# Particle Contamination in EUVL: Estimations on the Critical Particle Sizes

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## Motivation

Image Placement Error:

$$IPE \approx OPD/40 + IPD/4$$

→ what particle sizes are allowable?

## Plate Model

Analytical models in the literature are based on

- Plate bending

$$OPD = -\frac{h}{a^4}r^4 + \frac{4h}{a^2}r^2 \ln\frac{r}{a} + h\,, \quad a^4 = \frac{64hD}{p}\,,$$

$$IPD = -\frac{t_R}{2}\frac{\partial}{\partial r}OPD\,.$$

- Nano-indentation of semi-infinite half-space
- Cylindrical particle shapes

We extend the theory:

- General material laws (e.g. Romberg-Osgood type constitutive law)
- Frictional contact
- Gap dependant electro-static pressure $p(w)$

$$OPD = c_1 J_0(\alpha r) + c_2 I_0(\alpha r) + c_3 Y_0(\alpha r) + c_4 K_0(\alpha r) + \frac{\delta_d}{2k_d}\,, \alpha = \left(\frac{2k_d p_0}{D\delta_d}\right)^{1/4}$$

- Analytical solution for spherical particle shape

**Pros & Cons:**

- Simple closed form estimate
- Neglects *'plate shearing'*
- Neglects *'feature transfer'* of the mask-indentation to the front-side

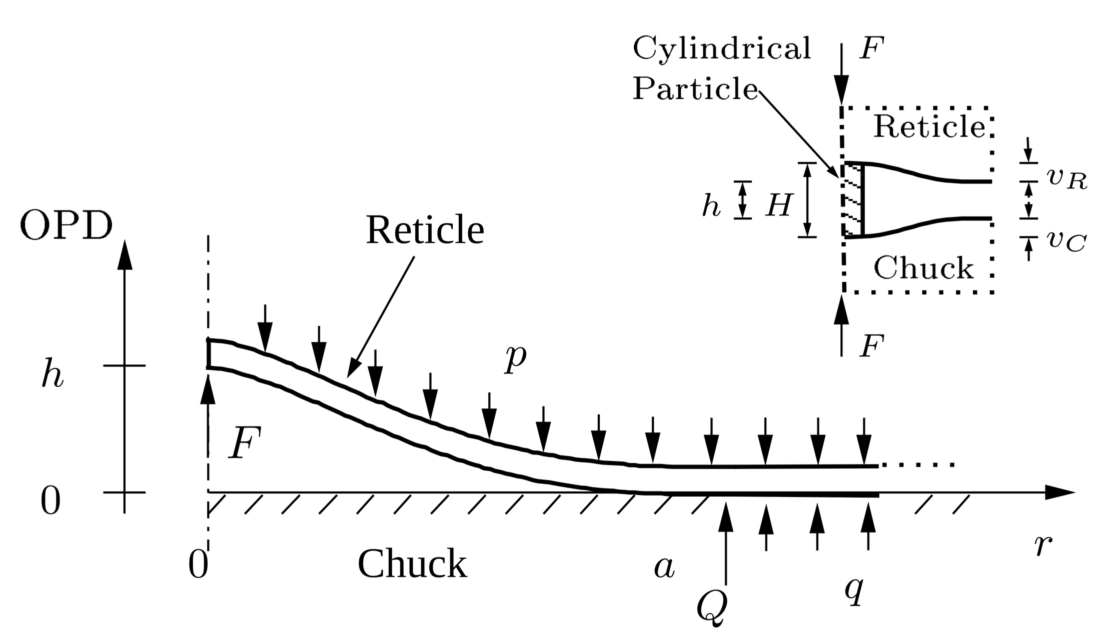


Figure 1: Schematic of the plate model.

## Hankel Model

We consider a new analytical approach to model the *'plate shearing'* and *'feature transfer'*-effect.

- Elasticity solution

$$OPD = \int_0^\infty \xi \left(\frac{d^2G}{dz^2} - \frac{\lambda + 2\mu}{\mu}\xi^2 G\right) J_0(\xi r) d\xi\,,$$

$$IPD = \int_0^\infty \frac{\lambda + \mu}{\mu}\xi^2 \frac{dG}{dz} J_1(\xi r) d\xi$$

where

$$G(\xi, z) = p(\xi)\Phi(\xi, z)$$

- Hankel transform of stress boundary condition

$$p(\xi) = \int_0^\infty p(r) J_0(\xi r) r dr$$

**Pros & Cons:**

- Exact 3D elasticity solution
- 'Con': Expensive numerical integration (but cheaper than FEM, still working on adaptive numerical integration schemes)

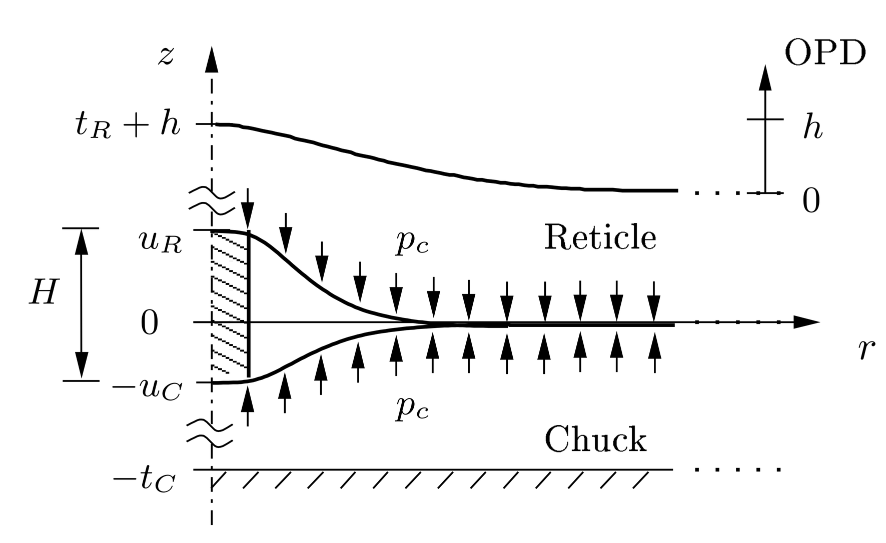


Figure 2: Schematic of the Hankel model.

## FE Model

- Current finite element models in the literature use de-coupled global and local models (*'feature transfer'*-effect neglected)
- We consider a recursive mesh refinement to simulate the fully coupled problem of three bodies in contact

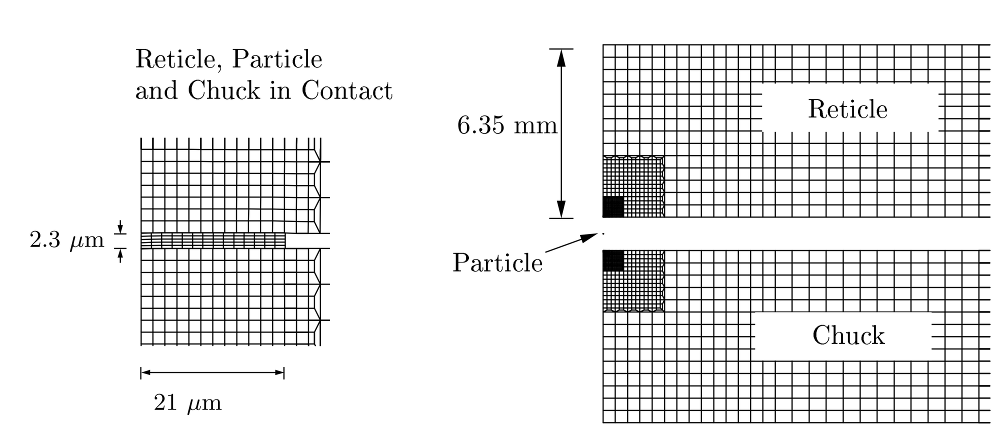


Figure 3: Recursive finite element mesh refinement.

## Benchmark Example

Comparing the models for a numerical example:

| | |
|---|---|
| ULE Reticle | $E_R = 67.6$ GPa, $\nu_R = 0.17$ |
| AlOxide Particle | $E_P = 406$ GPa, $\nu_P = 0.2$ |
| Ceramic Chuck | $E_C = 380$ GPa, $\nu_C = 0.2$ |

- We observe higher OPD response in the Hankel- and Finite Element Models:

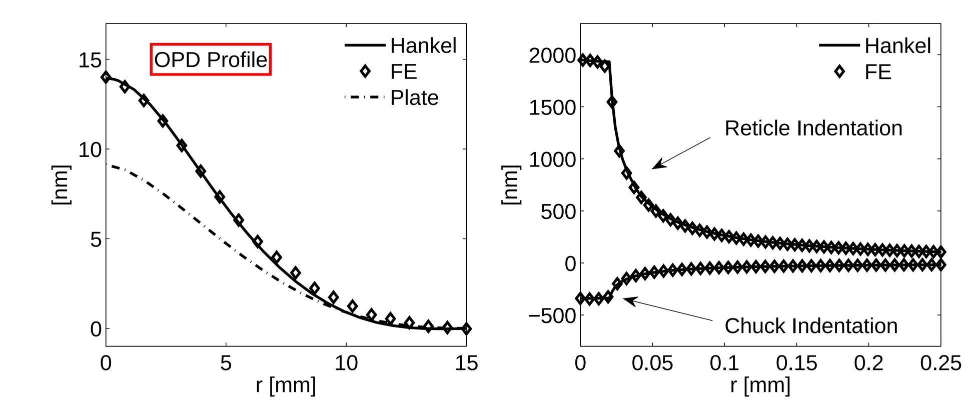


Figure 4: Example OPD profiles for different models at 15 kPa chucking stage.

- All models are close in their IPD-predictions:

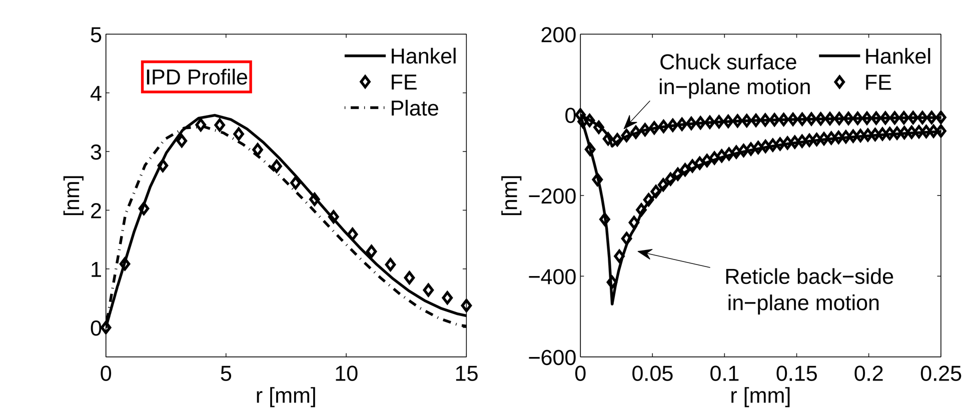


Figure 5: Example IPD profiles for different models at 15 kPa chucking stage.

- Comparing the models for various chucking pressures:

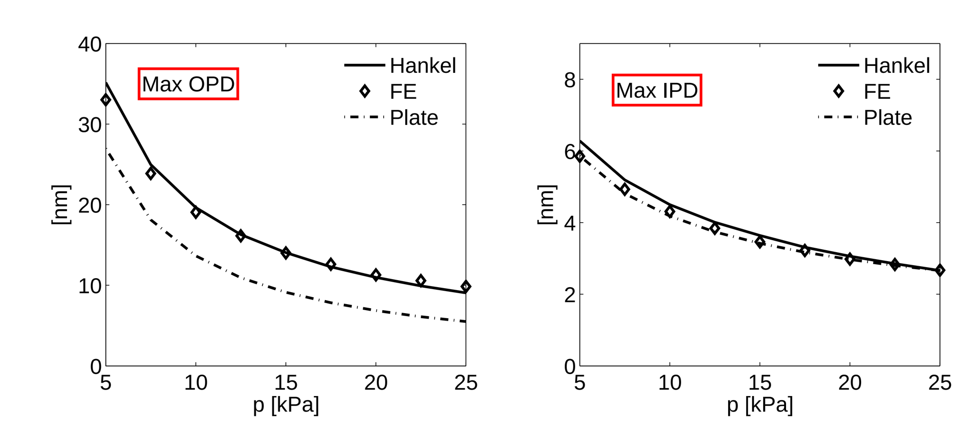


Figure 6: Example maximum OPD/IPD for various pressures.

## Example Result

The Hankel- or coupled Finite Element Model is needed to account for the *'feature transfer'*-effect to give the correct OPD response.

## Critical Particle Sizes

Given an image placement error budget, critical particle sizes are estimated for cylindrical particles and a ULE glass reticle:

- IPD has most contribution to the IPE.
- Softer materials will relax the bounds on the critical particle sizes.

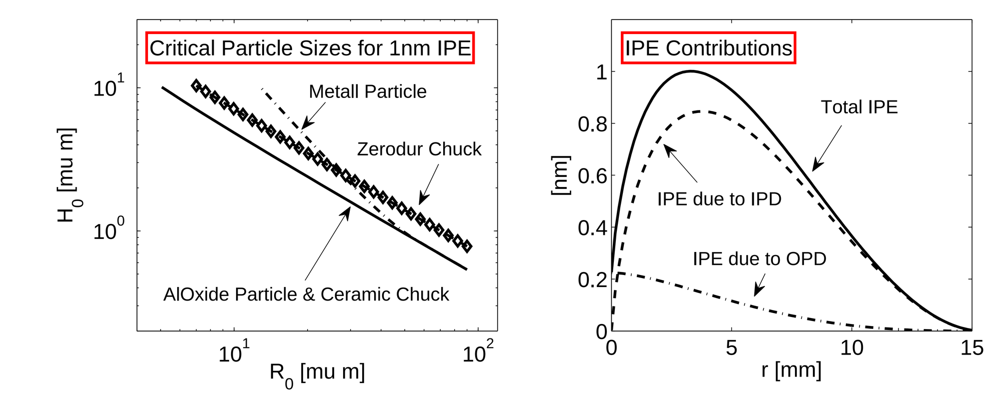


Figure 7: Left: Critical particle sizes for various material combinations at 15 kPa chucking stage. Right: Contributions to the Image Placement Error (IPE) due to the In-plane motion (IPD) and Out-of-plane deformation(OPD).

## Result

Given a 1 nm IPE budget, we find criticle particle size bounds at 15 kPa chucking stage:

- Cylindrical particles of 1 $\mu m$ height require radii of less than 47 $\mu m$.
- Cylindrical particles of 5 $\mu m$ height require radii of less than 9 $\mu m$.

## Secondary Effects

- CrN-layer on reticle back-side → increases OPD/IPD
- Gap dependant electrostatic pressure model → required only for very thin chuck-dielectric
- Frictional contact → increases OPD/IPD
- Chuck pins → decrease OPD/IPD.

Research funded by the Intel Corporation.