FE Simulation of Electrostatic Chucking in the Presence of Particles

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Acknowledgments

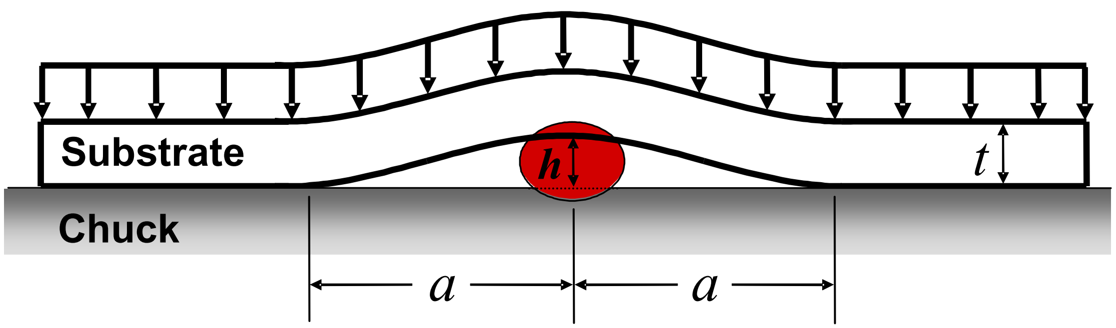
Support for this research has been provided by SEMATECH and Intel. Computer support provided by Intel Corporation and Microsoft. Technical support on the nanoindentation experiments was given by J. Beecher at the Forest Products Lab.

Chucking in the Presence of Particles

- Small pieces of debris can become lodged between the substrate and the chuck causing both out-of-plane distortions (OPD) and in-plane distortions (IPD) of the frontside surface of the substrate.

OPD and IPD of patterned surface

Clamping pressure



Micron-sized entrapped particle

Millimeter-sized gap radius (a)

- Experimental assessment of the effects of particle-induced distortions is extremely difficult without the results of computational studies using FE models.

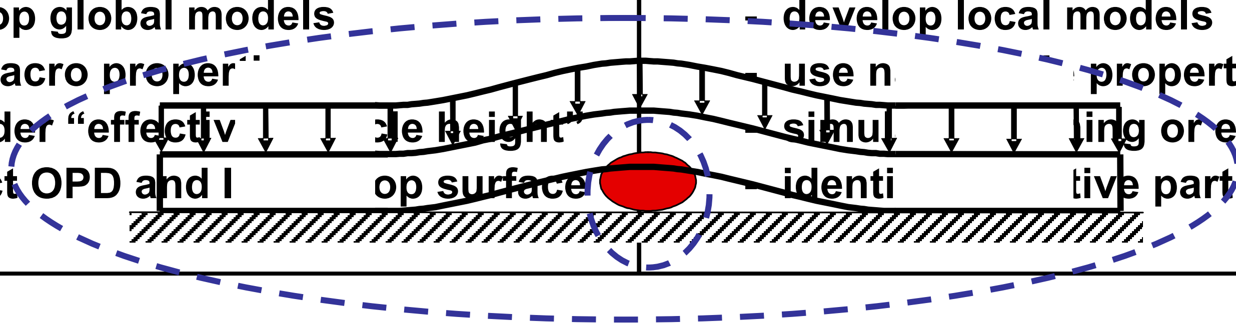
Predicting the Effects of Particle Entrapment

- The effects of entrapped particles are difficult to assess because the size, shape, number, and material properties of these contaminants are not well defined.

- It is also difficult to develop a model of a domain that is hundreds of millimeters in size, but contains sub-micron details.

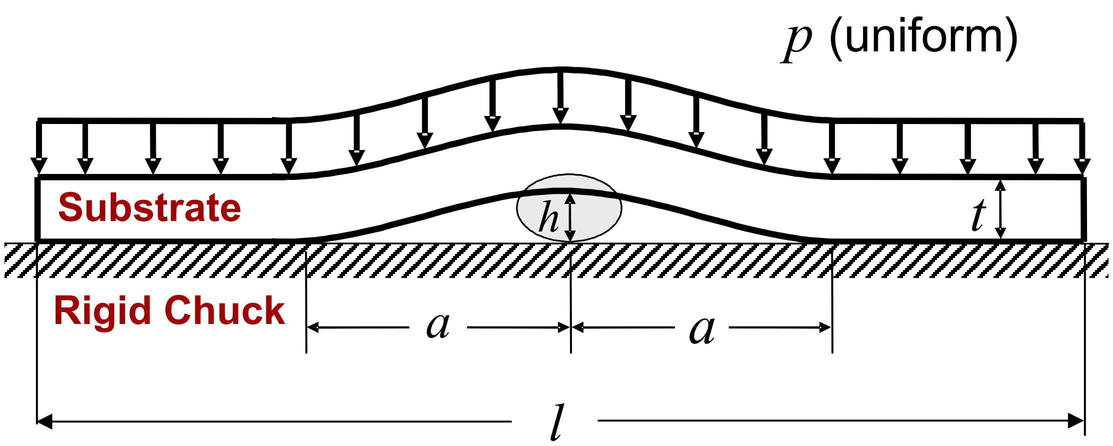
The problem can be divided into two principal categories:

"Macro" Response	"Micro" Response
- develop global models	- develop local models
- use macro proper	- use n properties
- consider "effectiv le height"	- simul ing or embedding
- predict OPD and I op surface	- identi tive particle height"



"Macro" Response of a Substrate

Analytical Model for Global Distortions



- l = substrate length
- t = substrate thickness
- p = chucking pressure
- a = gap radius
- h = effective particle height
- E = elastic modulus
- ν = Poisson's ratio

The relationship between the gap radius a and the effective particle height h is based upon classical flexural theory, thus shear effects are not considered.

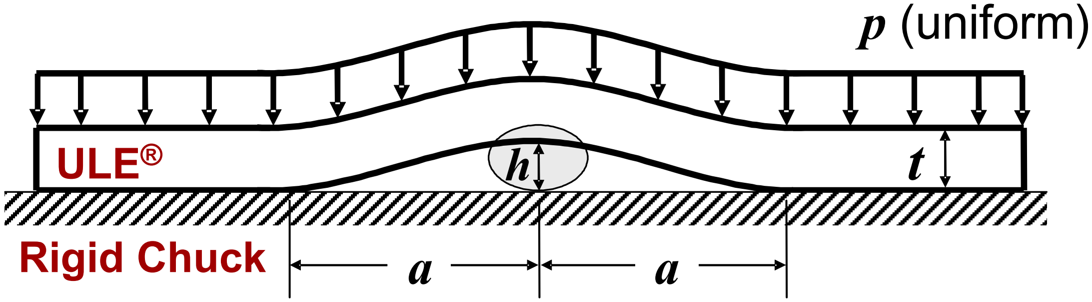
$$a = \left[\frac{16Eht^3}{3p(1-\nu^2)} \right]^{\frac{1}{4}}$$

For a/t < 10, shear compliance should also be assessed.

*Ref: R. Tejeda, R. Engelstad, E. Lovell, K. Blaedel, *JVSTB,* Vol. 20, 2002.

"Macro" Response of a Reticle

FE Simulation and Theory

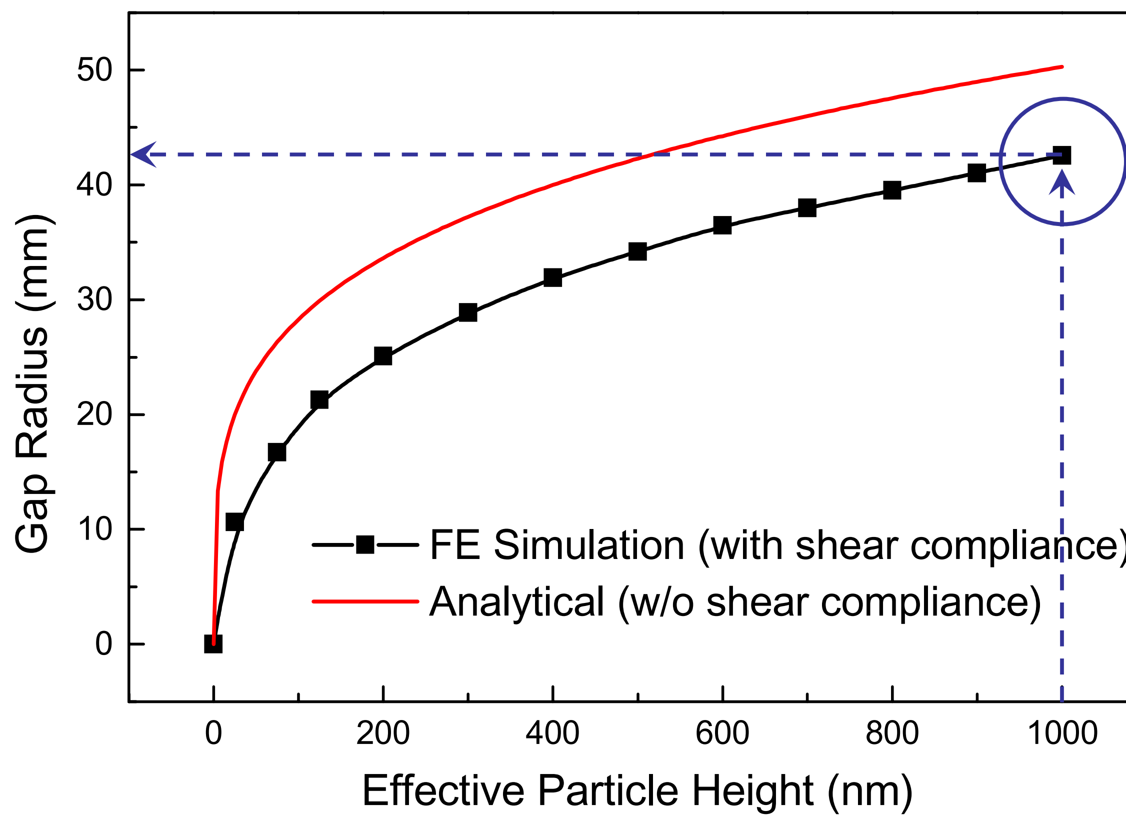


l = reticle length (152 mm)

t = reticle thickness (6.35 mm)

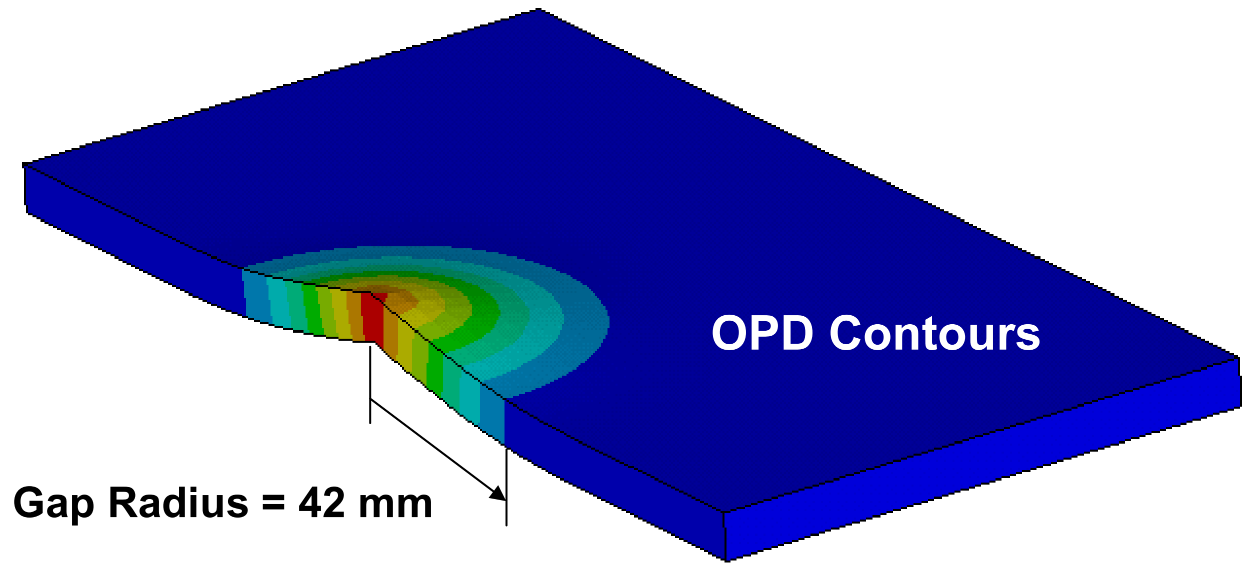
p = chucking pressure (15 kPa)

For a relatively thick EUVL reticle, FE simulations can be used to assess the additional effects of shear compliance when modeling the global response of the reticle.



Modeling the Macro Response
FE Simulation

- The reticle is assumed to be clamped to a perfectly flat and rigid chuck.
- Maximum OPD of the reticle is equal to the "effective particle height," i.e., the residual height of the particle after it has been crushed and/or embedded into the reticle.



Effective Particle Height = 1.0 μm

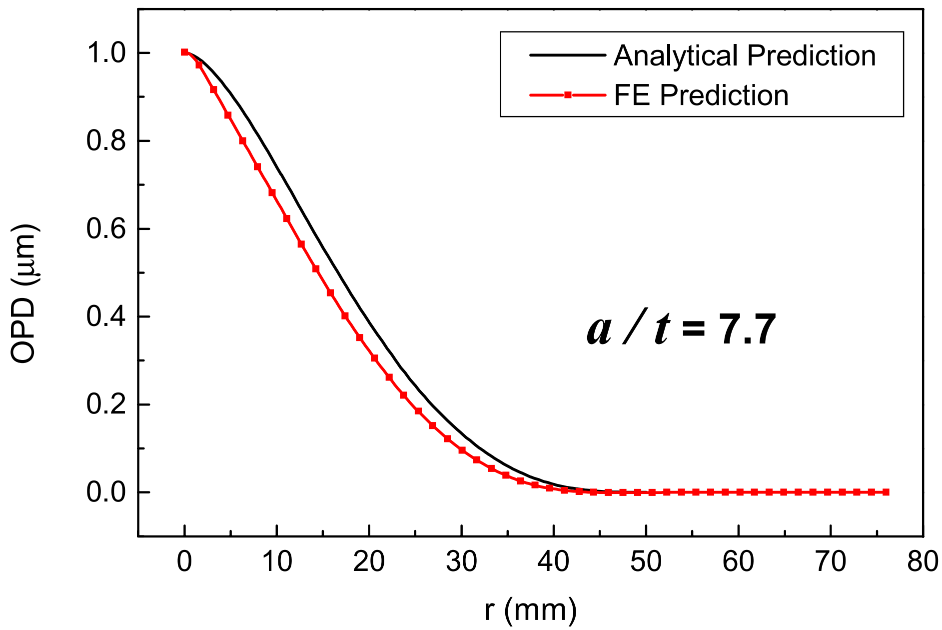
Max. OPD of reticle = 1.0 μm

Reticle length:	**152 mm**
Reticle thickness:	**6.35 mm**
Chucking pressure:	**15 kPa**

"Macro" Response of ULE® Reticle

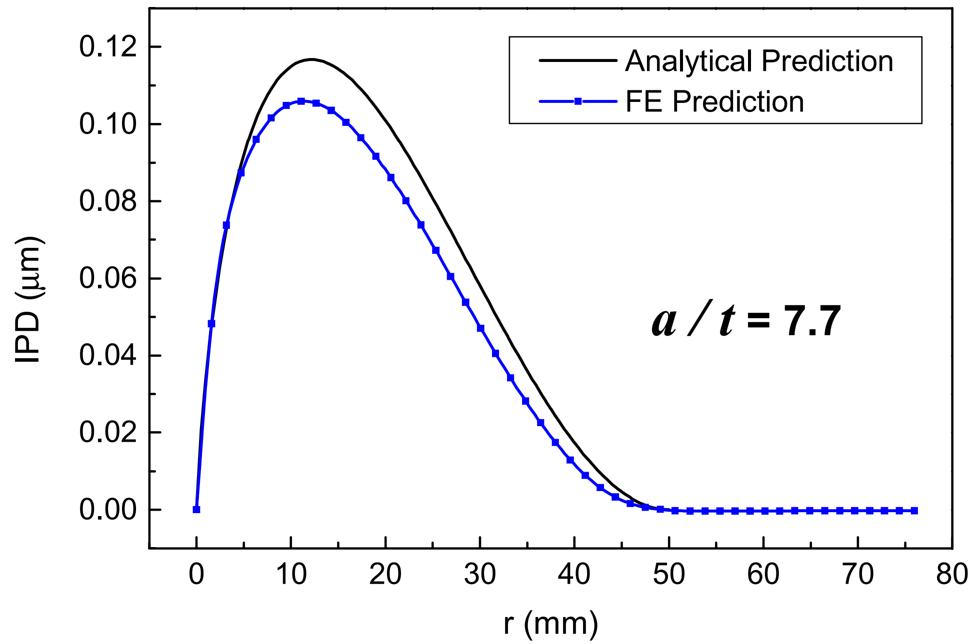
Reticle Top Surface

OPD Profile



$$OPD = h\left[1 + 4\left(\frac{r}{a}\right)^2 \ln\left(\frac{r}{a}\right) - \left(\frac{r}{a}\right)^4\right]$$

IPD Profile



$$IPD = \frac{2thr}{a^2}\left[\left(\frac{r}{a}\right)^2 - 2\ln\left(\frac{r}{a}\right) - 1\right]$$

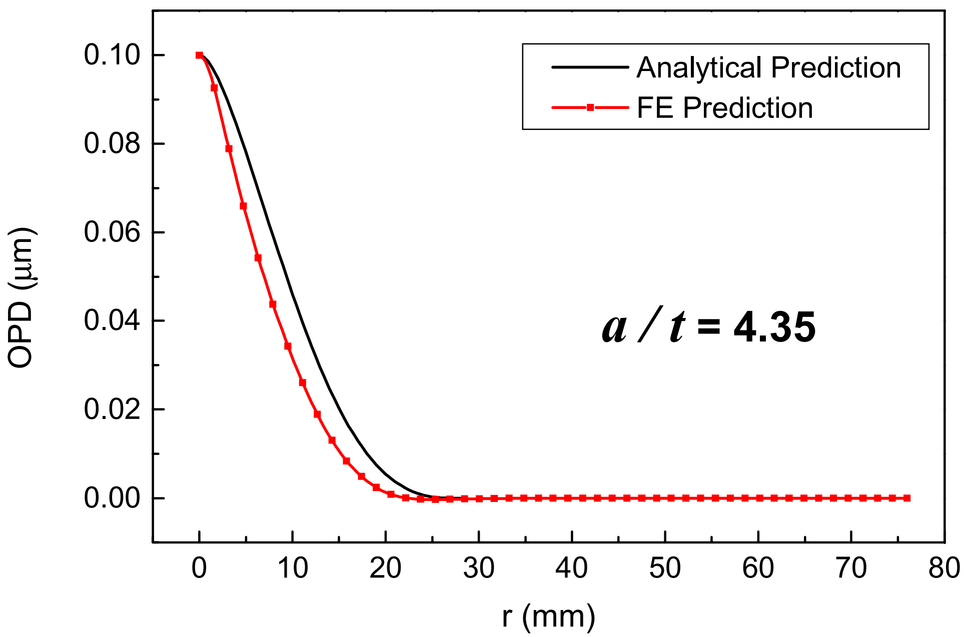
Effective Particle Height = 1.0 µm
Chucking pressure = 15 kPa

Reticle length = 152 mm
Reticle thickness = 6.35 mm

"Macro" Response of ULE® Reticle

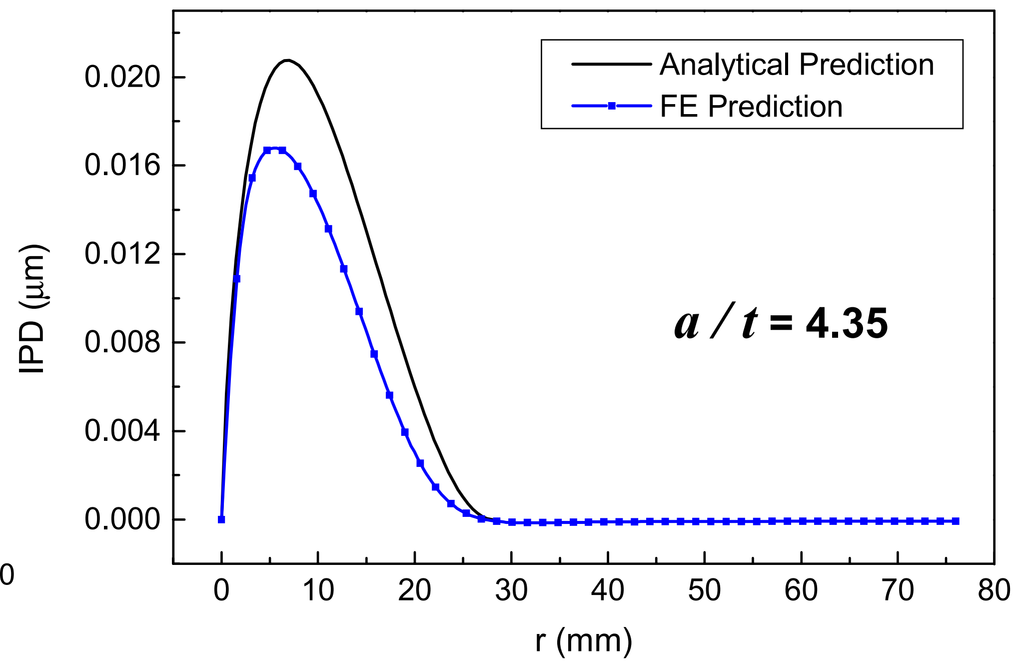
Reticle Top Surface

OPD Profile



$$OPD = h\left[1 + 4\left(\frac{r}{a}\right)^2 \ln\left(\frac{r}{a}\right) - \left(\frac{r}{a}\right)^4\right]$$

IPD Profile

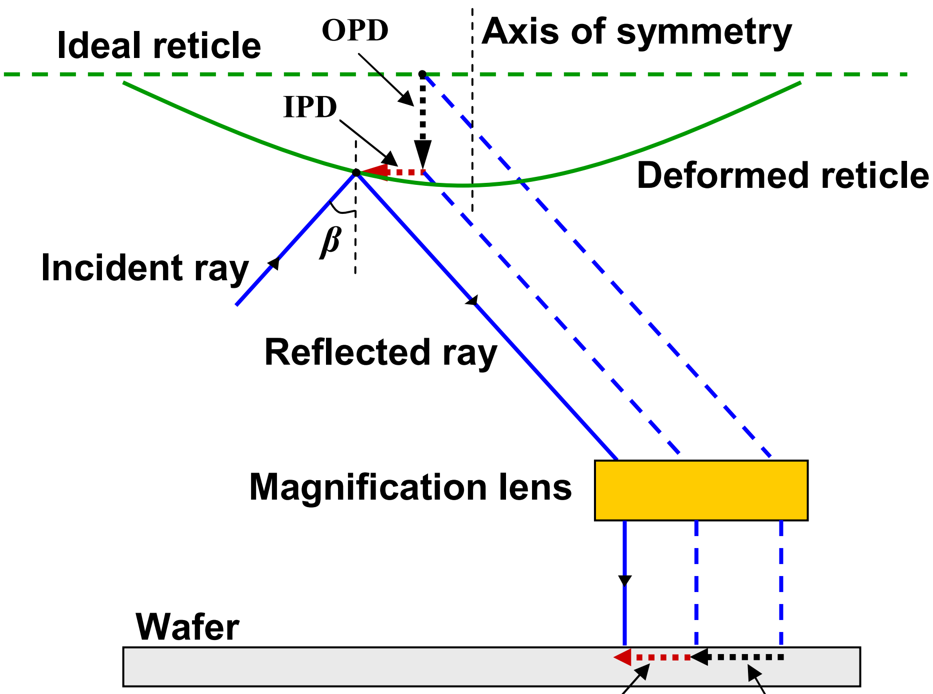


$$IPD = \frac{2thr}{a^2}\left[\left(\frac{r}{a}\right)^2 - 2\ln\left(\frac{r}{a}\right) - 1\right]$$

Effective Particle Height = 100 nm
Chucking pressure = 15 kPa

Reticle length = 152 mm
Reticle thickness = 6.35 mm

Particle-Induced IP Error



$$(\mathrm{IPE})_{\mathrm{Total}} = (\mathrm{IPE})_{\mathrm{IPD}} + (\mathrm{IPE})_{\mathrm{OPD}}$$

$$(\mathrm{IPE})_{\mathrm{IPD}} = \frac{\mathrm{IPD}}{\mathrm{M}}$$

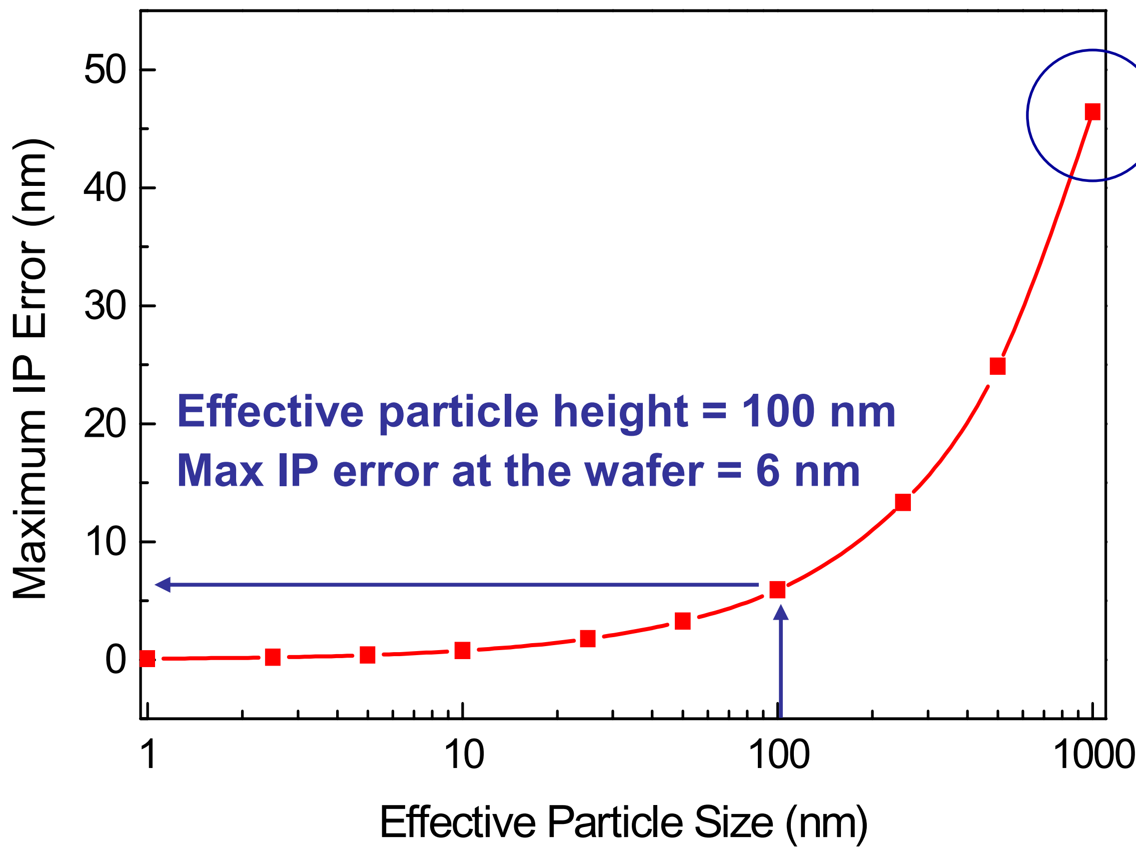
$$(\mathrm{IPE})_{\mathrm{OPD}} = \frac{\mathrm{OPD} \times \tan\beta}{\mathrm{M}}$$

Wafer defocus and reticle slope effects are not included

Prediction of Maximum IP Error

Results from Global FE Model

Total IP error (wafer-level): $(IPE)_{total} = (IPE)_{IPD} + (IPE)_{OPD}$



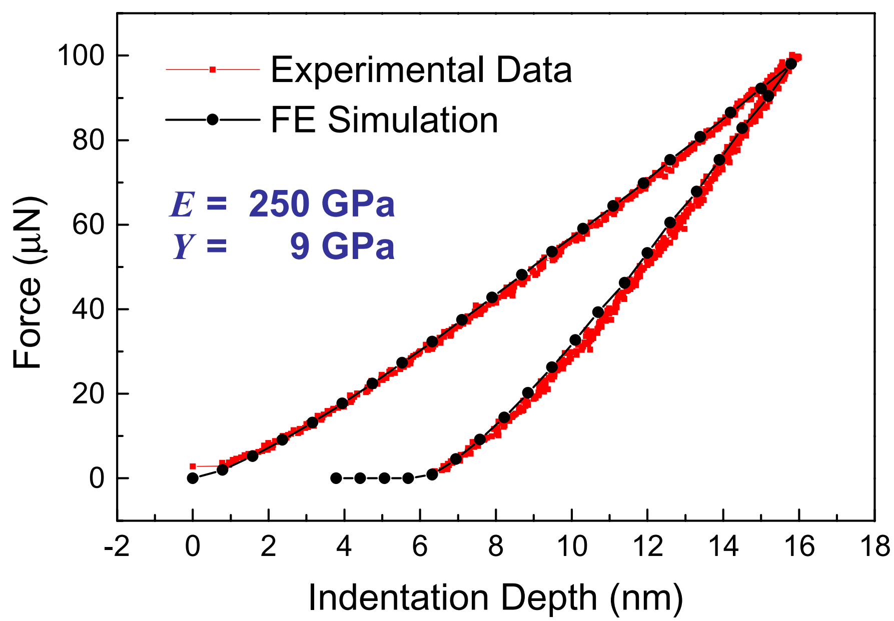
- Maximum absolute errors were obtained by combining the IPD and OPD contributions.
- Wafer defocus and reticle slope effects are not included.
- Image placement (IP) errors are primarily driven by OPD of the reticle.

“Micro” Response of the System

Nanoindentation Testing

- Micro- and nano-scale material properties differ from the bulk properties.
- Nanoindentation testing accompanied by FE simulations provide nano-scale nonlinear properties of the reticle, chuck, and particulates (i.e., ULE®, Zerodur®, deposited chrome, and dielectric materials).

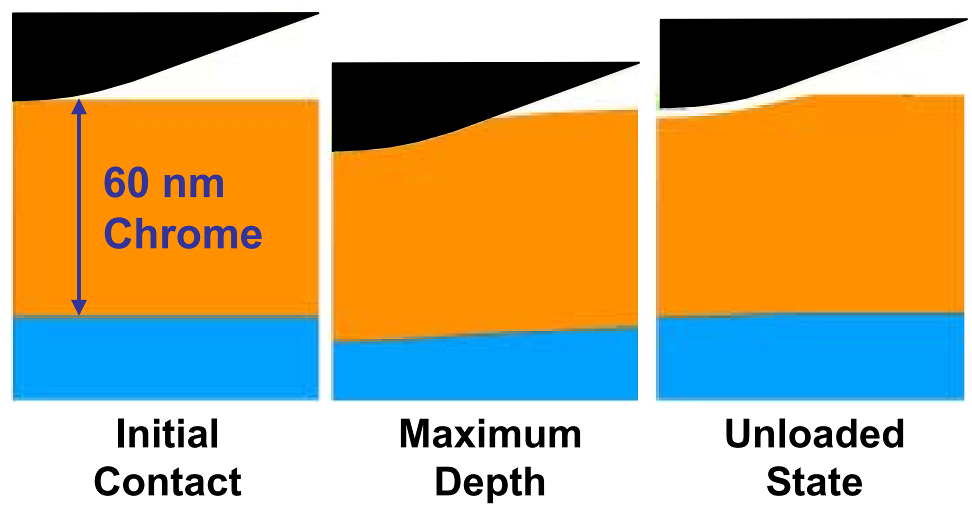
Force vs. Indentation Depth for Chrome on Fused Silica



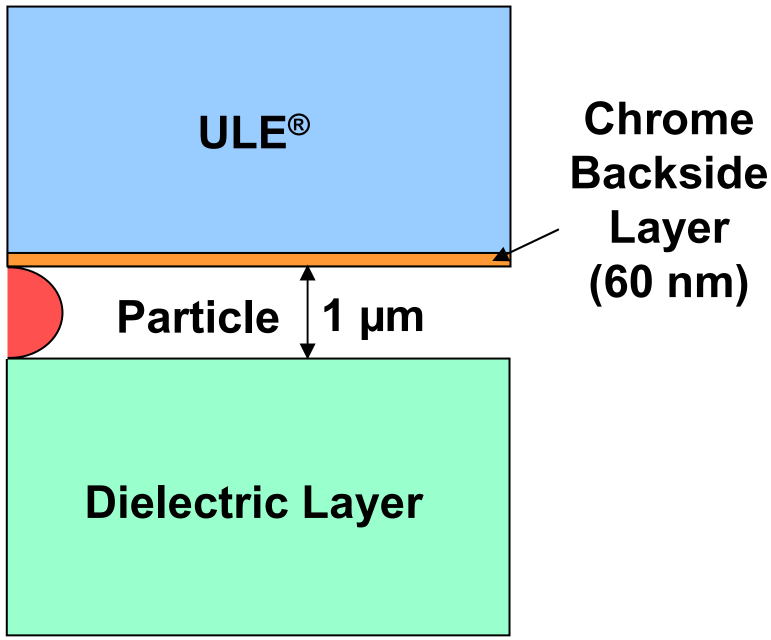
FE Simulation

Berkovich Tip Radius: 100 nm

Indentation Depth: 16 nm



Simulating the Micro Response
Axisymmetric Model

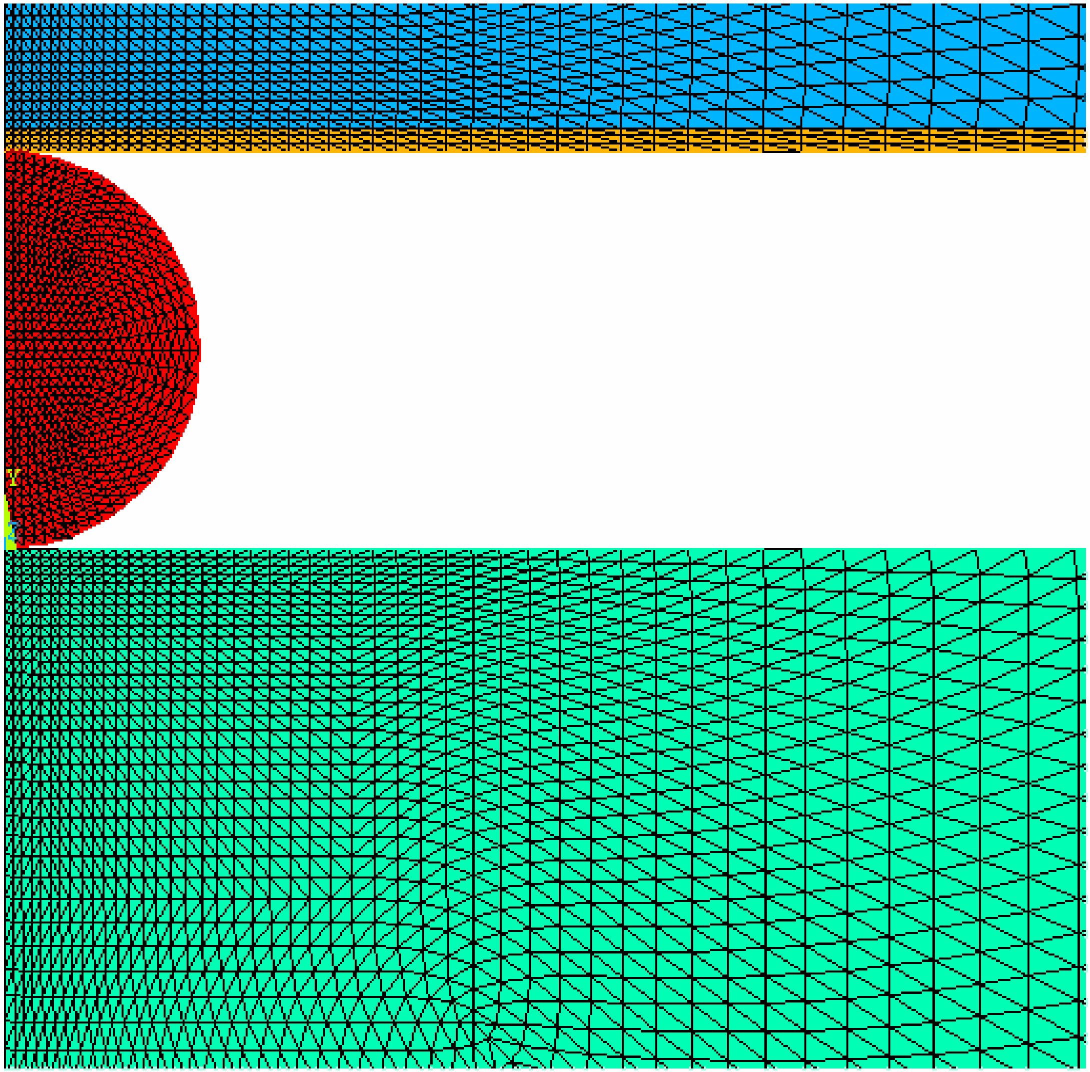


- The particle was assumed to be spherical with a diameter of 1.0 μm and of the same material as the dielectric layer.
- Material properties of the substrate and the backside layer were kept constant.
- The elastic-plastic properties were varied to illustrate the response.

Component	Material	Elastic Modulus (GPa)	Yield Strength (GPa)
Substrate	ULE®	66.3	8.5
Backside Layer	Chrome	250	9.0
Particle	Varied	100 to 400	5 to 15
Dielectric Film	Varied	100 to 400	5 to 15

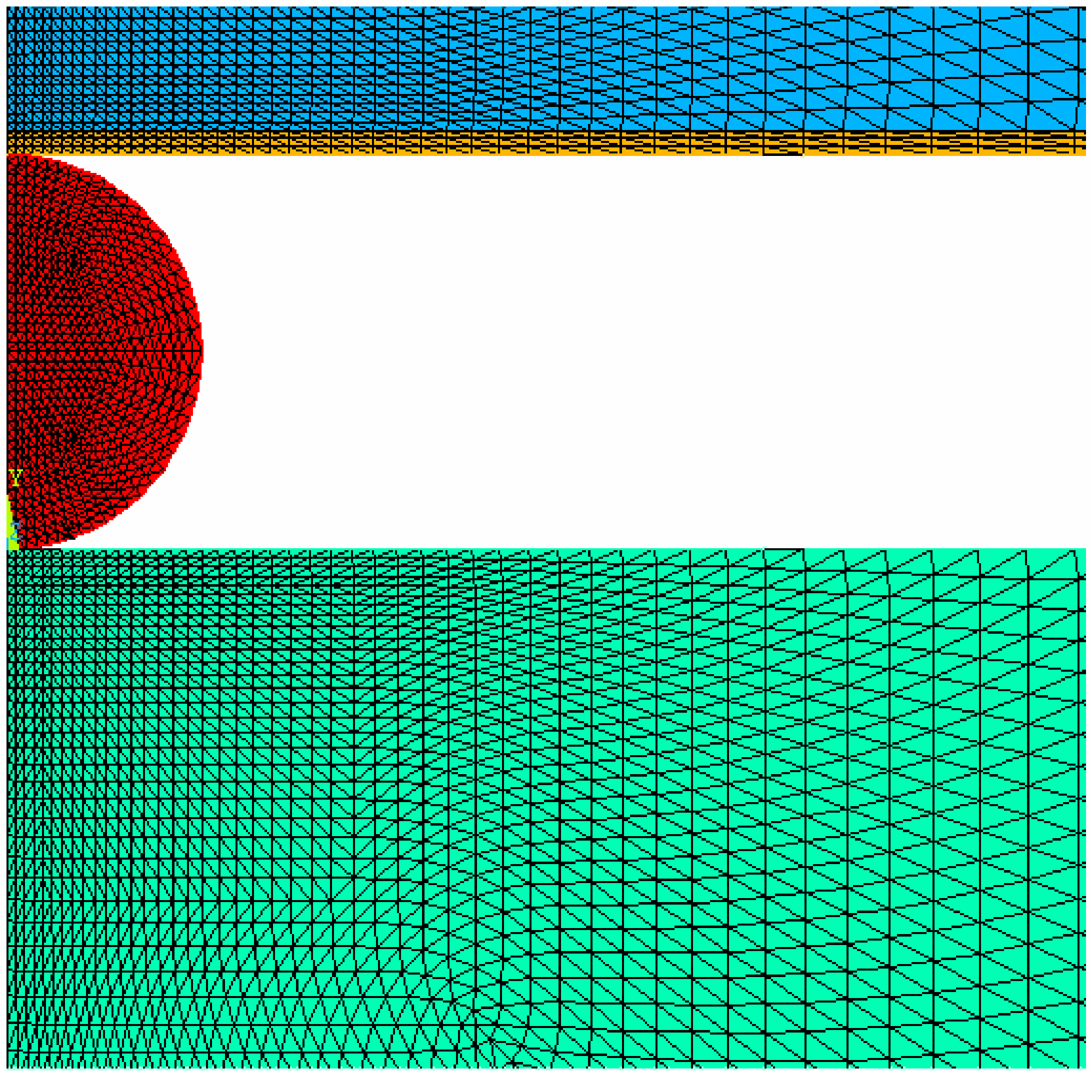
Modeling the "Micro" Response

Crushing of Particle



Modeling the “Micro” Response

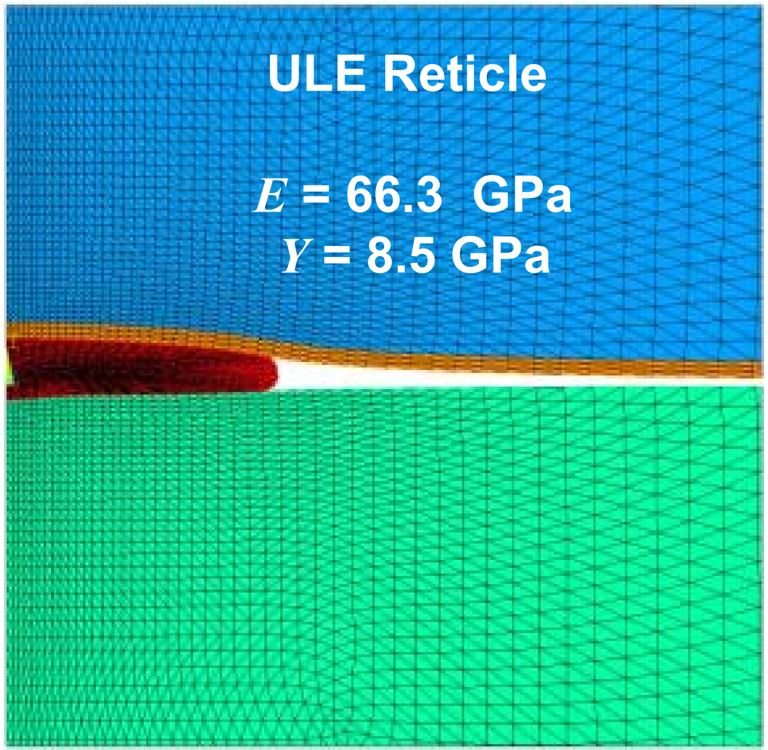
Embedding of Particle



FE Simulation Results

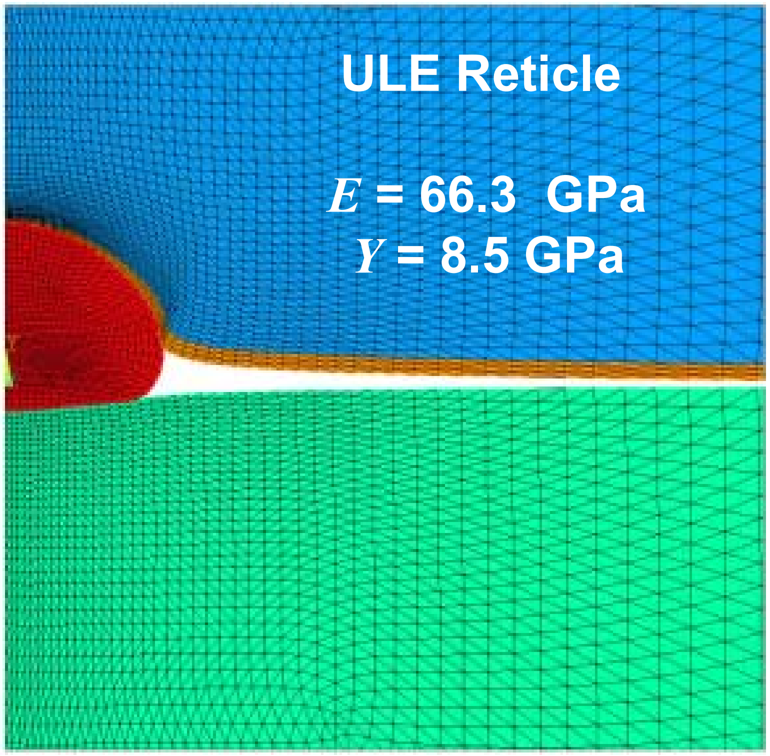
Effect of Dielectric / Particle Strength

Particle Crushing Dominates



Dielectric / Particle Properties
E = 300 GPa
Y = 5 GPa

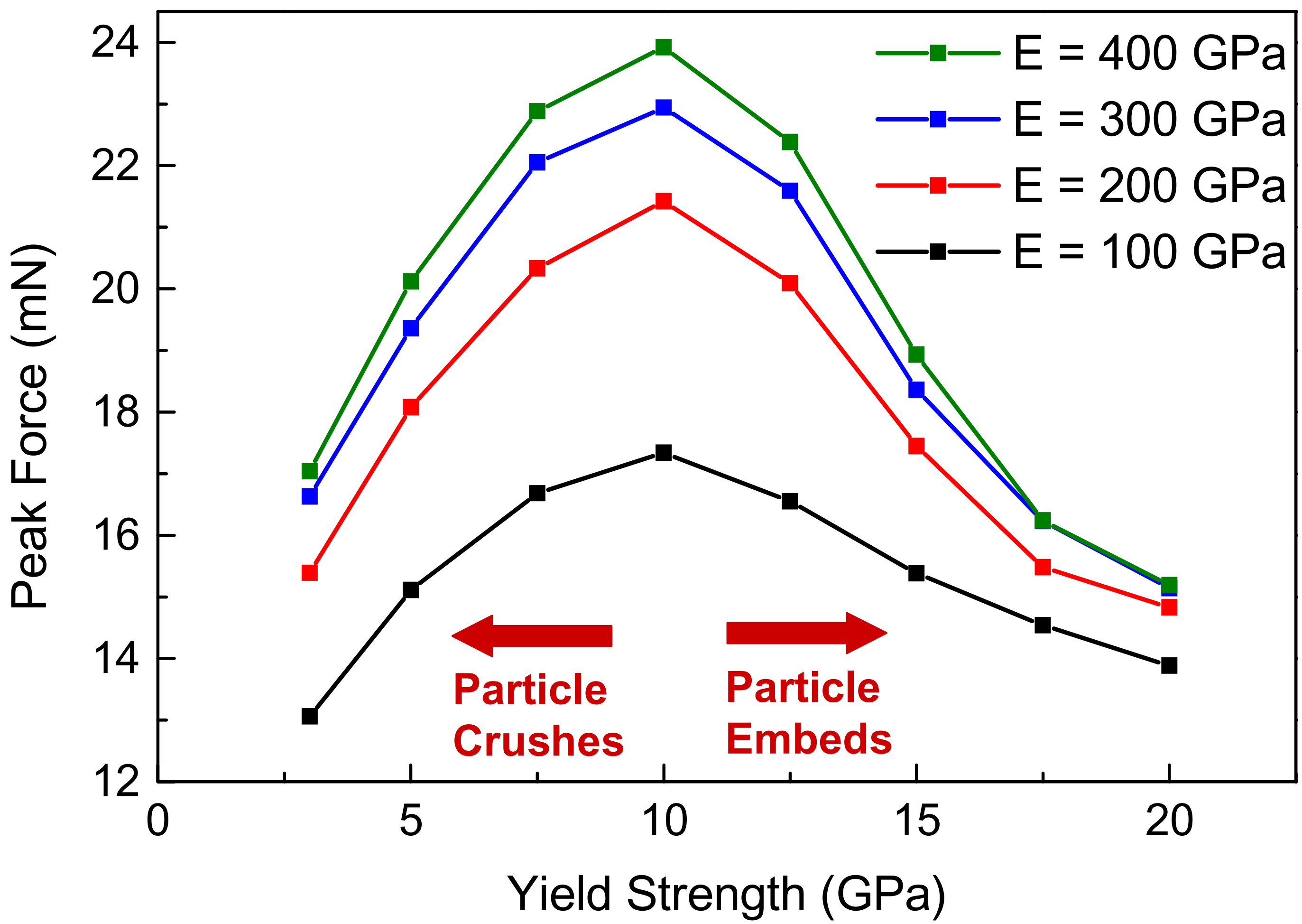
Particle Embedding Dominates



Dielectric / Particle Properties
E = 300 GPa
Y = 15 GPa

Peak Crushing / Embedding Force

FE Simulation Results



Comments on E-Chucking with Particles

- Image placement errors are driven by the residual height of particles after they have been crushed and / or embedded into the reticle.

- Macro-scale FE models predict the gap radius, OPD, and IPD of reticles while the micro-scale model predicts the crushing / embedding response of particles.

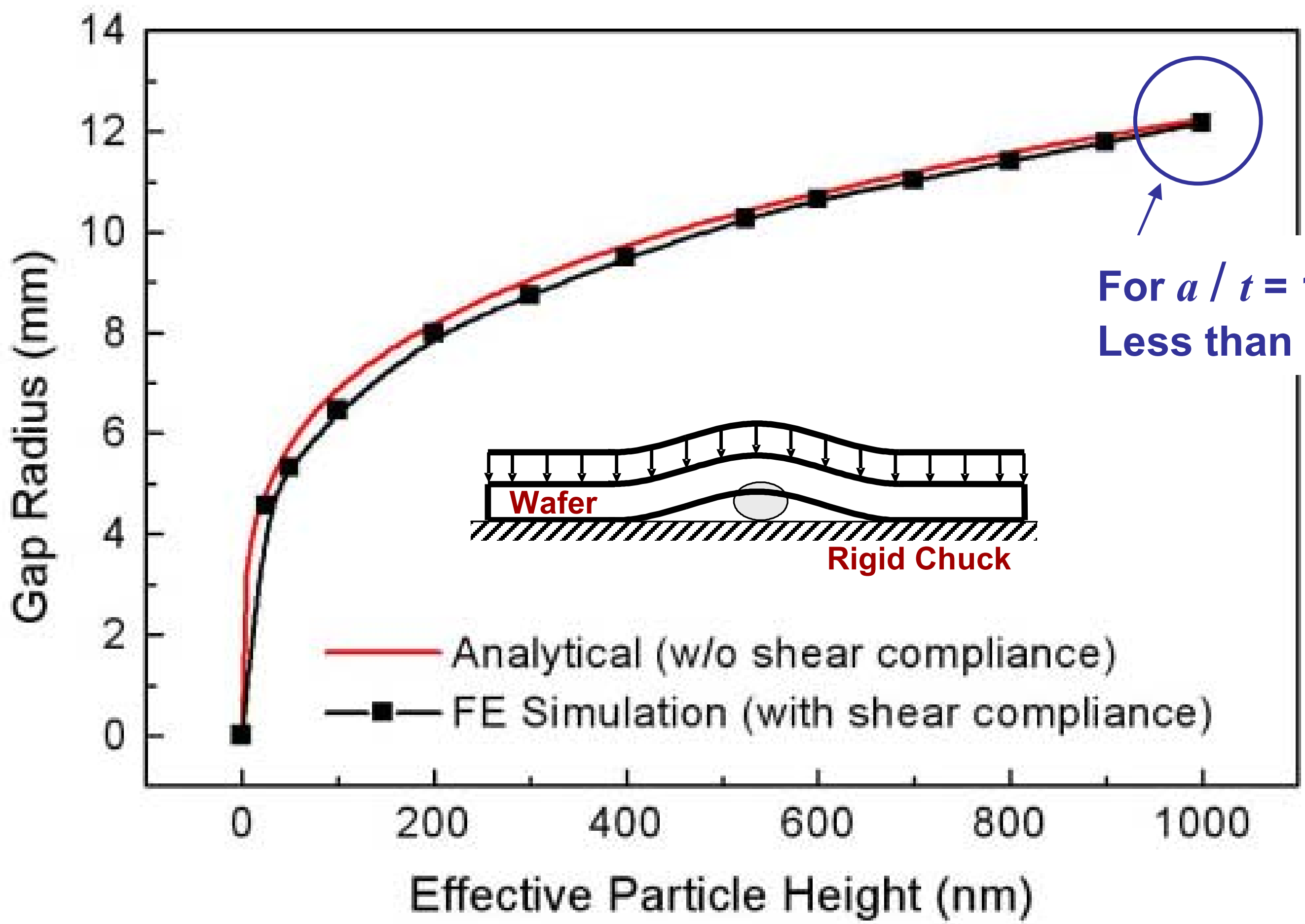
- In order to limit the IP error less than 6 nm, the effective particle height should be no more than approximately 100 nm (for a typical chucking pressure of 15 kPa).

- Pressure to embed particles will vary across the chuck surface due to reticle and chuck imperfections (i.e., nonflatness and surface roughness) complicating the EUVL chucking analyses.

Numerical Verification of Theory

FE Simulation of Wafer Chucking

- For illustrative purposes, consider chucking a silicon wafer, 725 μm thick, with a uniform pressure of 15 kPa. The chuck is assumed to be rigid.



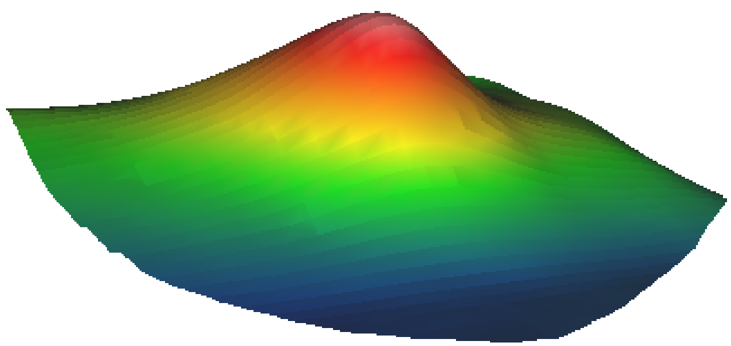
For $a / t = 17$
Less than 1% error

Experimental Verification of Theory

Electrostatic Chucking of a Silicon Wafer

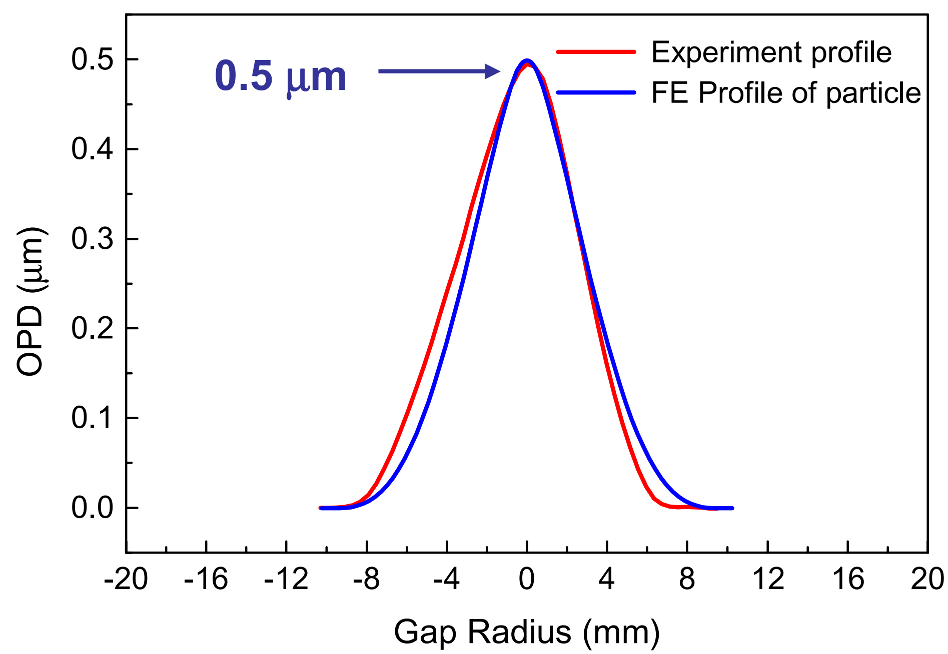
- **A silicon wafer (t = 725 μm) with a lithographically-defined particle (0.5 mm × 0.5 mm, h = 0.5 μm) was chucked electrostatically.**

Interferometric Measurement of OPD



3-D profile of the wafer top surface (circular area with diameter of 19 mm). Peak-to-valley value is 0.49 μm.

Comparison of Wafer OPD Experiment vs. Simulation



Ref: K. Turner and S. Veeraraghavan, UW-CMC