NSF Center for Micro and Nanoscale Contamination Control

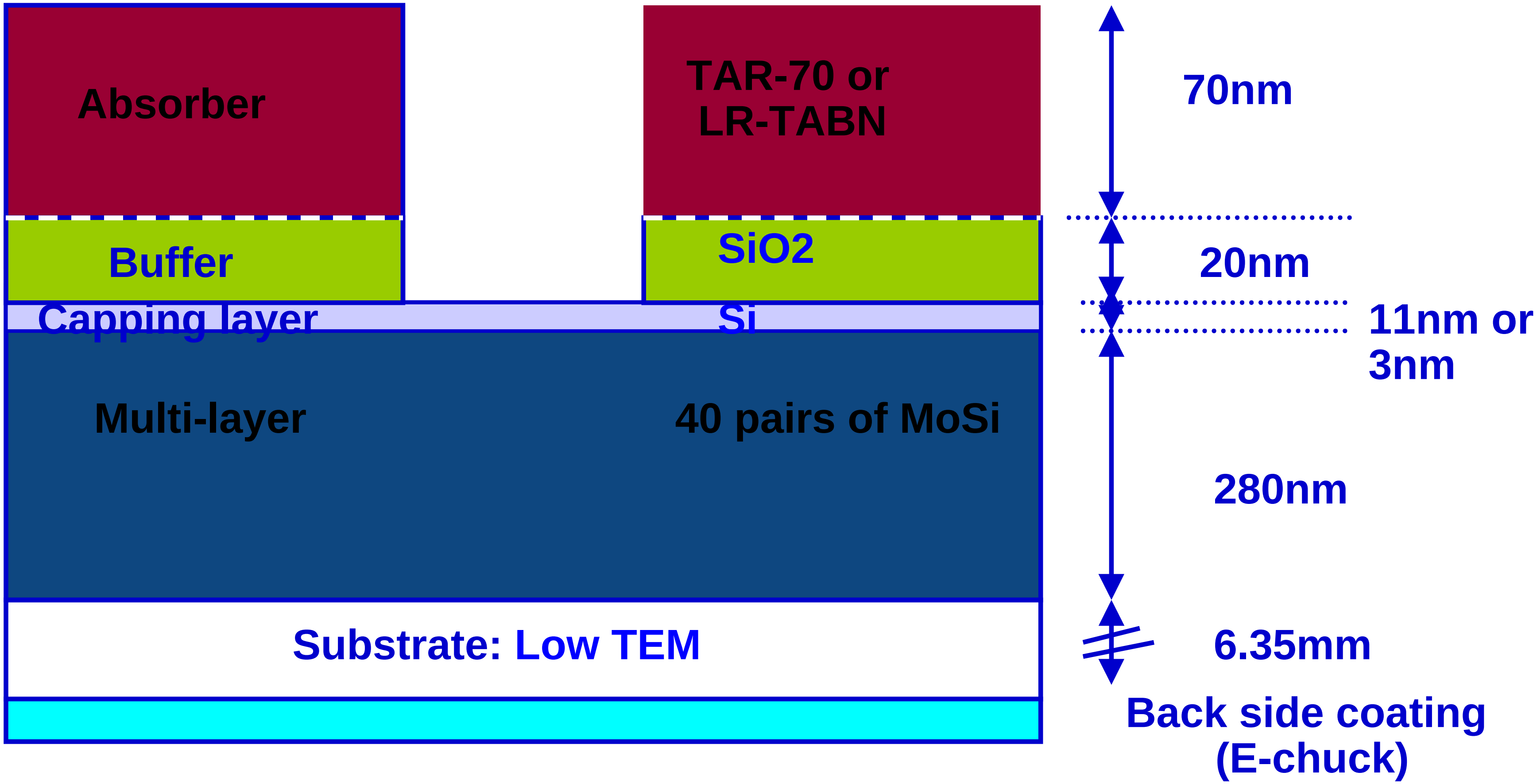
Metrology and Removal of Nanoscale Particles from EUV Substrates

O. Guldiken[1], S. Hu[1], Ahmed Busnaina[1] and Jin-Goo Park[2]
Guojing Zhang[3], Florence Eschbach[3] and Arun Ramamoorthy[3]
(1) NSF Center for Microcontamination Control,
Northeastern University, Boston, MA 02115-5000
Tel: 617 373-2992, Fax: 617 373-2921
Email: a.busnaina@neu.edu, www.cmc.neu.edu
(2) Hanyang University, Ansan, Korea
(3) Intel Corporation, Santa Clara, CA

Introduction

- EUV lithography wafer patterning operates without a pellicle.
- The reticle may be subject to particulate and chemical contamination, in the absence of a pellicle.
- There is a need to develop a cleaning process that would remove all contaminants according to EUV cleaning requirements.
- EUV cleaning requirements are:
  - Removal of all particles larger than 30nm
  - Eliminate residual organic contamination
  - Cleaning should not degrade EUV (13.4nm) mask reflectivity by more than 0.5% with cumulated cleans
  - The process should not induce pattern or substrate damage with cumulated cleans
  - The clean process should adhere to the environmental safety standards.

EUV Mask


Absorber
TAR-70 or LR-TABN
70nm
Buffer
SiO2
20nm
Capping layer
Si
11nm or 3nm
Multi-layer
40 pairs of MoSi
280nm
Substrate: Low TEM
6.35mm
Back side coating (E-chuck)

Particle Adhesion Force: van der Waals

- **van der Waals Force**

$$F_0 = \frac{AR}{6z_0^2}$$

- **Adhesion-Induced Deformation**

Elastic Deformation

$$\mu = \frac{32}{3\pi}\left[\frac{2Rw_A^2}{\pi E^{*2} z_0^3}\right]^{1/3}$$

μ>1 JKR Model

$$a = \left(\frac{6\pi w_A R^2}{K}\right)^{1/3}$$

μ<1 DMT model

$$a = \left(\frac{\pi w_A R^2}{K}\right)^{1/3}$$

where $K = \frac{4}{3}\frac{1}{\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}}$

Plastic Deformation (when pressure > hardness)

MP Model

$$a = \left(\frac{2w_A R}{3Y}\right)^{1/2}$$

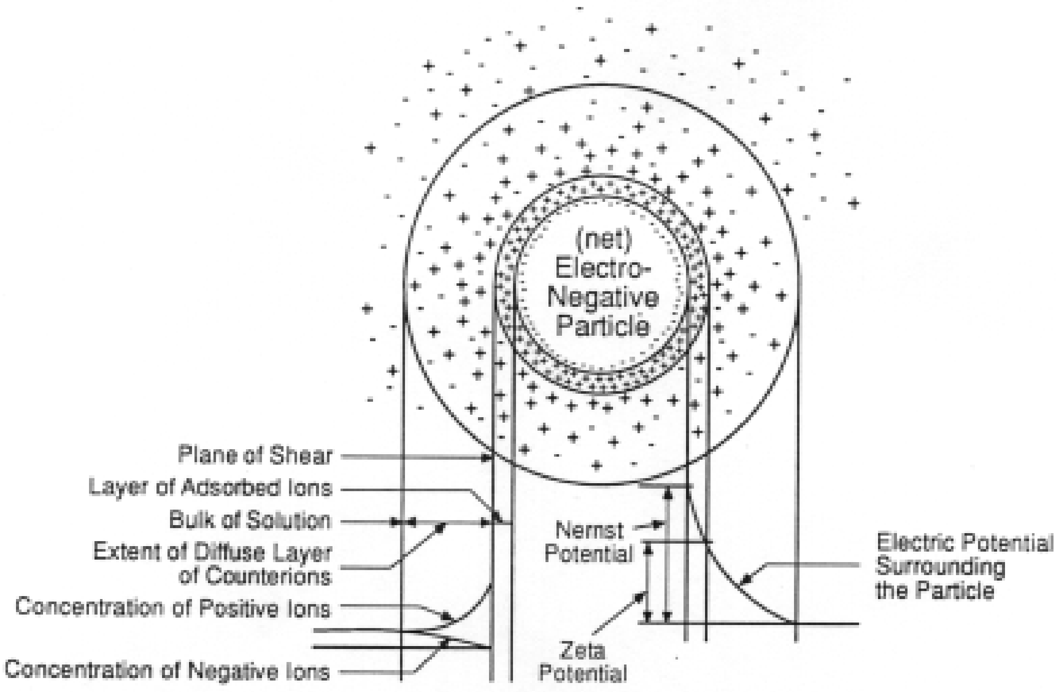
- **Total Adhesion Force**

$$F_a = F_{vdW} + F_{deformation} = \frac{AR}{6z_0^2}\left(1 + \frac{a^2}{Rz_0}\right)$$

Electrical double layer force

- **Origin of electrical double layer force**

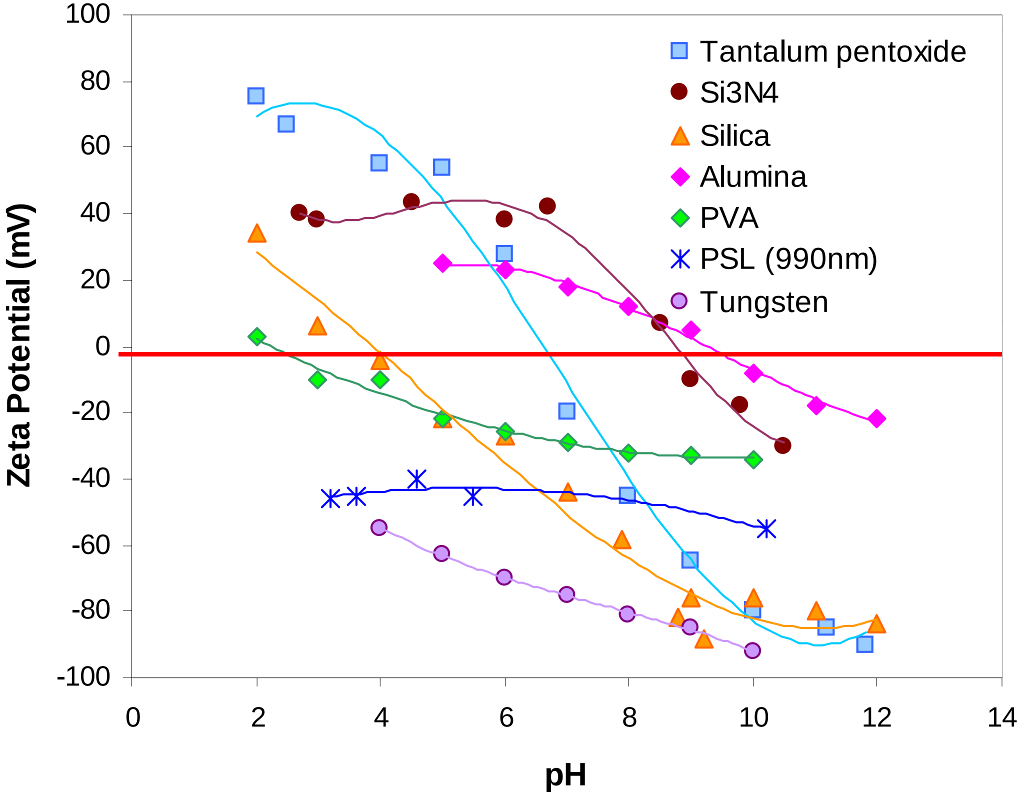
Osmotic pressure makes the counterions leave the surface against the attractive Coulombic force pulling them back and maintains the diffuse double layer.



- Particles in solution become Charged
- Stern layer + Diffuse layer = Double layer
- Potential at shear plane = Zeta Potential
- Function of pH

Electrical double layer force

Zeta Potential



- At the pH of water, silica, PSL, PVA, and W particles are all negatively charged.
- The high negative zeta potentials are measured at high pH solution for SiO_2, Si_3N_4, Al_2O_3, tantalum pentoxide, tungsten, polyvinyl alcohol (PVA), and also for Si and PSL.

Electrical Double Layer Force

different approximate expressions

- **Hogg-Healy-Fuerstenau (HHF) equation under constant potential**

  Based linear P-B equation and using Derjaguin approximation

$$F(D) = 2\pi\varepsilon_r\varepsilon_0 R\left(\Psi_{01}^2 + \Psi_{02}^2\right)\frac{\kappa e^{-\kappa D}}{1-e^{-2\kappa D}}\left[\frac{2\Psi_{01}\Psi_{02}}{\Psi_{01}^2+\Psi_{02}^2} - e^{-\kappa D}\right]$$

$$\kappa^2 = (e^2/\varepsilon\varepsilon_0 kT)\sum_i z_i^2\rho_{i\infty}$$

- **HHF equation under constant charge**

$$F(D) = 2\pi\varepsilon_r\varepsilon_0 R\left(\Psi_{01}^2 + \Psi_{02}^2\right)\frac{\kappa e^{-\kappa D}}{1-e^{-2\kappa D}}\left[\frac{2\Psi_{01}\Psi_{02}}{\Psi_{01}^2+\Psi_{02}^2} + e^{-\kappa D}\right]$$

- **Linear superposition approximation (LSA)**

$$F(D) = \frac{128\pi\rho_\infty kTR\gamma_1\gamma_2}{\kappa}\exp(-\kappa D)$$

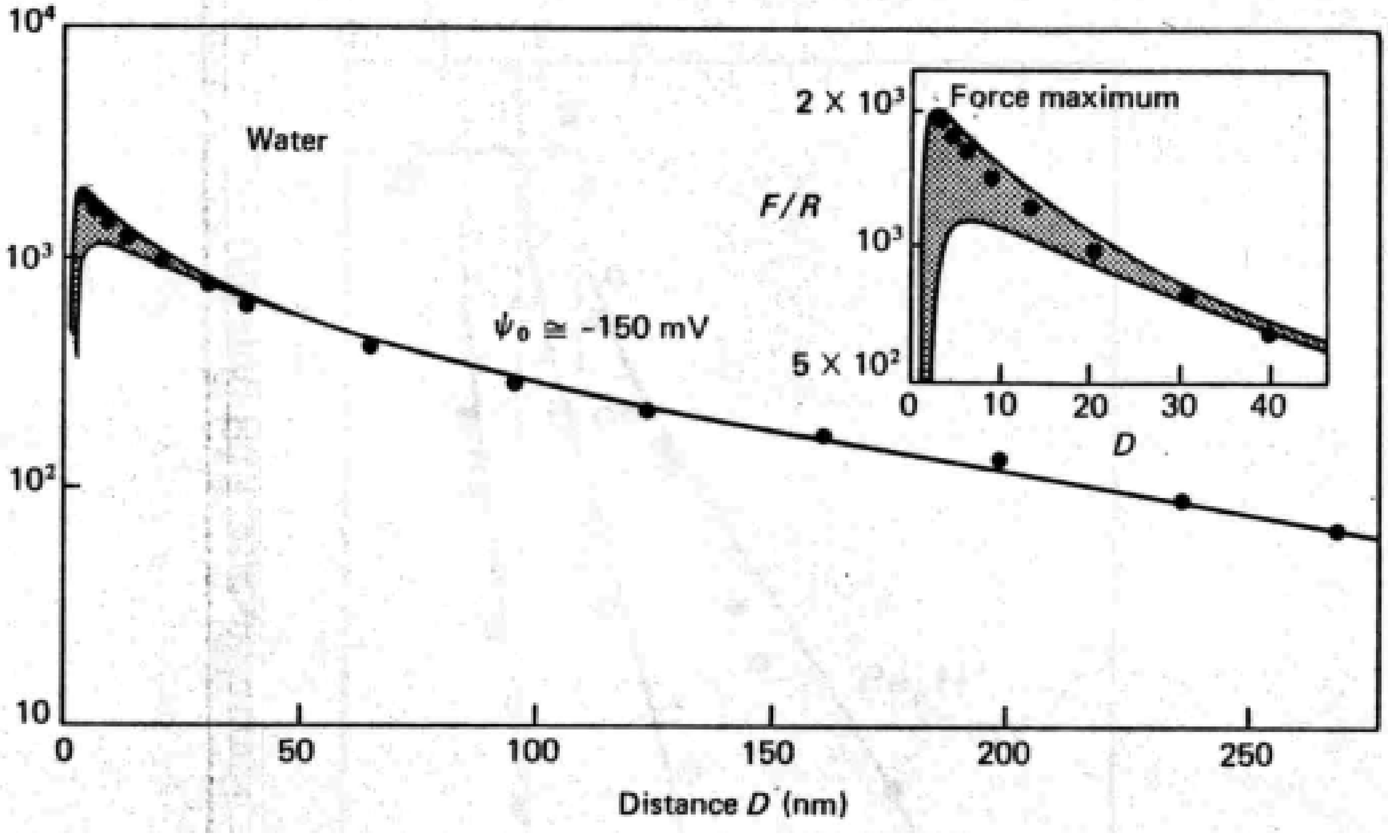
$$\gamma = \tanh(ze\Psi/4kT) = \frac{\exp(ze\Psi/2kT)-1}{\exp(ze\Psi/2kT)+1}$$

- **"Compression" approximation (constant charge)**

$$F(D) = \frac{4\pi R\rho_\infty kT}{\kappa}\left[2\bar{y}\ln\left(\frac{B+\bar{y}\coth(\kappa D/2)}{1+\bar{y}}\right) - \ln(\bar{y}^2 + \cosh\kappa D + B\sinh\kappa D) + \kappa D\right]$$

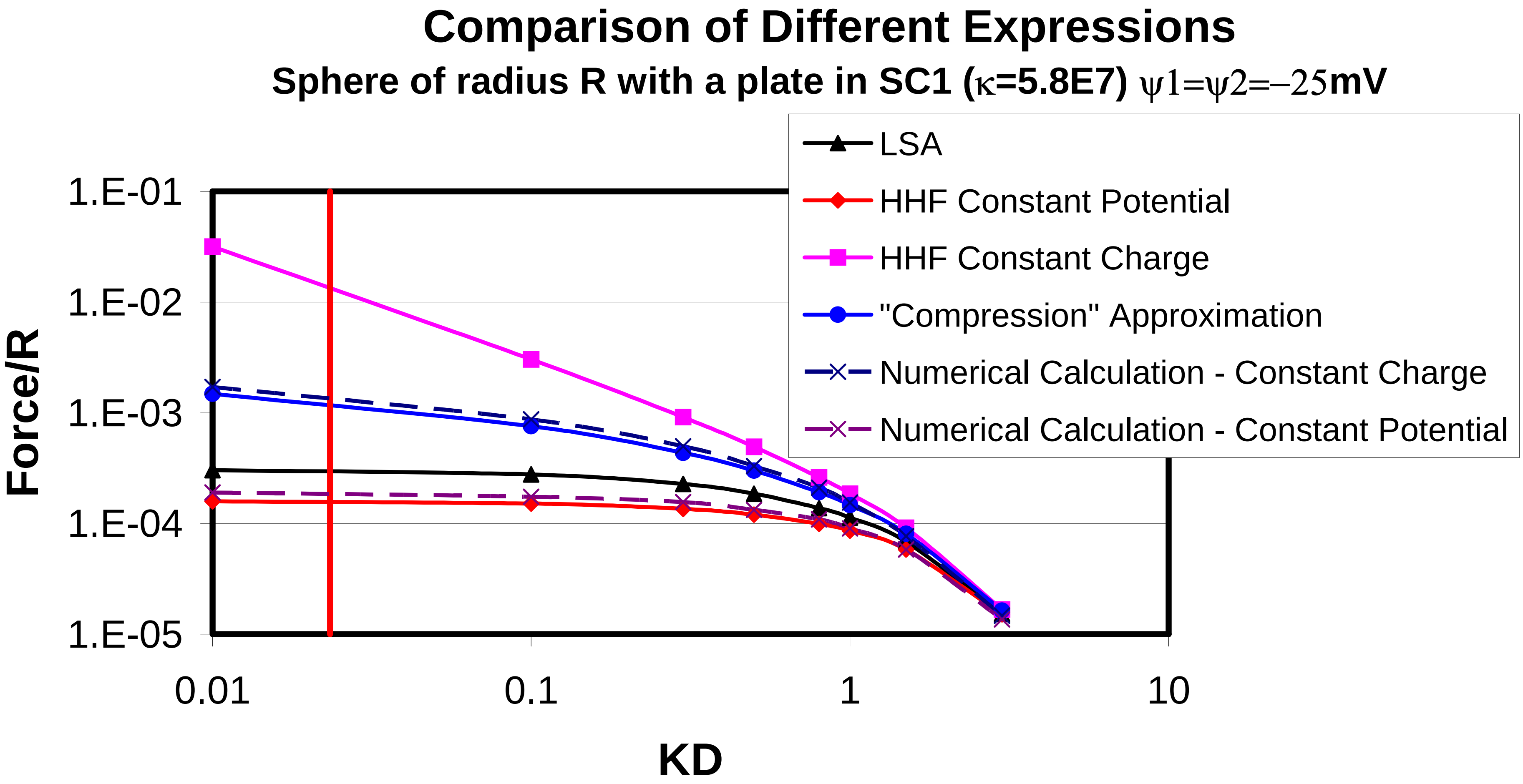
where $\bar{y} = (y_1 + y_2)/2 \quad and \quad y = ze\psi/kT$ **and** $B = [1+\bar{y}^2\,\mathrm{csc}\,h^2(\kappa D/2)]^{1/2}$

Experimental Measurements



Direct force measurement between mica-mica surfaces by Israelachvili, J. N., and Adams, G. J. Chem. Soc. Faraday Trans 1, 74, 975, 1978. (Two solid lines are constant-charge and constant-potential limits)

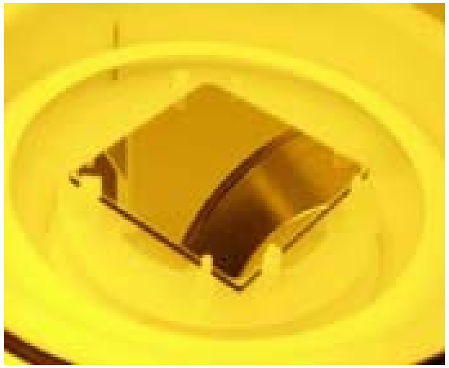
Electrical Double Layer Force



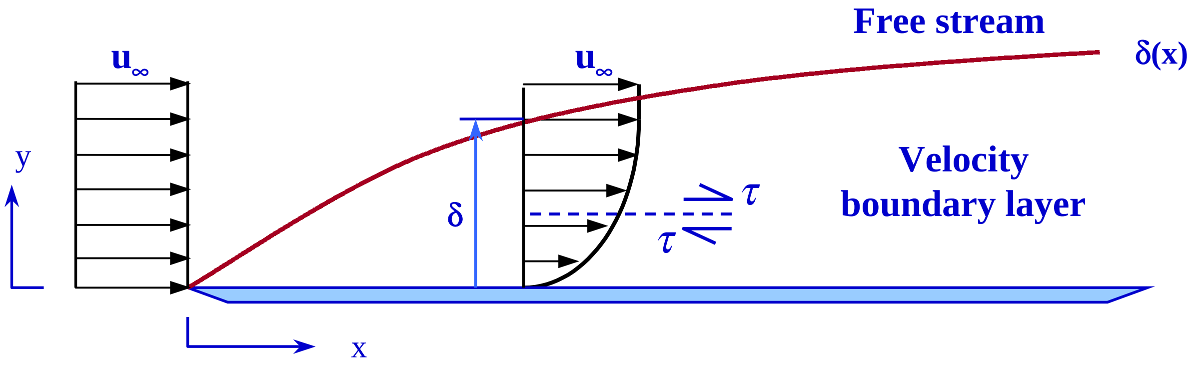
(The vertical red line represents κz_0, where κ is the value of SC1 and z_0=0.4nm, the separation distance between particle and plate)

Chuck using in Cleaning and Rinsing

EUVL masks consist of a patterned absorber of EUV radiation placed on top of an ML reflector deposited on a robust and solid substrate.



Acoustic Boundary Layer Thickness



Velocity boundary layer on a flat plate

- **Acoustic boundary layer thickness**:

$$\delta_{ac} = \left(\frac{2\nu}{\omega}\right)^{\frac{1}{2}}$$

in water, f=850KHz, δ_{ac}=0.61μm

f=760KHz, δ_{ac}=0.65μm

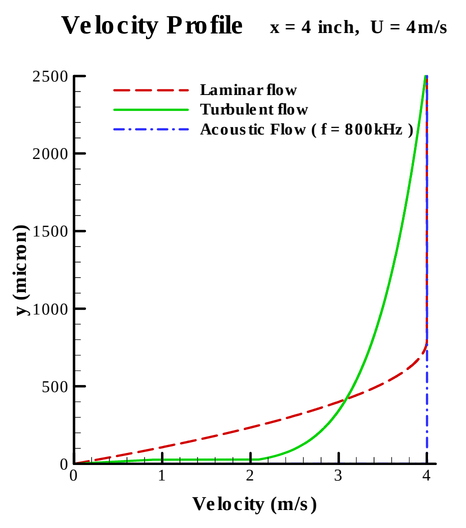
f=360KHz, δ_{ac}=0.94μm

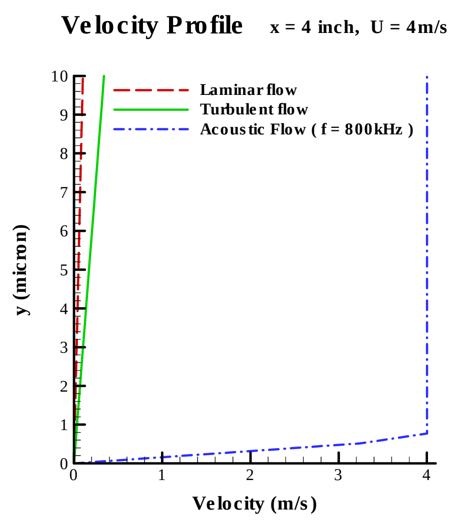
- **The hydrodynamic boundary layer thickness**:

$$\delta_{H,Turbulent} = 0.16\left(\frac{\nu}{Ux}\right)^{\frac{1}{7}} \cdot x \propto x^{\frac{6}{7}}$$

$$\delta_{H,Laminar} = 5.0\left(\frac{\nu}{Ux}\right)^{\frac{1}{2}} \cdot x \propto x^{\frac{1}{2}}$$

in water, u=4m/s, at center of an 8” wafer, δ_H=2570 μm





Particle Removal Mechanism

- The experimental results show that when MR >1, 80 % of particles are removed.

- Why smaller particles are more difficult to remove?

  Existence of boundary layer;

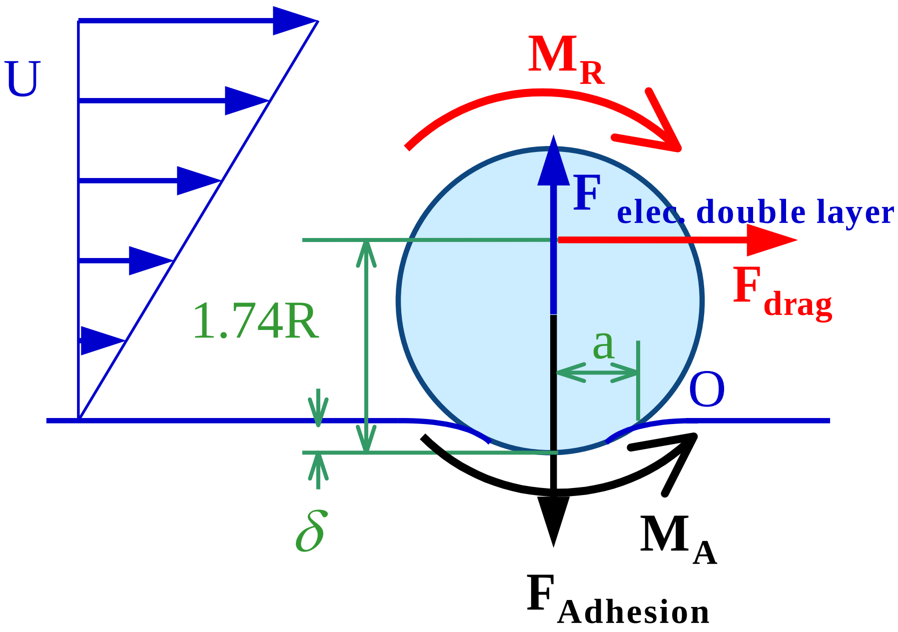
  Drag force $\propto d^2$ but Adhesion force $\propto d$

- Advantage of megasonic cleaning

  Much thinner boundary layer thickness

$$\delta_{ac} = \left(\frac{2\nu}{\omega} \right)^{\frac{1}{2}}$$

- Electrical double layer force plays an important role in particle removal



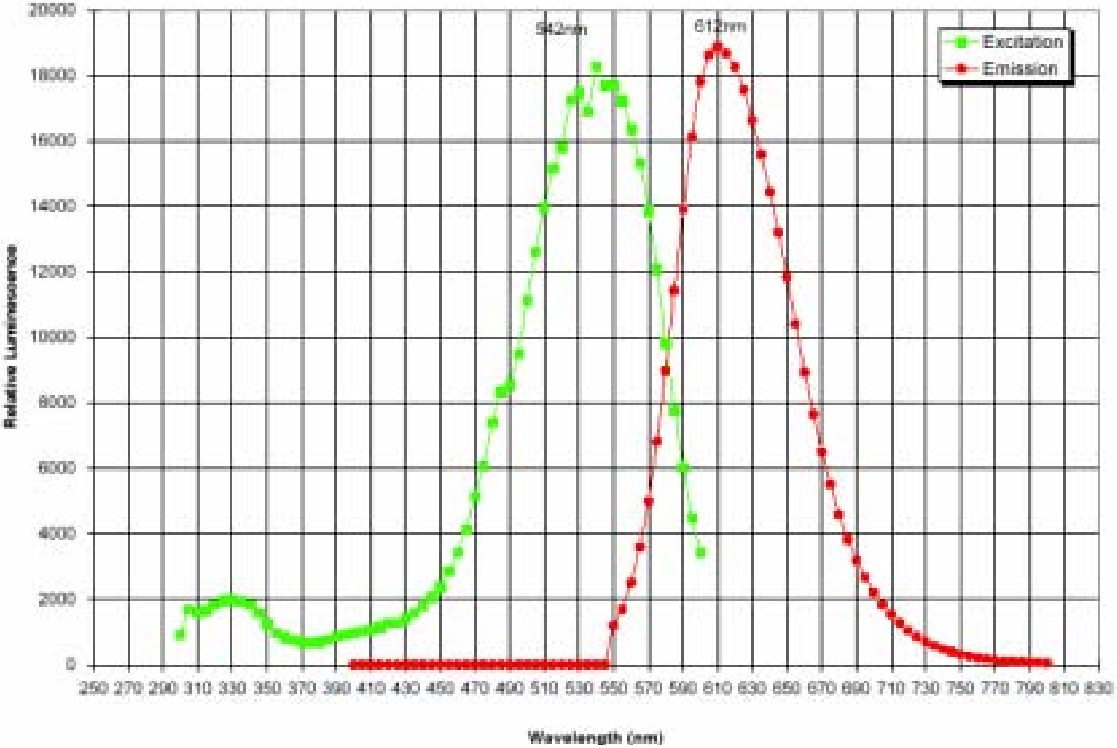
Rolling removal mechanism

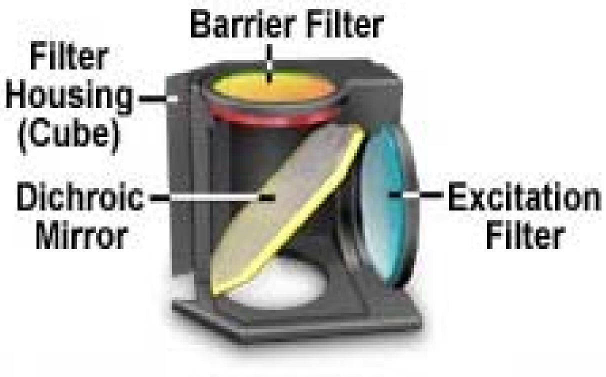
$$MR = \frac{\text{Removal moment}}{\text{Adhesion resisting moment}}$$

$$MR = \frac{F_d(1.74R - \delta) + F_{dl} \cdot a}{F_a \cdot a}$$

Introduction
Visualization of Fluorescent Particles

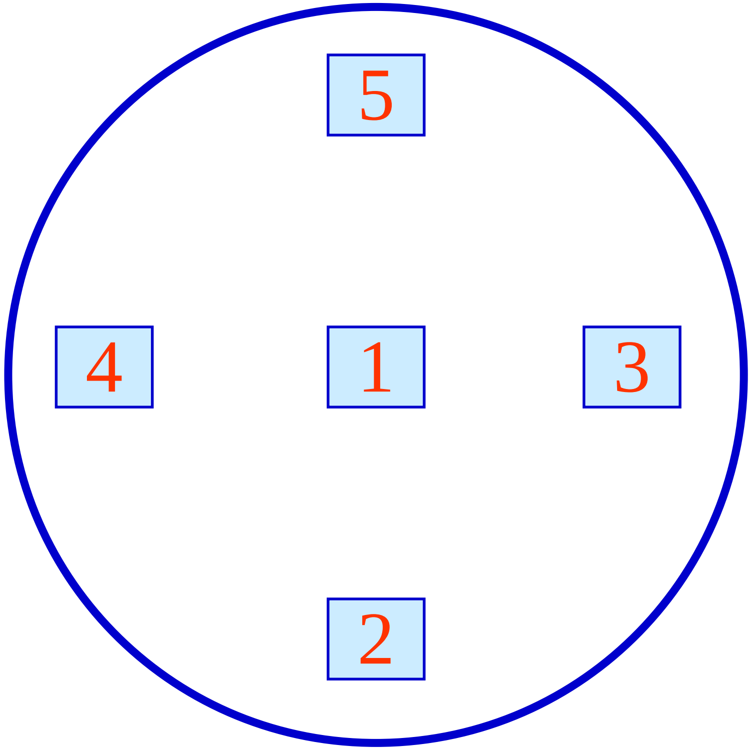
- Nikon's OPTIPHOT200 optical microscope with auto stage
- Nikon G block filter
- 75 W Xenon arclamp
- Extra N.D filter





Fluorescent Cube

Wafer Cleaning Results
(Removal of 63 nm PSL Particles)



- Particles are counted at 5 locations as shown in the sketch.

- The width and the height of the each area to be scanned is 2000 micron.

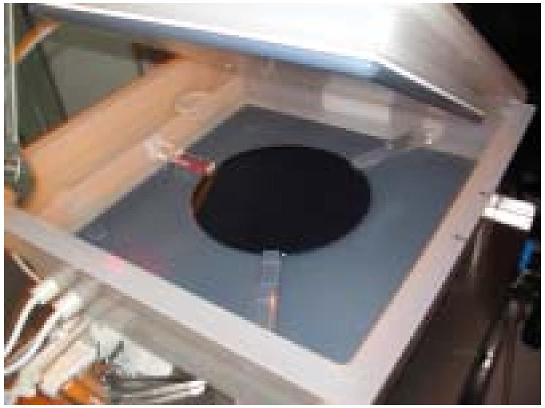
- Particles are counting using the Image Pro-Plus Program.

Experimental conditions:
Cleaning parameters
Power: 87 % (640 watt max.)
Temp.: 50 ° C (DI water), 38 ° C (SC1)
Time: 2,4,6,8 min.
Frequency: 760 kHz

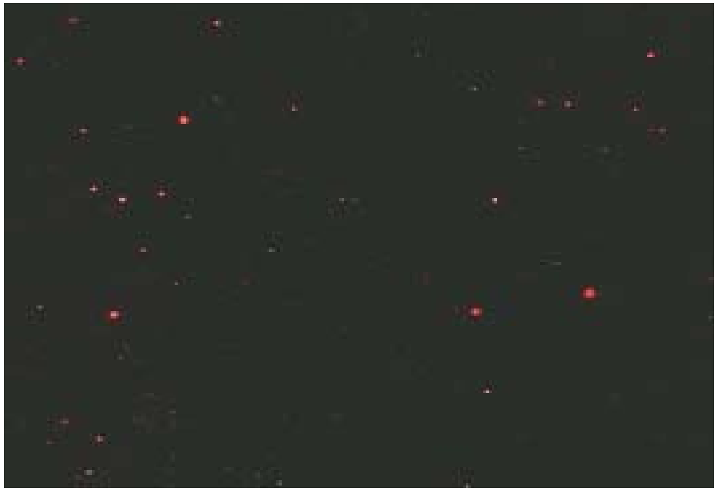
Nano-Particle Removal with Megasonics Has been Demonstrated Using Fluorescence Microscopy

Removal of nanoscale PSL Florescent Particles

90 and 63 PSL particles were removed from bare silicon wafers using the Single wafer megasonic cleaning tank.

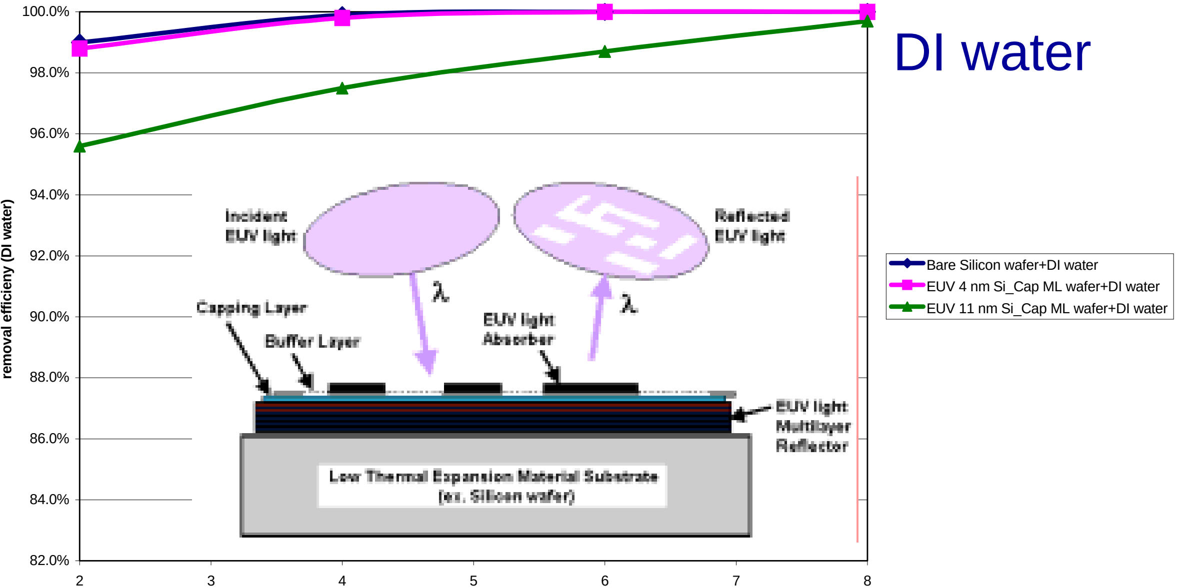


63 nm Before



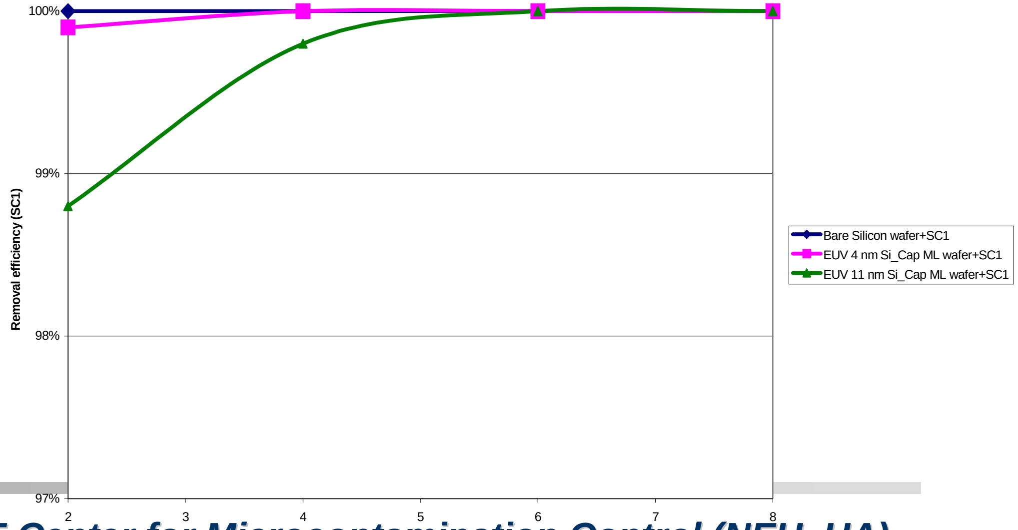
63 nm After

Nanoparticle (63 nm PSL) Removal Using Acoustic Streaming



DI water

Dilute SC1 chemistry



Nanoparticle (50 nm PSL) Removal Using Acoustic Streaming

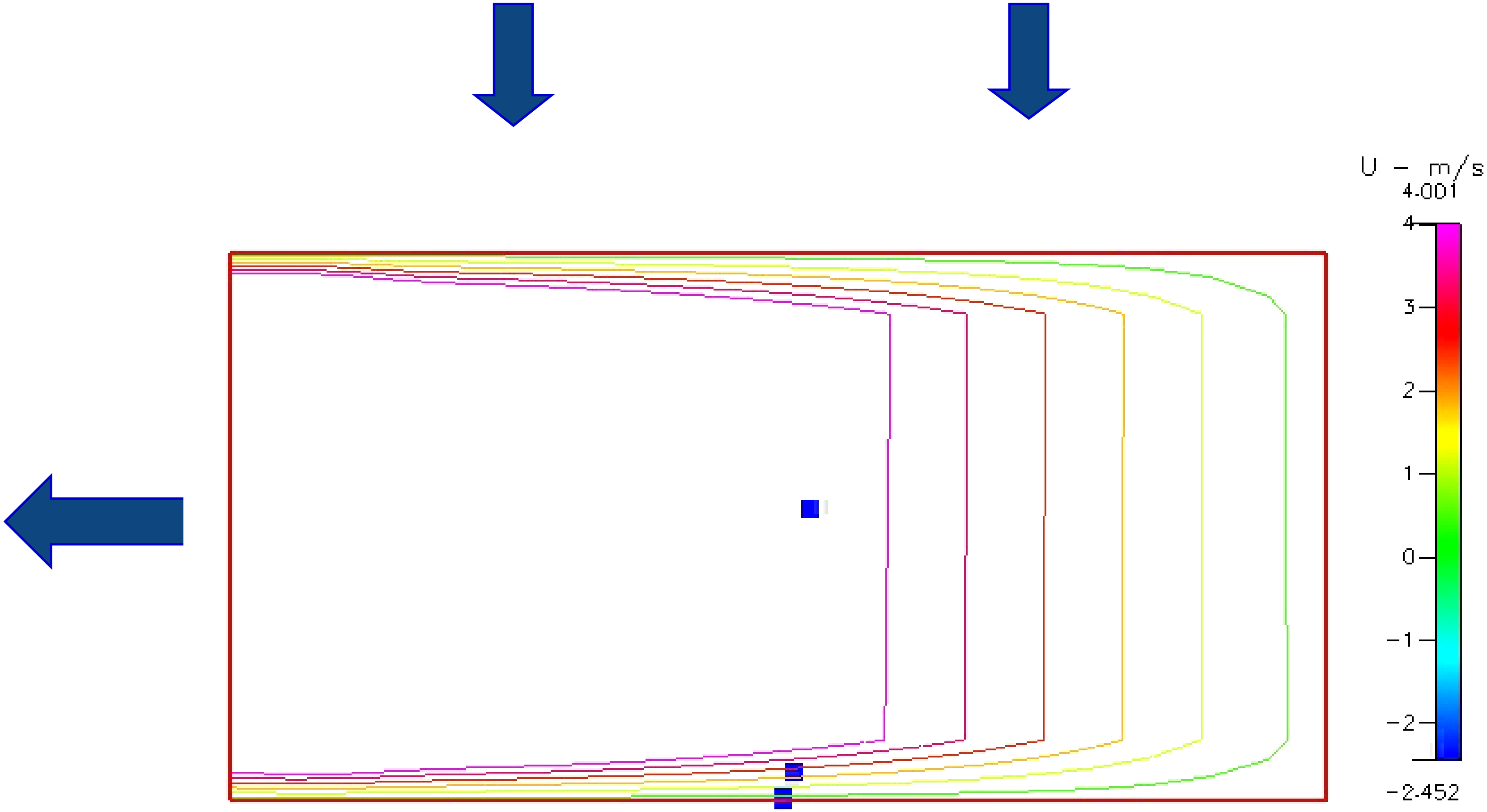
50nm Particle Removal from 11nm Using SC1	Power (%)	Time (mins)	Temperature (^{O}C)	Before	After	Removal Efficiency (%)
1.	87	7	37.5	1082	0	100
2.	62.5	4.5	37.5	1398	0	100

50nm Particle Removal from 11nm Using DI water	Power (%)	Time (mins)	Temperature (^{O}C)	Before	After	Removal Efficiency (%)
1.	87	7	35	695	12	98.3
2.	87	8	35	938	21	97.8

Why does it take time to remove the particles?

- Why does it take 8 minutes to remove nanoparticles compared to one minute when dealing with submicron particles?
- Physical modeling using Computational Fluid Dynamics (CFD) can shed some light on the effect of time.

Why does it take time to remove 63 nm particles?



CFD Animation: time = 0.01 second, Height= 1 cm, width=2 cm

Summary and Conclusions

- **Double layer Force Calculations**

- **Electrical double layer force can be described using the assumption of either constant charge or constant potential.**
- **HHF equation describes the constant potential limit well.**
- **"Compression" approximation describes the constant charge limit better than HHF equation which overestimates the interaction force.**
- **Direct force measurement results show that data lie in-between constant charge and constant potential limits and closer to constant charge limit.**
- **Compression approximation is used in our calculation.**

Summary and Conclusions

- The local removal of nanoscale particles (63 nm monodispersed polystyrene spheres; PSL) using megasonic cleaning is investigated experimentally in this study.
- The following substrates were used in the megasonic cleaning experiments; 4 nm Si_cap ML wafers, 11 nm Si_cap ML wafers.
- The results show that complete local removal of 63 nm PSL particles can be obtained in a short time for the Si wafer and 4 nm Si_cap ML wafers.
- However, when megasonics is used with dilute SC1 complete local removal of 63 nm PSL particles is achieved under most cleaning conditions.
- Removal of nanoparticles takes longer than submicron particles
- The time effect can be explained by modeling the acoustic streaming phenomenon and its effect on particles.
- Particles also oscillate within the boundary layer before they leave the surface.
- Future work is underway to quantify global removal of 63nm PSL particles and understand mechanisms of particulates redeposition.

Acknowledgement

- Intel
- National Science Foundation
- PCT Systems