SCALING OF THE ADHESION BETWEEN PARTICLES AND SURFACES FROM MICRON-SCALE TO THE NANOMETER SCALE FOR PHOTOMASK CLEANING APPLICATIONS

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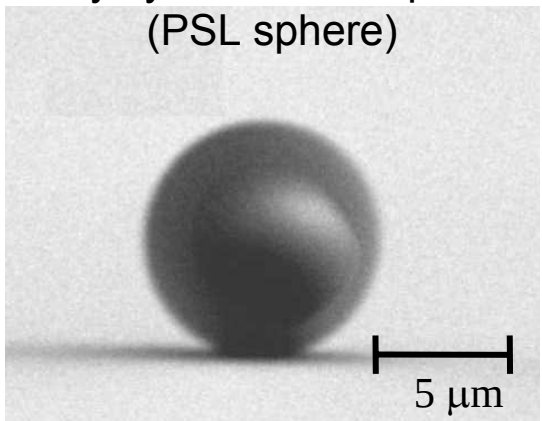
Rationale

- Mask cleaning processes can be more quickly optimized if the magnitude of particle-mask adhesion forces known
- Mask layers and contaminants offering most difficult cleaning challenge can be identified
- Effects of solution properties on contaminant adhesion can be evaluated
- Range of adhesion forces for given contaminant/mask layer can be determined

Particle Characteristics

The Academic System

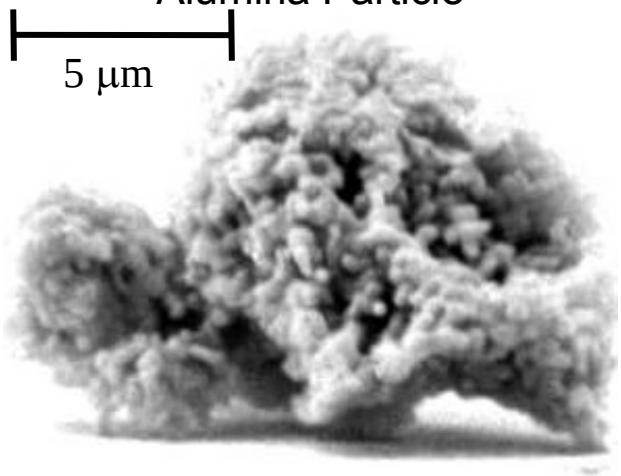
Polystyrene Latex Sphere
(PSL sphere)



- Ideal geometries
- Can model contact area using classic approaches
  - Contact mechanics (JKR, DMT…)
  - DLVO
- Uniform microscopic morphology
  - Empirical, semi-empirical approaches

The Real World

Alumina Particle



- Unusual geometry
- Random microscopic morphology
- Compression/deformation of surface asperities
- Chemical heterogeneities
- Settling (tilting, shifting)
- Statistical information

Macroscopic Adhesion Model: DLVO Theory

$$F_A = F_{vdW} + F_{EDL}$$

Total Adhesion Force

van der Waals Force

$$F_{vdW} = f(A, d, a, h)$$

Electrostatic Double Layer Force

$$F_{EDL} = f(\varepsilon, \zeta, \kappa, d, h)$$

$$\zeta = f(I, pH)$$

$$\kappa = f(I)$$

A = System Hamaker constant

d = Particle diameter

a = Contact radius

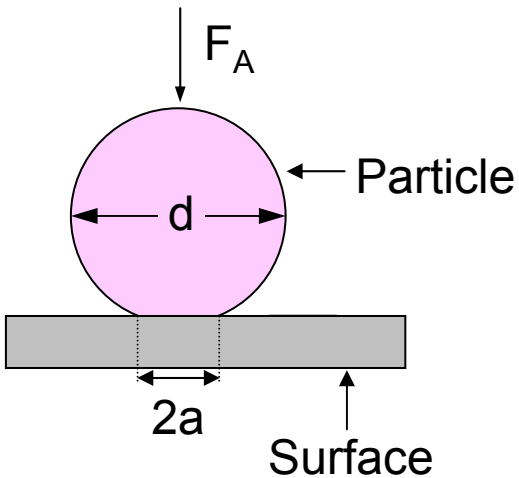
h = Particle-surface separation distance

ε = Medium dielectric constant

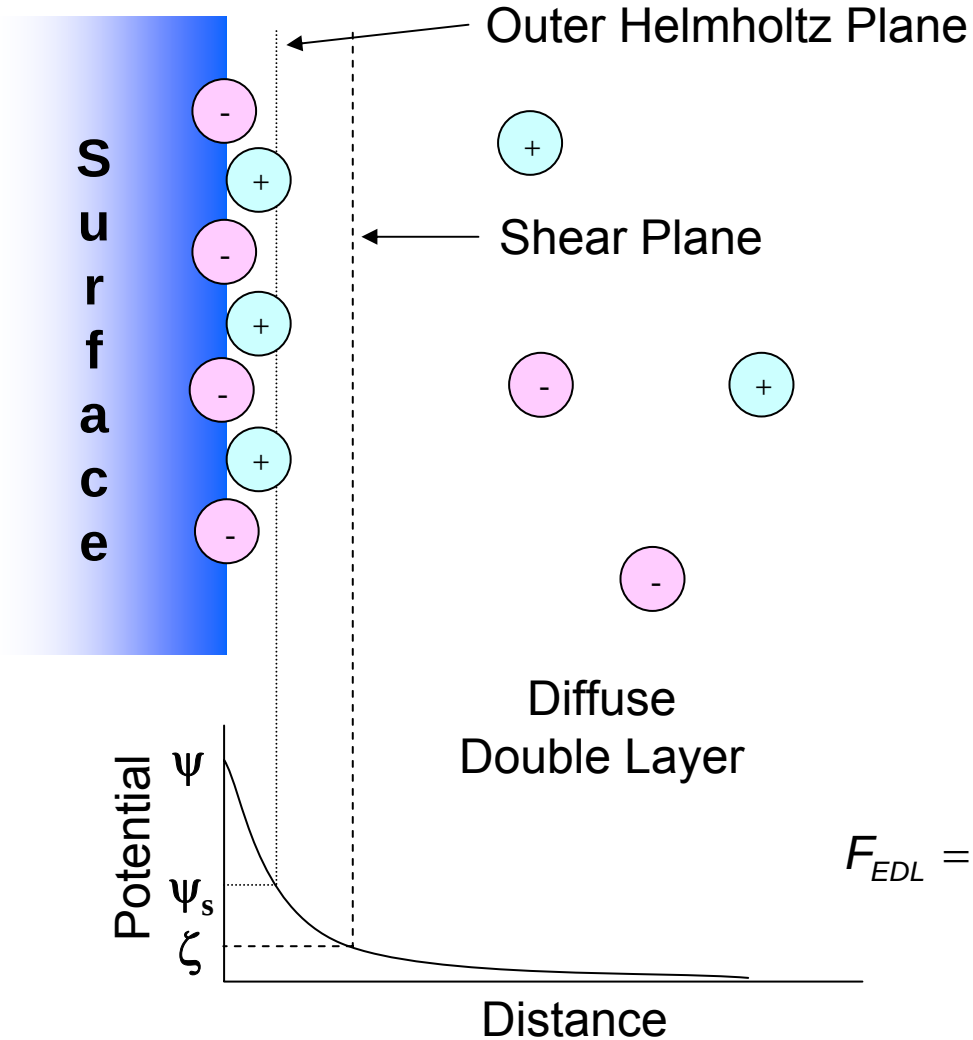
ζ = Zeta potential

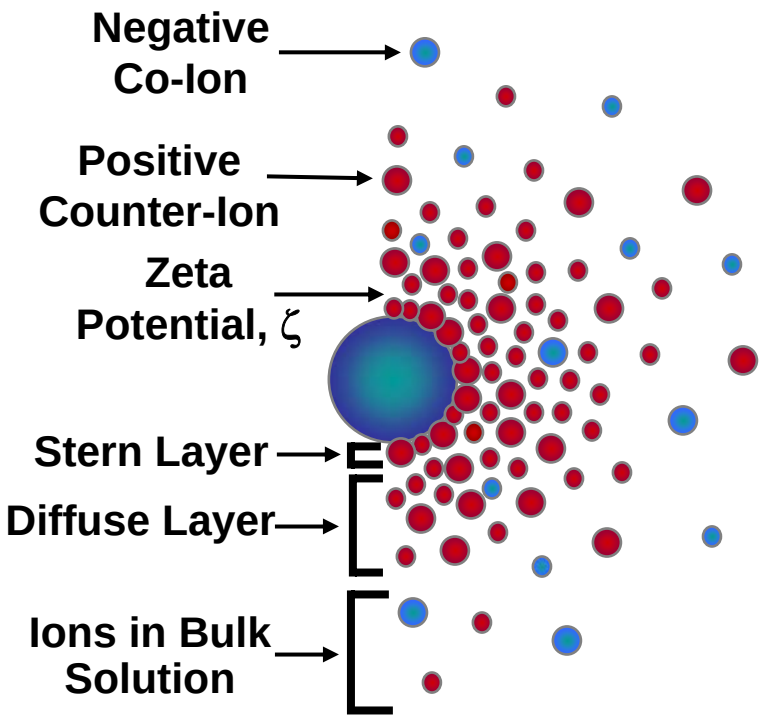
κ = Reciprocal double-layer thickness

I = Medium ionic strength



Electrostatic Double Layer (EDL) Force





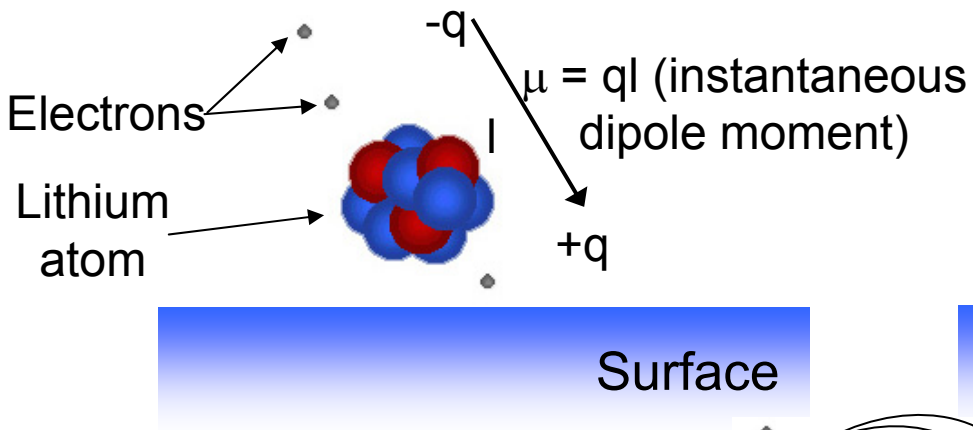
$$F_{EDL} = \frac{\varepsilon\varepsilon_0 d\left(\psi_p^2 + \psi_s^2\right)}{4} \cdot \frac{\kappa e^{-\kappa h}}{1 - e^{-2\kappa h}} \cdot \left[\frac{2\psi_p\psi_s}{\psi_p^2 + \psi_s^2} - e^{-\kappa h}\right]$$

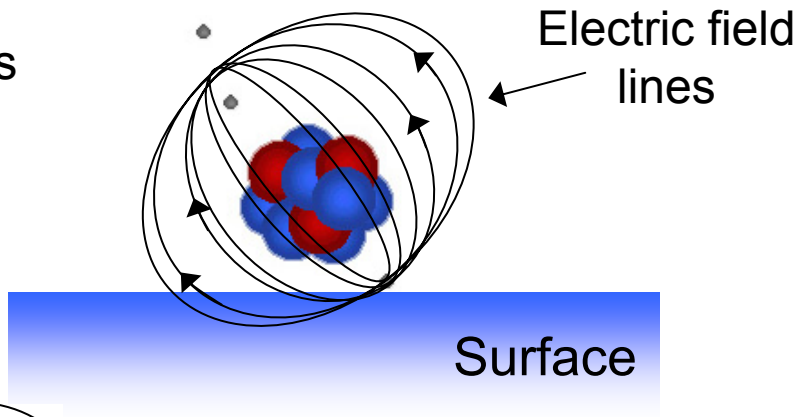
ψ approximated by ζ

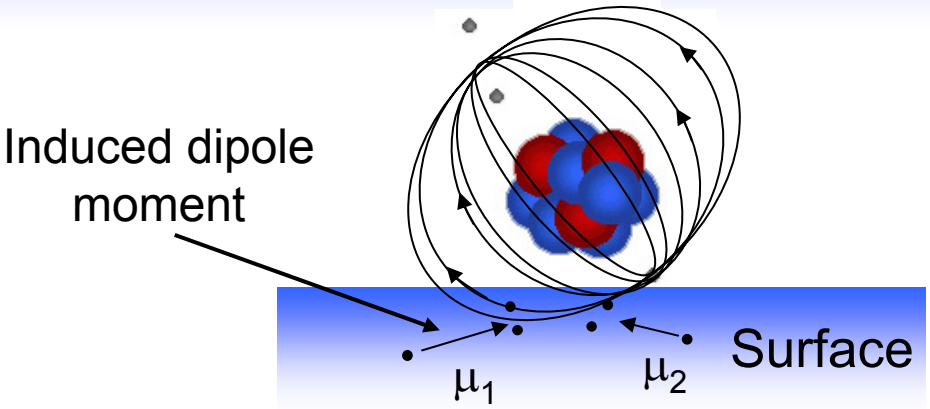
van der Waals (vdW) Force

$$F_{vdW} = F_{Keesom} + F_{Debye} + F_{London}$$

induced-permanent | permanent-permanent | induced-induced

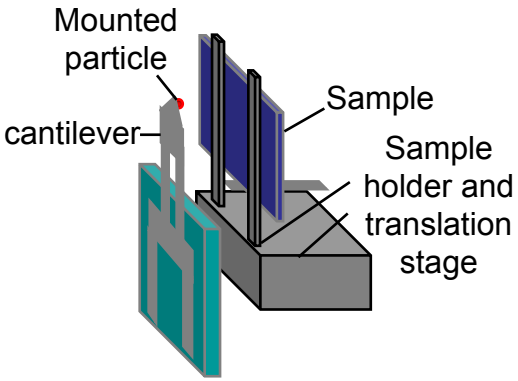




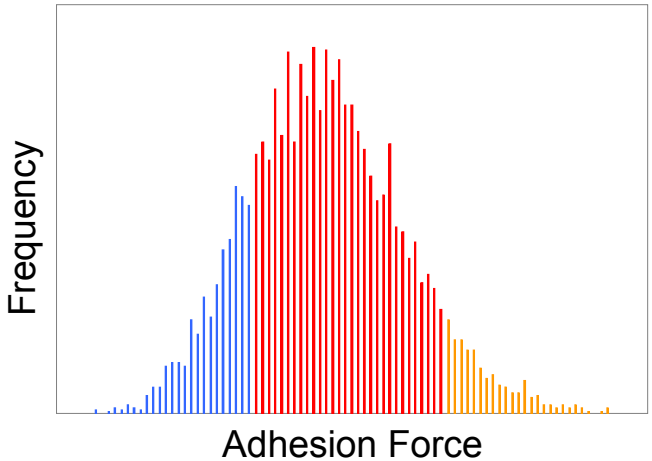


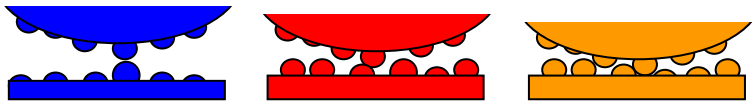
Particle Adhesion Measurements

AFM Schematic



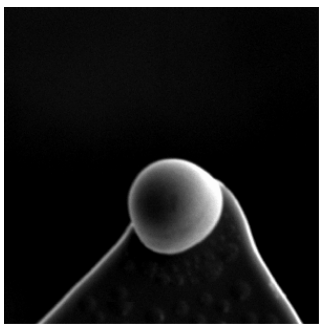
Distribution of Forces



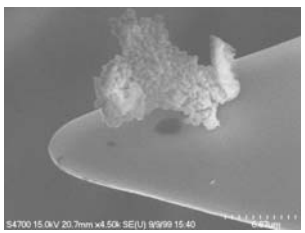


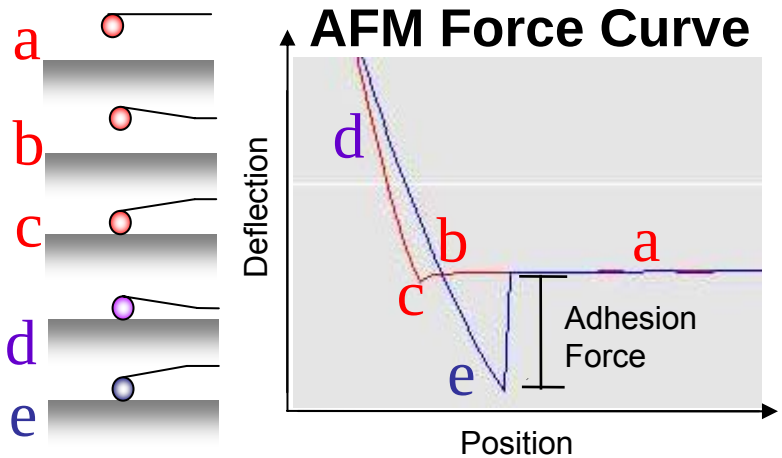
Particles Mounted on AFM Cantilevers

PSL Particle



Al_2O_3 Particle

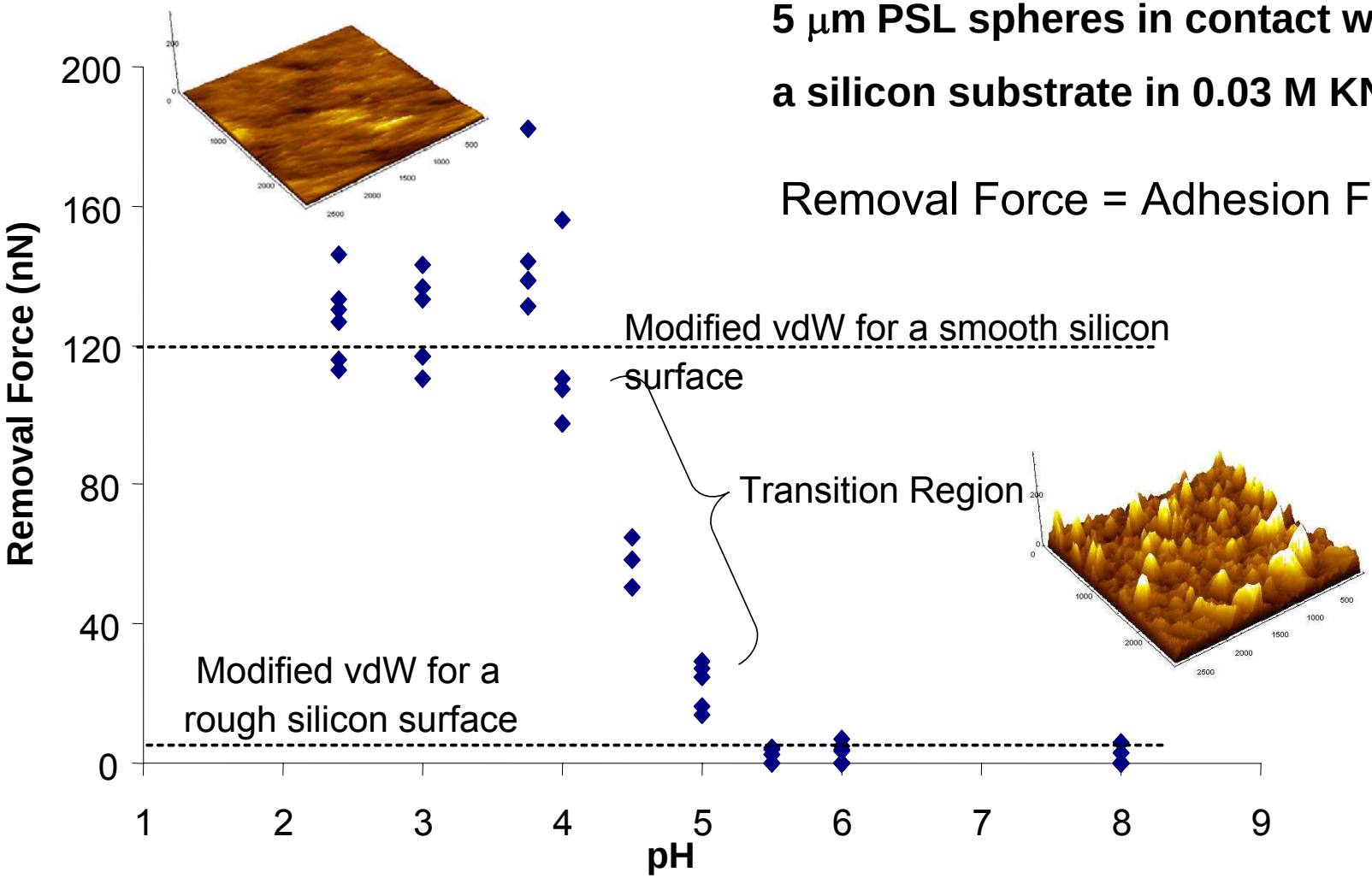




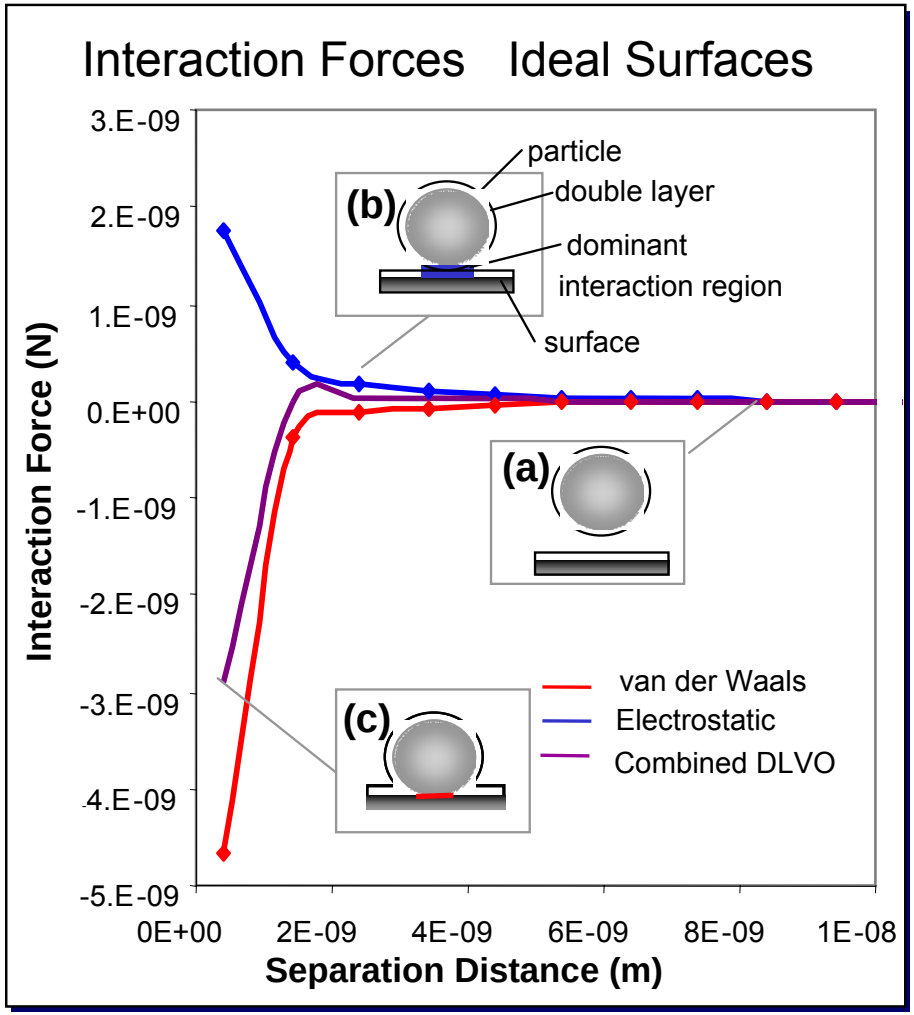
Surface Roughness and Adhesion

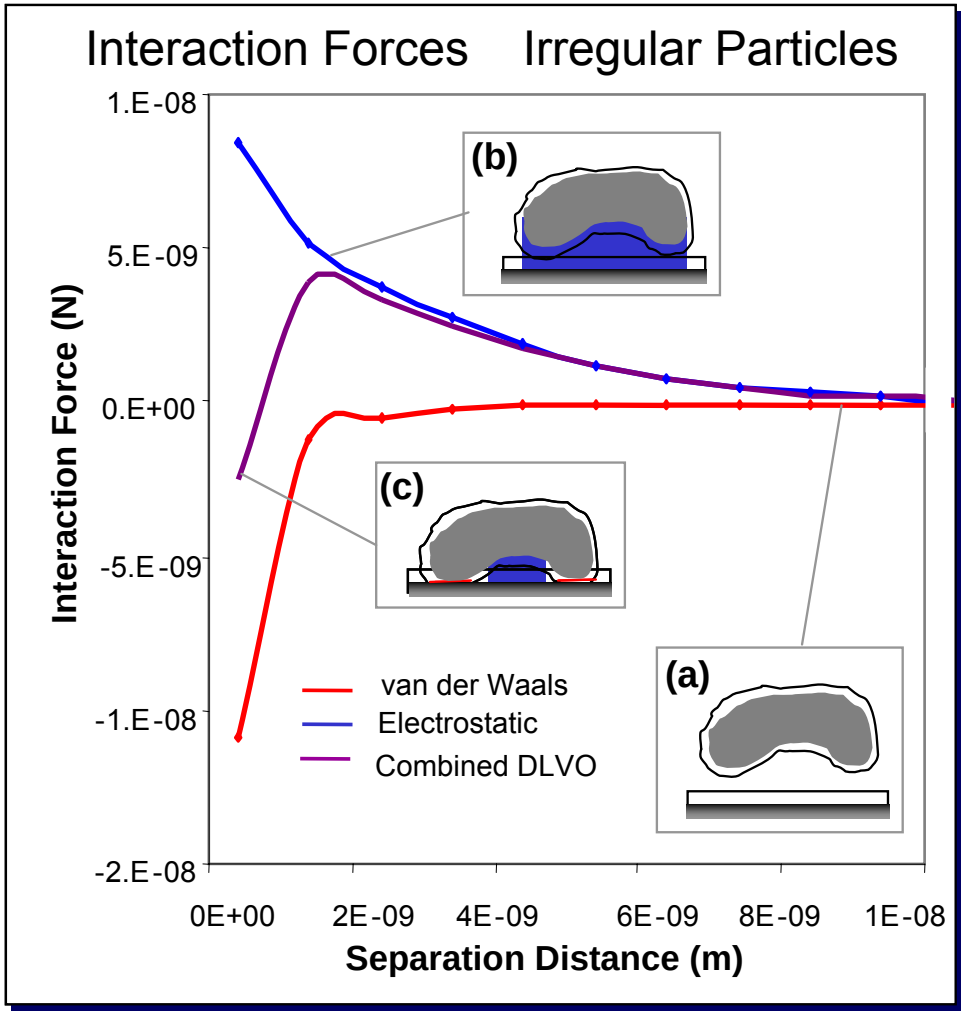
5 μm PSL spheres in contact with a silicon substrate in 0.03 M KNO_3

Removal Force = Adhesion Force

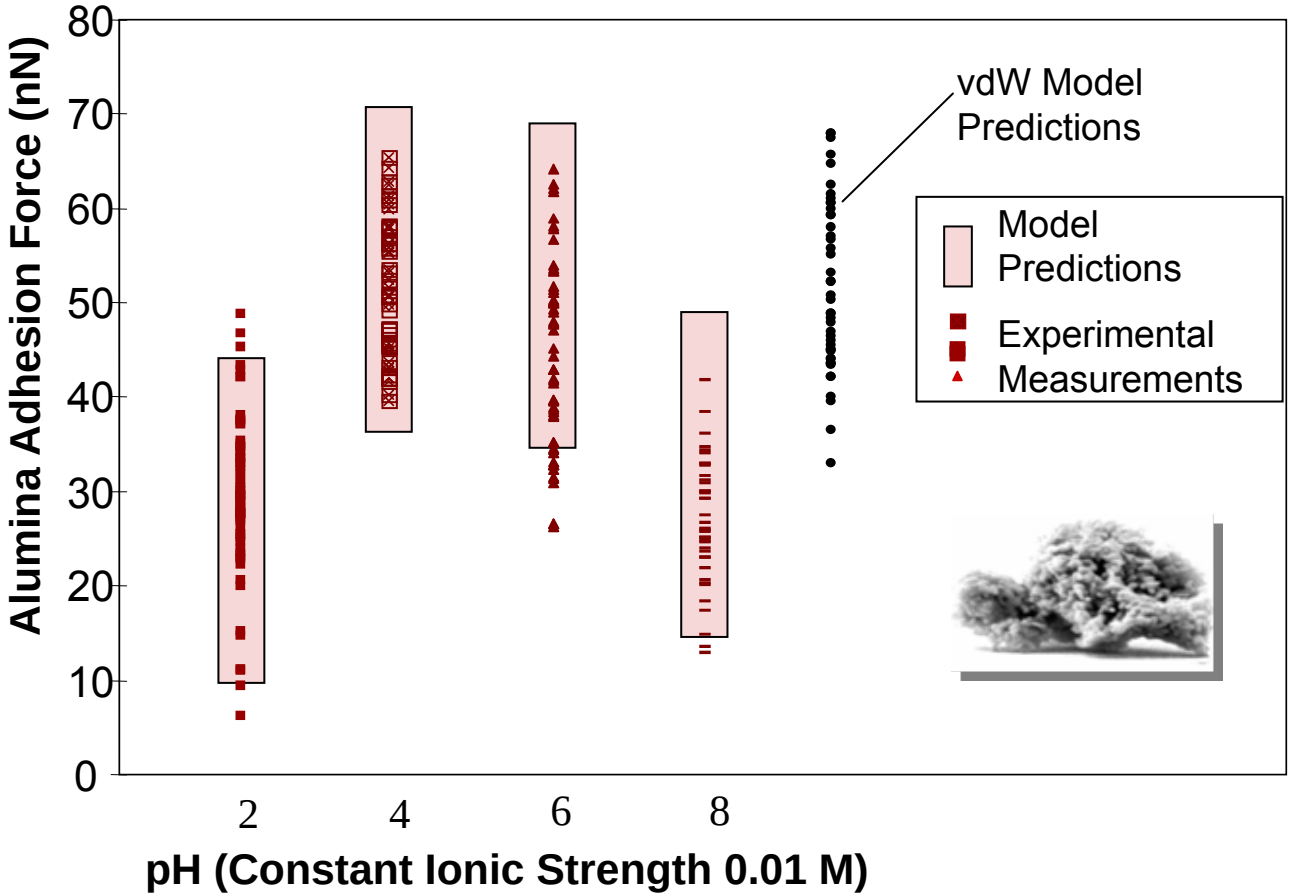


Geometry and Adhesion



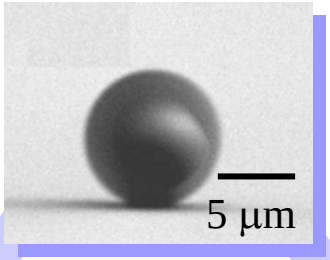


Alumina Interactions with SiO_2



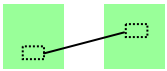
- Electrostatic interactions do affect the adhesion force, which varies with pH
- Large area between particle and wafer out of contact
- Small contact area

How to Describe?



van der Waals

Point-by-point additivity



$$dU_{12} = -\frac{C_{12}\rho_1\rho_2 dV_1 dV_2}{\left\{(x_2-x_1)^2+(y_2-y_1)^2+(z_2-z_1)^2\right\}^3}$$

Hamaker Constant, A_{12}

Approximate Solutions

$$F = \frac{A_{12}R_1}{6h^2}$$

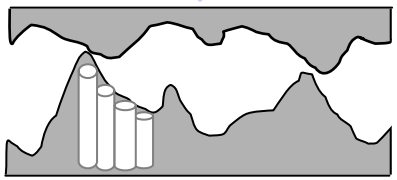
+

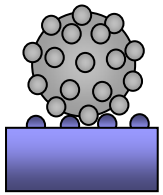
$$F = \frac{-A}{6h}\frac{R_1R_2}{R_1+R_2}$$

+

$$F = \frac{A_{12}}{12\pi h^3}$$

Computational Solutions





Combination of ideal shapes

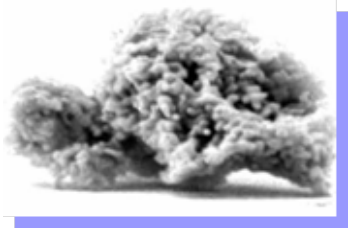
sphere-plate

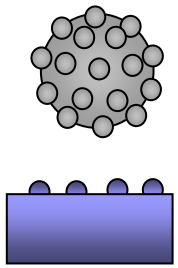
+

sphere-sphere

+

plate-plate





Electrostatics

Poisson-Boltzmann Equation

$$\nabla^2\psi = \kappa^2\psi$$

$$\kappa = \sqrt{\frac{e^2\sum_i z_i^2 n_{io}}{\varepsilon_0\varepsilon_r k_B T}}$$

Approximate Solutions

$$F = \frac{\varepsilon\varepsilon_0 d}{4}\frac{\kappa e^{-\kappa h}\left(\psi_p^2+\psi_s^2\right)}{\left(1-e^{-2\kappa h}\right)}\left(\frac{2\psi_p\psi_s}{\left(\psi_p^2+\psi_s^2\right)}+e^{-\kappa h}\right)$$

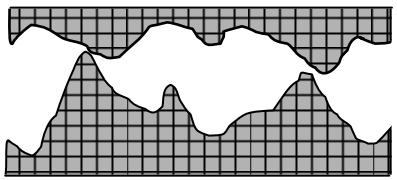
+

$$F = \frac{\kappa^2\varepsilon_0\varepsilon_r}{2\sinh^2(\kappa h)}\left(2\psi_1\psi_2\cosh(\kappa h)-\psi_1^2-\psi_2^2\right)$$

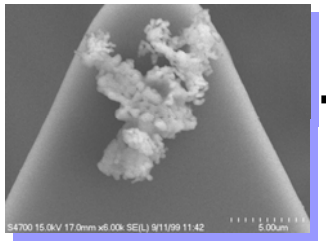
+

$$F = \frac{\kappa^2\varepsilon_0\varepsilon_r}{2\sinh^2(\kappa h)}\left(2\psi_1\psi_2\cosh(\kappa h)-\psi_1^2-\psi_2^2\right)$$

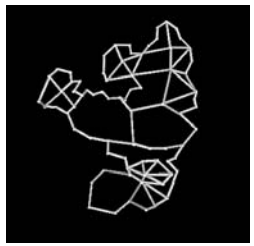
Computational Solutions



Combined vdW, ES Interaction Models

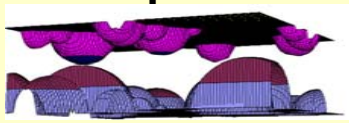


SEM
(Geometry)



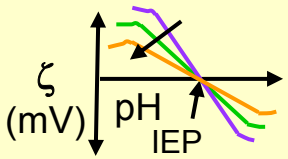
3-D
Reconstruction

Generate Mathematical Surface Representations



AFM
(Topographic Data)

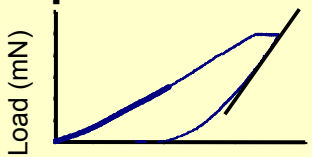
Surface Potential



Contact Surfaces

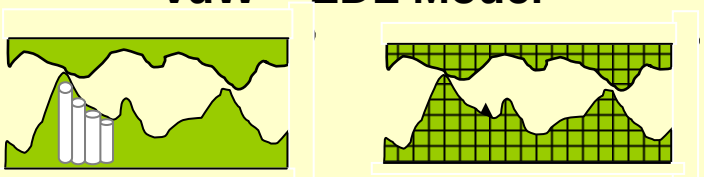
Applied Load

Compression/Deformation



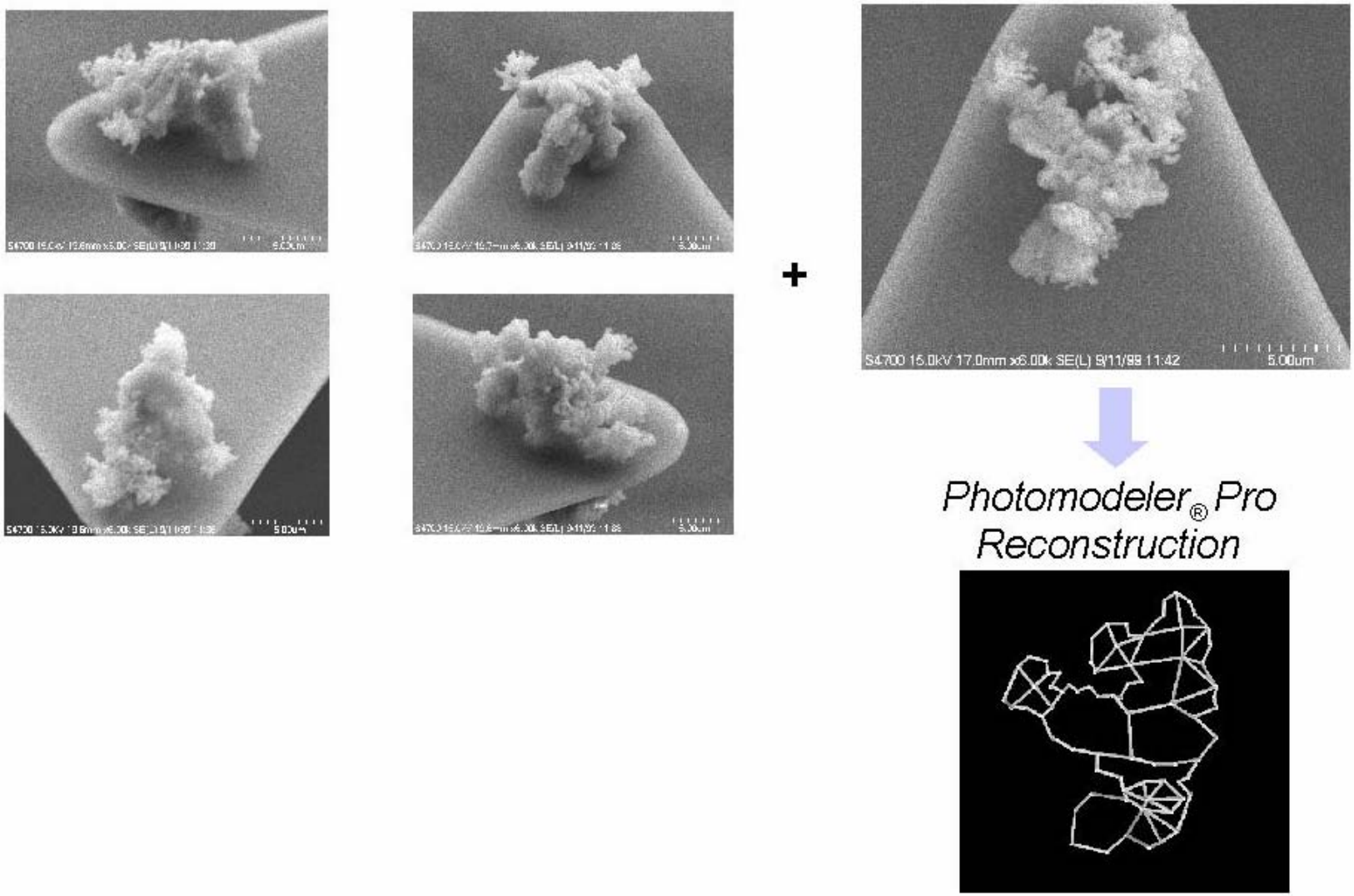
force/depth
profile

vdW + EDL Model



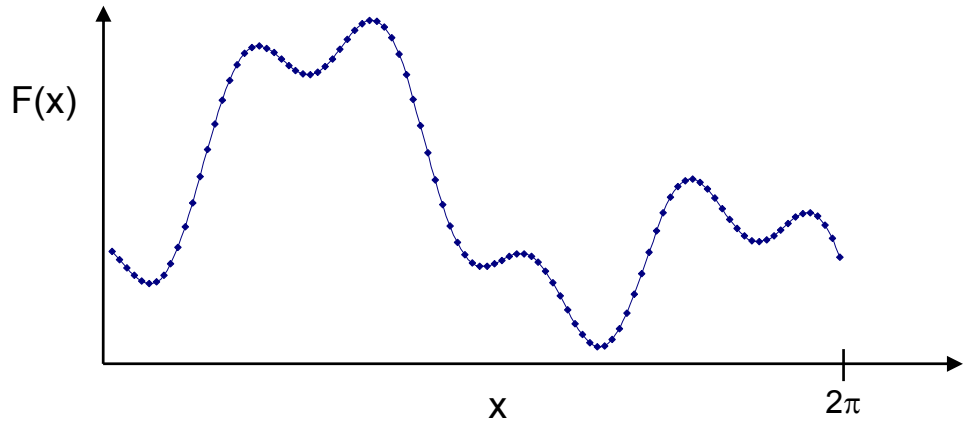
Removal Force Statistics ↔ **AFM Force Measurements**

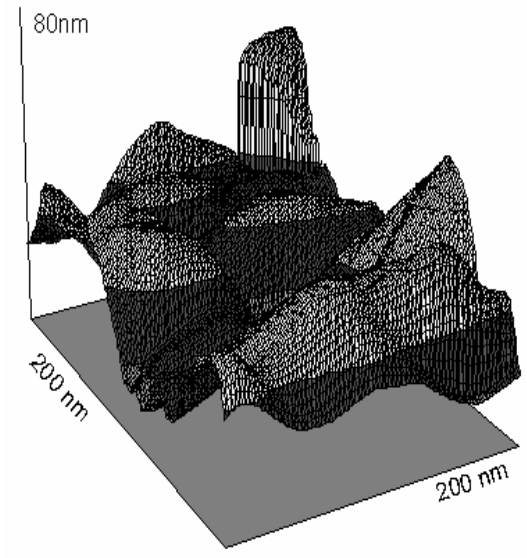
Geometric Models



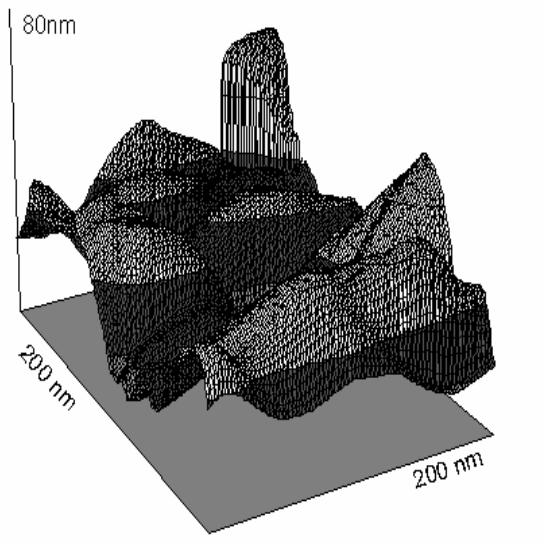
FFT Roughness Model

- Fourier transform of surface profile
- Reconstruction of surfaces generated with random phase angles

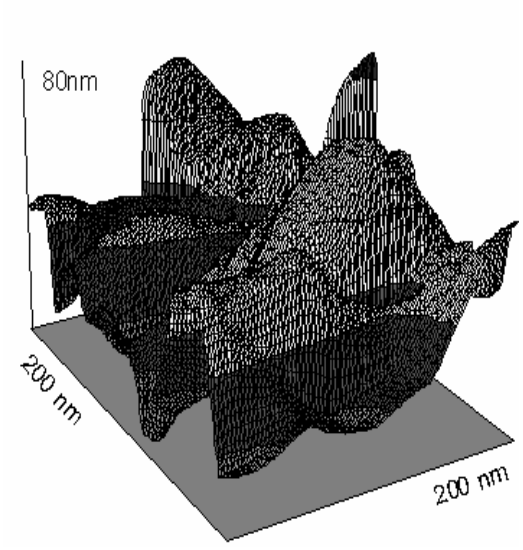




AFM scan of actual Cu surface



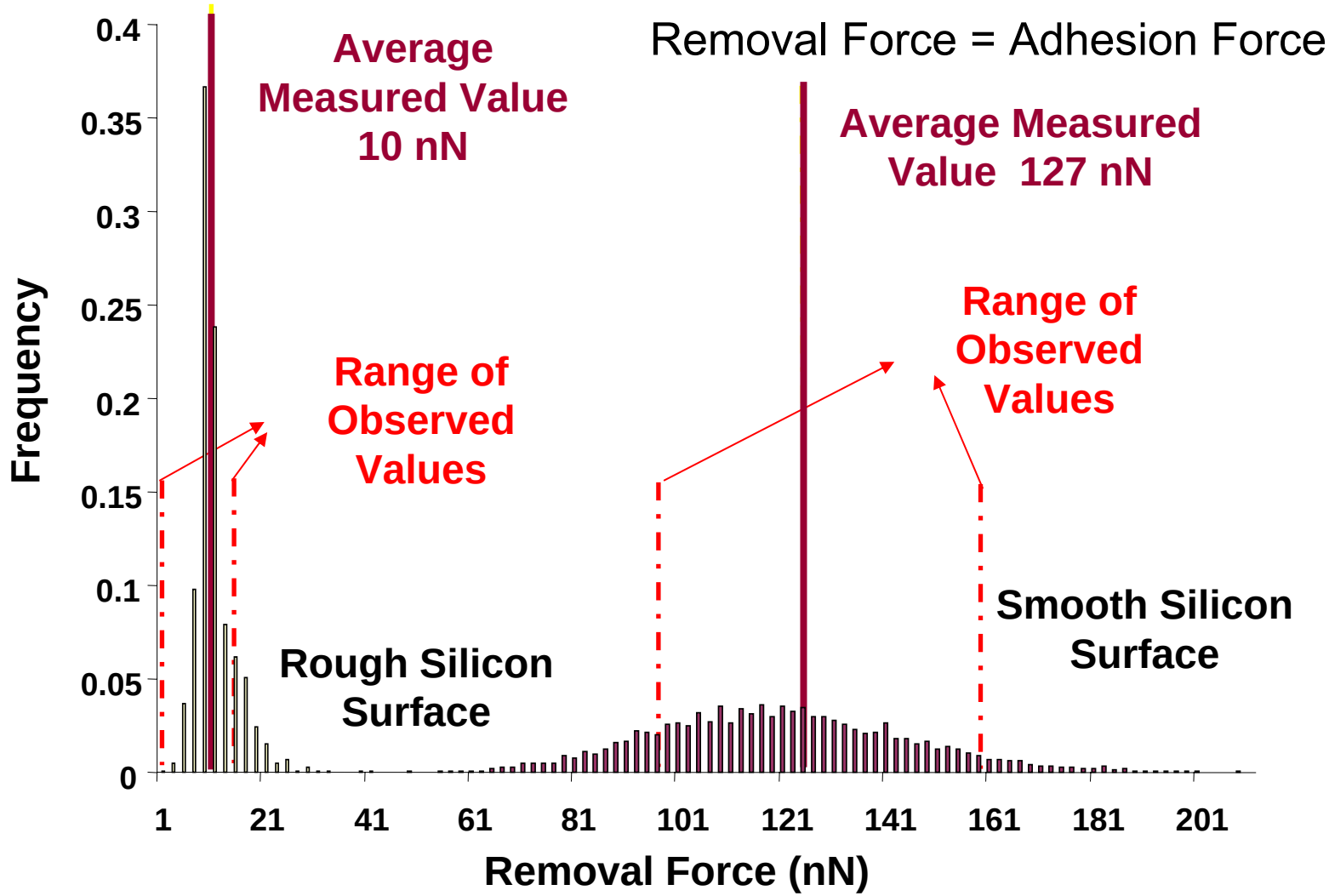
FFT model Cu surface



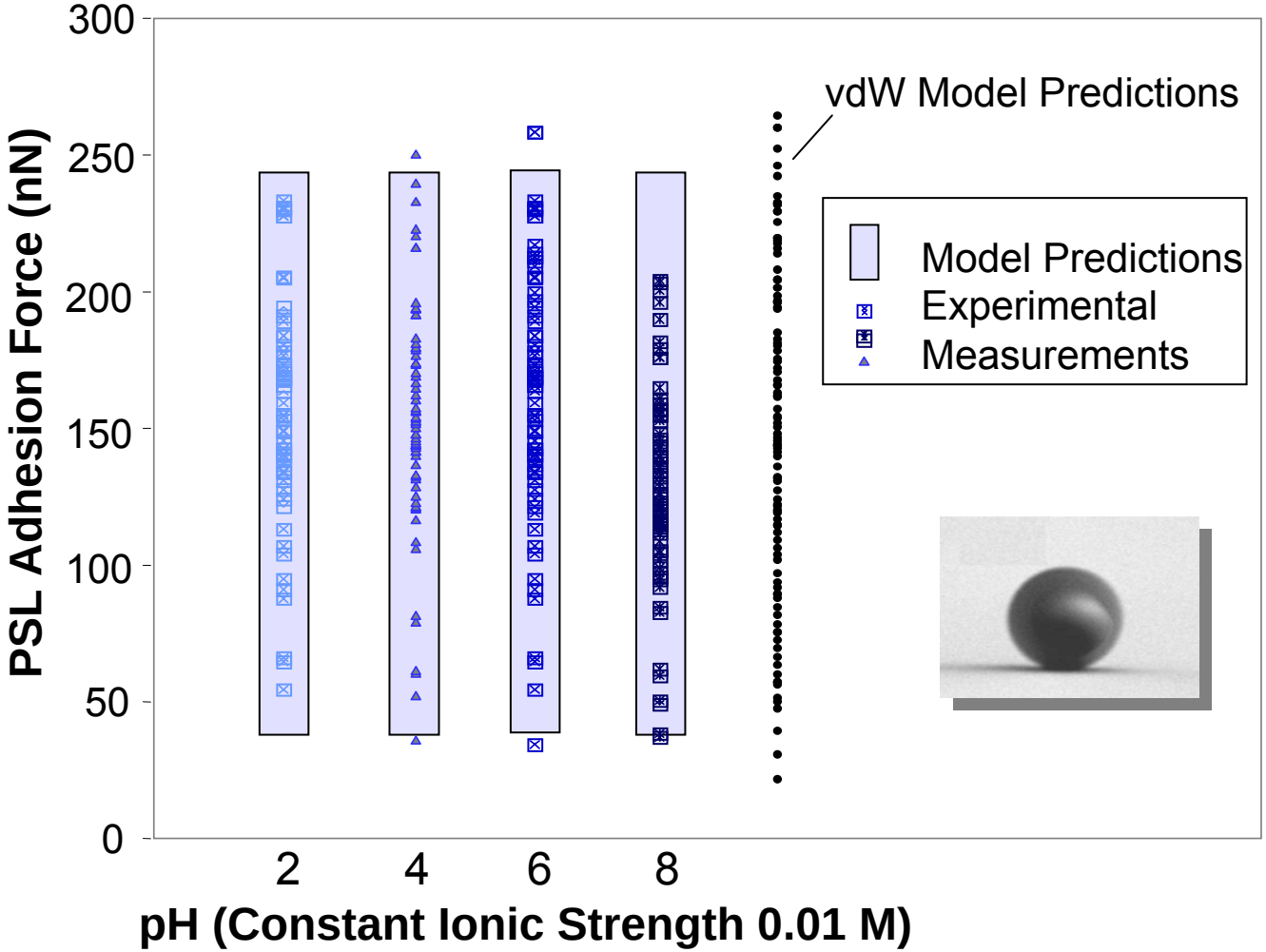
FFT with random phase

Validation: PSL Adhesion to Evolving Surfaces

Only vdW forces needed to describe adhesion

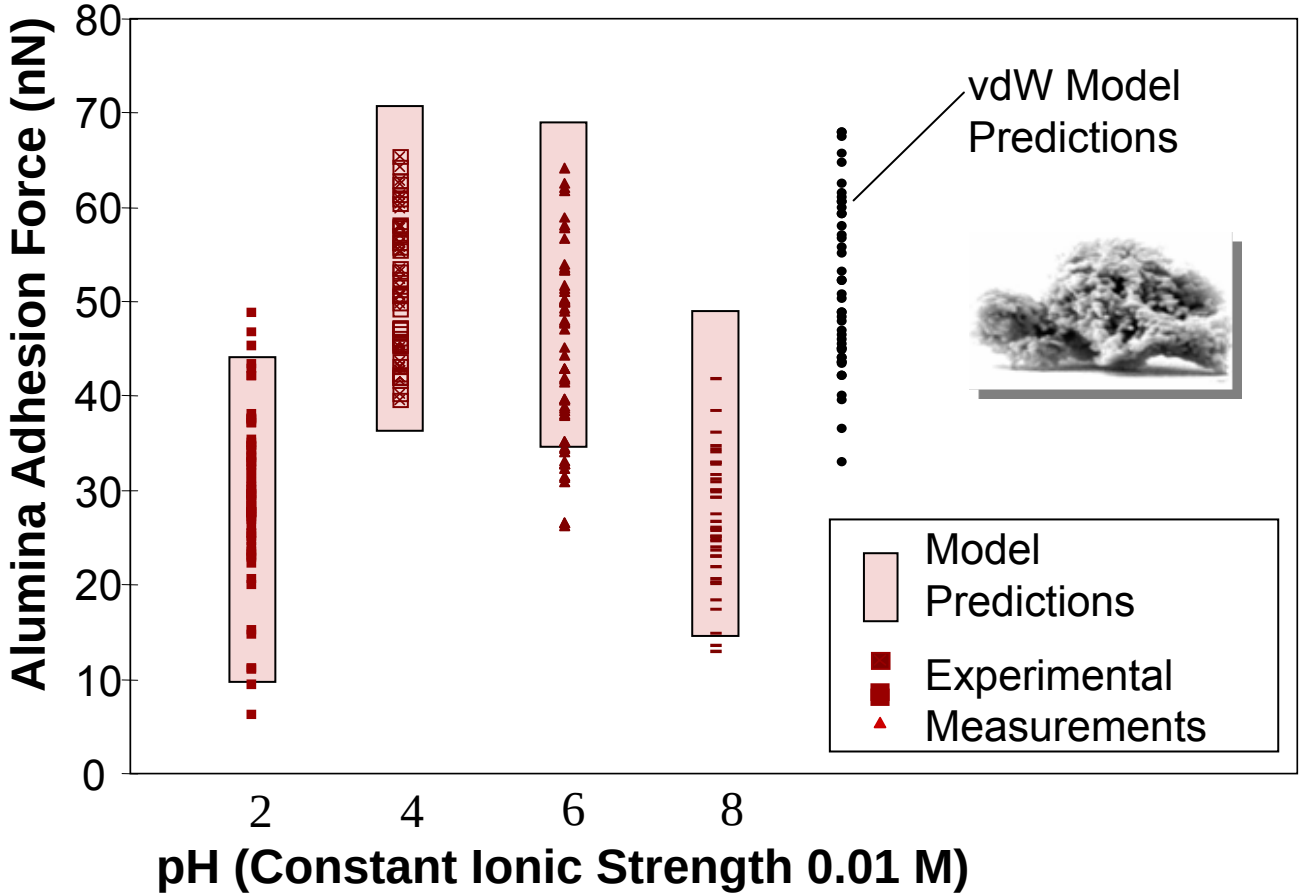


PSL Interactions with SiO_2



- Electrostatic interactions do not have a significant effect at different pHs
- Large contact area between sphere and wafer dominated by vdW

Alumina Interactions with SiO_2

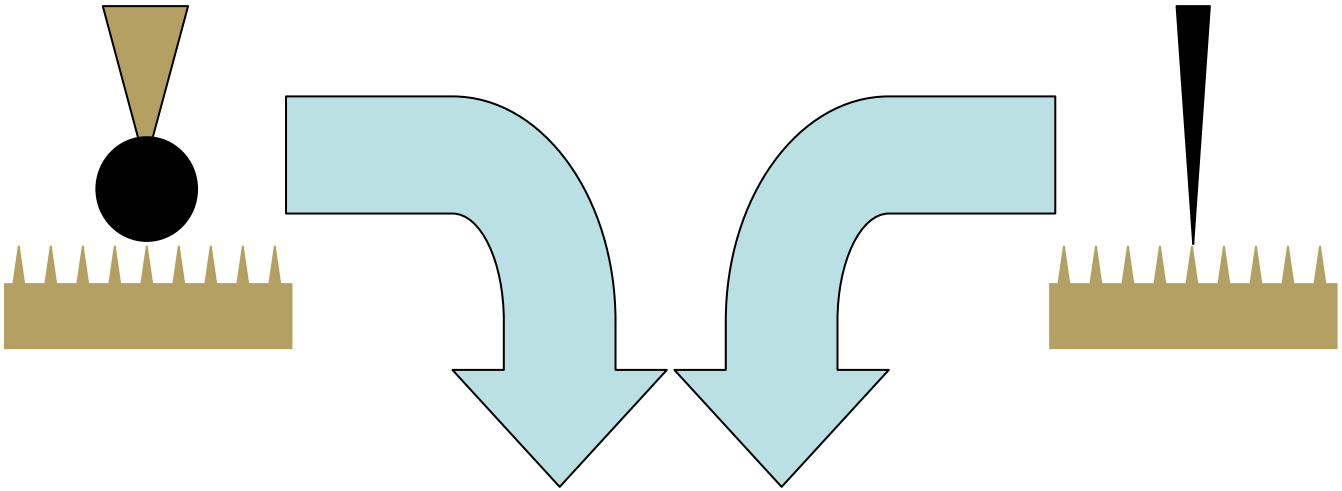


- Electrostatic interactions do affect the adhesion force, which varies with pH
- Large area between particle and wafer out of contact
- Small contact area

Nanoscale Adhesion Approach

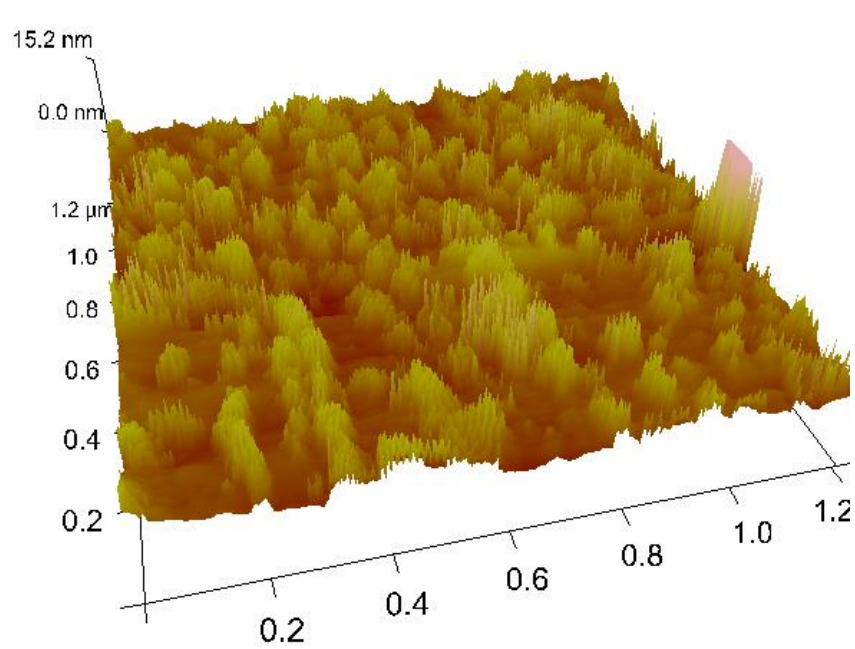
- Measure, model micron-scale adhesion
- Extract vdW, ES constants

- Measure nano-scale adhesion
- Model adhesion using constants from micron-scale

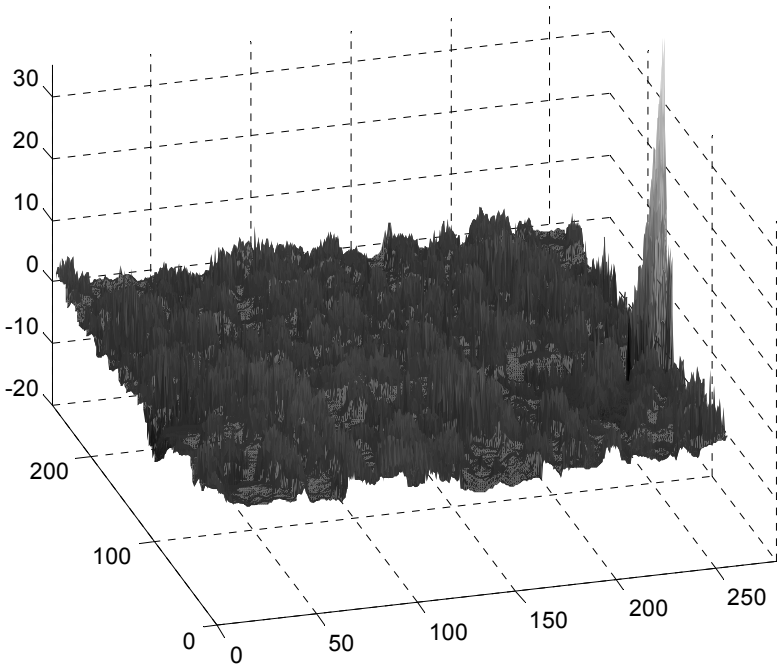


- Can measure nano-scale adhesion
- Can model roughness and geometry effects
- Can predict nano-scale adhesion

Silicon Dioxide Surface

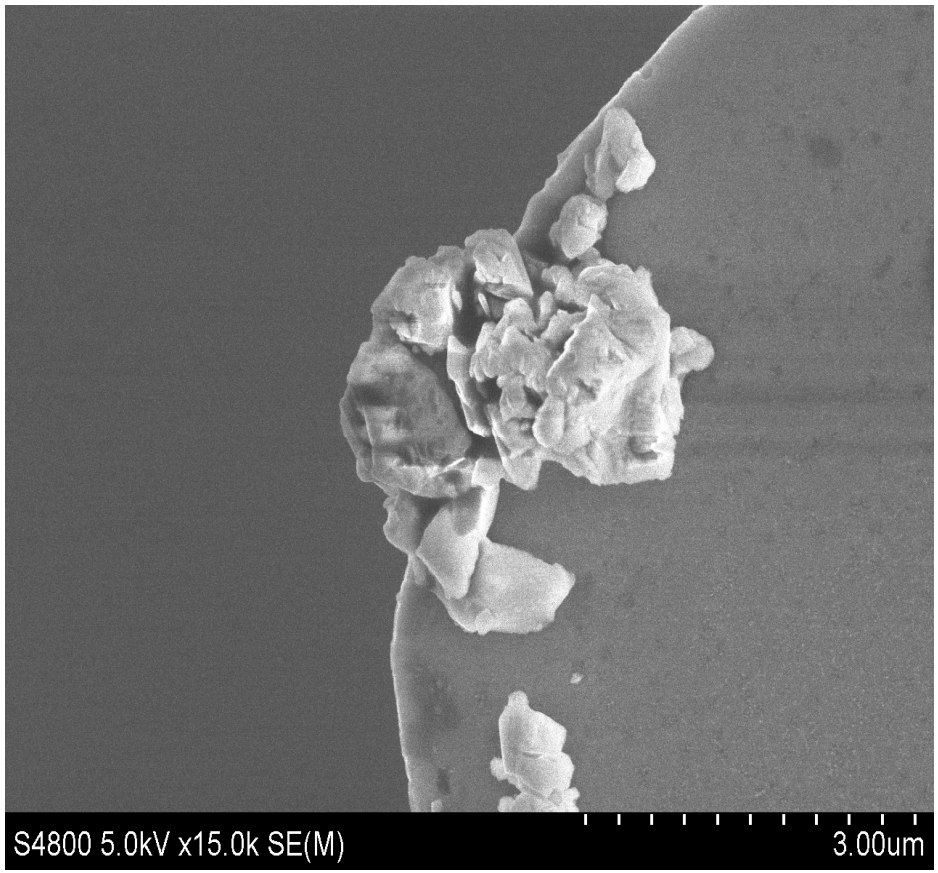


AFM Image

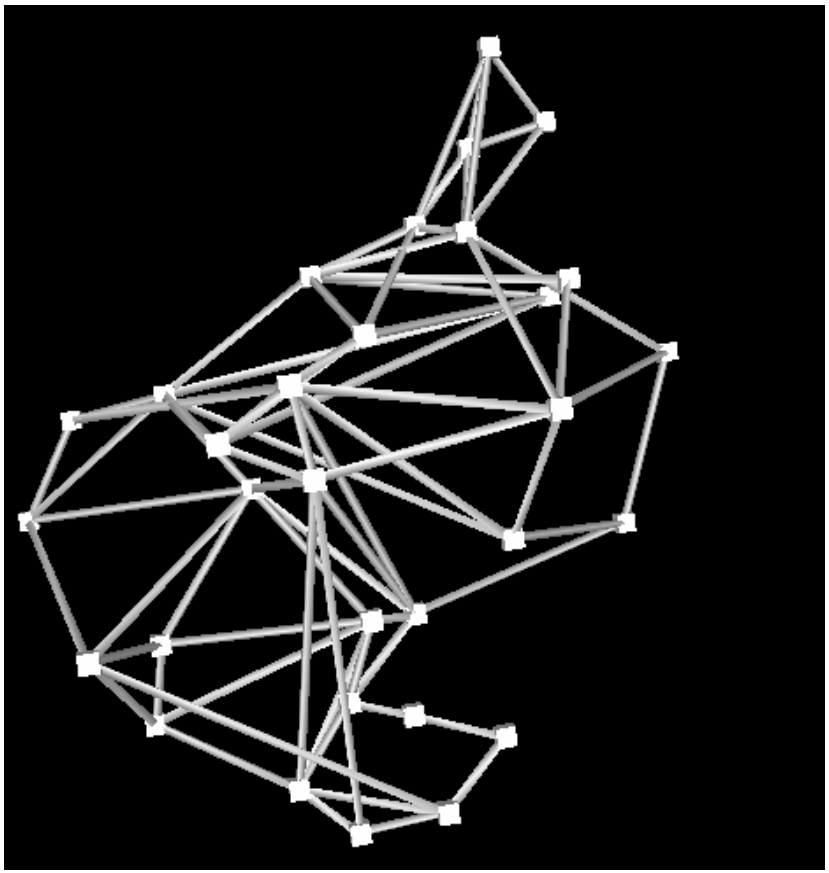


FFT model Regeneration

Silicon Nitride Particle: Micron-Scale

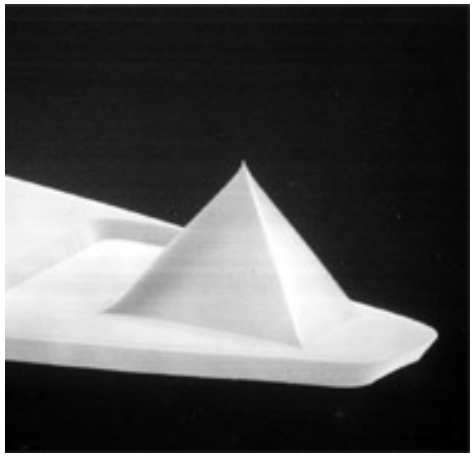


FESEM image of a Si_3N_4 particle mounted on an AFM cantilever



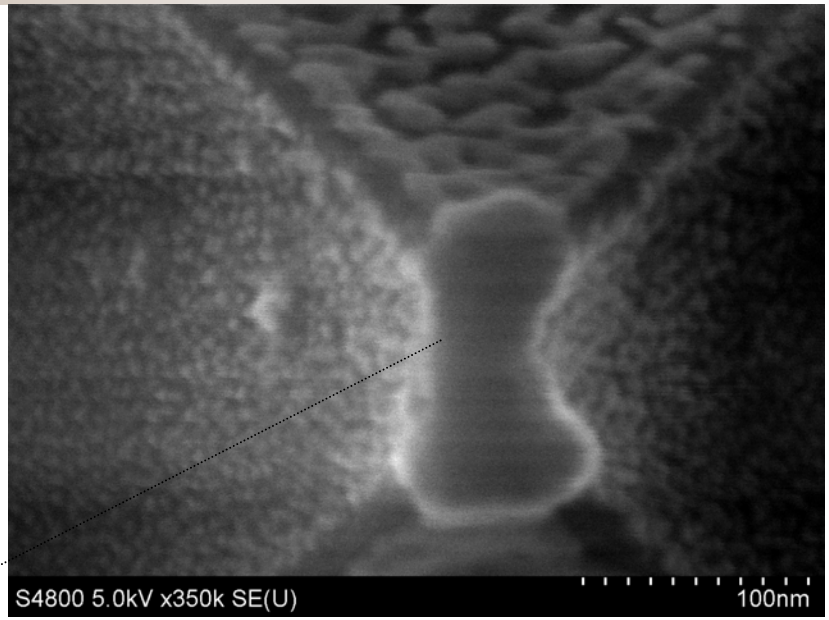
Photomodeler Pro® model for the nitride particle

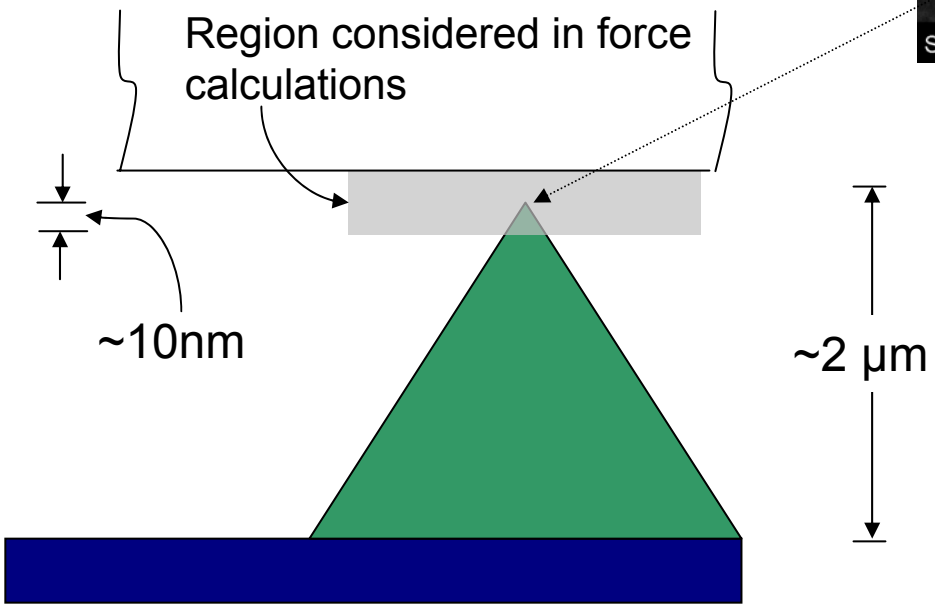
Silicon Nitride Cantilevers: Nanoscale



Sharpened silicon nitride probe

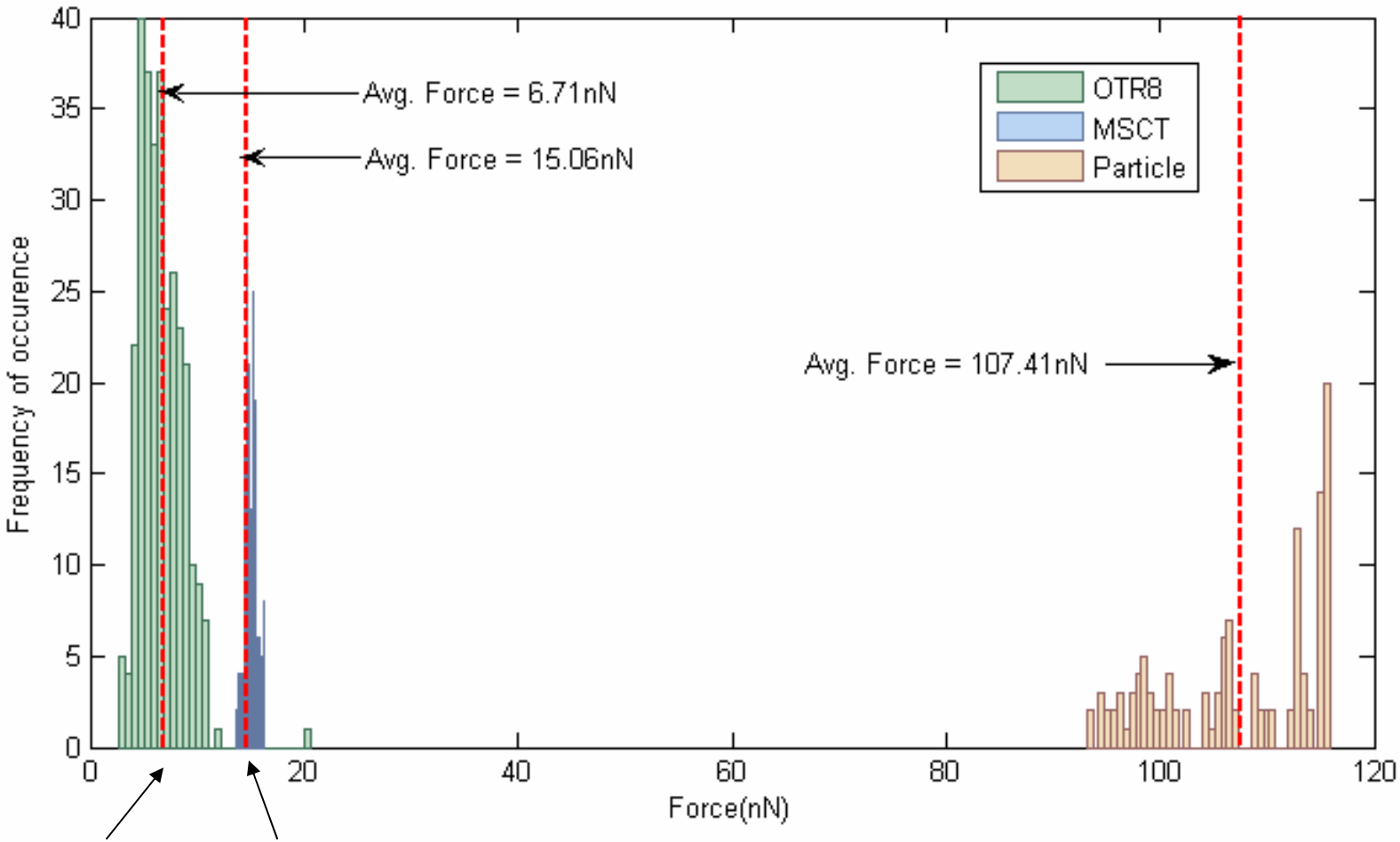
Max ROC ~ 40nm





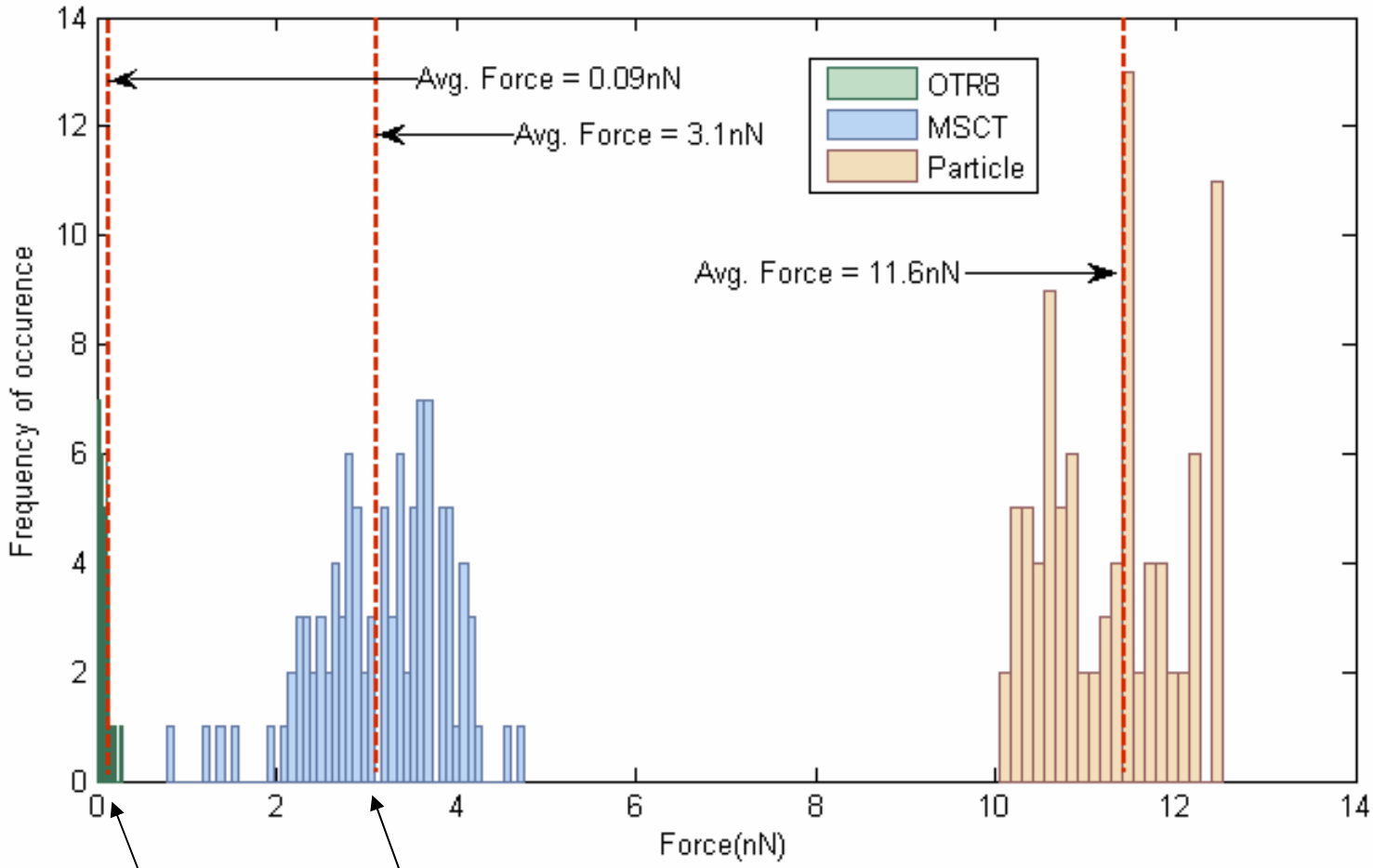
Geometry considered in modeling the force between nanoscale cantilevers and substrates

Silicon Nitride Adhesion to Silicon Dioxide in Air



Tip ROC=12nm Tip ROC=36nm

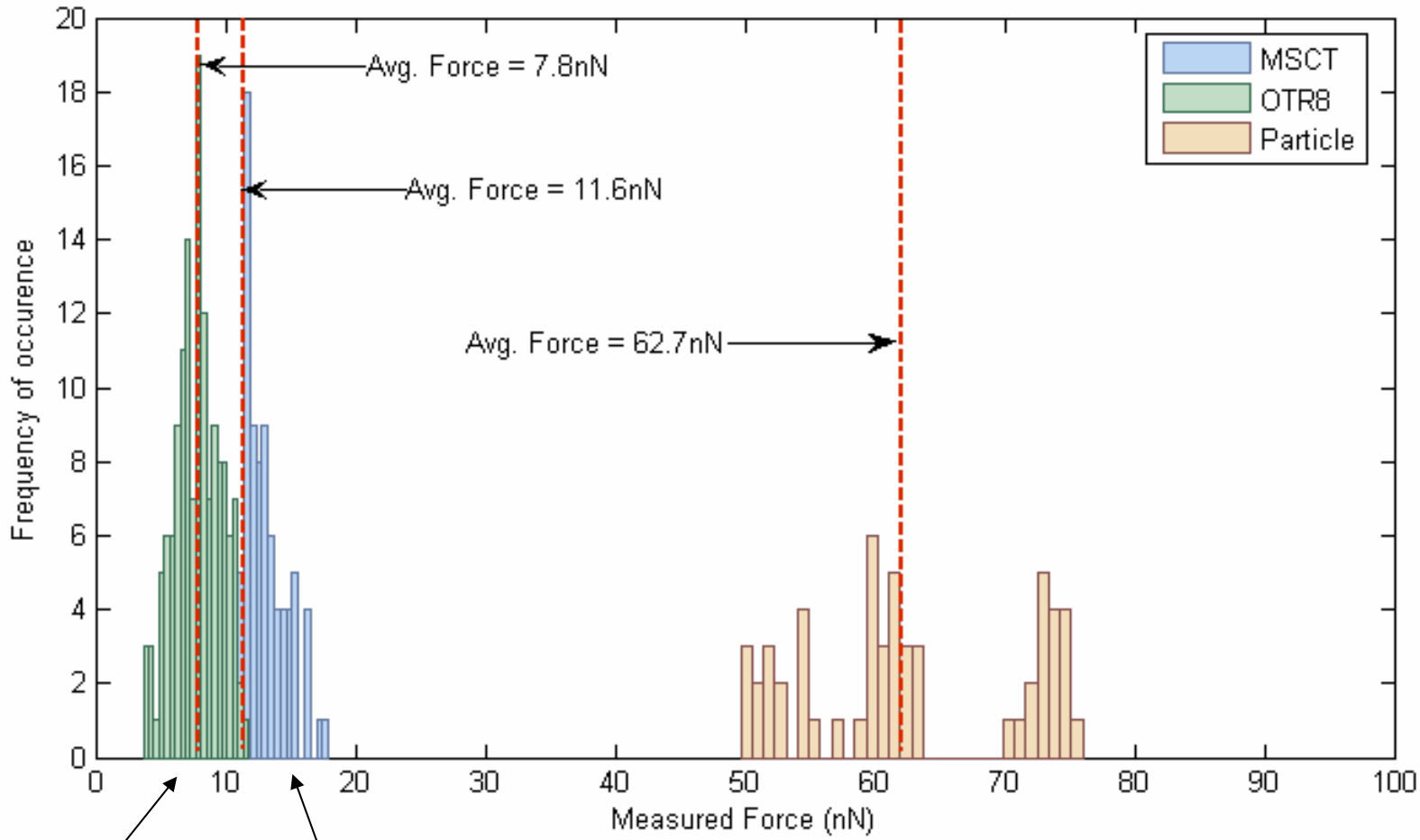
Silicon Nitride Adhesion to Silicon Dioxide in Water



Tip ROC=10nm

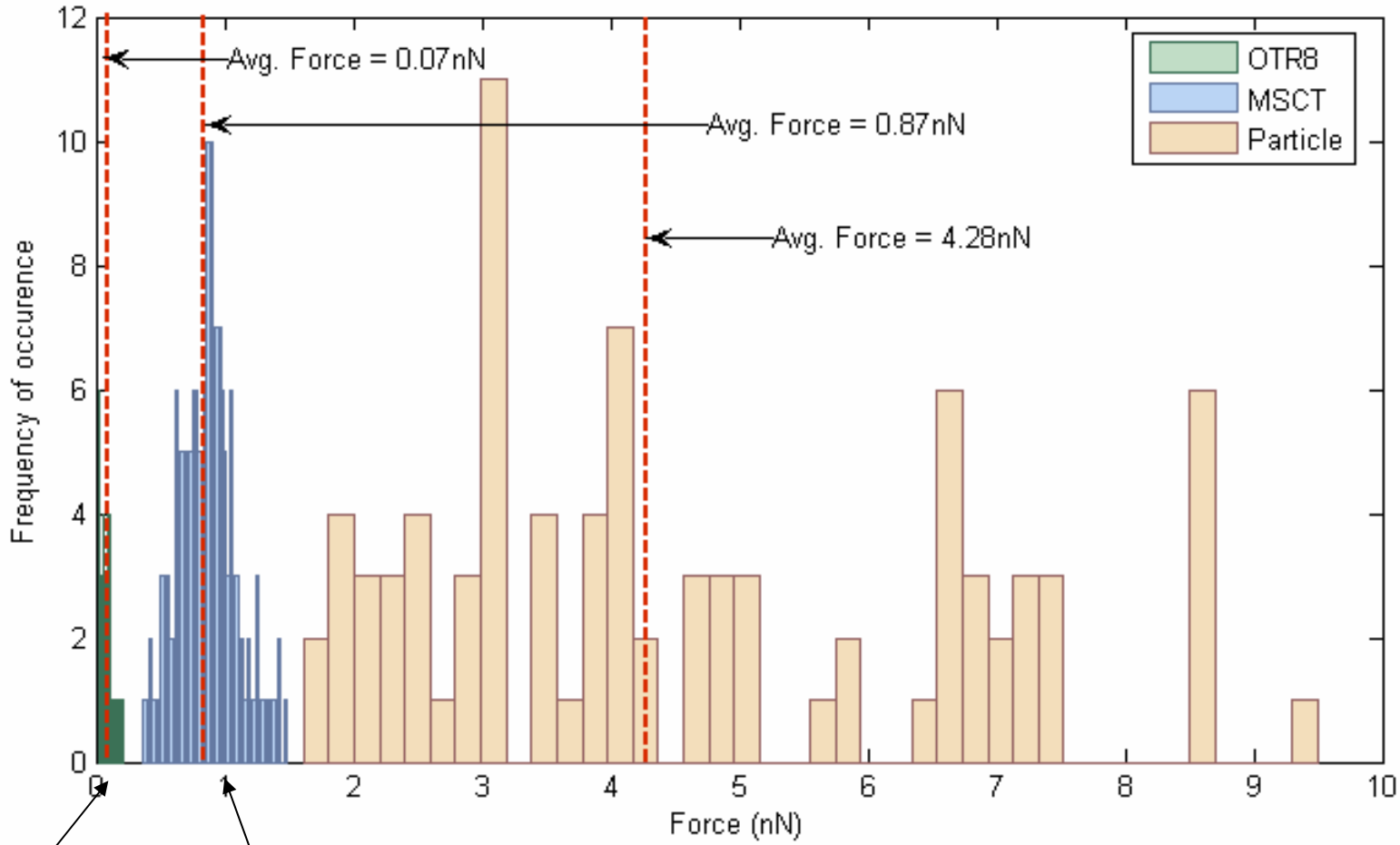
Tip ROC=41nm

Silicon Nitride Adhesion to Quartz in Air



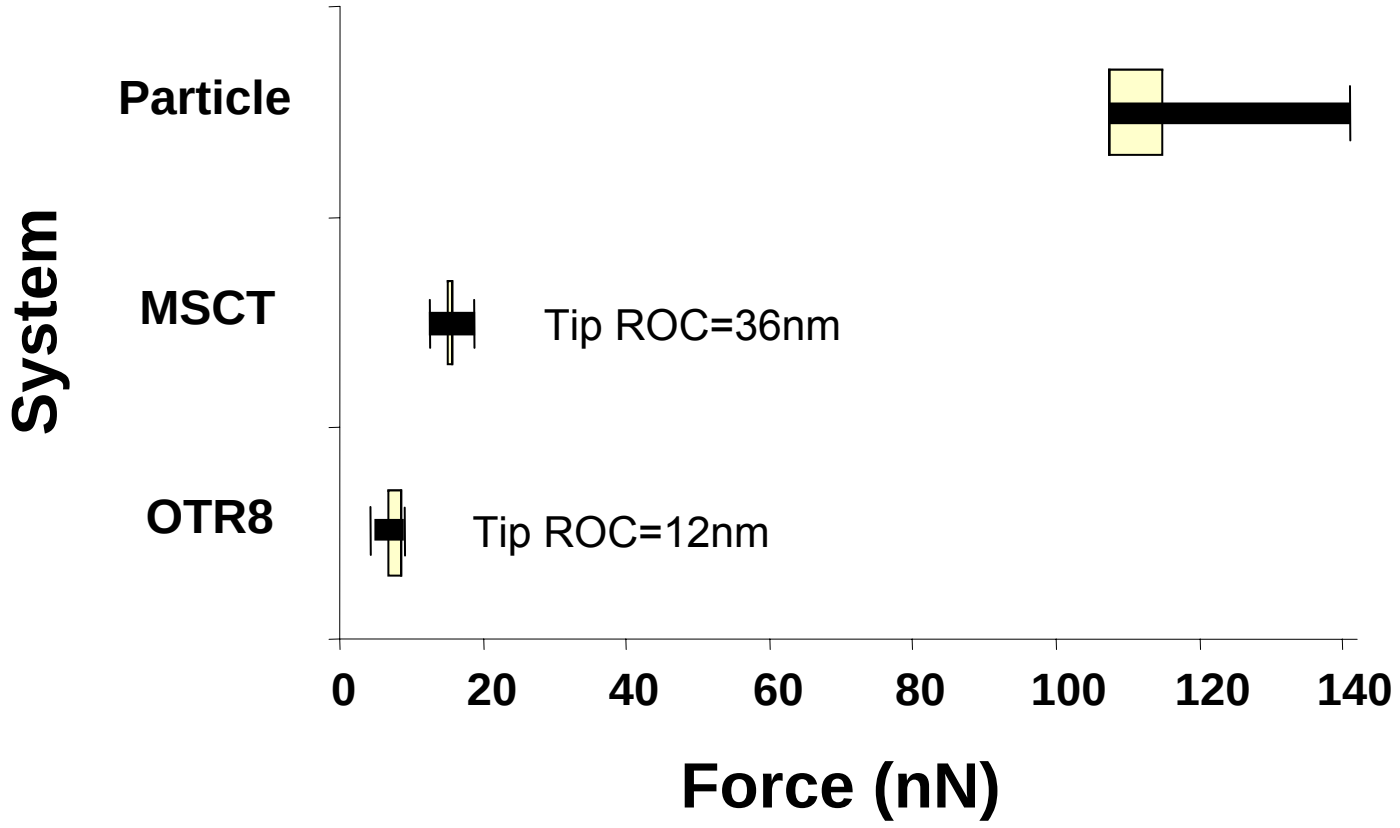
Tip ROC=14nm Tip ROC=32nm

Silicon Nitride Adhesion to Quartz in Water

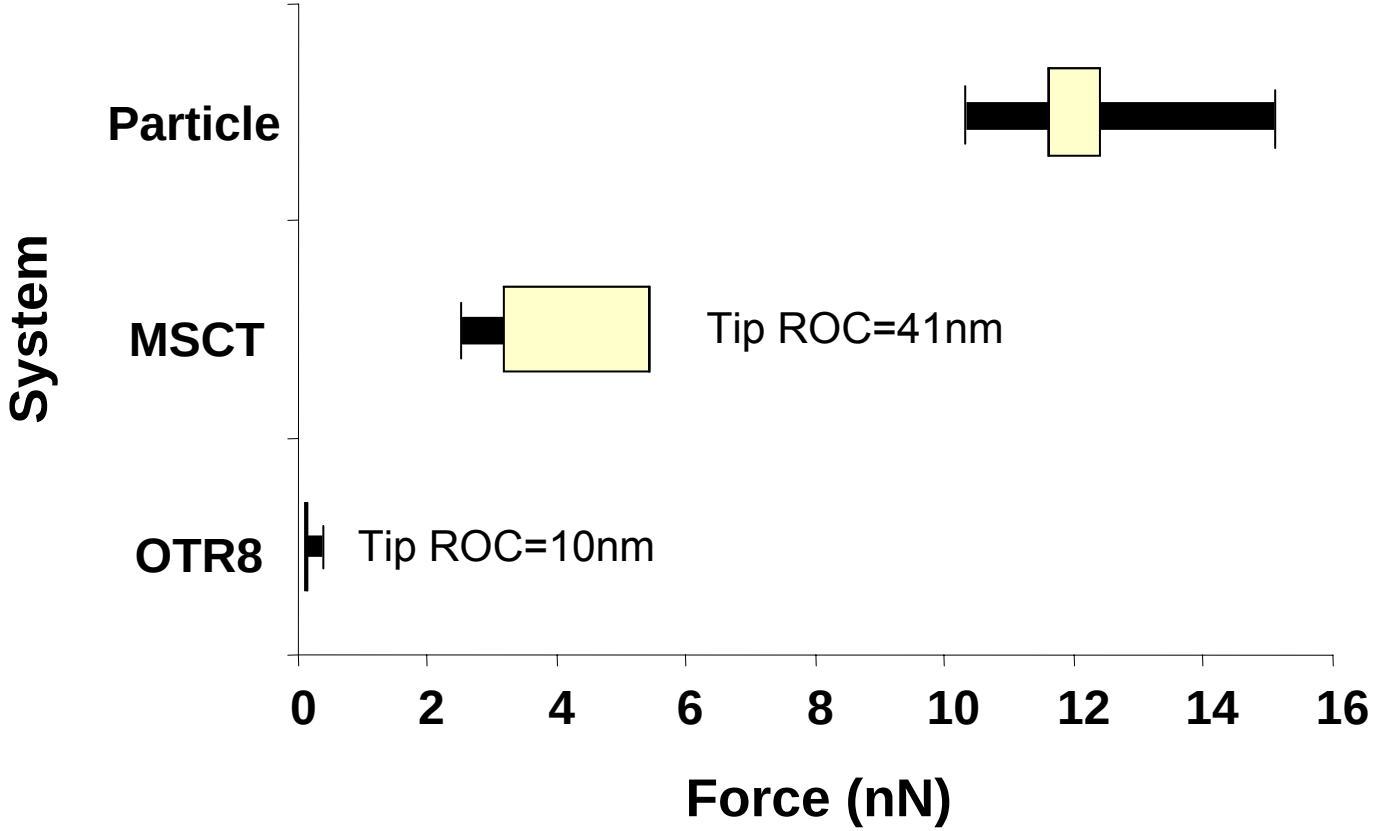


Tip ROC=14nm Tip ROC=32nm

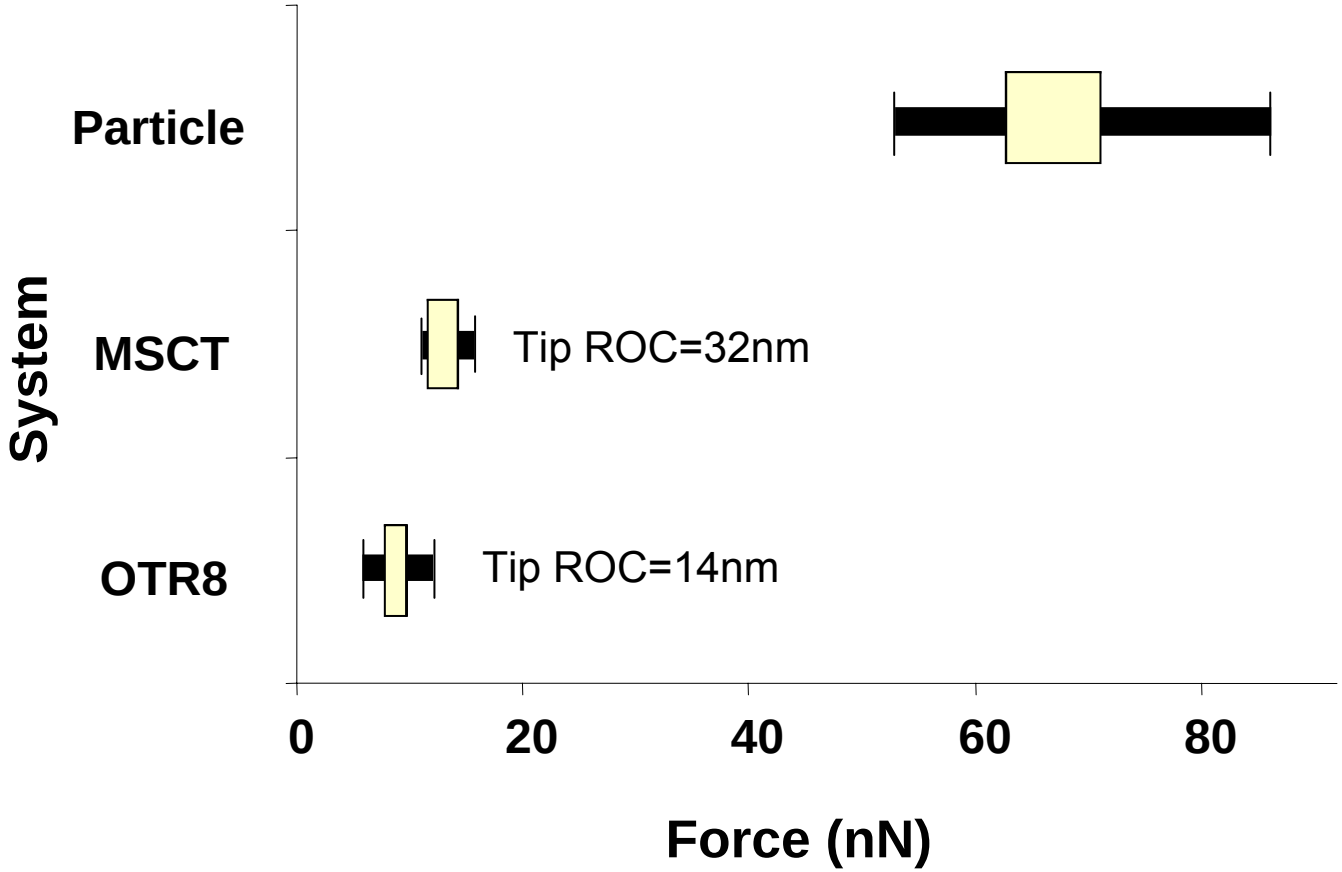
Theory and Experiment: Silicon Nitride Adhesion to Silicon Dioxide in Air



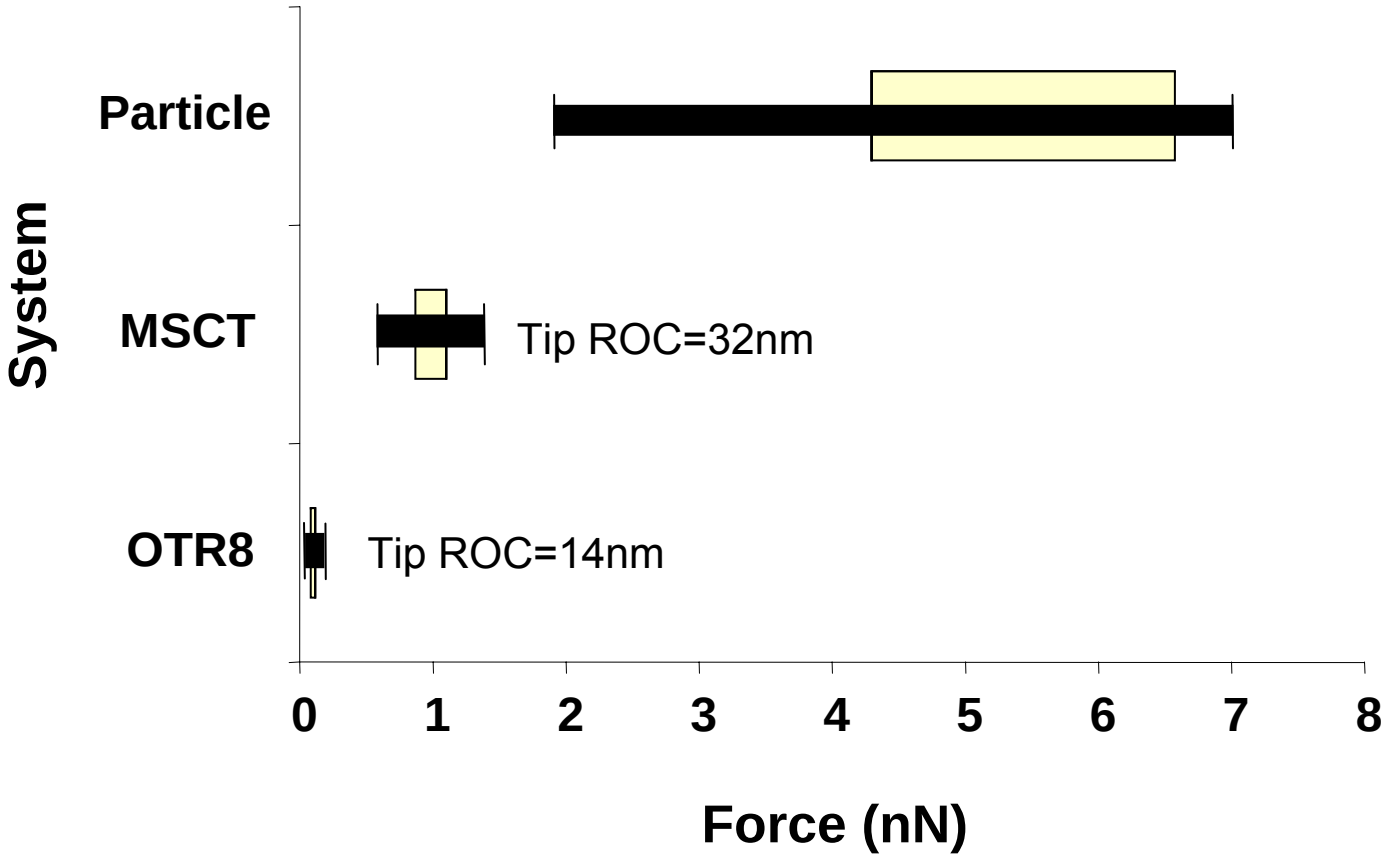
Theory and Experiment: Silicon Nitride Adhesion to Silicon Dioxide in Water



Theory and Experiment: Silicon Nitride Adhesion to Quartz in Air



Theory and Experiment: Silicon Nitride Adhesion to Quartz in Water



Conclusions

- Micron- and nano-scale particle adhesion can be described by vdW and electrostatic force models
- Proper accounting for roughness and geometry is required
- Particle adhesion characterized by a distribution of adhesion forces
  - Reflective of the interaction of two rough surfaces
- Particles with highly nonuniform geometry can be influenced by electrostatic forces even when in contact with a substrate

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