Comparison of Coulombic and Johnsen-Rahbek Electrostatic Chucking for EUV Lithography

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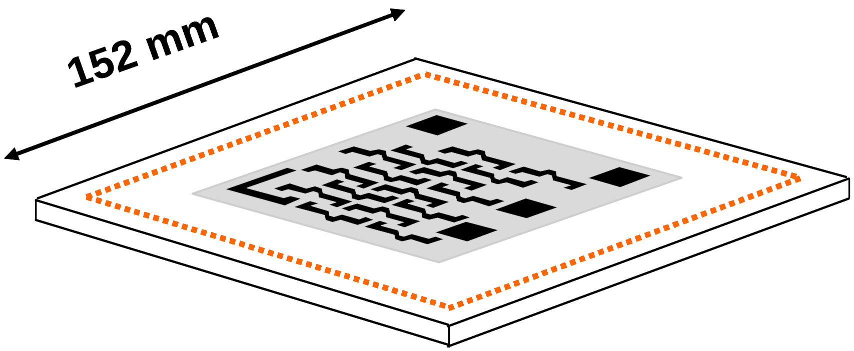
Presentation Outline

- Motivation and objectives
- Characteristics of electrostatic chucking
- Finite element (FE) model description and simulation results
- Chuck comparisons and conclusions
  - Clamping performance
  - Effects of reticle non-flatness
  - Effects of particle entrapment

EUVL Flatness Requirements
SEMI Standard P37 and P40

- **The flatness of the EUVL mask is a key issue to minimize image placement errors due to non-telecentric illumination.**
- **Achieving this level of flatness requires the use of an electrostatic chuck to hold the reticle.**

Specifications in the EUVL Mask Standard (SEMI P37):



Quality Area = 142 mm × 142 mm

Frontside and Backside in Quality Area (QA):

~ 30 - 100 nm *p-v* flatness

Low Order Thickness Variation (LOTV) in QA:

~ 30 - 100 nm *p-v* flatness

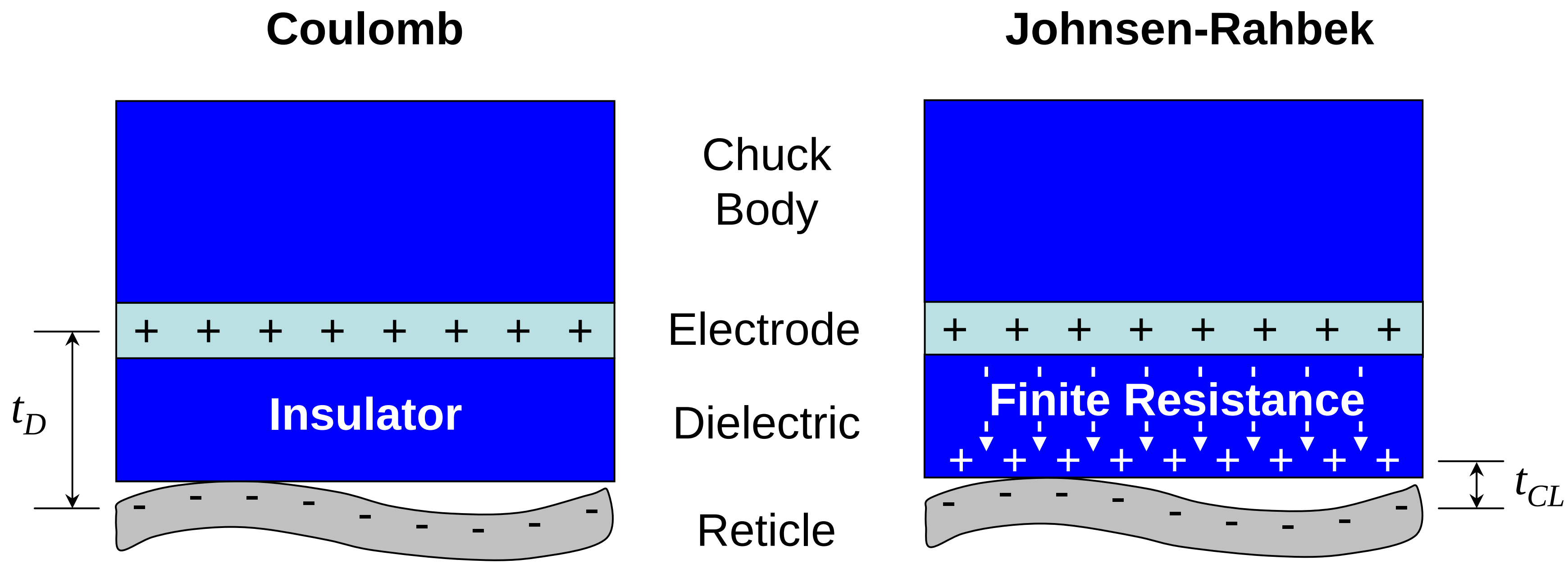
Specifications in the EUVL Mask Chucking Standard (SEMI P40):

-- **stiffness ≥ 30 kN-m**

-- **flatness ≈ 50 nm (*p-v*)**

Electrostatic Chucking

Types of Chucks



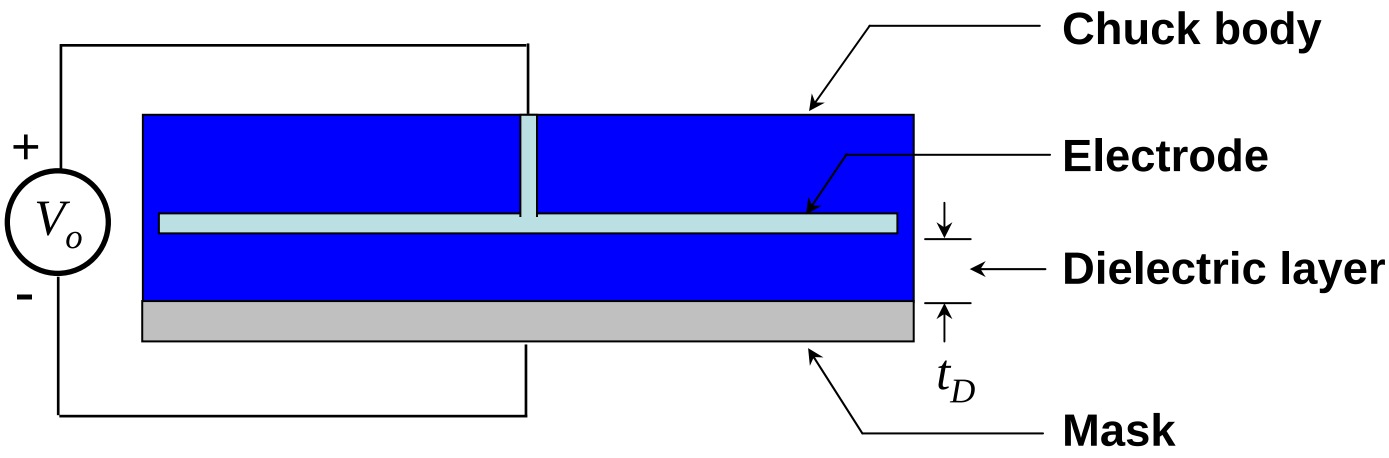
- **Type of chuck is characterized by the dielectric material and the resulting mechanism of force generation.**
- **Chucks can be either monopolar or bipolar.**
- **Slab-type or pin-type based on the surface characteristics. A pin-type chuck is proposed to minimize the effects of particles.**

Coulomb Chuck

Schematic and Working Principle

Monopolar Chuck

$$P = \frac{F}{A} = \frac{\varepsilon_o V_o^{\,2} K^2}{2(t_D + K\delta)^2}$$



Bipolar Chuck

$$P = \frac{F}{A} = \frac{\varepsilon_o V_o^{\,2} K^2}{8(t_D + K\delta)^2}$$

P = **electrostatic pressure**

F = **electrostatic force**

A = **area of the electrode**

V_o = **applied voltage**

ε_o = **permittivity of free space (or air gap)**

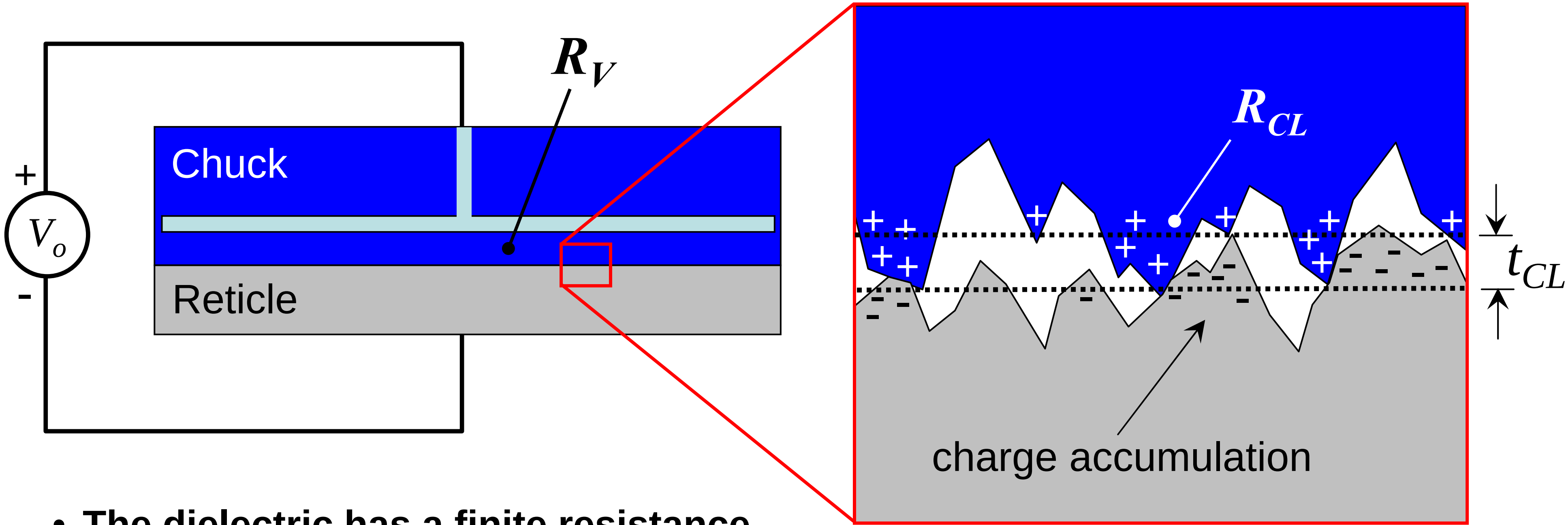
K = **relative permittivity of the dielectric material**

t_D = **the dielectric film thickness**

δ = **total gap between the backside of the mask and the dielectric surface**

Johnsen-Rahbek (J-R) Chuck

Schematic and Working Principle



- **The dielectric has a finite resistance.**
- **Current flowing through the dielectric and the substrate creates a charge layer at the dielectric-substrate interface (contact layer thickness t_{CL}), yielding a strong attractive force.**

t_{CL} = contact layer thickness (mean charge separation distance)
R_V = volume resistance of the dielectric
R_{CL} = effective resistance of contact layer

t_{CL} is related to surface roughness

Johnsen-Rahbek Chuck
Phenomenological Model

$$P = \frac{\varepsilon_0 V_0^2}{2}\left[\underbrace{\left(\frac{K}{t_D + K(\delta + t_{CL})} \right)^2}_{\text{Coulomb term}} + \alpha \underbrace{\left(\frac{(R_{CL}/R_V)}{t_{CL}\{1+(R_{CL}/R_V)\}} \right)^2}_{\text{J-R term}} \right]$$

ε_o: permittivity of free space
K: relative dielectric constant
R_{CL}: resistance of the contact layer
R_V: volume resistance of the dielectric material
δ: physical gap between reticle and dielectric
α: empirical factor of the nonuniform charge distribution on the interface

V_o: applied voltage
t_D: dielectric layer thickness
t_{CL}: contact layer thickness

In practice, R_{CL} and R_V can be measured; t_{CL} is then obtained from a measurement of pressure at a given voltage.

Often the Coulomb term is negligible, because $t_D >> t_{CL}$ in many cases.

Contrasting Chuck Properties

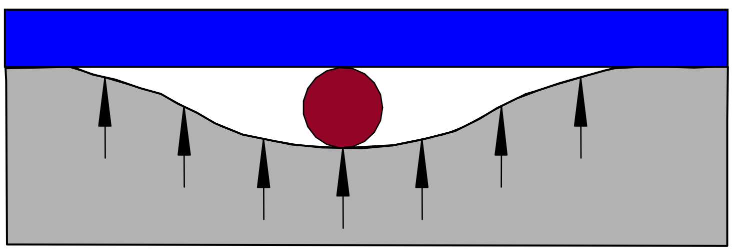
Coulomb Characteristics

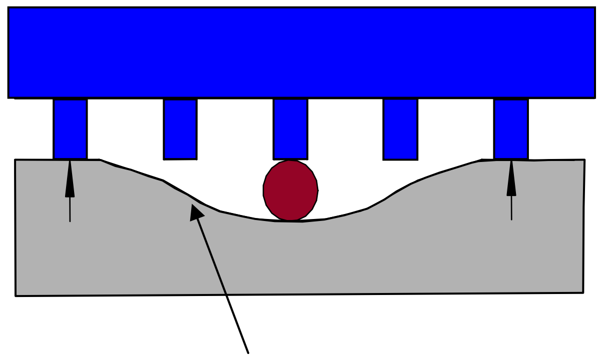
- **Clamping pressure exists everywhere between reticle and chuck.**
- **Effects of nonflat substrates or particles don't affect the clamping force very much (for small gaps).**

J-R Characteristics

- **J-R force depends on contact between substrate and dielectric.**
- **How effectively will it deal with non-flat substrates or the presence of particles?**

entrapped particle

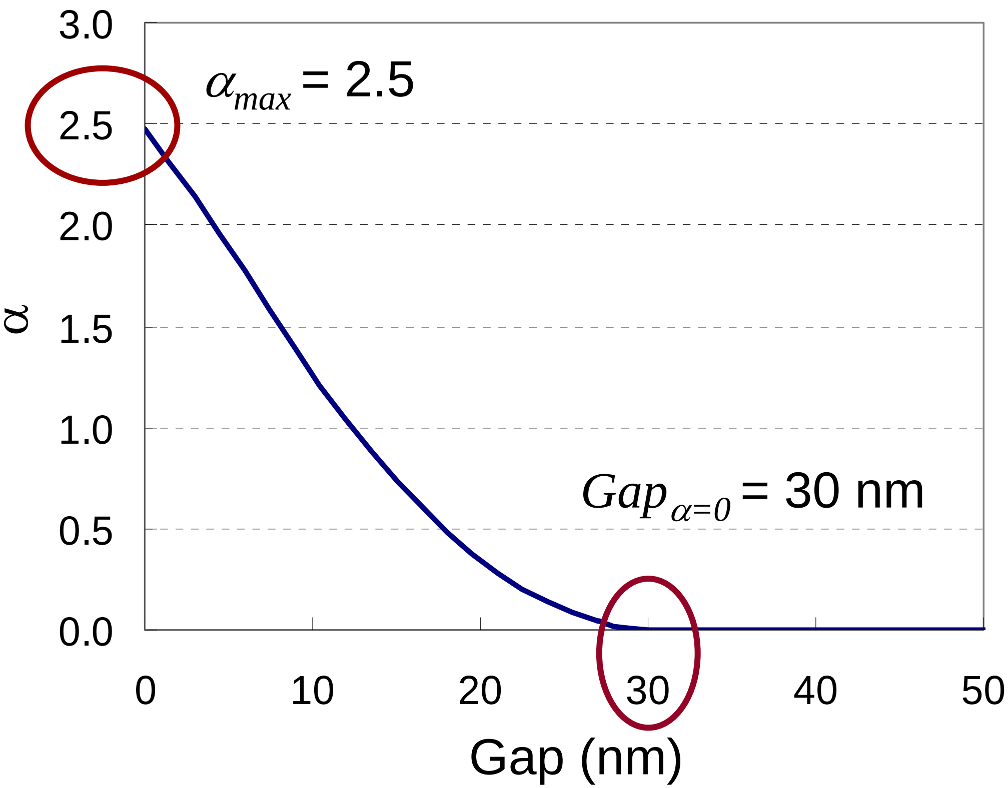




No J-R force here because no physical contact

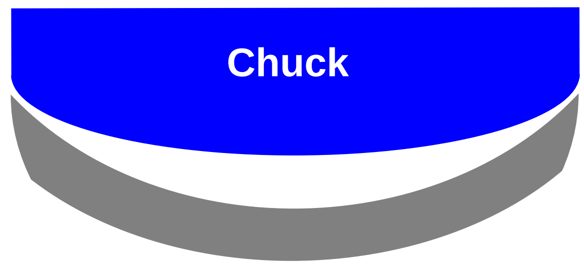
Nonuniform Distribution of Charge

- The empirical factor α represents the effect of the nonuniform distribution of charge on the interface surfaces.
- A relationship for α as a function of gap has been assumed for modeling purposes and was initially introduced to help with FE model convergence.
- However, short range forces exist over a comparable distance:
  - van der Waals ($\propto$ 1 / gap^3)
  - Casimir ($\propto$ 1 / gap^4)
- So this gap dependence is physically reasonable.

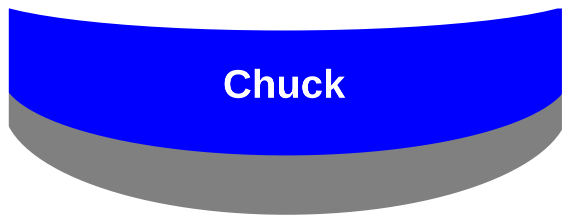


FE Simulation of Electrostatic Chucking

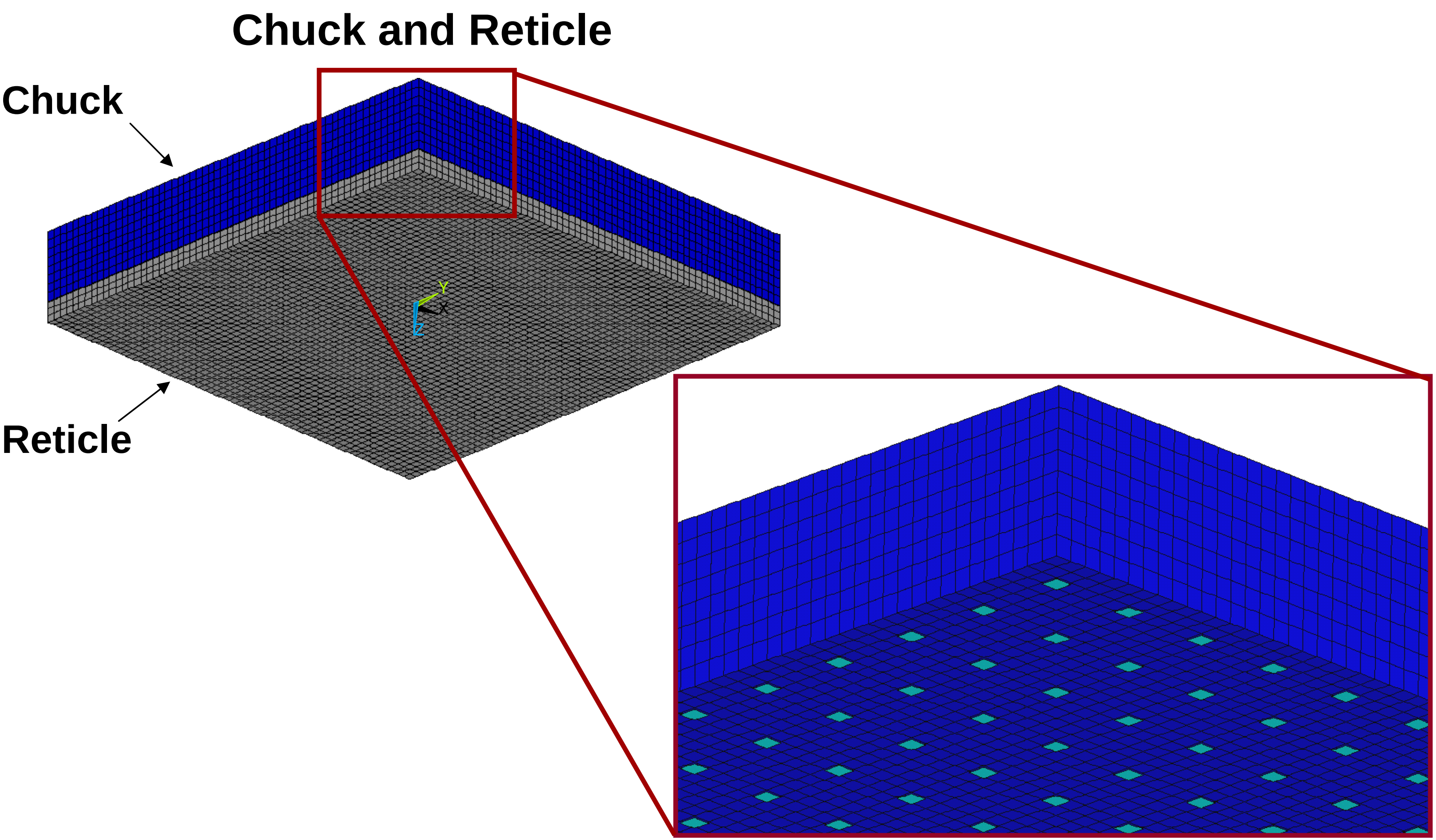
- Full 3-D FE models developed for both Coulomb and J-R chucks.
- Nonflatness measurements of the frontside and backside surfaces of the reticle, as well as the top surface of the chuck, are used as input.
- The non-flatness values are consistent with SEMI P37, P40
- Models include:
  - -- gap-dependent pressures
  - -- contact friction (μ = 0.2)
  - -- stiffness of the chuck
- FE simulations predict:
  - -- final flatness of reticle patterned surface
  - -- final flatness of reticle backside surface
  - -- final bow of the chuck
  - -- final gap between the reticle and chuck



Gravity neglected.



FE Electrostatic Chucking Models

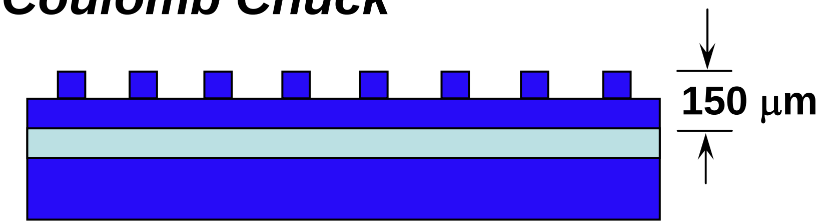


Chuck with Pin Array
(with no reticle)

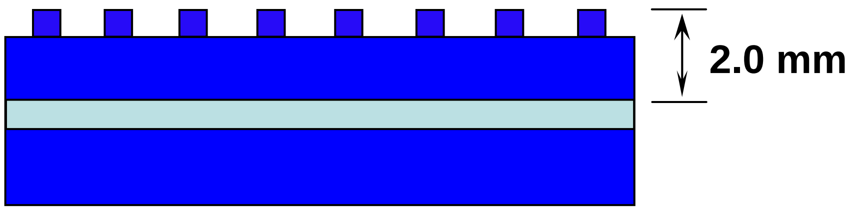
Chuck Geometry and Stiffness

Dielectric Layer

Coulomb Chuck



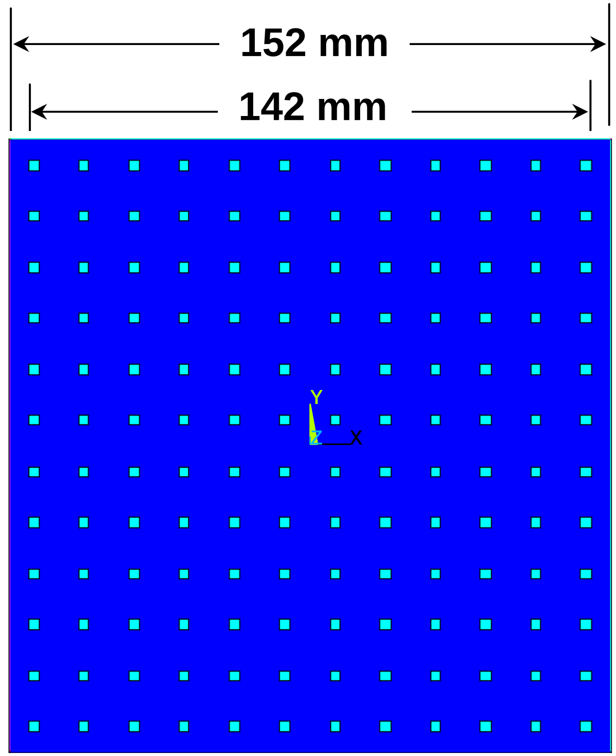
J-R Chuck



Chuck Body (Bulk Layer)

Effective stiffness = 380 kN-m
Elastic modulus = 380 GPa
Poisson's ratio = 0.24

Pin Layout



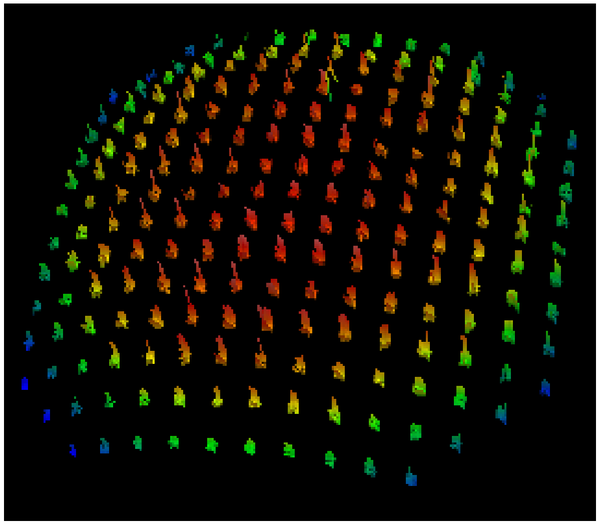
Pin coverage area: 142 mm × 142 mm
Pin size: 2.5 mm × 2.5 mm × 10 μm
Pin pitch: 12.67 mm
Pin coverage: 4%

Nonflatness of Electrostatic Chuck

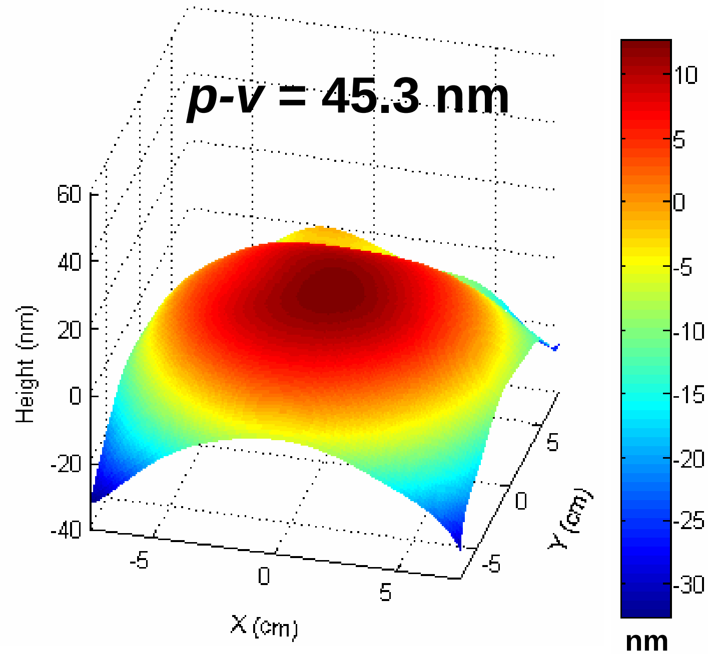
- Nonflatness of a Coulomb chuck was measured interferometrically.
- Measured chuck data scaled to meet the flatness specified in the EUVL chucking standard.

Coulomb Pin Chuck

Interferometric Measurement of Chuck Surface



Mathematical Fit

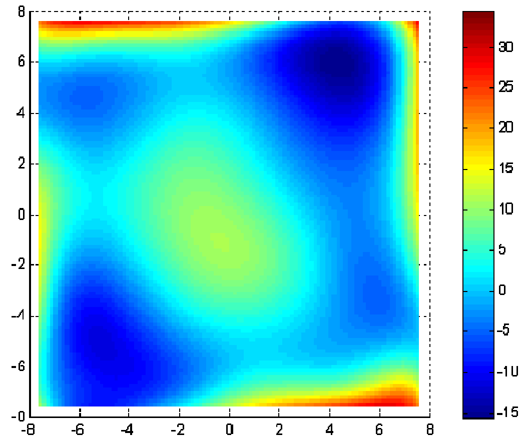


Interferometric measurement of the chuck surface is represented by Legendre polynomials and used as input into the FE models.

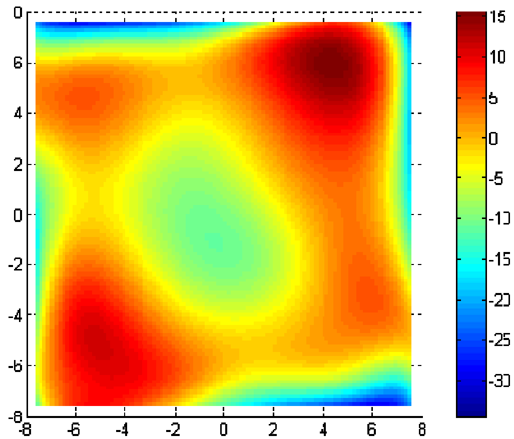
Polished Nonflatness of Reticle

Example Case

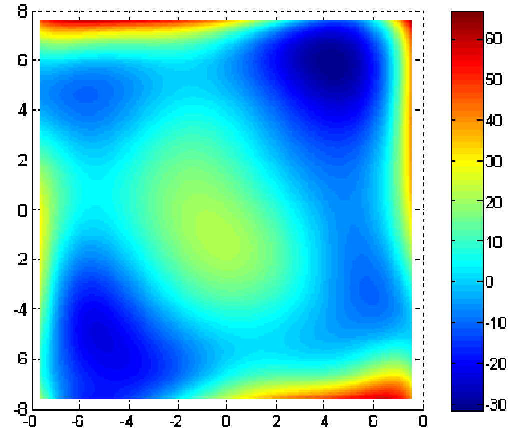
Frontside (FS)

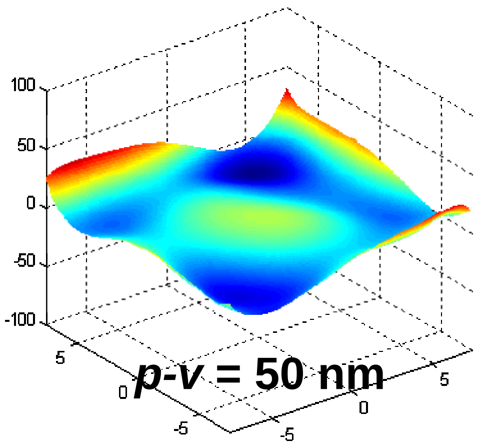


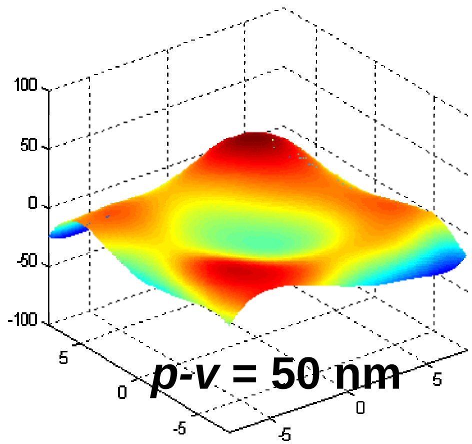
Backside (BS)



Thickness Variation







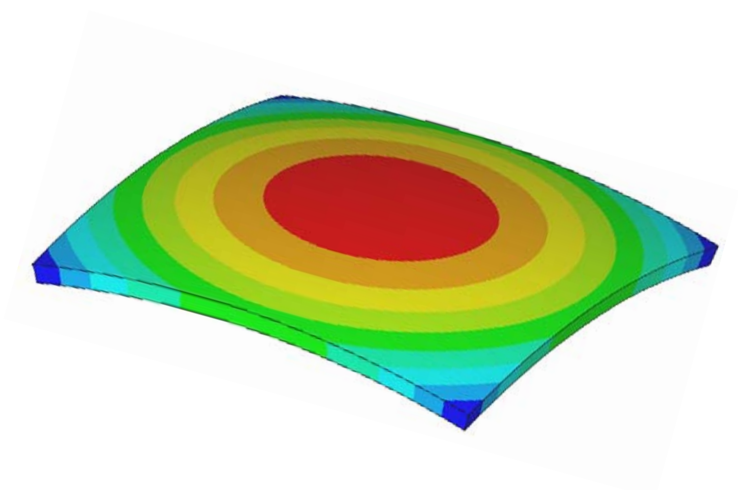
Max = 100 nm

- **Thickness variation was calculated by subtracting the backside flatness data from the frontside flatness data.**

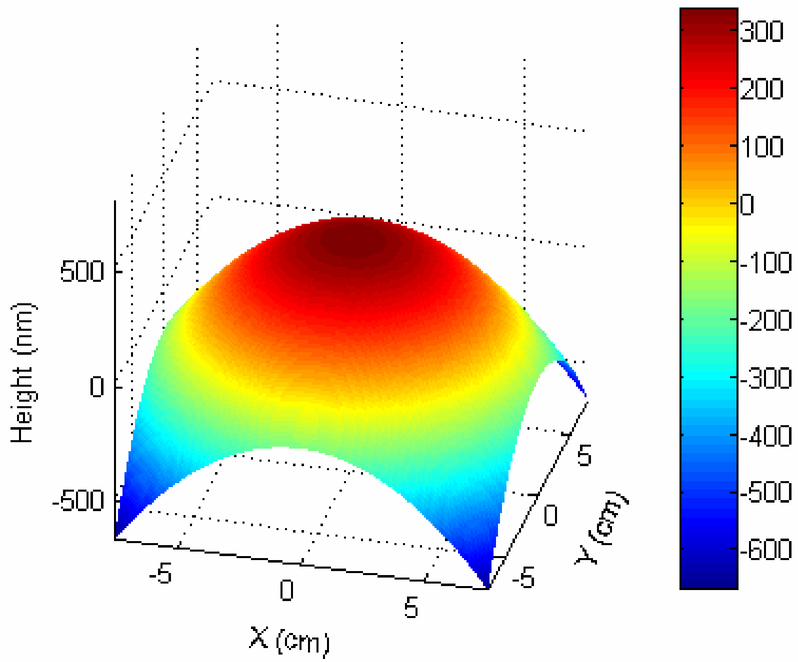
Interferometric measurements represented by Legendre polynomials are used as input into the FE models.

Simulating Reticle Multi-layer
Thin Film Deposition

- **After generating the FE model of the EUV substrate with the FS and BS nonflatness, the deposition of the ideal (uniform stress and thickness) layers is simulated.**
- **For the Example Case, the out-of-plane distortion (OPD) of the FS is 1000 nm *p-v*. The shape is convex due to the net compressive stress.**



FE Model illustrating OPD contours.



OPD Frontside (*p-v* = 1000 nm)

Pressure as a Function of Gap

Ave. Pressure of 3 kPa

Coulomb Chuck Parameters (insulating dielectric)

t_D =150 µm V_o = 633 V

t_{CL} = 1 µm K =10

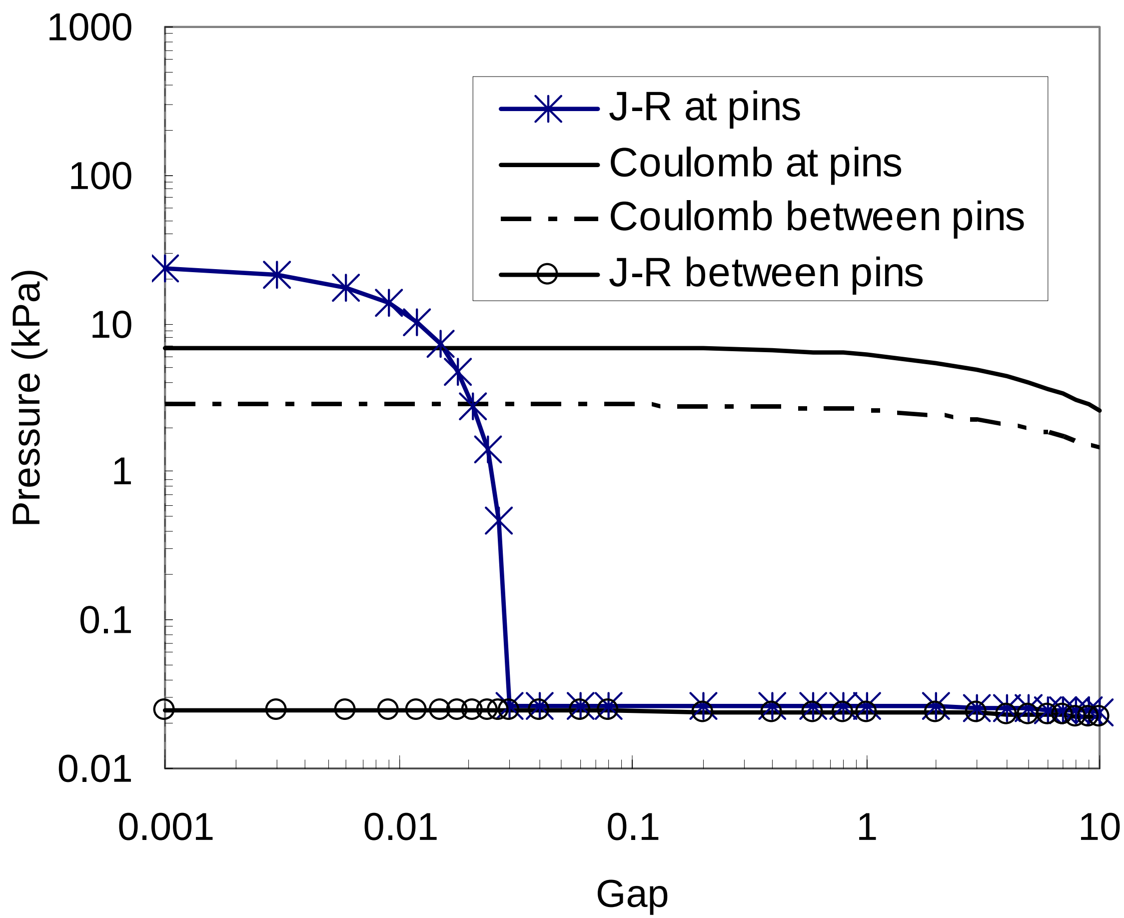
Pin height = 10 µm

J-R Chuck Parameters (finite resistance dielectric)

t_D = 2 mm V_o = 492 V

t_{CL} = 1 µm K = 10

Pin height = 10 µm R_{CL} / R_V = 0.2

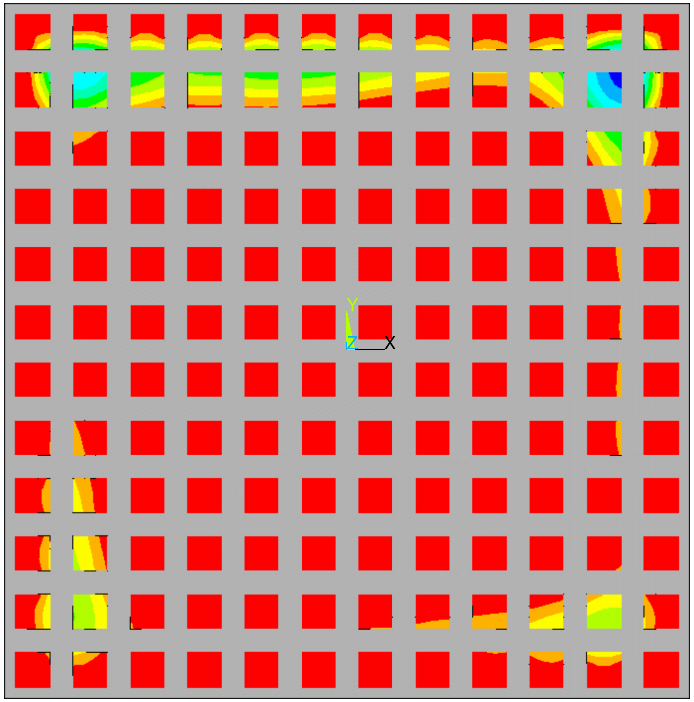


Final Resulting Gap

After Chucking with *P* = 3 kPa

Coulomb

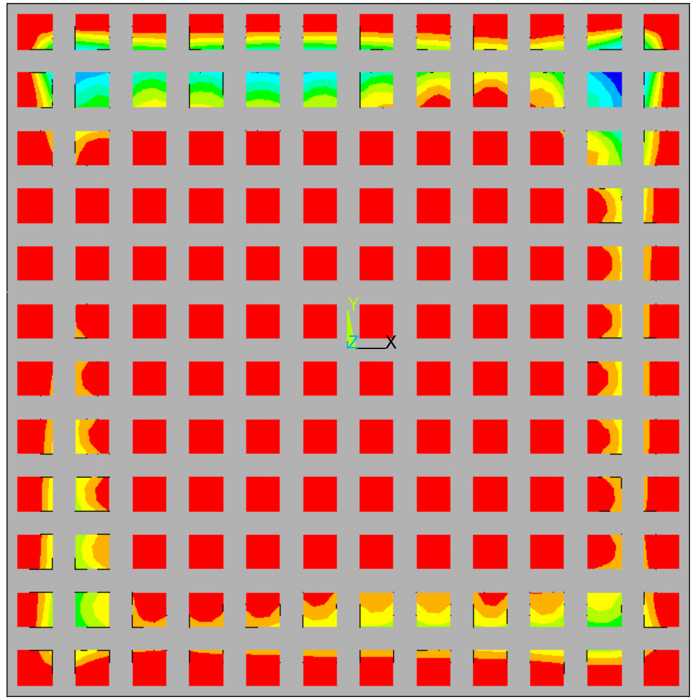
V_o = 633 V



Max gap = 6.8 nm

Johnsen-Rahbek

V_o = 492 V



Max gap = 6.3 nm

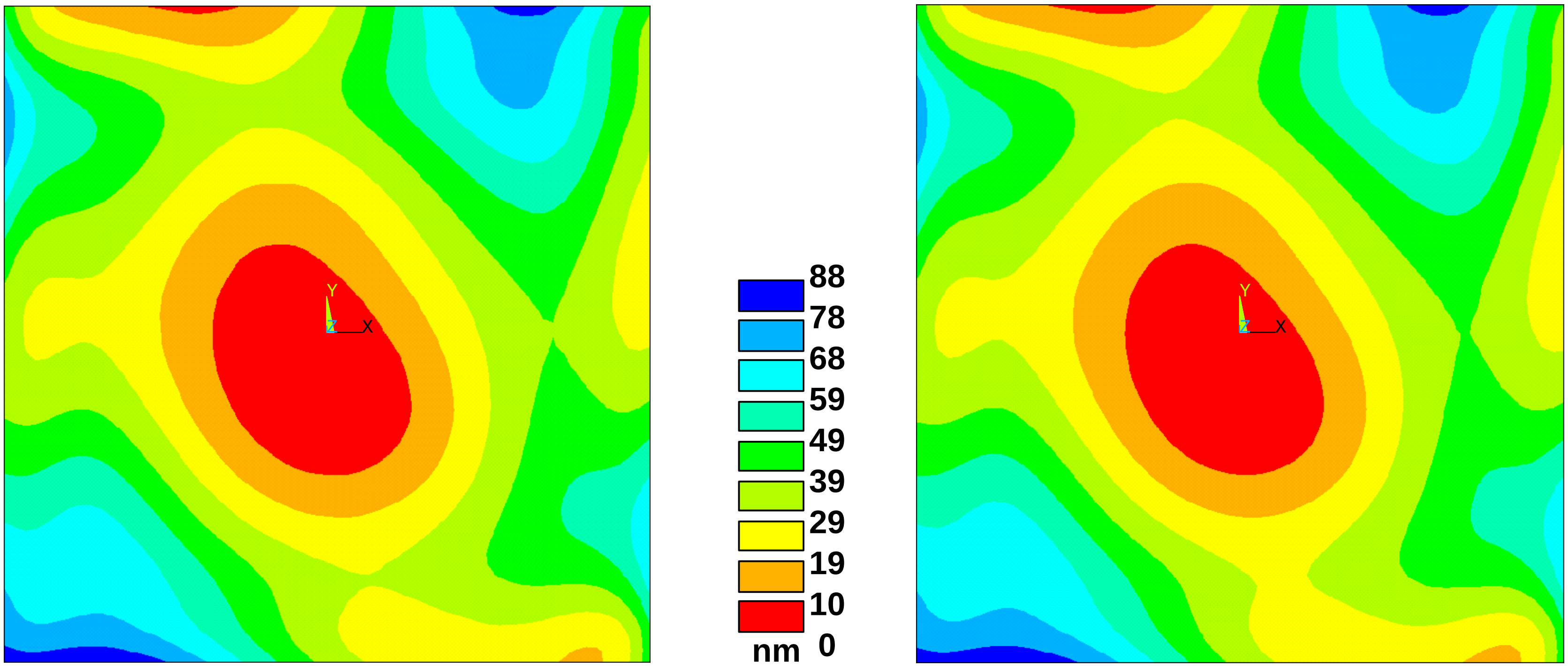
Gap Before Chucking
Max: 1 µm

Note: Size of pin areas exaggerated for display purposes.

Finite Element Reticle Pattern Surface
Nonflatness after Chucking with P = 3 kPa

Coulomb | **Johnsen-Rahbek**

V_o = 633 V | V_o = 492 V



p-v = 87.8 nm
QA *p-v* = 75.2 nm

p-v = 86.7 nm
QA *p-v*: 74.8 nm

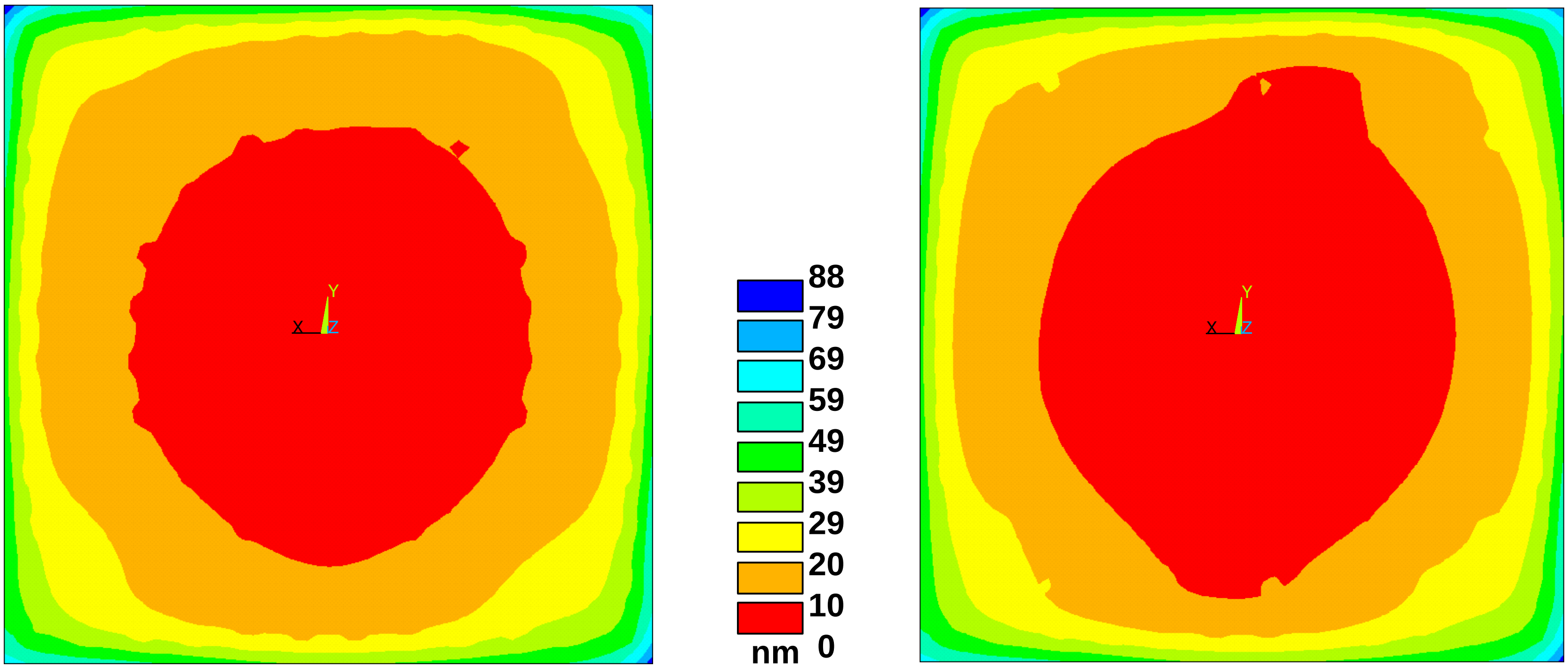
Before Chucking
p-v = 1.0 µm

Finite Element Reticle Chucking Surface

Nonflatness after Chucking with *P* = 3 kPa

Coulomb V_o = 633 V

Johnsen-Rahbek V_o = 492 V



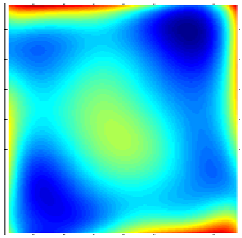
Coulomb: *p-v* = 88.3 nm
QA *p-v*: 47.8 nm

Johnsen-Rahbek: *p-v*: 85.5 nm
QA *p-v*: 47.2 nm

Before Chucking
p-v = 1.0 µm

Reticle Pattern Surface From Analytical Prediction

Thickness Variation + **Chuck Nonflatness** = **Reticle Flatness Prediction**



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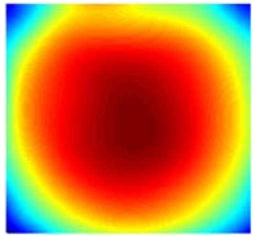

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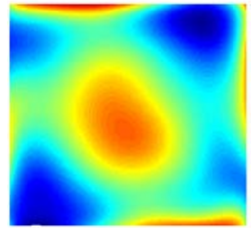
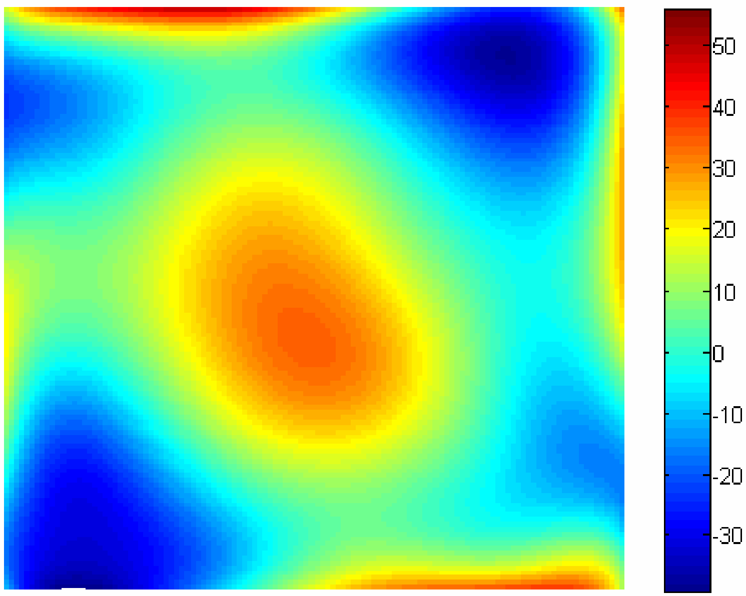
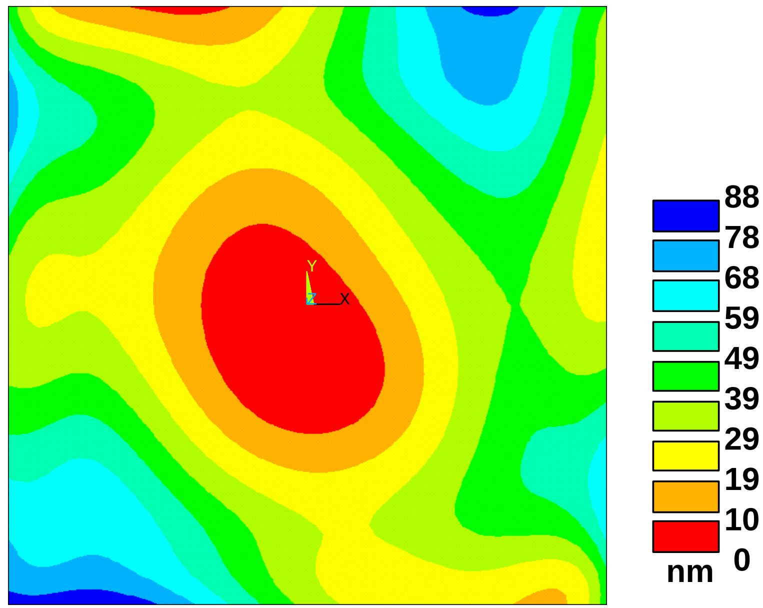


Complete Chucking Final Flatness (from interferometer measurements only)



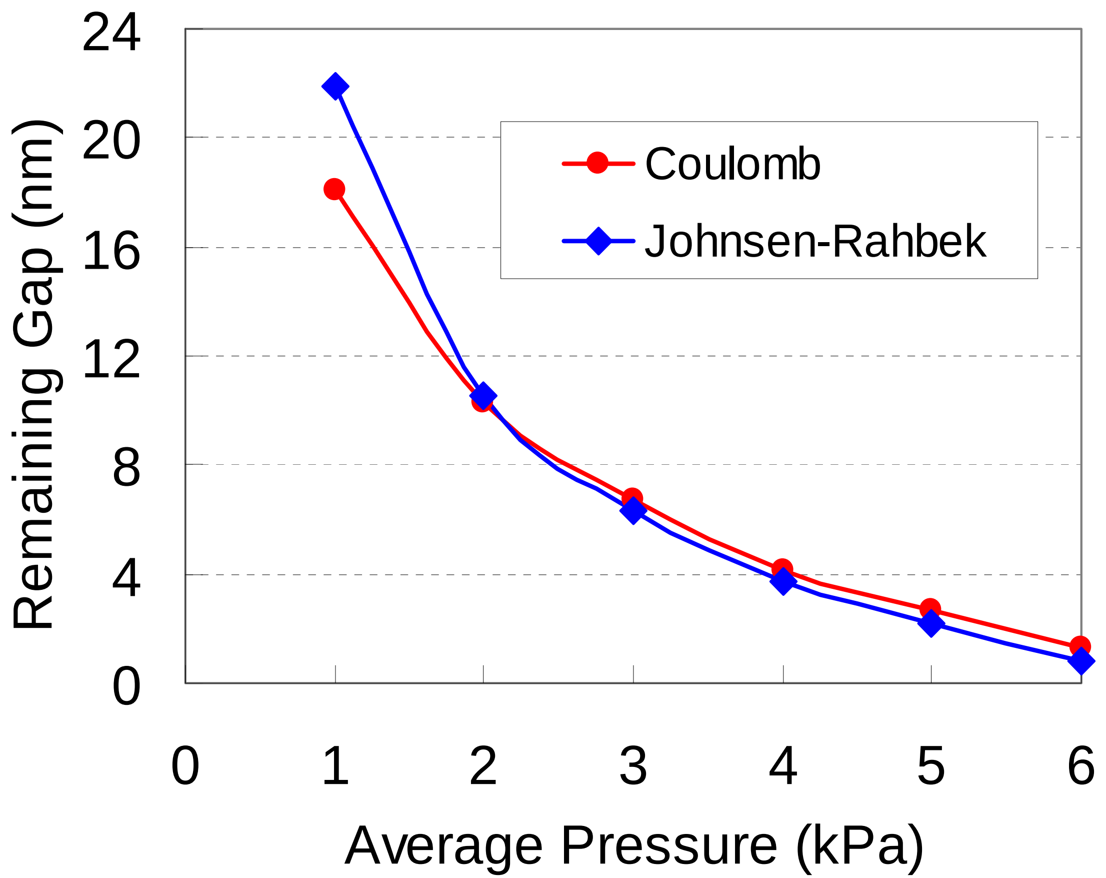
p-v = 94.9 nm

J-R Chuck Final Flatness (from FE model)



p-v = 86.7 nm

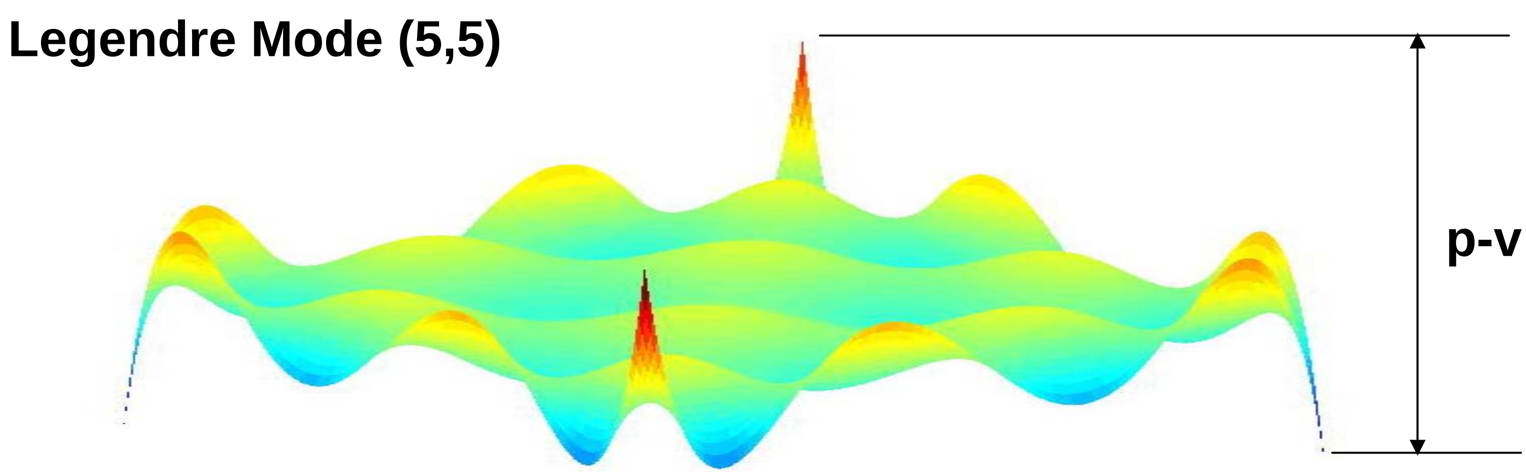
Summary of Simulation Results



- **Conclude there is little difference in basic clamping properties between Coulomb and Johnsen-Rahbek chucks**

Reticle Nonflatness Results

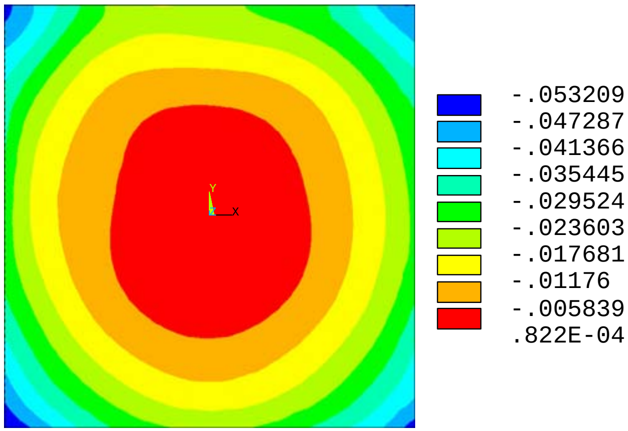
- The effects of reticle blank non-flatness (before application of the multi-layers) were also studied.
- Non-flat blanks were simulated using 2D Legendre polynomials. Below is Legendre mode (5,5).



Legendre Mode (5,5); p-v: 100 nm

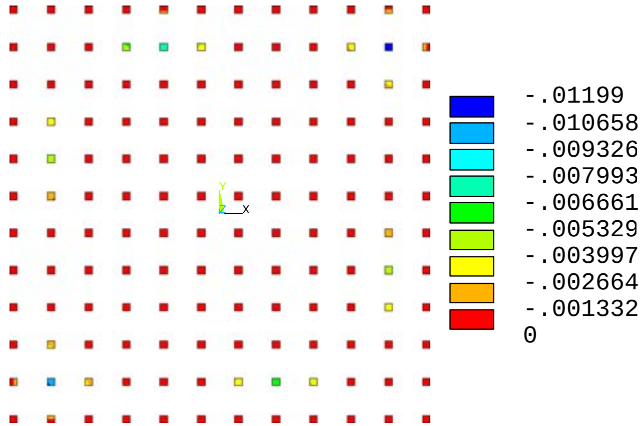
JR Chuck Model

Final Chuck Shape



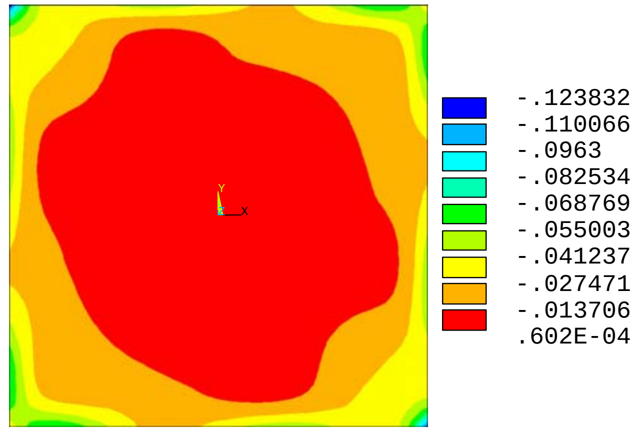
p-v: 53.3 nm

Residual Gap



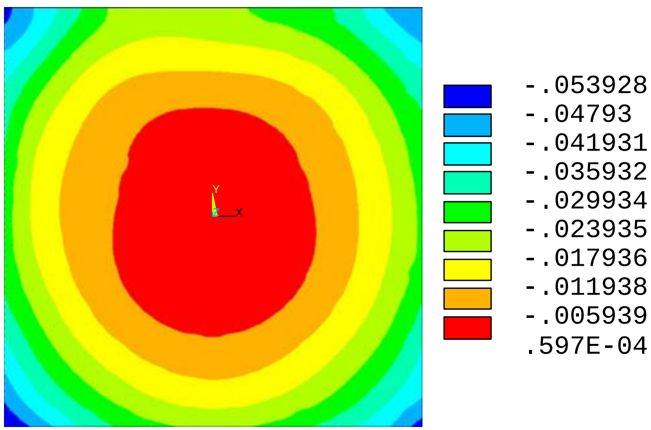
Max gap: 12.0 nm

Final Reticle Pattern Surface

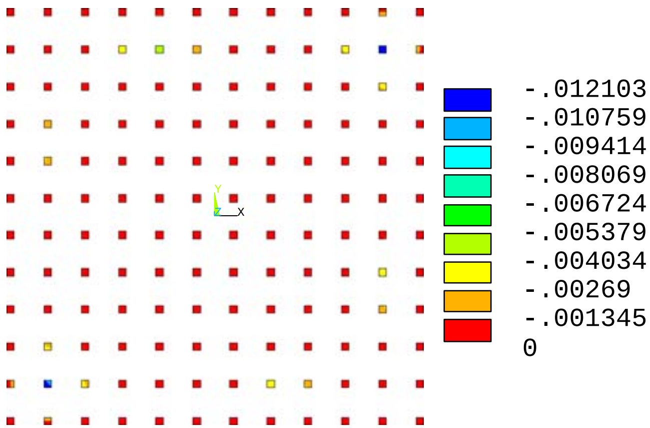


p-v: 123.9 nm
qa p-v: 51.9 nm

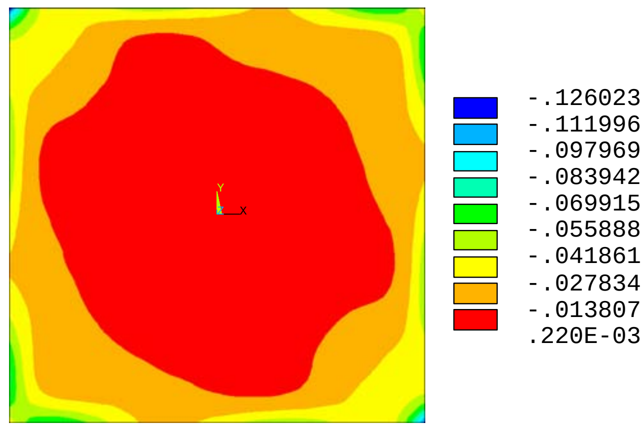
Coulomb Chuck Model



p-v: 54.0 nm



Max gap: 12.1 nm



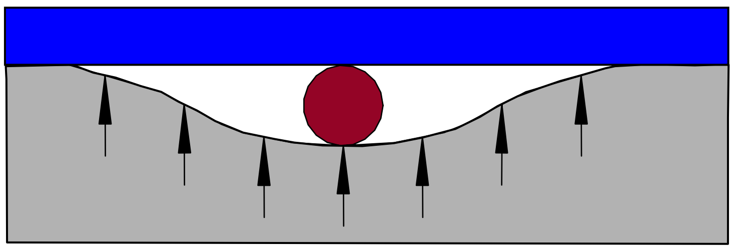
p-v: 126.2 nm
qa p-v: 52.9 nm

Effects of Particle Entrapment: Coulomb vs. Johnsen-Rahbek Electrostatic Chucks

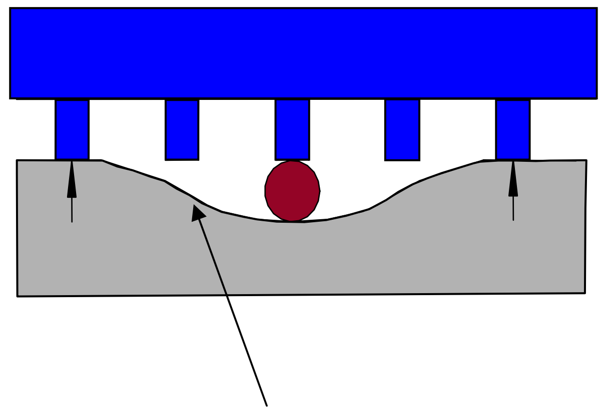
Coulomb Chuck

J-R Chuck

entrapped particle



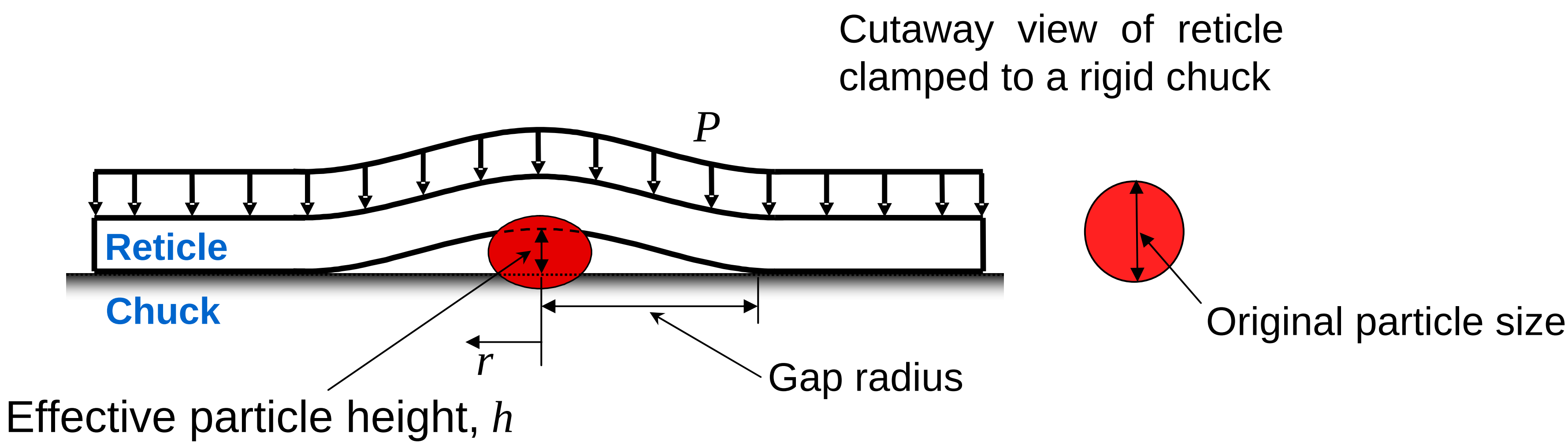
Force generated everywhere



No J-R force here because
no physical contact

- **Do entrapped particles have similar effects on both types of chuck?**

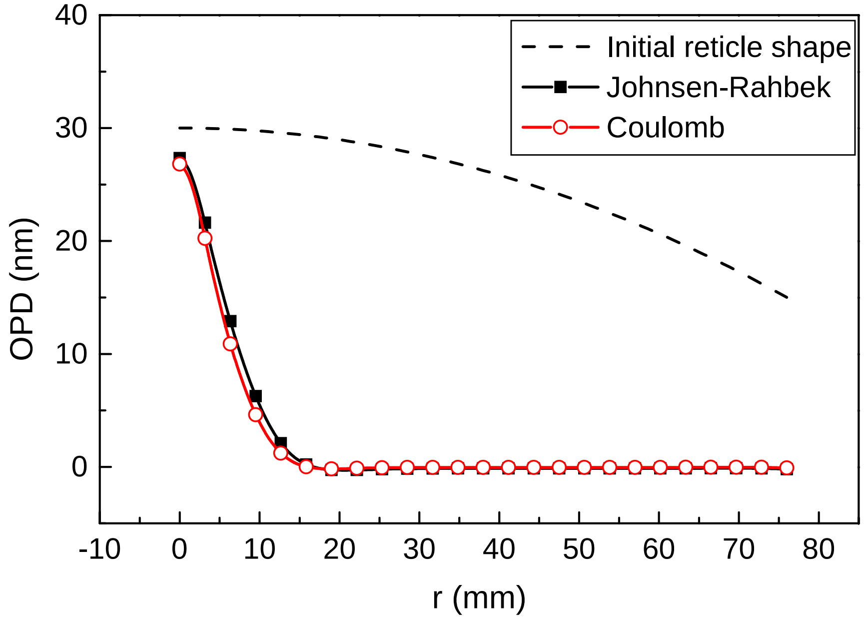
Particle Macro-Scale Model Details

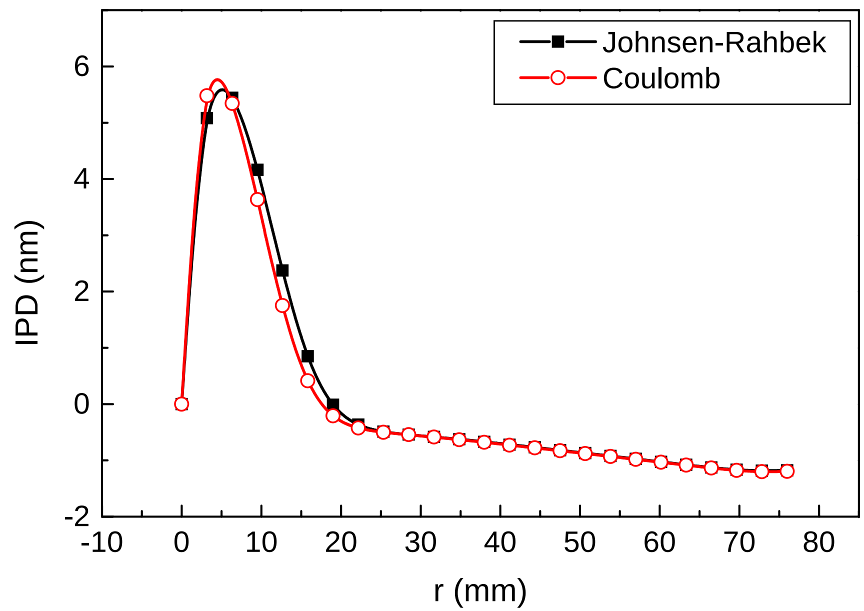


- Reticle is assumed to be of ULE® material and initially bowl shaped
- Chuck is perfectly flat and rigid
- Effective particle height (h) is the residual height of the deformed particle (neglecting local deformation of the chuck and reticle surfaces). Pressure loading (P) is gap dependent with a maximum pressure of 15 kPa occurring at zero gap. Note: in this model the effective particle height says nothing about the original particle size.
- r is the radial coordinate from the location of the particle

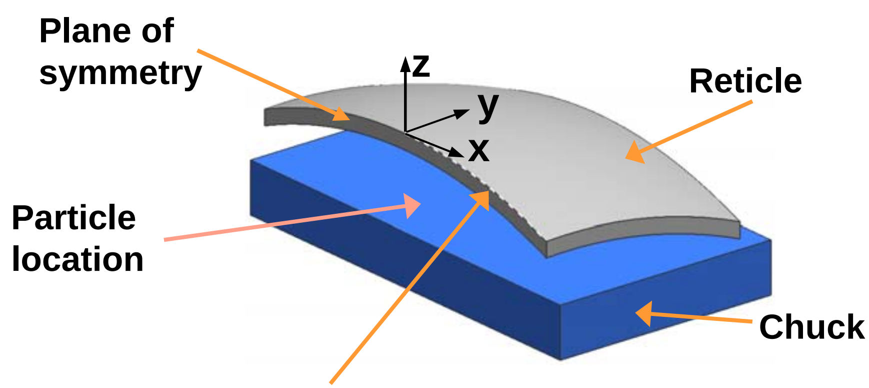
Effective Particle Height: 30 nm

Initial Reticle Profile: Bowl





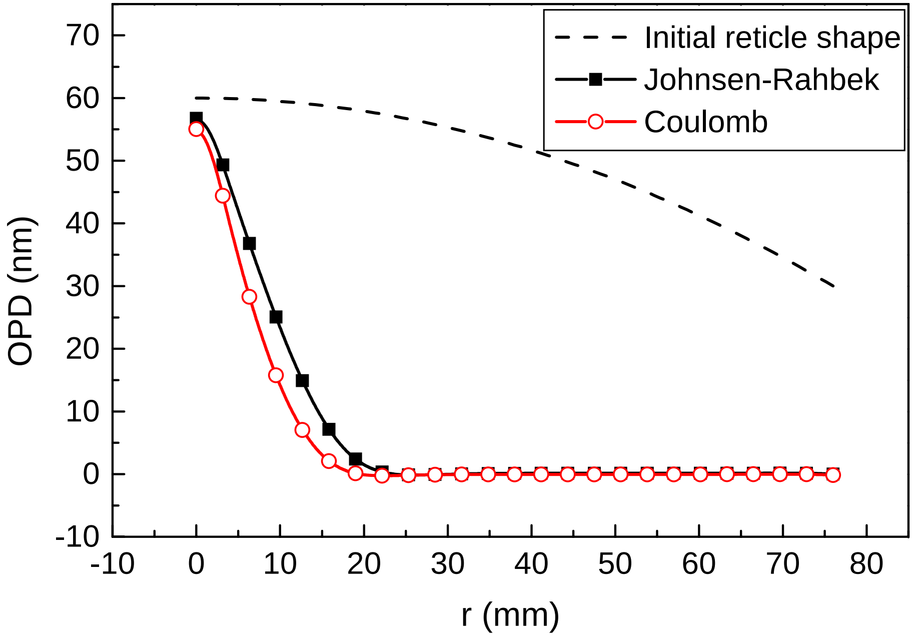
Half Symmetry Model

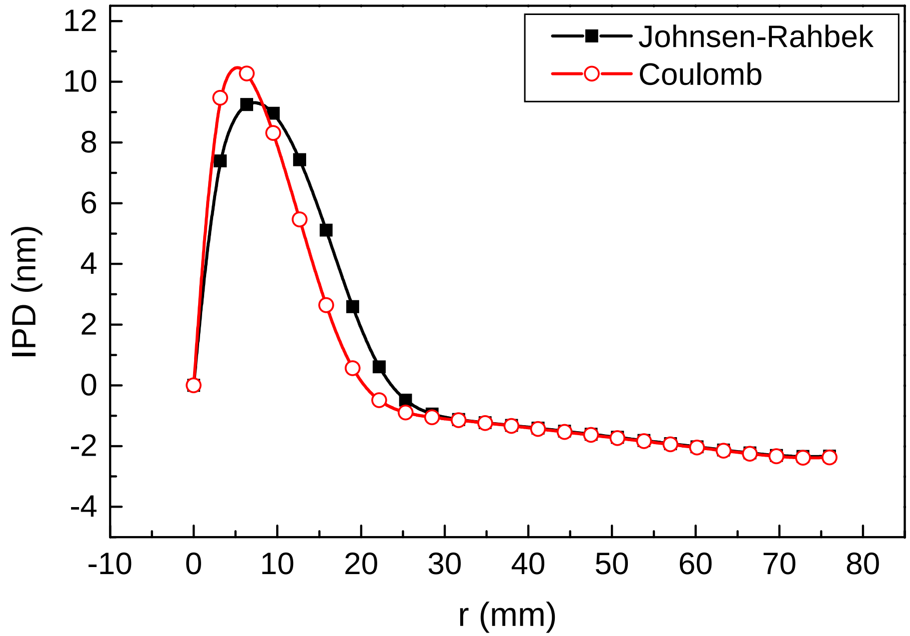


Results reported are for nodes along $0 \leq x \leq 76$ mm on the top surface of the reticle

Effective Particle Height: 60 nm

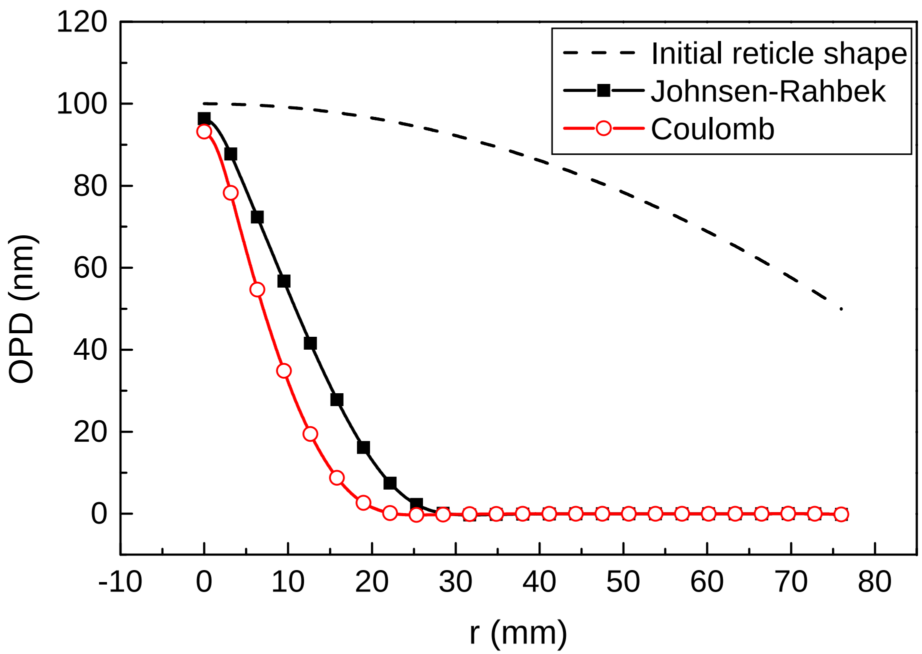
Initial Reticle Profile: Bowl

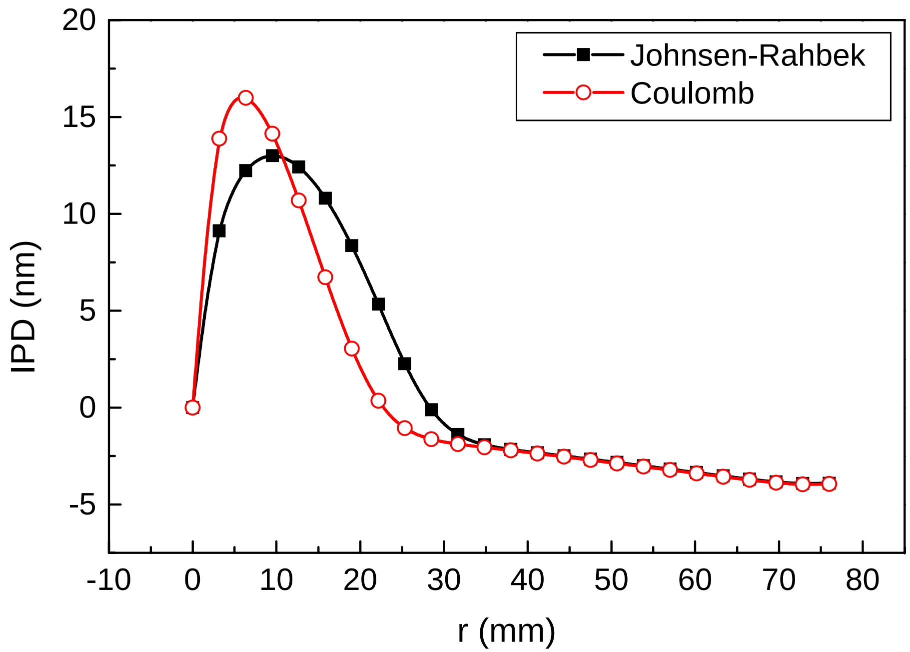




Effective Particle Height: 100 nm

Initial Reticle Profile: Bowl





Effective Particle Height: 500 nm

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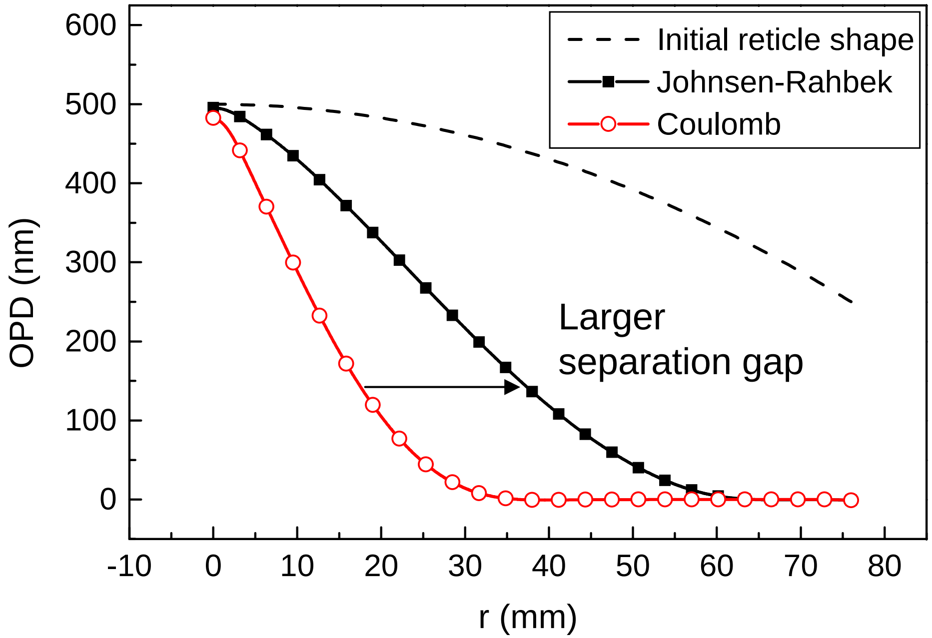

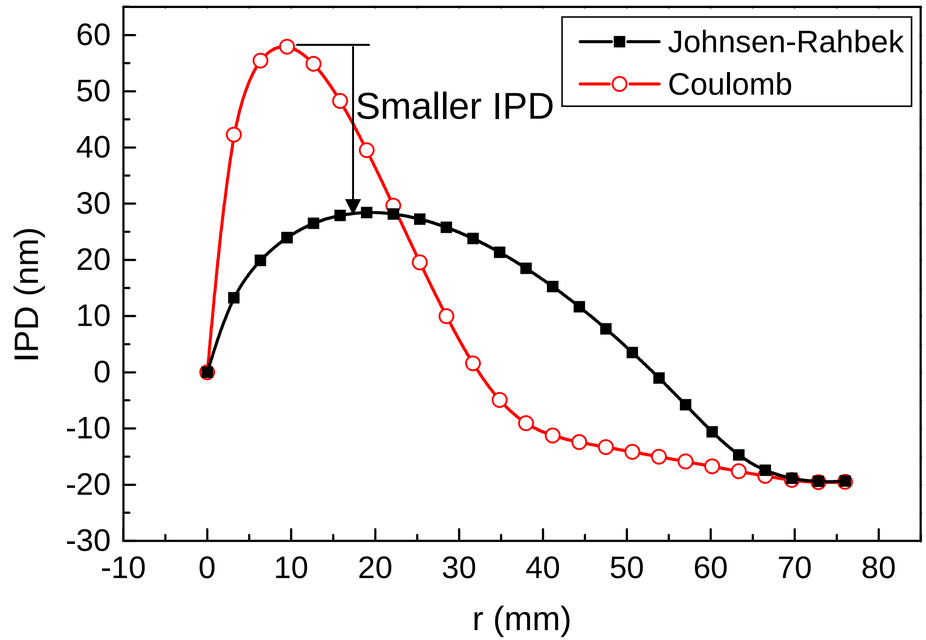

- **The larger separation gap means the J-R chuck doesn't clamp as strongly.**
- **But the IPD is significantly smaller than for the Coulomb chuck.**

Conclusions

- The J-R chuck is not as effective in “flattening” trapped particles as the Coulomb chuck for large effective heights, but the associated IPD is smaller.
- However for effective particle heights comparable to the SEMI non-flatness specs (< 100 nm), there is little difference between the two types of chuck.
- Effective particle height can be significantly less than real particle size.
- The quantitative effects of particle and chuck/substrate deformation are being investigated.

Chuck Comparison

	Coulomb		Johnsen-Rahbek	
	Advantages	**Disadvantages**	**Advantages**	**Disadvantages**
Lithography industry experience	considerable			limited
Applied voltage		limited clamping force - requires high voltage	higher force per volt in contact areas	
Force	force insensitive to gap, spatially uniform	some distortion of reticle between pins	no distortion of reticle between pins	force highly dependent on gap, not spatially uniform
Tolerance to particles	force not dependent on particle presence	needs tall pins to tolerate particles – this reduces force	pin height is irrelevant – more particle tolerant	less able to handle particles on pins
Heat generation				some ohmic heating due to leakage current; not serious problem

Summary and Conclusions

- The successful implementation of EUV lithography requires the use of an electrostatic chuck to support and flatten the mask during scanning exposure.
- A phenomenological model describing the force-gap relationship for a J-R chuck is presented and compared to the Coulomb response.
- Full 3-D FE structural models have been developed to compare the clamping performance of the two types of chucks. The relative advantages and disadvantages of both have been identified.
- The effects of entrapped particles on the clamping performance of the two kinds of chuck have been examined in a global model.
- FE simulation results are currently being used to establish specifications for chuck geometry and to identify the range of flatness variations that can be accommodated with electrostatic chucking.