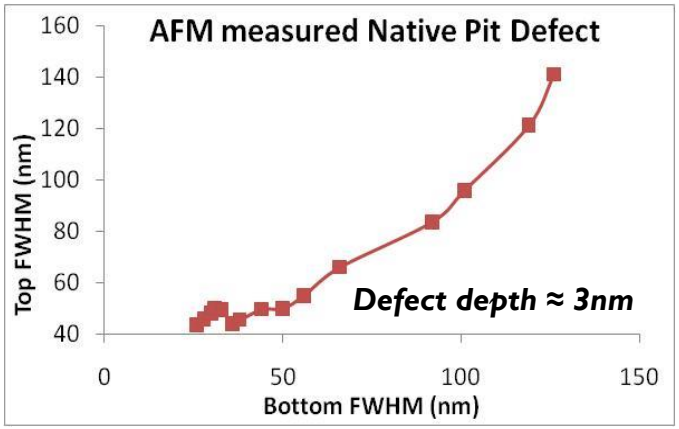
- Based on results from the two real defects, we demonstrate the accuracy of our multilayer growth model as well as robustness of FDTD and Waveguide algorithms to simulate native EUV mask defects.

Correlating Native and regular-shaped Mask Defects





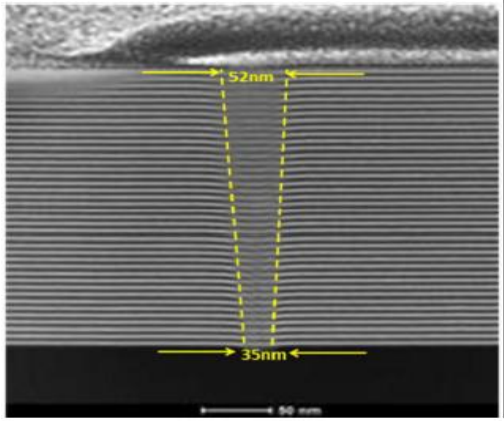


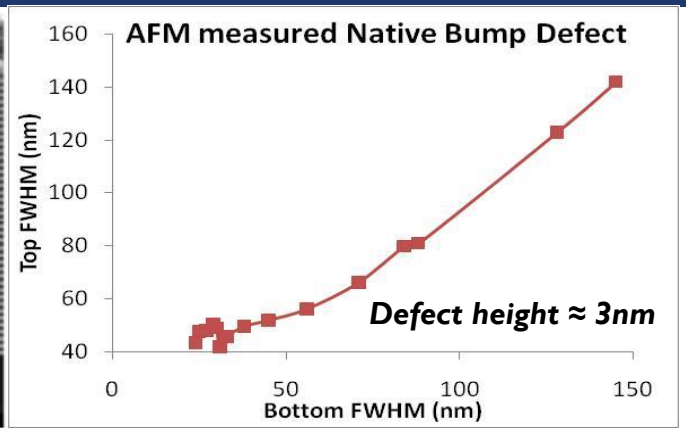


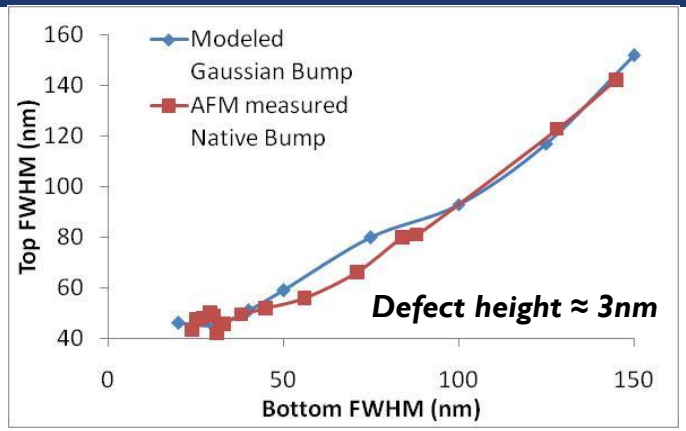
- Multilayer growth over native defects investigated and substrate defect width correlated to defect width at multilayer top (for a defect height / depth of approximately 3 nm).

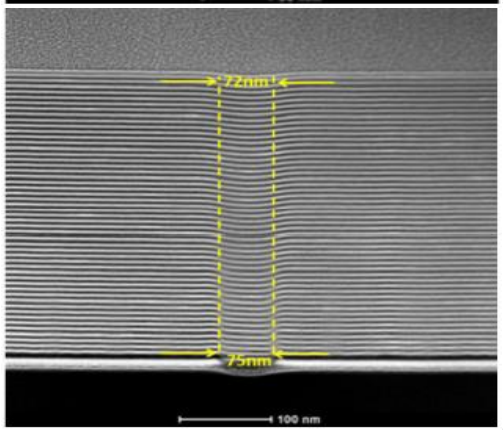
Reference: Il-Yong Jang et al., Proc. SPIE, **8679**, 86790H (2013).

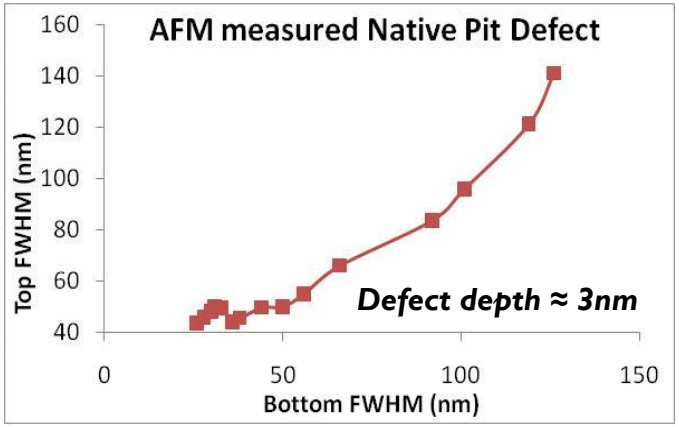
Correlating Native and regular-shaped Mask Defects

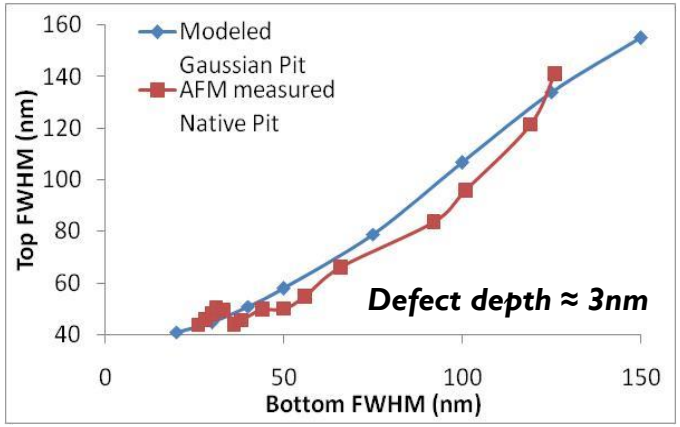










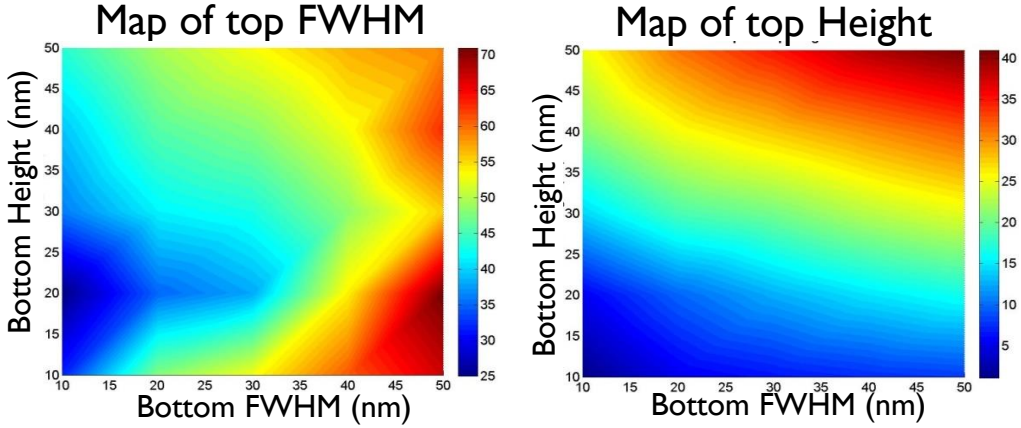


- Reasonable comparison between modeled multilayer growth over Gaussian defects (3 nm high/deep) and the actual multilayer growth over native defects (3 nm high/deep).

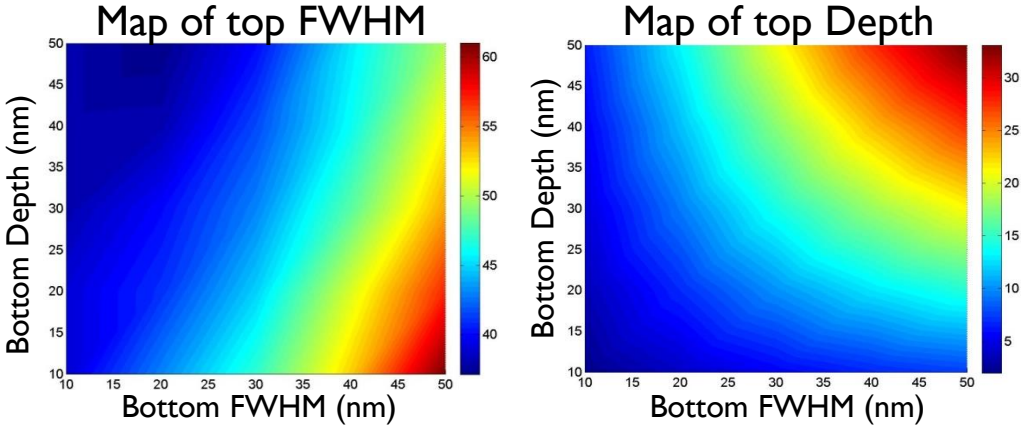
Reference: Il-Yong Jang et al., Proc. SPIE, **8679**, 86790H (2013).

Mapping Multilayer Top FWHM and Height vs Bottom Defect Profile

GAUSSIAN BUMP



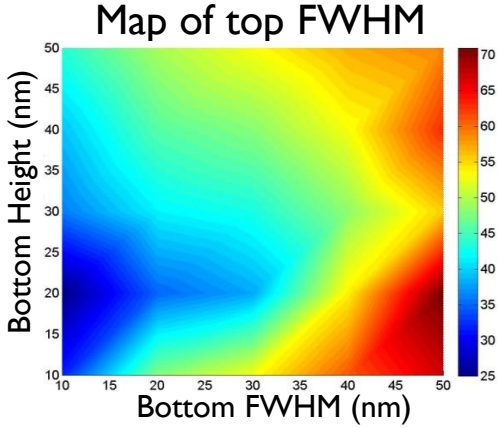
GAUSSIAN PIT

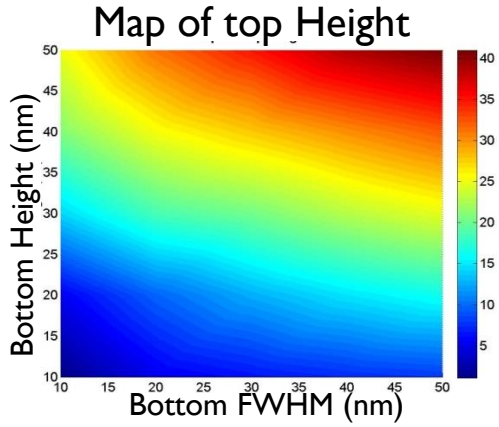


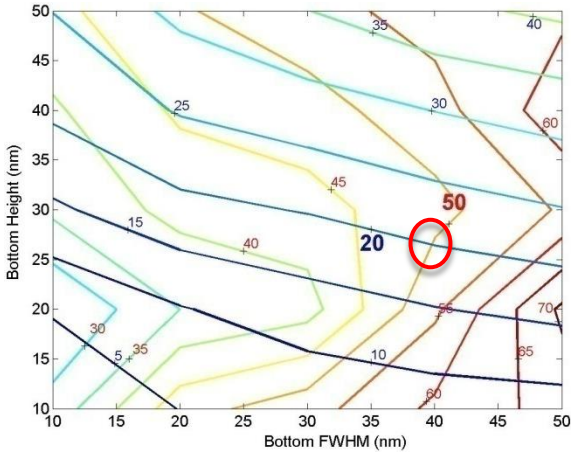
- Given AFM of a native defect at top of the multilayer, we can use these maps to determine the Gaussian-equivalent-FWHM-and-height (GEFH) of the defect at the substrate.

Mapping Multilayer Top FWHM and Height vs Bottom Defect Profile

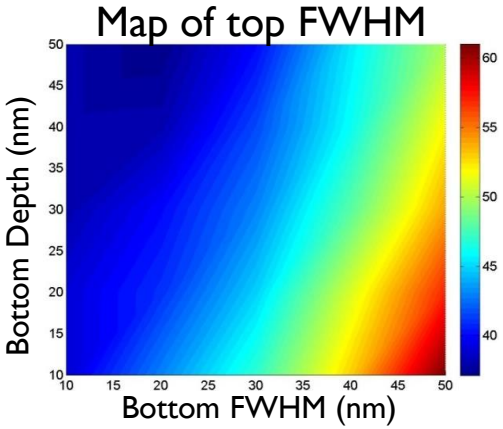
GAUSSIAN BUMP

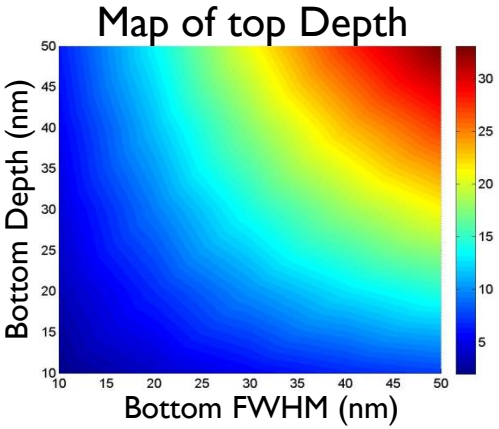


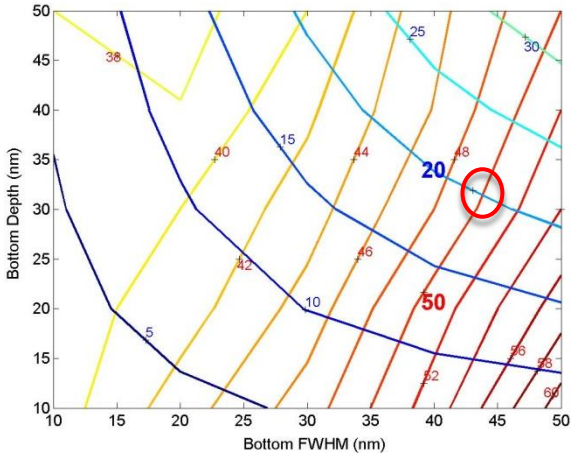




GAUSSIAN PIT



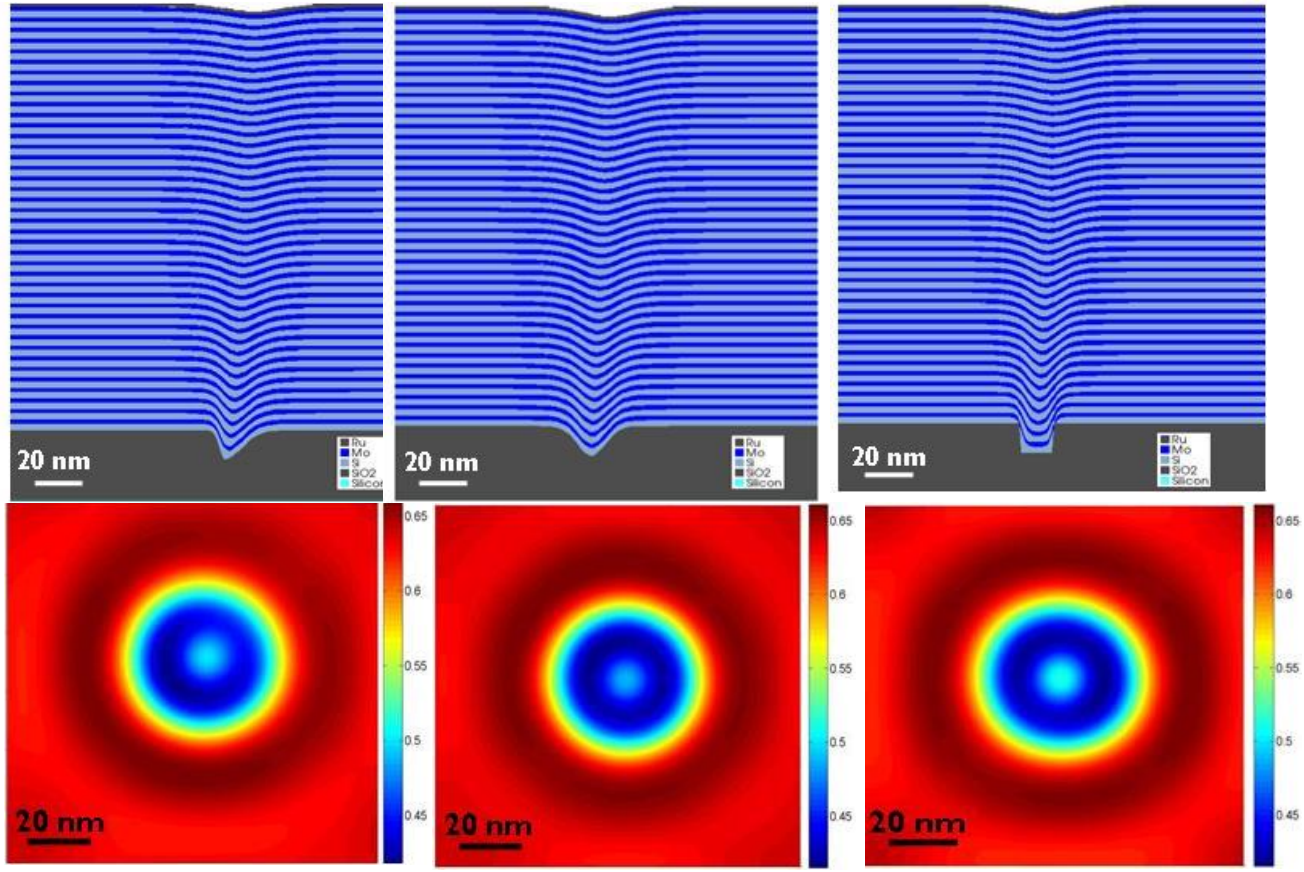


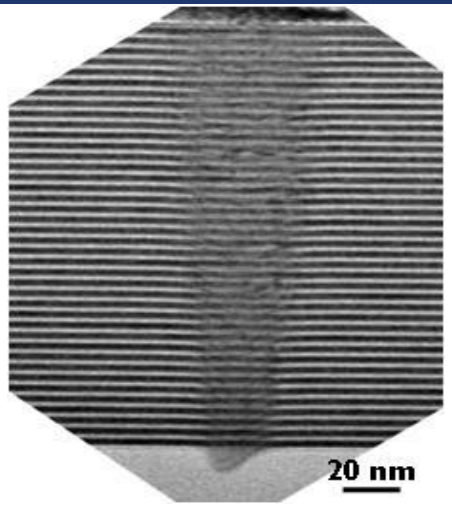


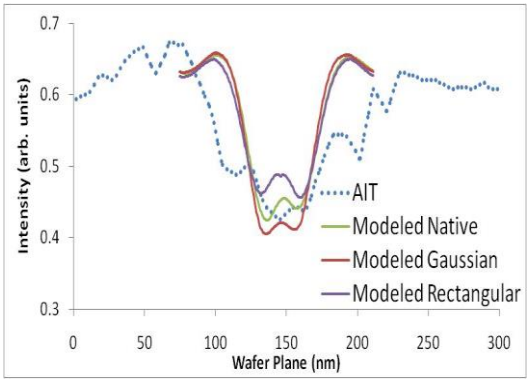
- This will allow us to model printability using ONLY top AFM.

<u>Assumption</u>: Defect at substrate.

Native vs Gaussian vs Rectangular Defects (Pit-type defect)



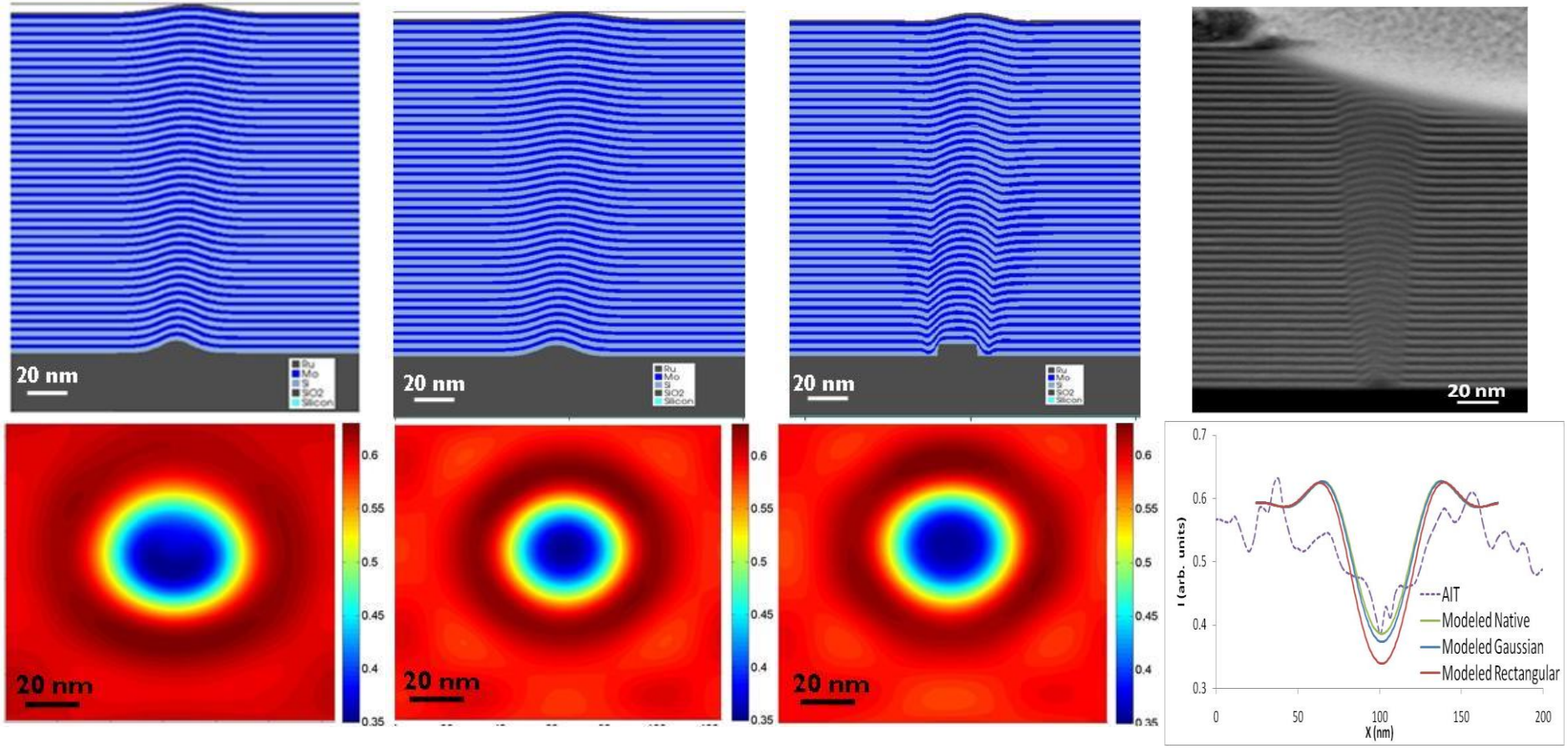




- AIT and modeled native aerial images match well, and Gaussian approximation of defect yields relatively accurate match to AIT.

<u>Contrast Difference</u>:
AIT – Modeled Native ≈ 1%
AIT – Modeled Gaussian ≈ 3%
AIT – Modeled Rectangular ≈ 8%

Native vs Gaussian vs Rectangular Defects (Bump-type defect)



- AIT and modeled native aerial images match well, and Gaussian approximation of defect yields relatively accurate match to AIT.

Contrast Difference:
AIT – Modeled Native ≈ 0%
AIT – Modeled Gaussian ≈ 1%
AIT – Modeled Rectangular ≈ 6%

Conclusions

- Observed a good comparison between AIT and simulation results for the native EUV mask defects with the use of a new level-set multilayer growth model.
- Multiple algorithms all agreed with AIT results, and Waveguide algorithm was 500 times faster than FDTD.
- Gaussian approximation for native defects at substrate (having similar profiles) yielded similar printability results.

AFM at Multilayer Top —*Contour Plots* / *GEFH (substrate)*→ **Level-set Growth Model** —FDTD / Waveguide→ **Aerial Image Contrast**

Thank You…..

Questions?