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

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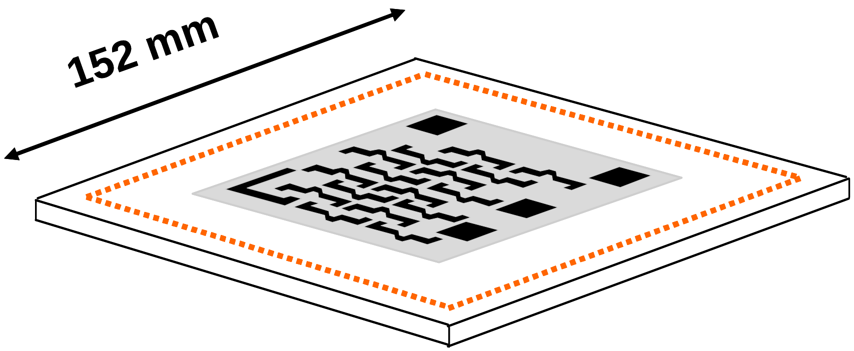
# Presentation Outline

- 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

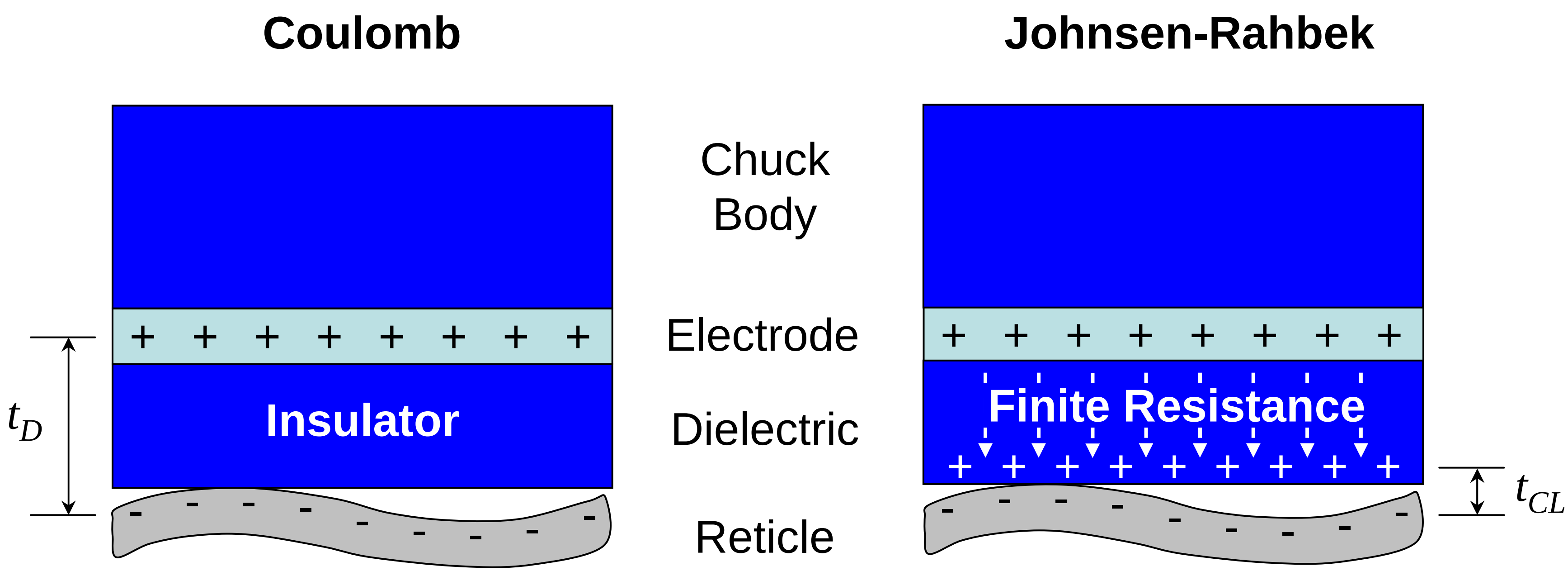
**Specifications in the EUVL Mask Chucking Standard (SEMI P40):**

-- **stiffness ≥ 30 kN-m**

-- **flatness ≈ 50 nm (*p-v*)**

# Electrostatic Chucking

## Types of Chucks



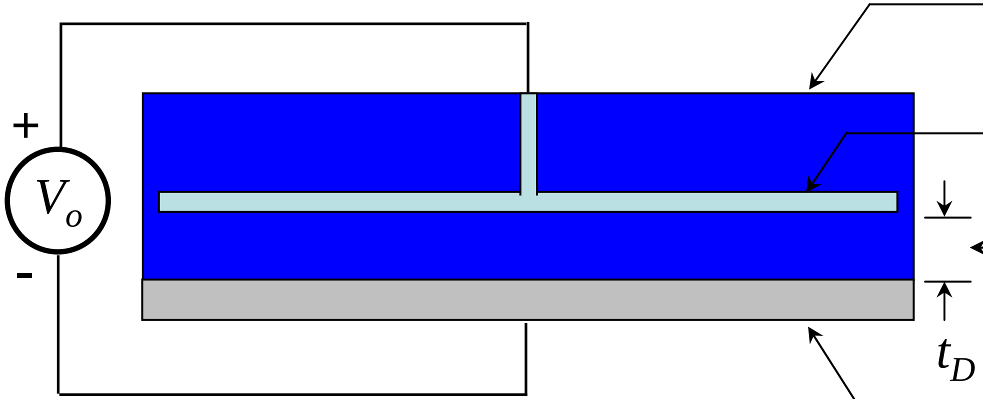

- **Type of chuck is characterized by the dielectric material and the resulting mechanism of force generation.**
- **Chucks can be either monopolar or bipolar.**
- **Slab-type or pin-type based on the surface characteristics. A pin-type chuck is proposed to minimize the effects of particles.**

# Coulomb Chuck

## Schematic and Working Principle

### Monopolar Chuck

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




$P$ = electrostatic pressure

$F$ = electrostatic force

$A$ = area of the electrode

$V_o$ = applied voltage

$\varepsilon_o$ = permittivity of free space (or air gap)

$K$ = relative permittivity of the dielectric material

$t_D$ = the dielectric film thickness

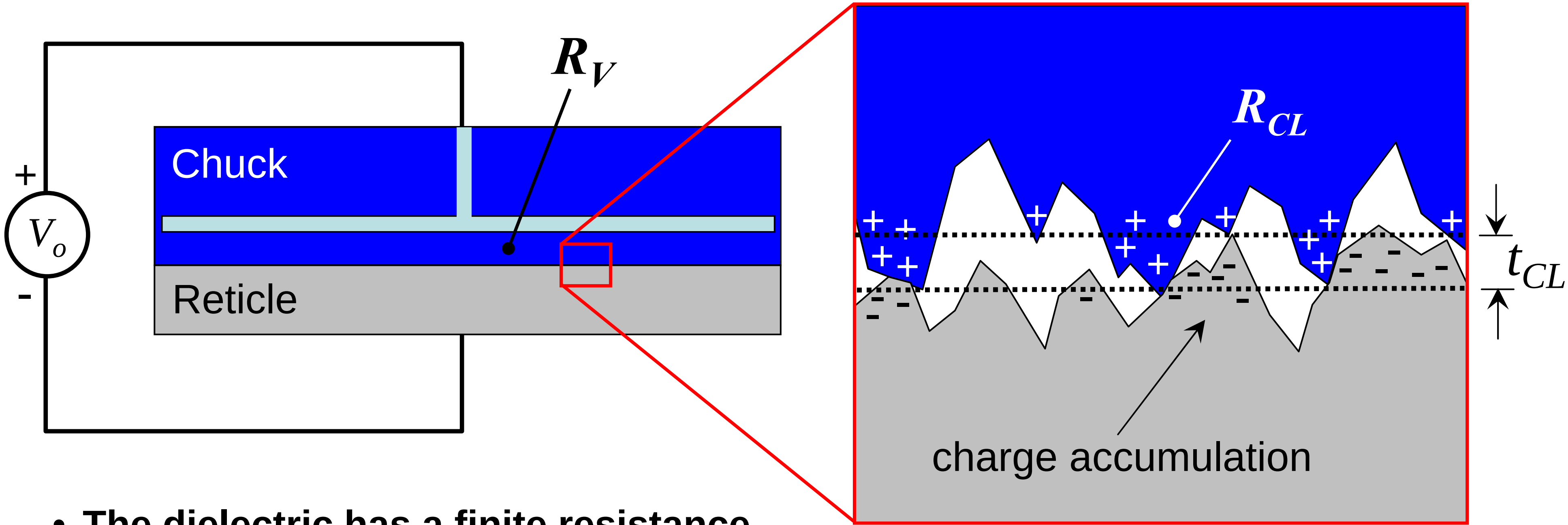
$\delta$ = total gap between the backside of the mask and the dielectric surface

### Bipolar Chuck

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

# 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

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

$\varepsilon_o$: permittivity of free space
$K$: relative dielectric constant
$R_{CL}$: resistance of the contact layer
$R_V$: volume resistance of the dielectric material
$\delta$: physical gap between reticle and dielectric
$\alpha$: 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.

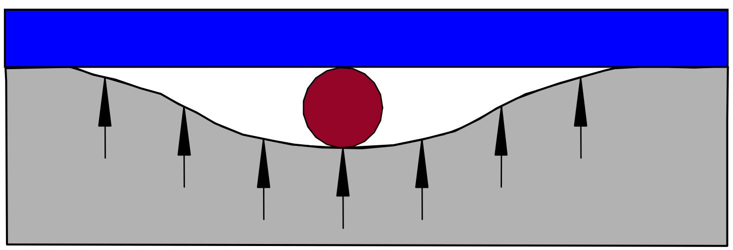
# Contrasting Chuck Properties

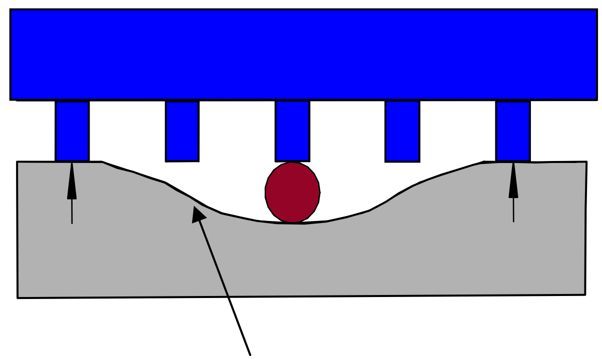
## Coulomb Characteristics

- 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?



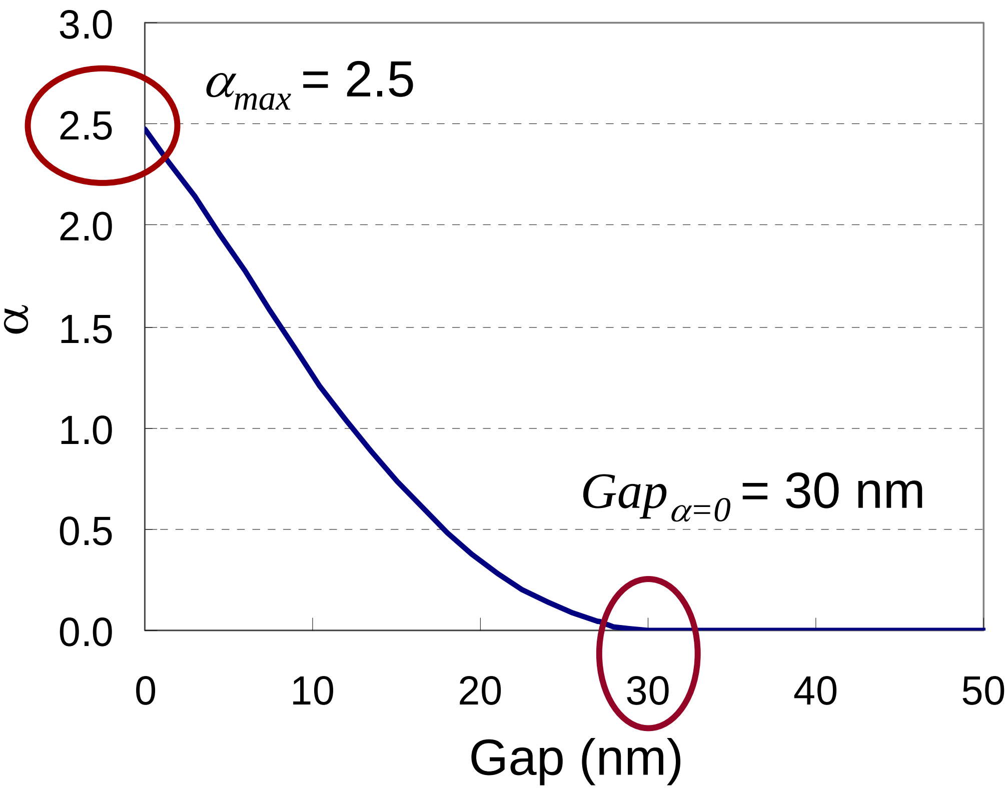



# Nonuniform Distribution of Charge

- The empirical factor $\alpha$ represents the effect of the nonuniform distribution of charge on the interface surfaces.

- A relationship for $\alpha$ 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.



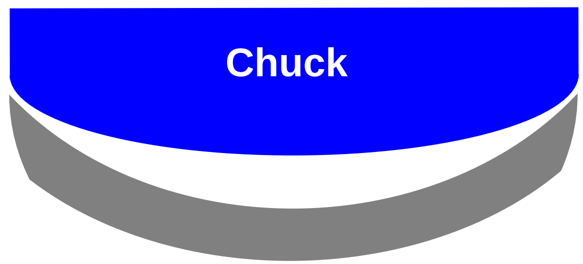
# FE Simulation of Electrostatic Chucking

- 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.

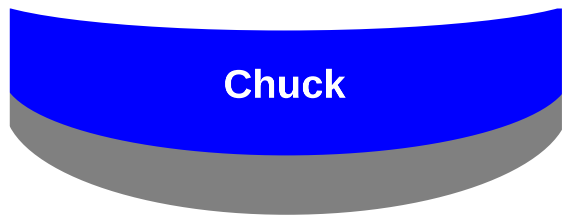
- The non-flatness values are consistent with SEMI P37, P40

- Models include:
  - -- gap-dependent pressures
  - -- contact friction ($\mu$ = 0.2)
  - -- stiffness of the chuck

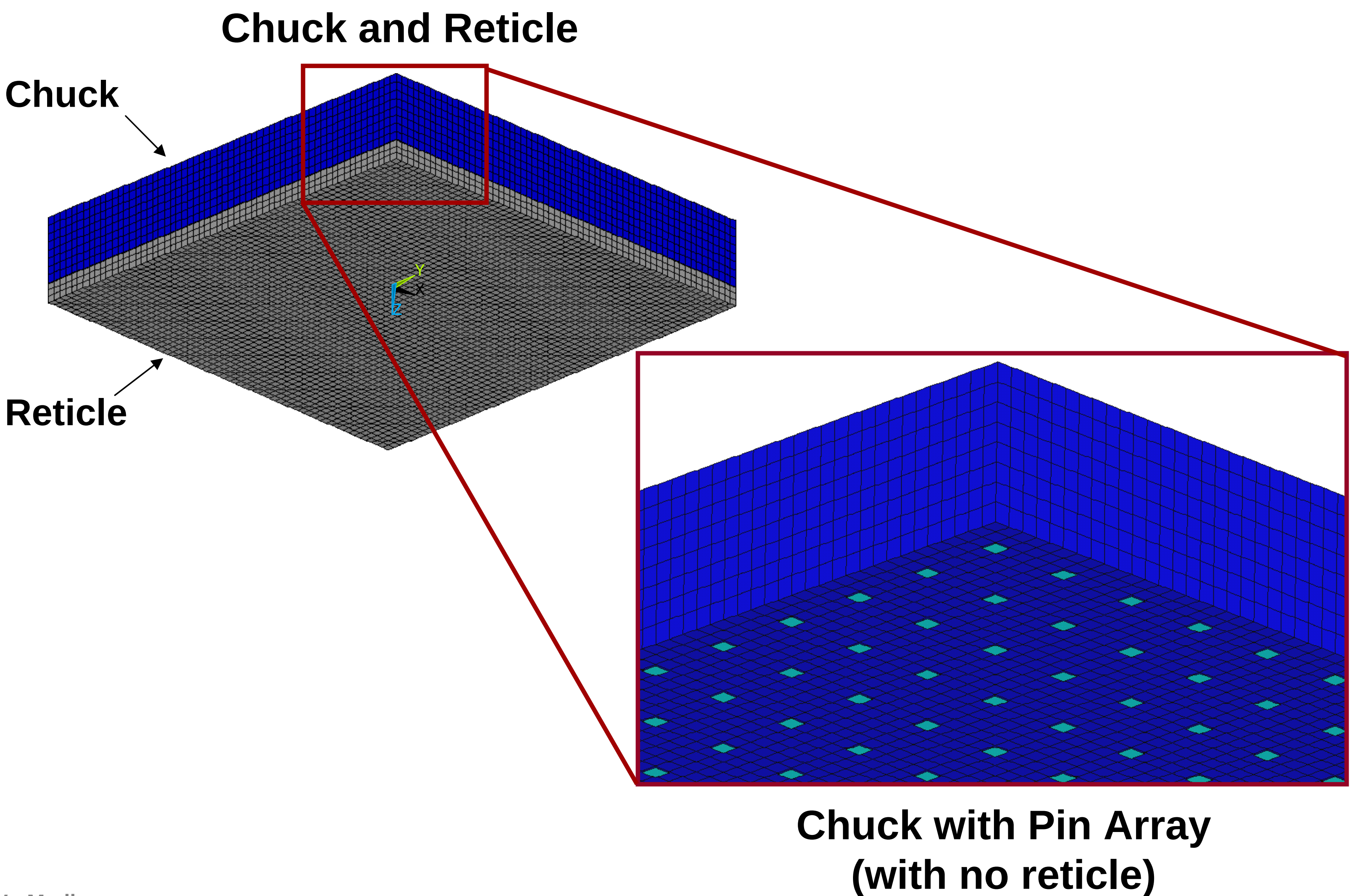



Gravity neglected.

- 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



# FE Electrostatic Chucking Models

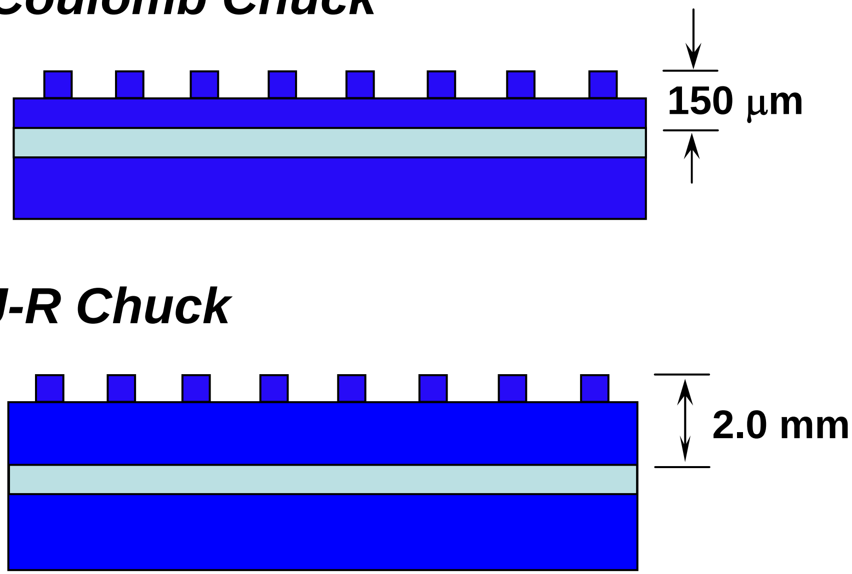


# Chuck Geometry and Stiffness

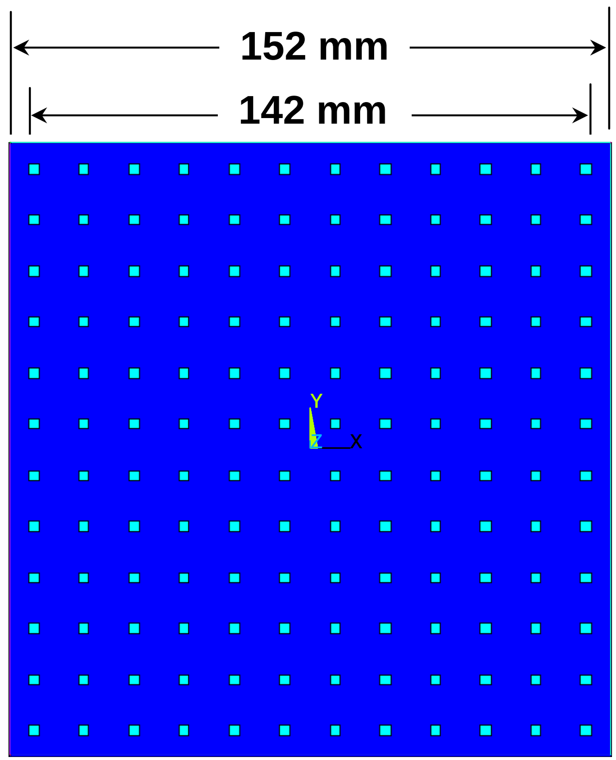
## Dielectric Layer

*Coulomb Chuck*

*J-R Chuck*




## Pin Layout




## Chuck Body (Bulk Layer)

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

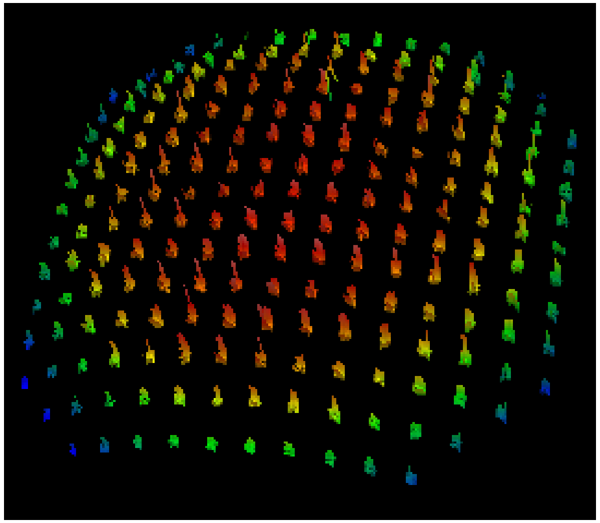
Pin coverage area: 142 mm × 142 mm
Pin size: 2.5 mm × 2.5 mm × 10 µm
Pin pitch: 12.67 mm
Pin coverage: 4%

# Nonflatness of Electrostatic Chuck

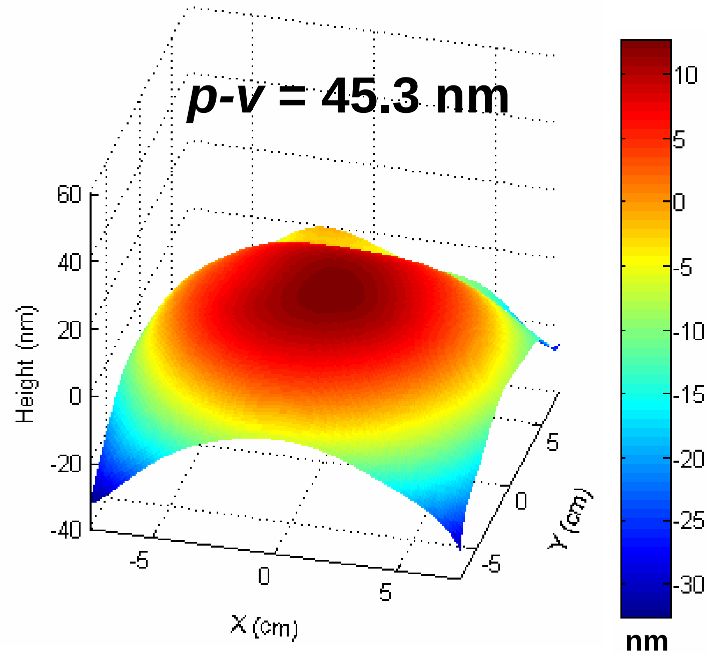
- Nonflatness of a Coulomb chuck was measured interferometrically.
- Measured chuck data scaled to meet the flatness specified in the EUVL chucking standard.

**Coulomb Pin Chuck**

**Interferometric Measurement of Chuck Surface**



**Mathematical Fit**

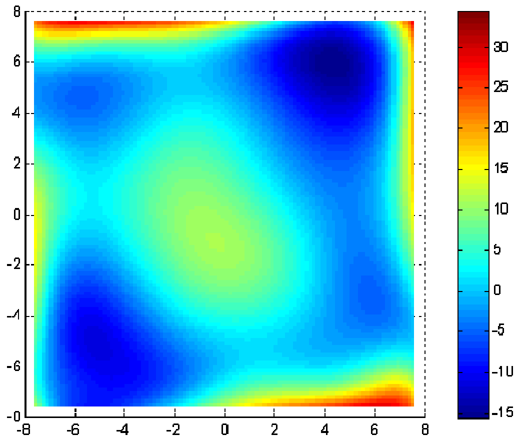


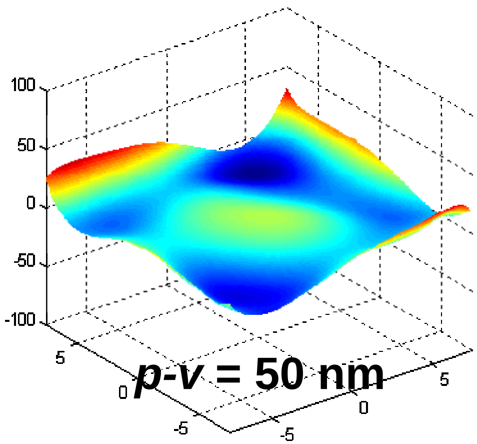

**Interferometric measurement of the chuck surface is represented by Legendre polynomials and used as input into the FE models.**

# Polished Nonflatness of Reticle

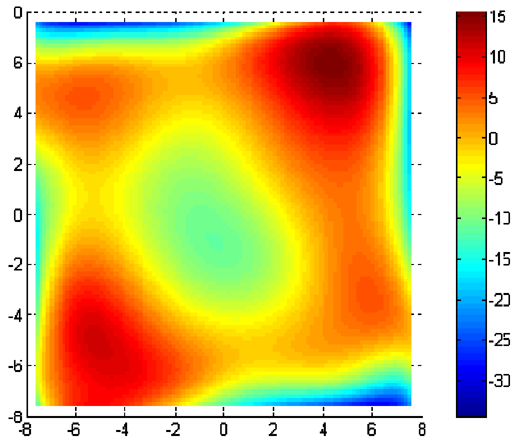
## Example Case

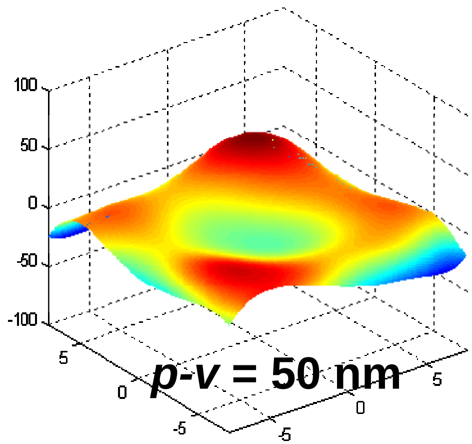
**Frontside (FS)**



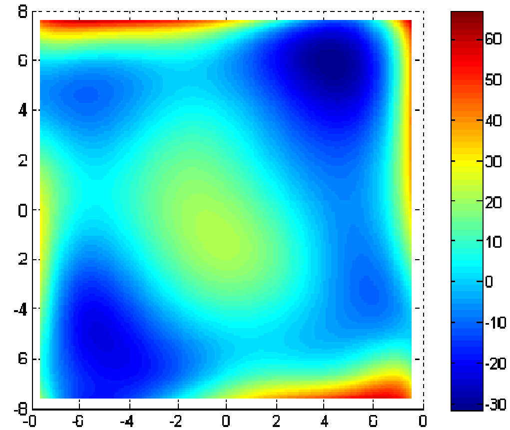



**Backside (BS)**






**Thickness Variation**



**Max = 100 nm**

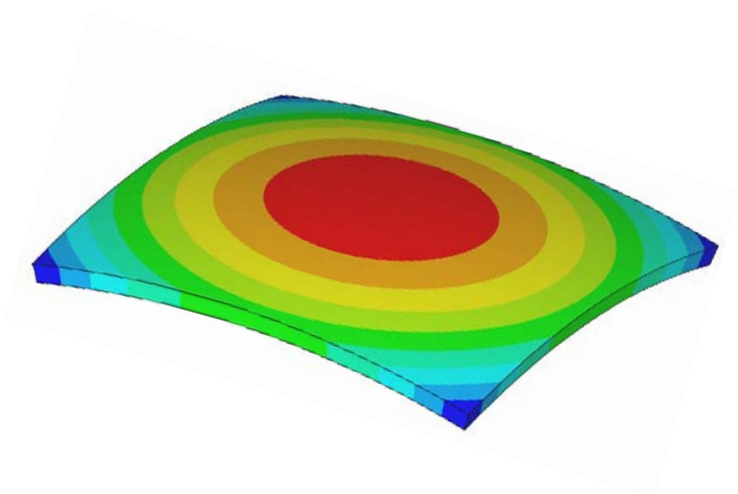
- **Thickness variation was calculated by subtracting the backside flatness data from the frontside flatness data.**

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

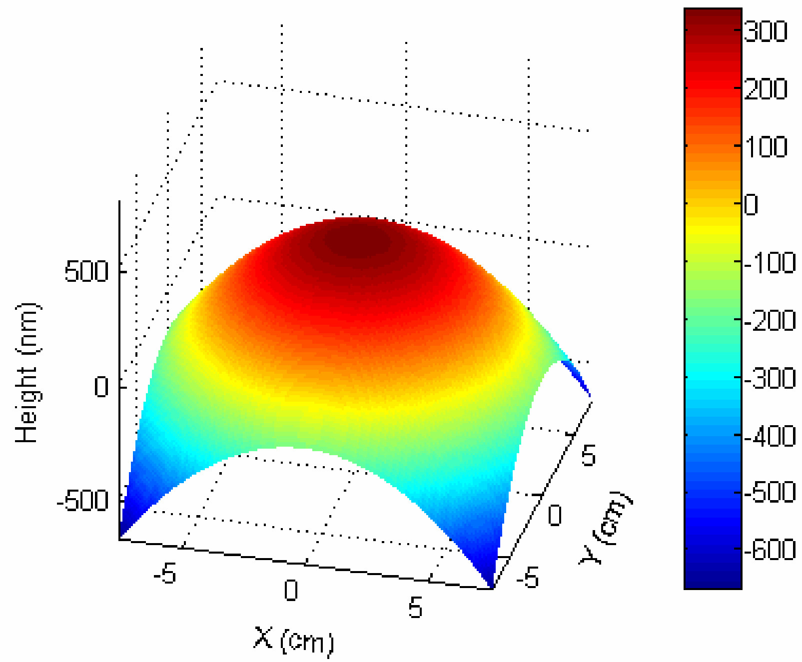
# Simulating Reticle Multi-layer
## Thin Film Deposition

- **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

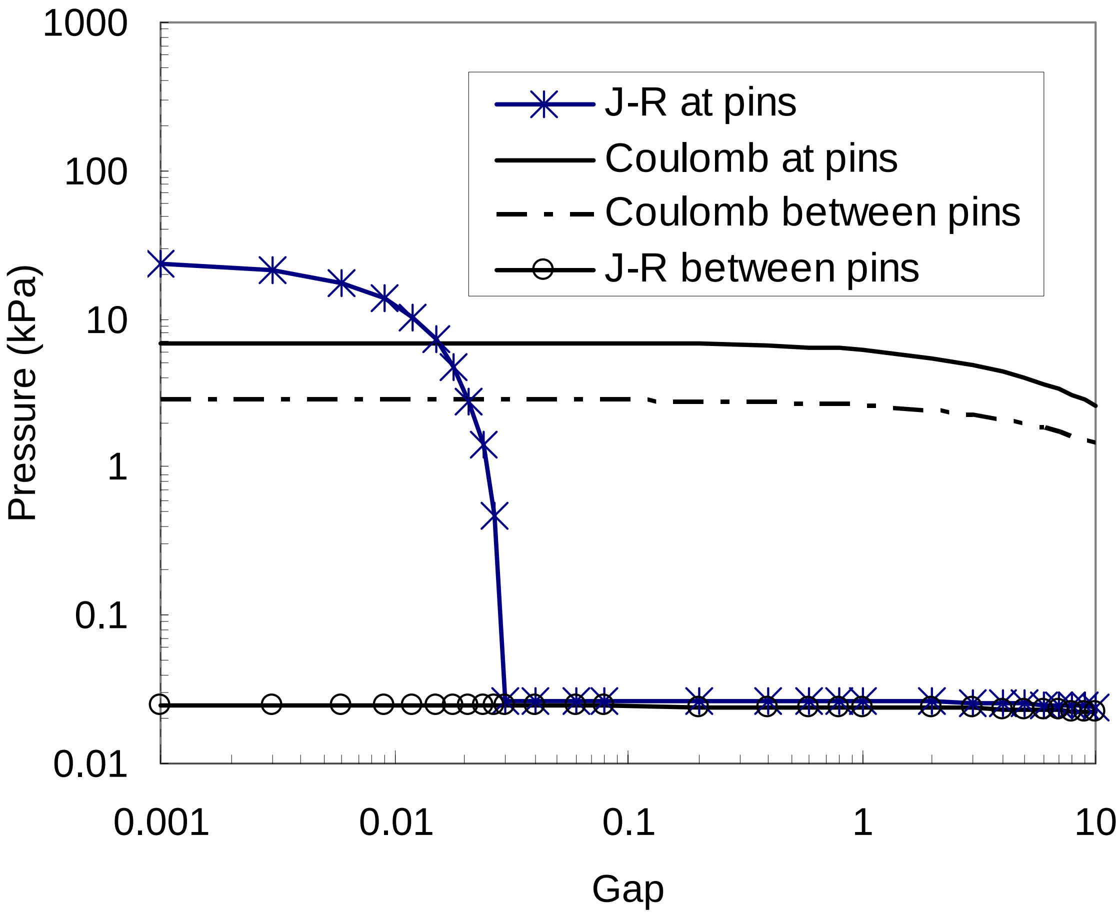
Pin height = 10 µm

**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

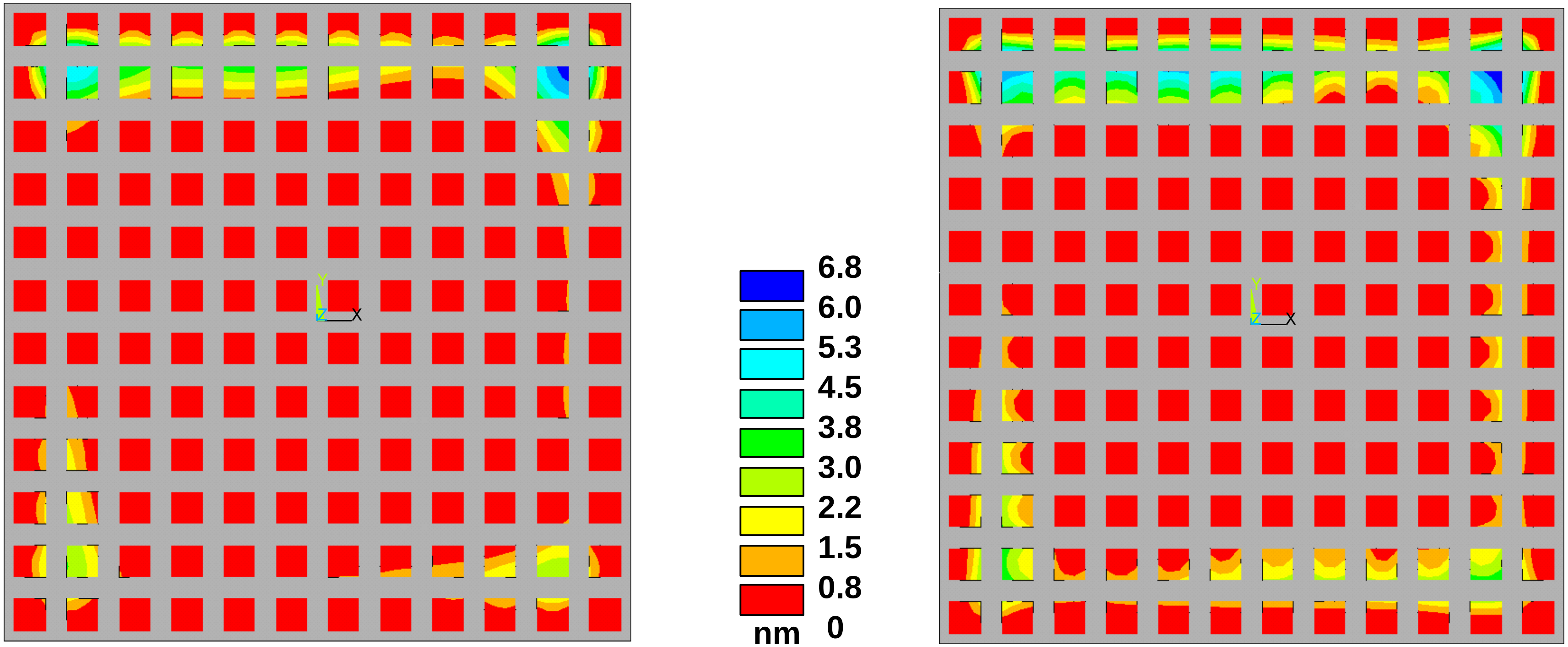
## After Chucking with $P$ = 3 kPa

**Coulomb**

$V_o$ = 633 V

**Johnsen-Rahbek**

$V_o$ = 492 V




Max gap = 6.8 nm

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

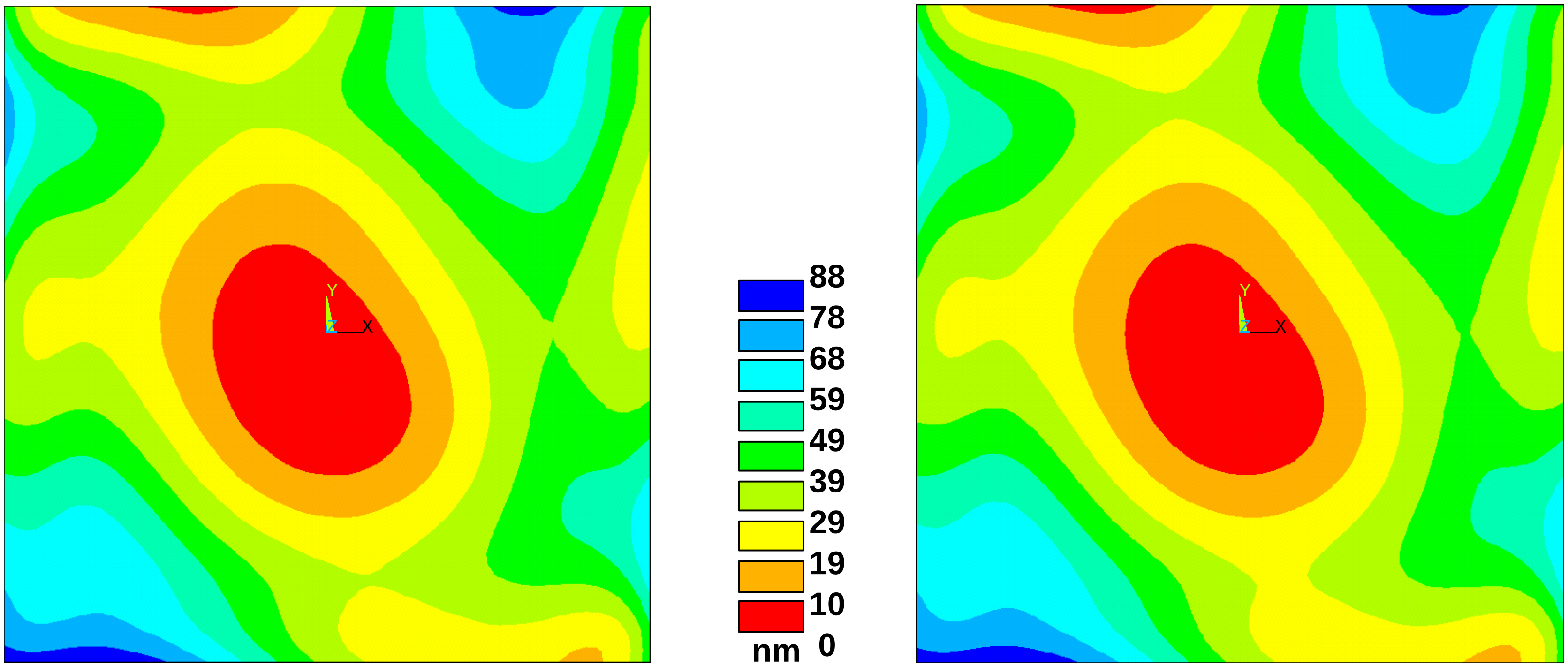
## Nonflatness after Chucking with *P* = 3 kPa

**Coulomb**

$V_o$ = 633 V

**Johnsen-Rahbek**

$V_o$ = 492 V




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

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

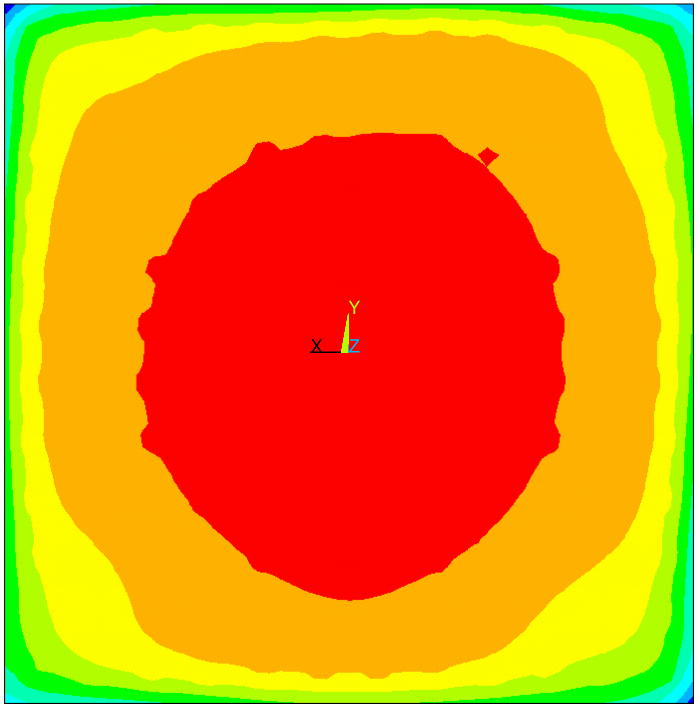
Before Chucking
*p-v* = 1.0 µm

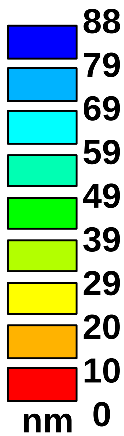
# Finite Element Reticle Chucking Surface

## Nonflatness after Chucking with *P* = 3 kPa

**Coulomb**

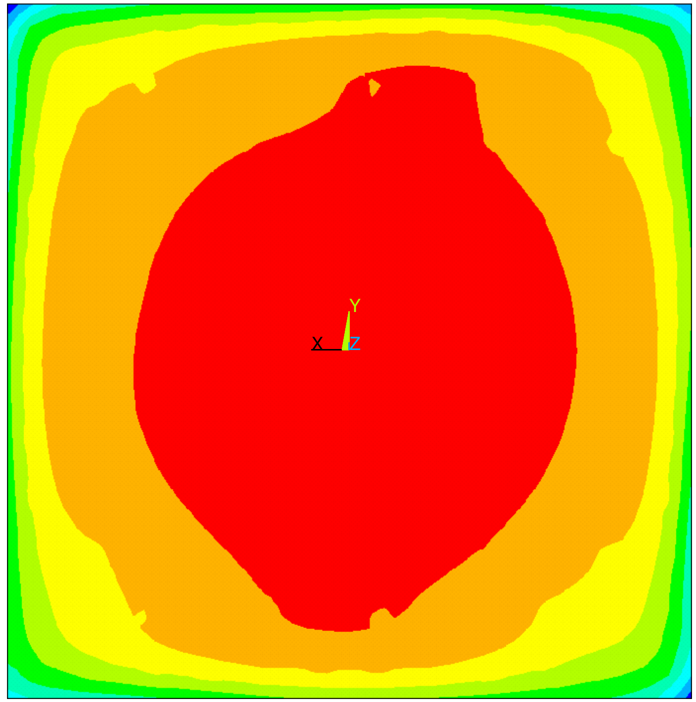
$V_o$ = 633 V




**Johnsen-Rahbek**

$V_o$ = 492 V



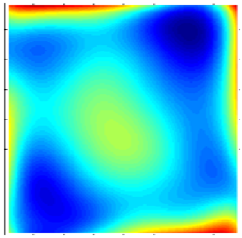

*p-v* = 88.3 nm
QA *p-v*: 47.8 nm

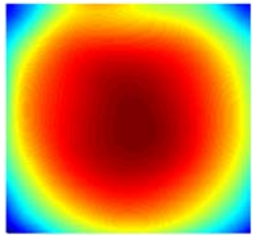
*p-v*: 85.5 nm
QA *p-v*: 47.2 nm

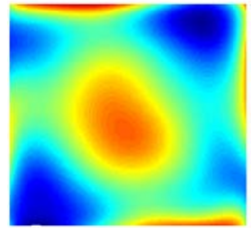
Before Chucking
*p-v* = 1.0 µm

# Reticle Pattern Surface From Analytical Prediction

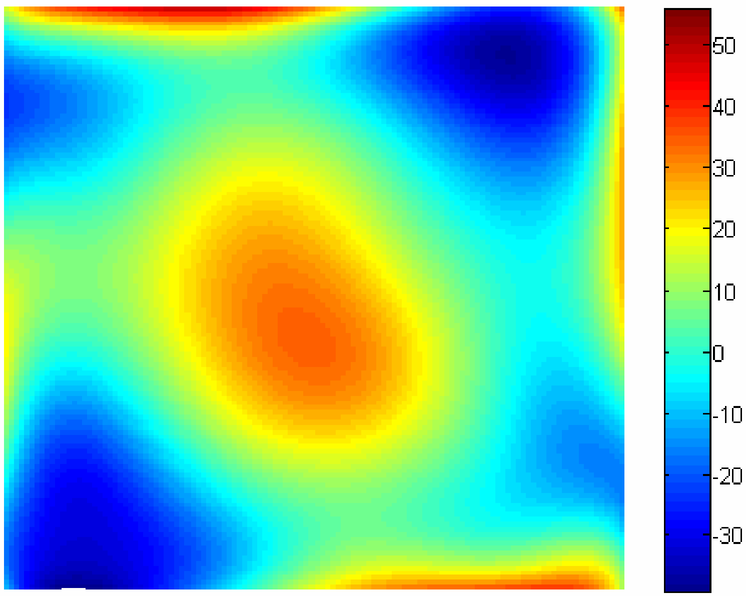
**Thickness Variation** + **Chuck Nonflatness** = **Reticle Flatness Prediction**





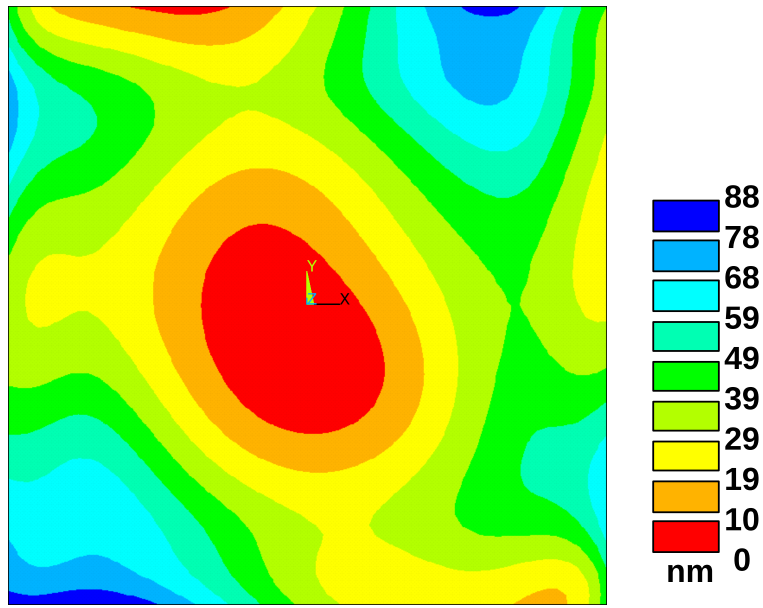


**Complete Chucking Final Flatness (from interferometer measurements only)**



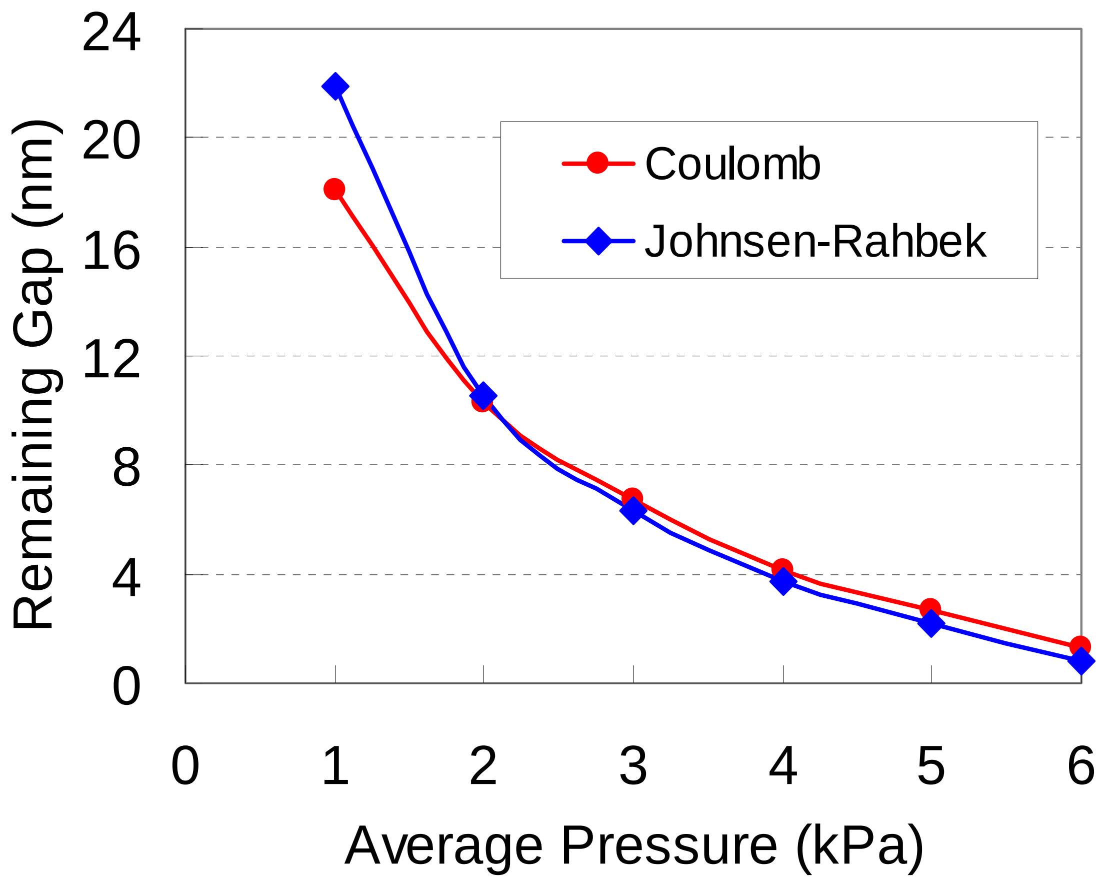

*p-v* = 94.9 nm

**J-R Chuck Final Flatness (from FE model)**




*p-v* = 86.7 nm

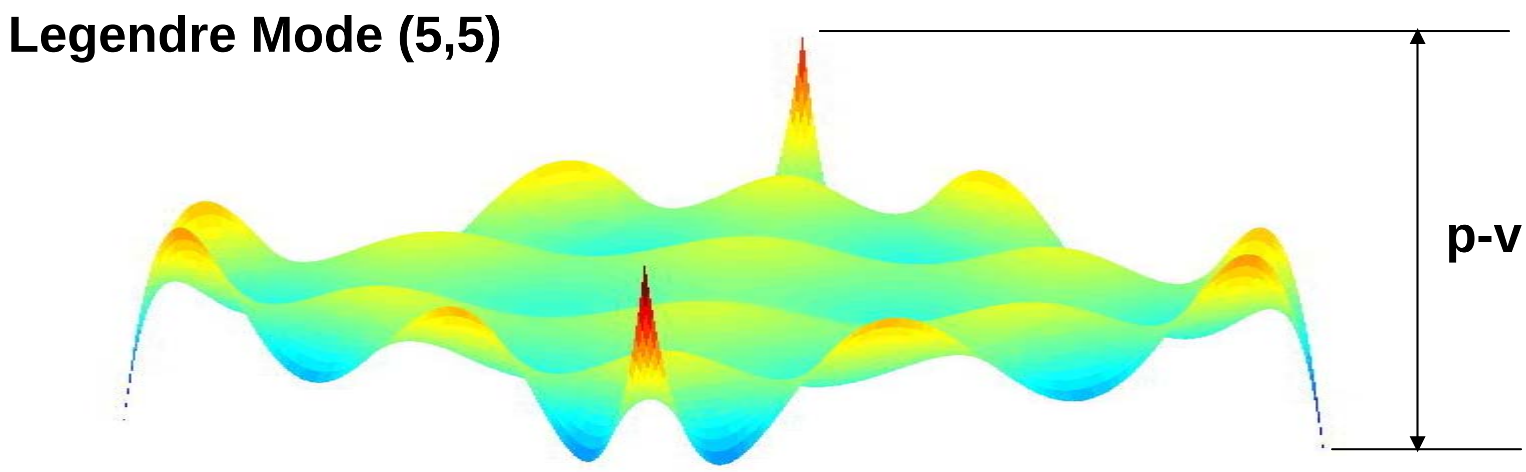
# Summary of Simulation Results




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

# Reticle Nonflatness Results

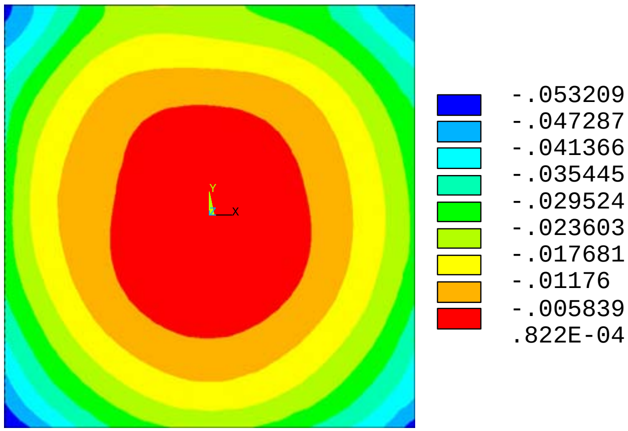
- The effects of reticle blank non-flatness (before application of the multi-layers) were also studied.
- Non-flat blanks were simulated using 2D Legendre polynomials.  Below is Legendre mode (5,5).



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

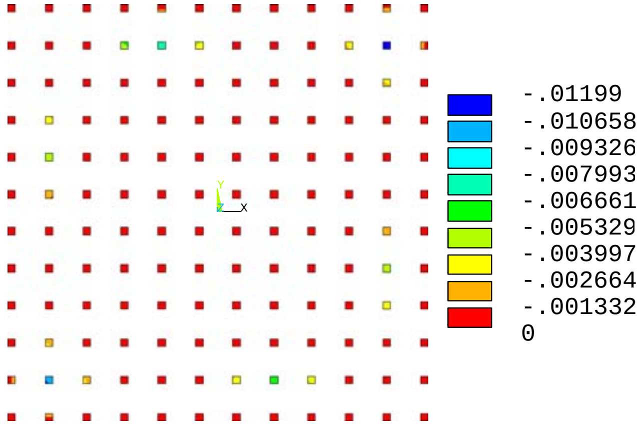
## JR Chuck Model

**Final Chuck Shape**



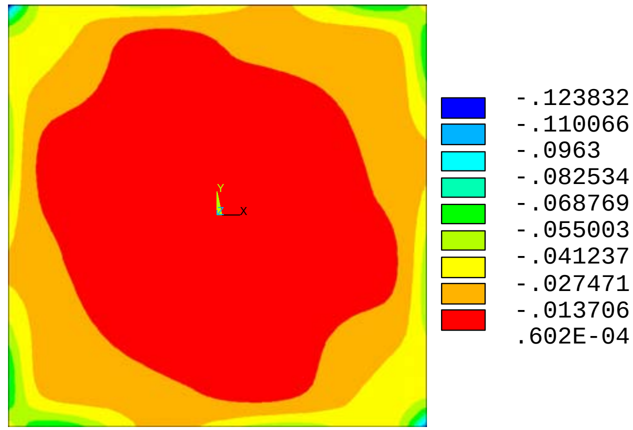

p-v: 53.3 nm

**Residual Gap**



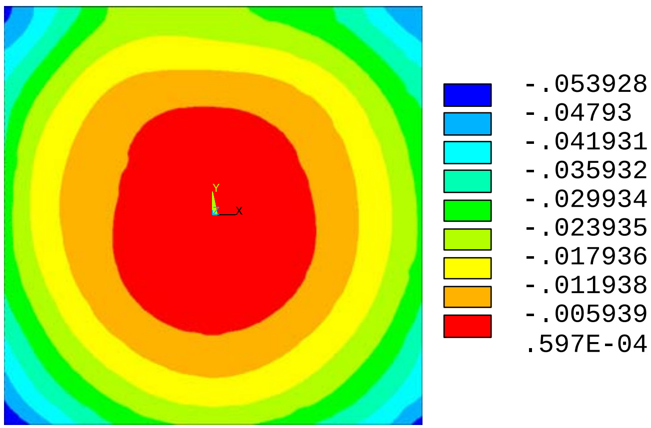

Max gap: 12.0 nm

**Final Reticle Pattern Surface**

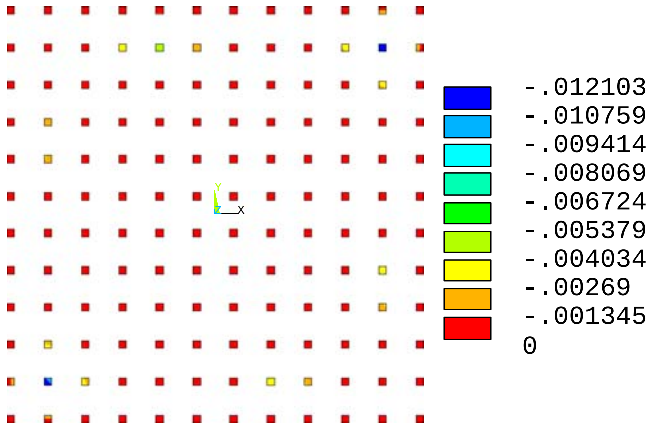



p-v: 123.9 nm
qa p-v: 51.9 nm

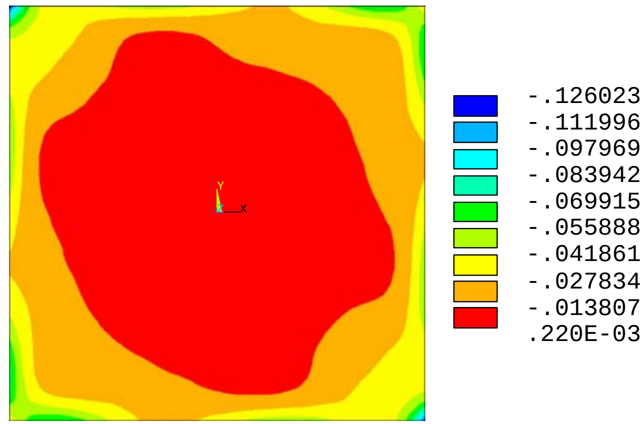
## Coulomb Chuck Model




p-v: 54.0 nm




Max gap: 12.1 nm

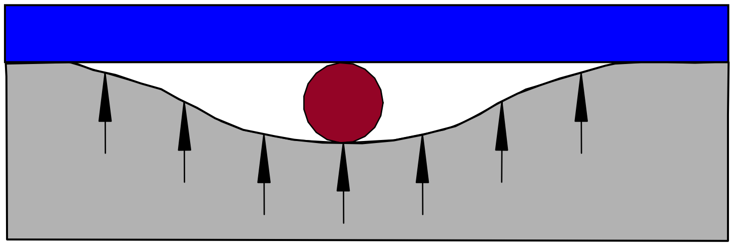



p-v: 126.2 nm
qa p-v: 52.9 nm

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

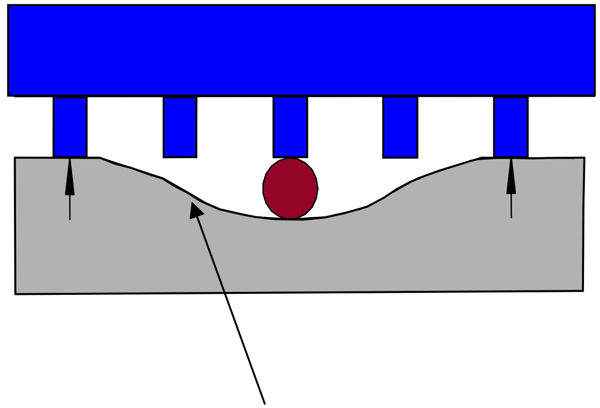
## Coulomb Chuck

entrapped particle



Force generated everywhere

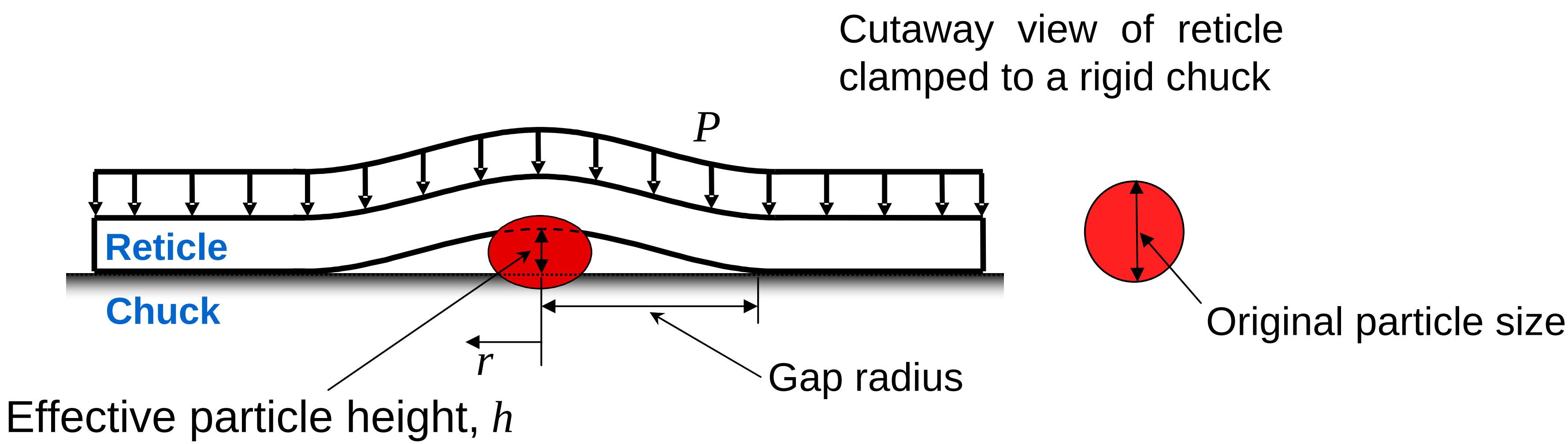
## J-R Chuck



No J-R force here because no physical contact

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

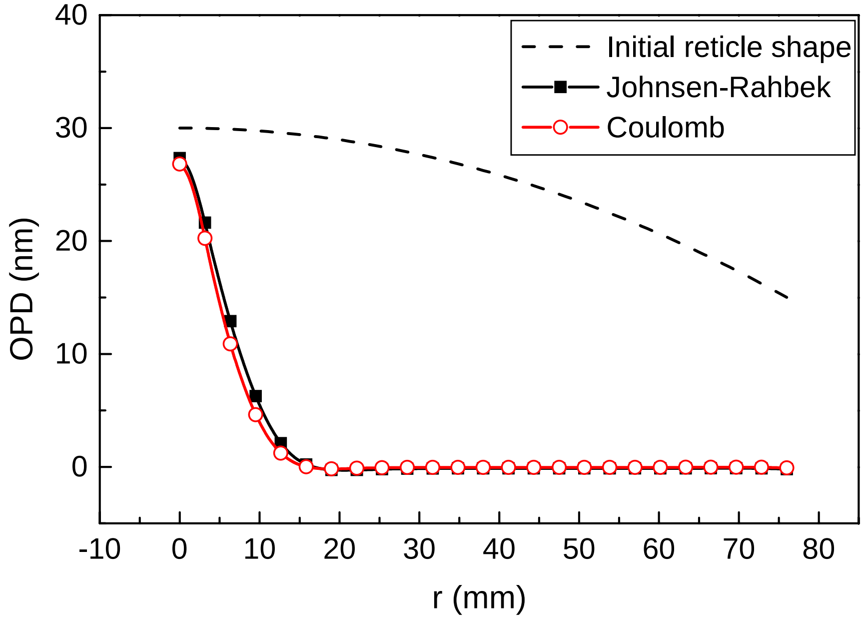
# Particle Macro-Scale Model Details

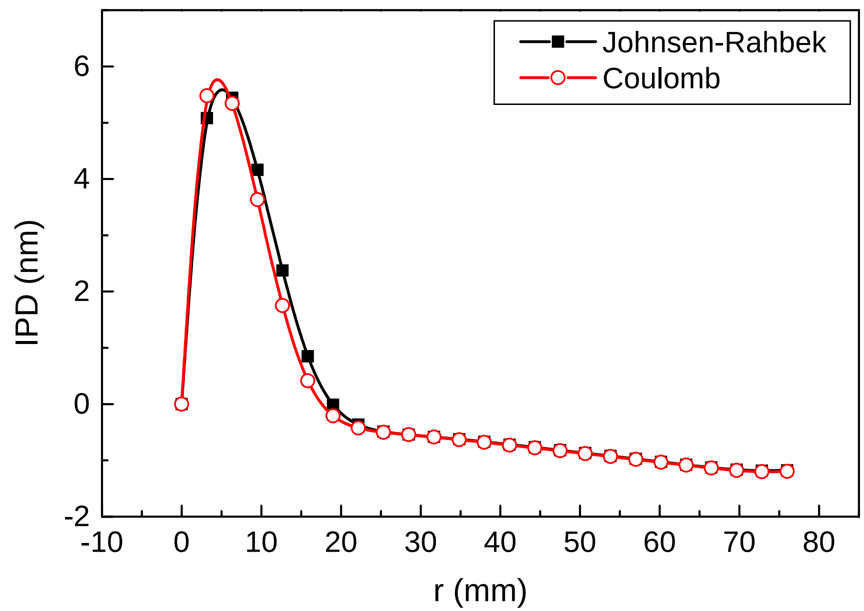



- Reticle is assumed to be of ULE® material and initially bowl shaped
- Chuck is perfectly flat and rigid
- Effective particle height ($h$) is the residual height of the deformed particle (neglecting local deformation of the chuck and reticle surfaces). Pressure loading ($P$) is gap dependent with a 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

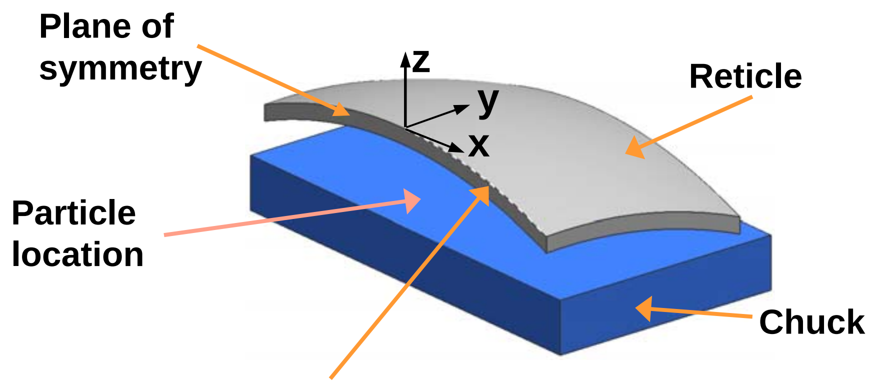
# Effective Particle Height: 30 nm

## Initial Reticle Profile: Bowl



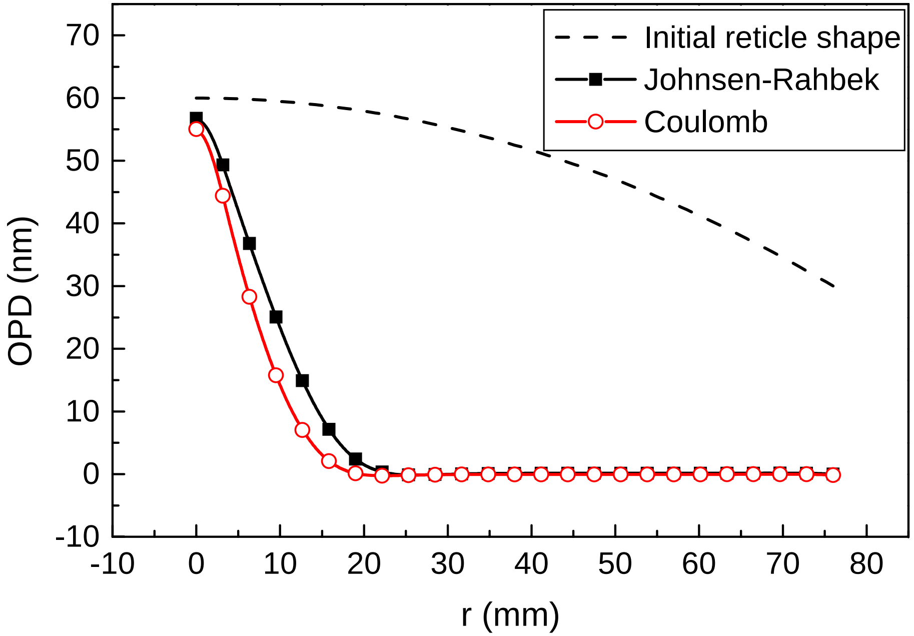

### Half Symmetry Model

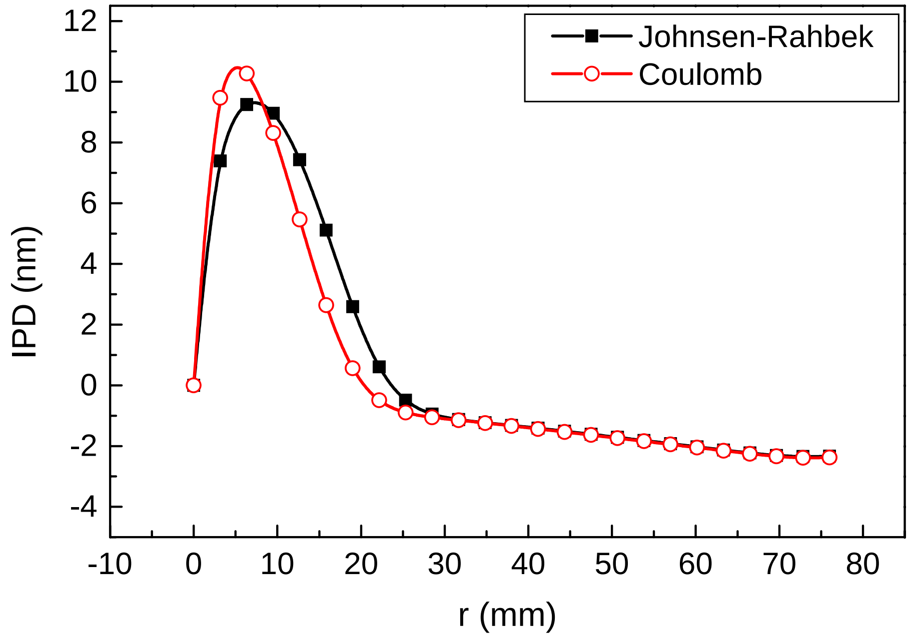



Results reported are for nodes along $0 \le x \le 76$ mm on the top surface of the reticle

# Effective Particle Height: 60 nm

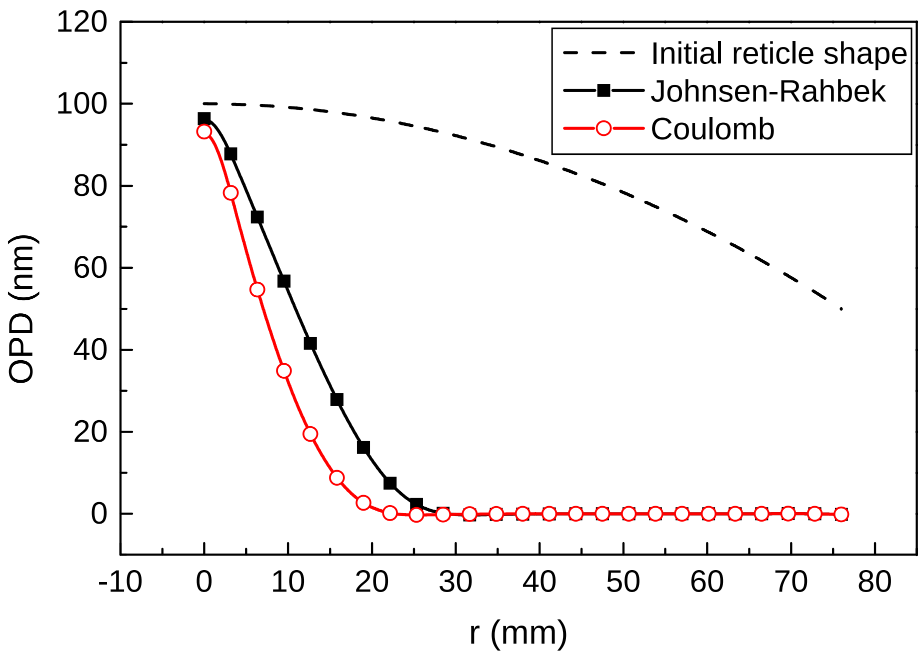
## Initial Reticle Profile: Bowl

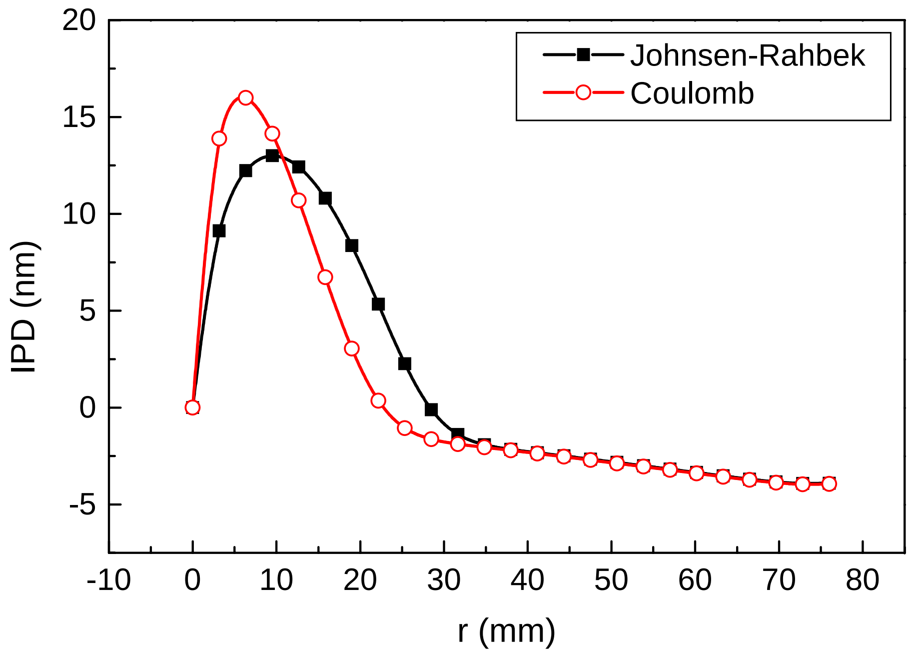


# Effective Particle Height: 100 nm

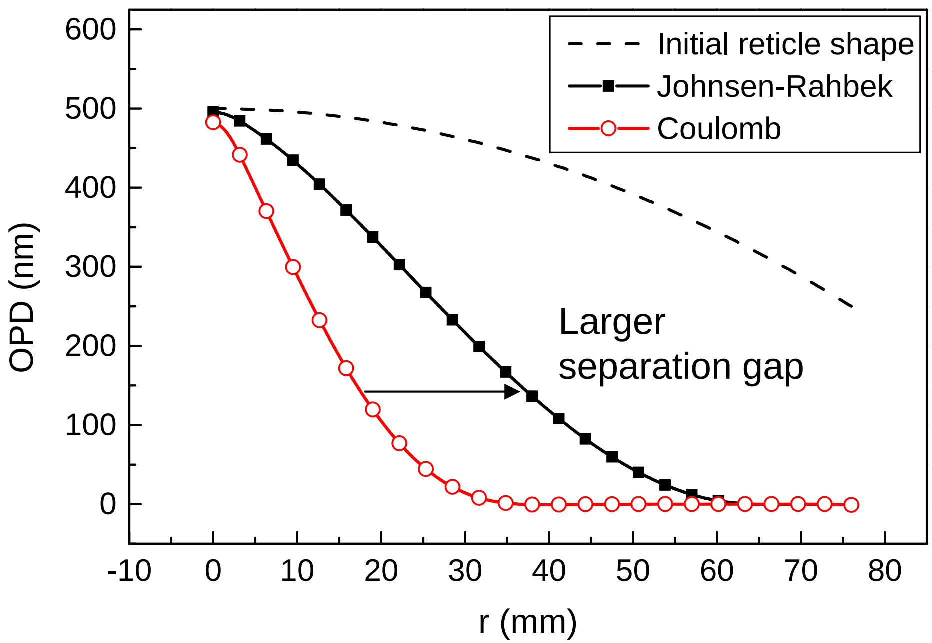
## Initial Reticle Profile: Bowl

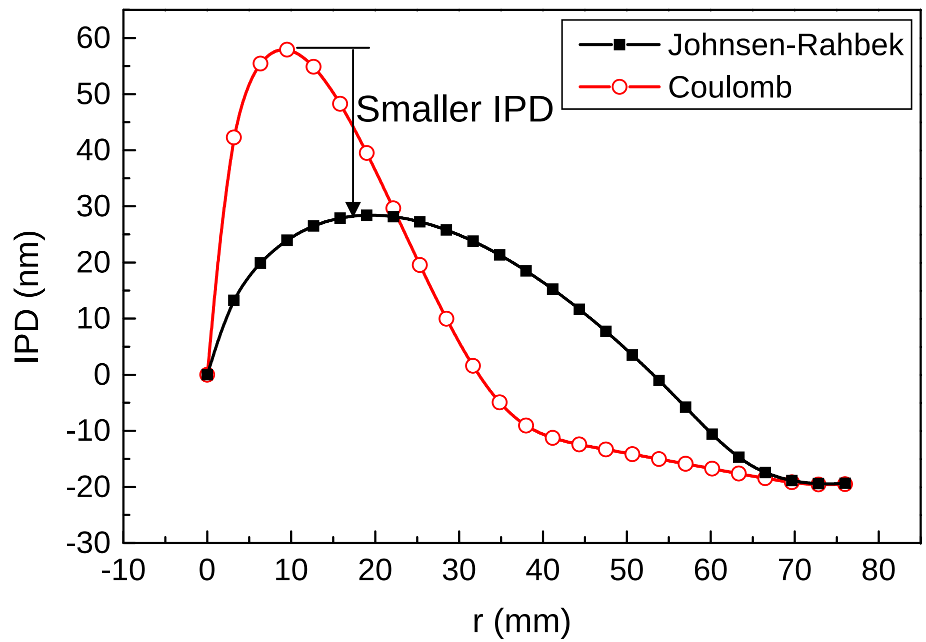


# Effective Particle Height: 500 nm

## Initial Reticle Profile: Bowl




- **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.