Particle Adhesion to Photomasks

Gautam Kumar, Ravi Jaiswal, Shanna Smith and Stephen Beaudoin

Purdue University
School of Chemical Engineering
Forney Hall of Chemical Engineering
480 Stadium Mall Dr.
West Lafayette, Indiana 47907-2100
Phone: (765) 494-7944
sbeaudoi@purdue.edu

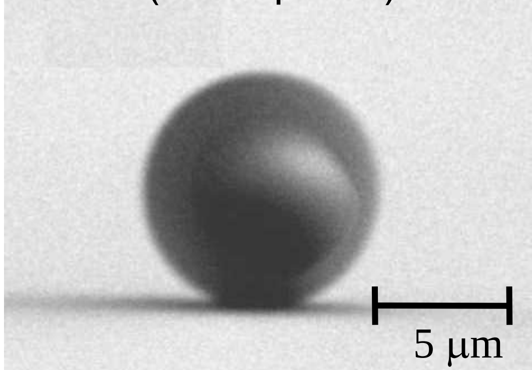
Introduction

- Knowledge of how strongly particles adhere to surfaces is vital to the microelectronics industry
- Removal of particulate contaminants at the micron scale tends to be less of a problem – application of removal force is easier
- Removal of nano-scale particulate contaminants is very difficult even though the adhesion force is very small
- Effects of solution properties on contaminant adhesion need to be evaluated to mimic conditions used in cleaning protocols
- Scaling of adhesion forces need to be understood to be able to predict removal criteria for nano-scale contaminants

Particle Characteristics

The Academic System

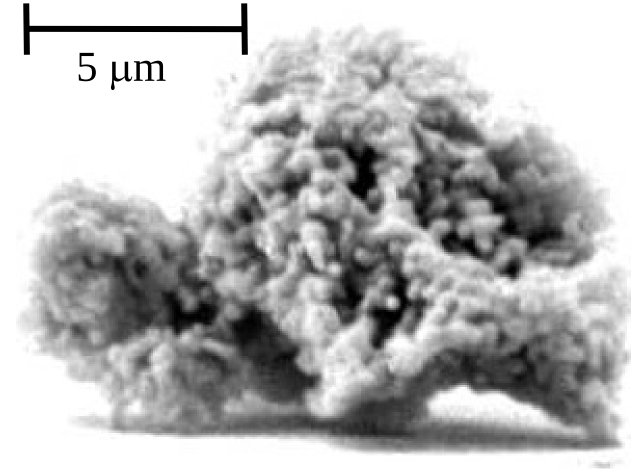
Polystyrene Latex Sphere
(PSL sphere)



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

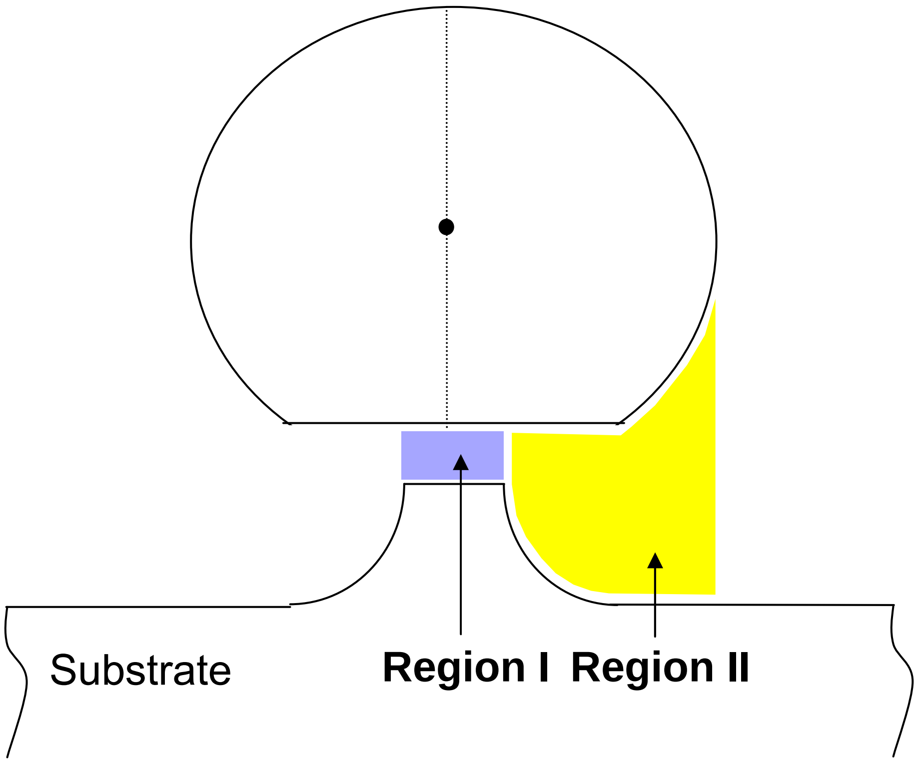
The Real World

Alumina Particle



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

Where do Different Forces Matter?



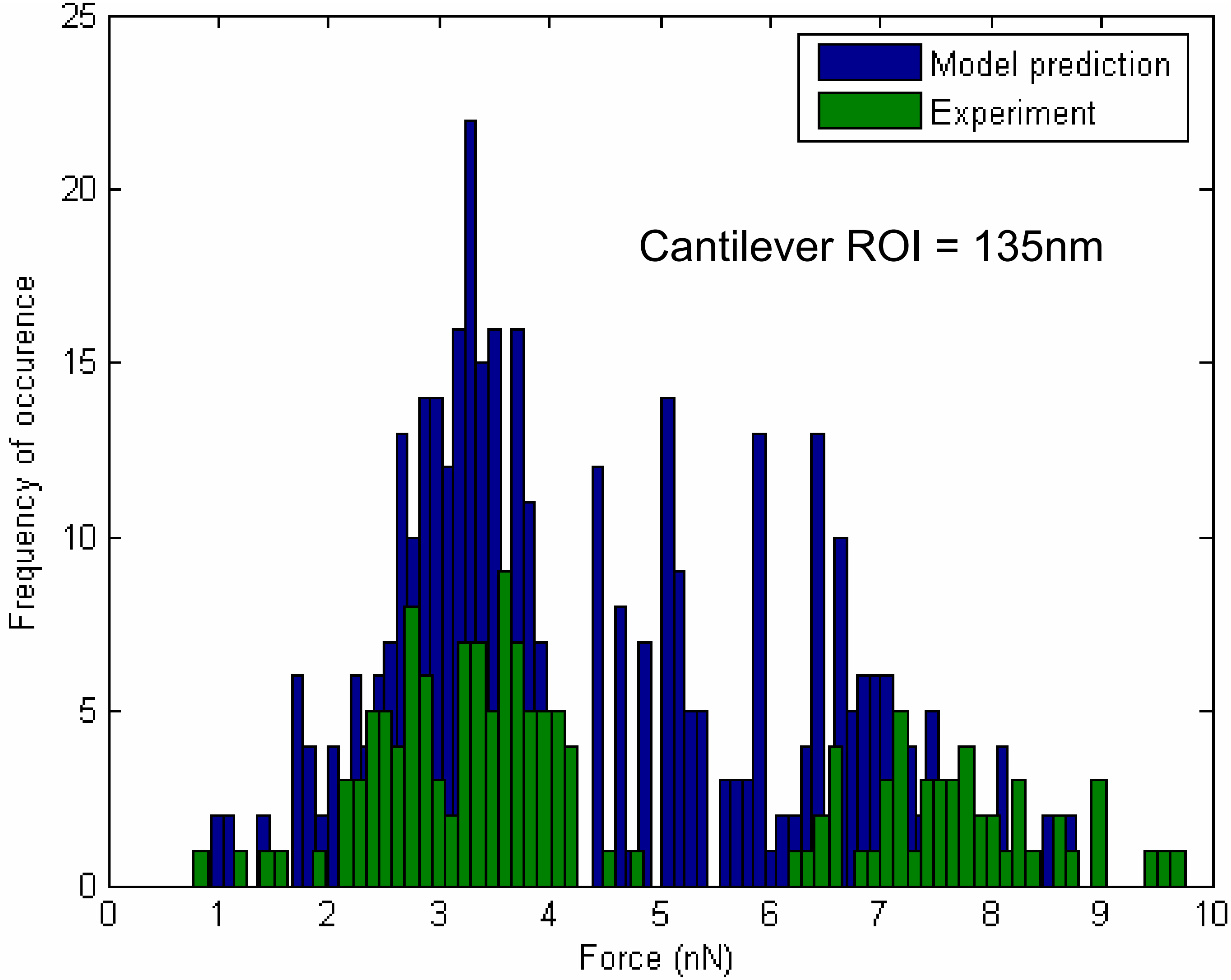
Depending on system

- vdW forces dominant at separation distances ~20 to ~50 nm
- ES forces dominant at larger separations

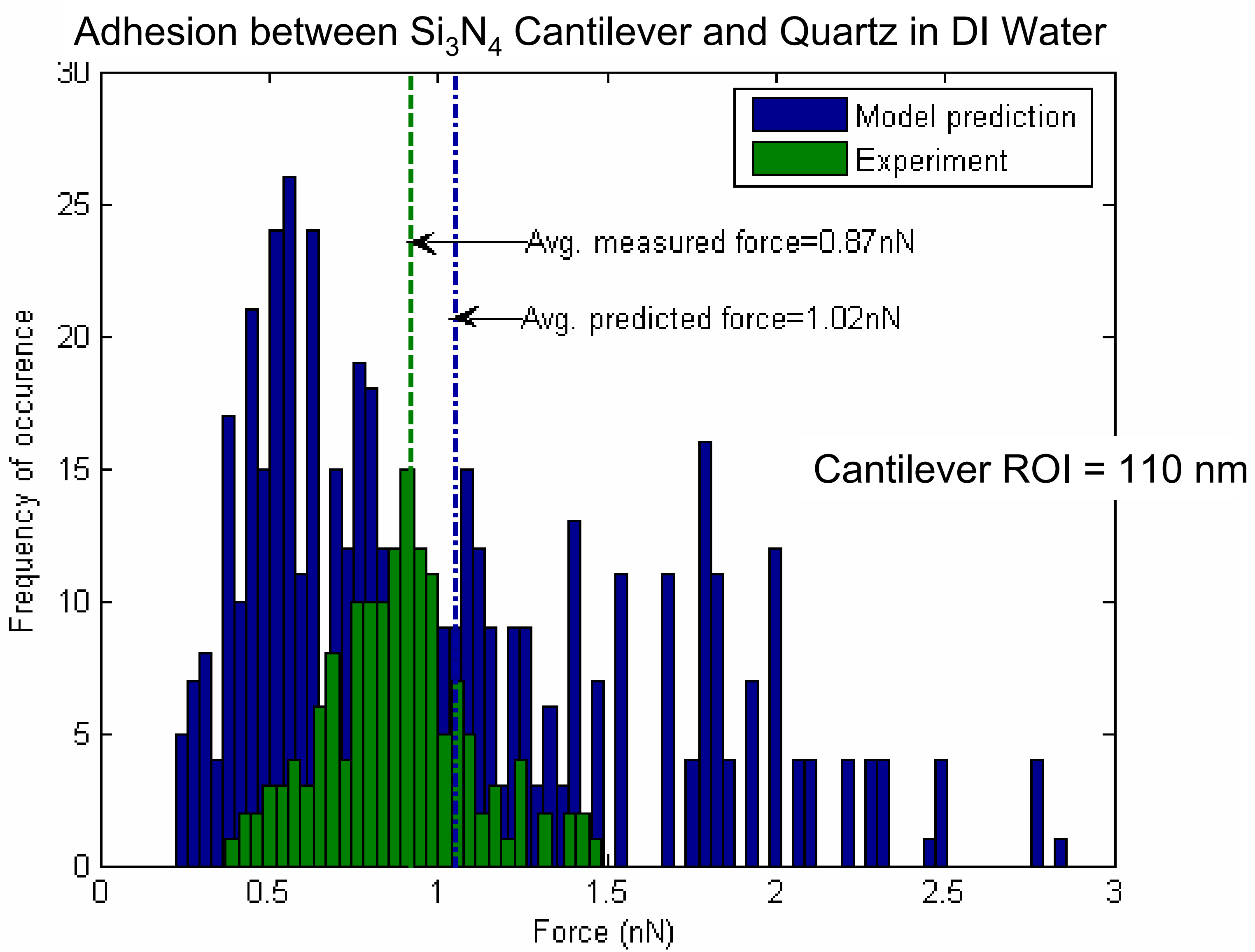
- In Region I, vdW forces are always dominant
- In Region II, electrostatic forces become dominant

Force Distributions: Multiple Contacts I

Adhesion between Si_3N_4 Cantilever and TEOS-Sourced Oxide in DI Water

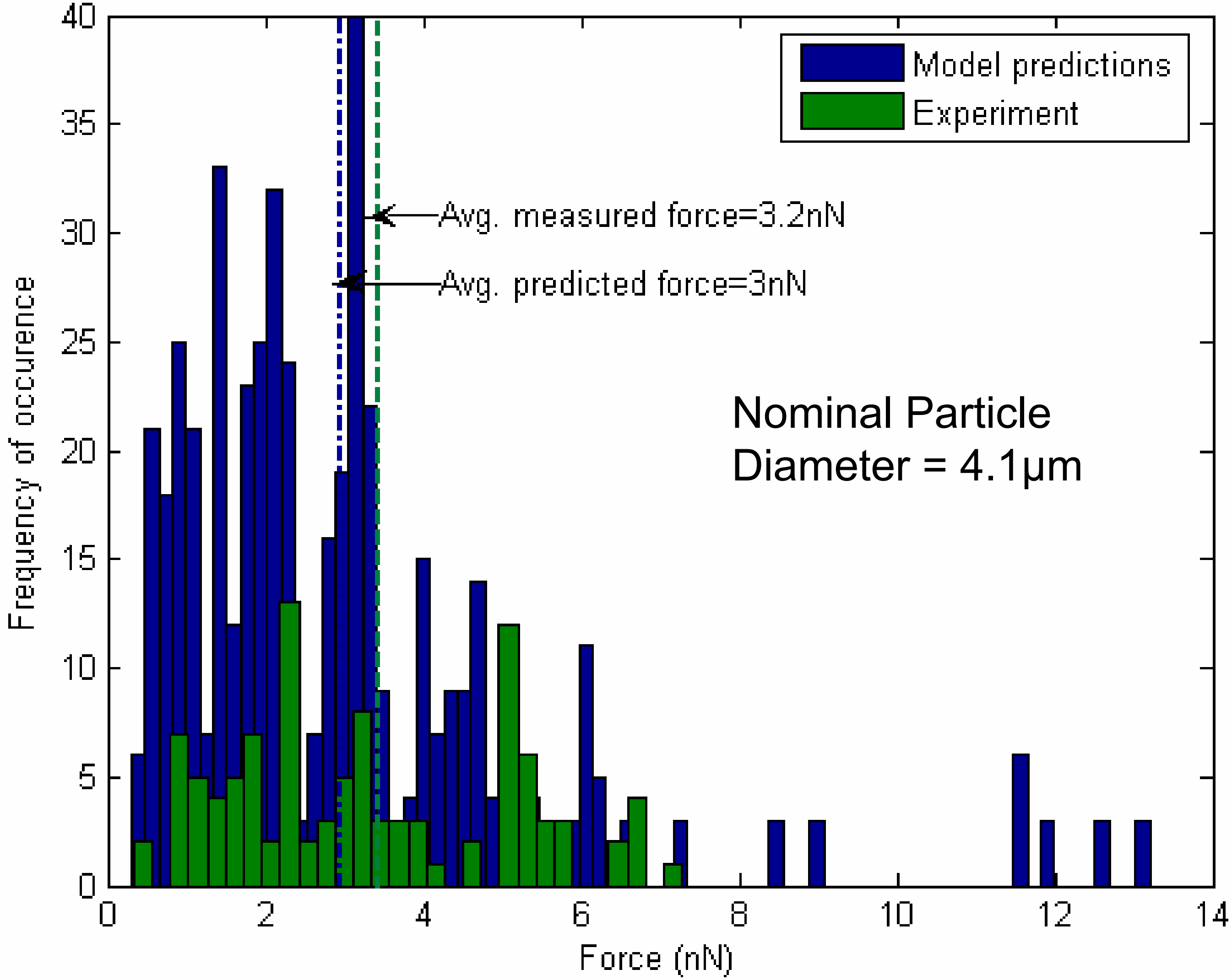


Force Distributions: Multiple Contacts II

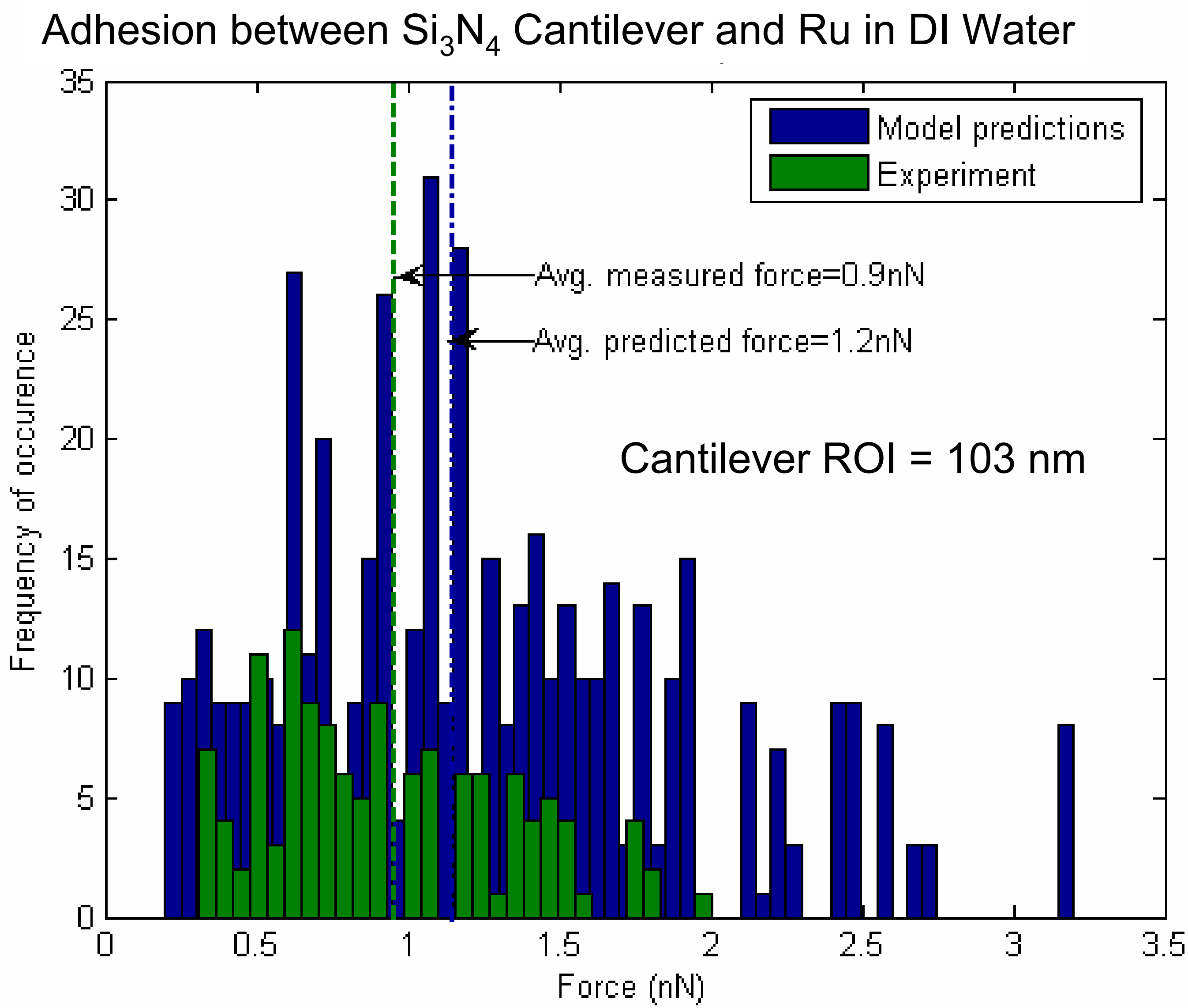


Force Distributions: Multiple Contacts III

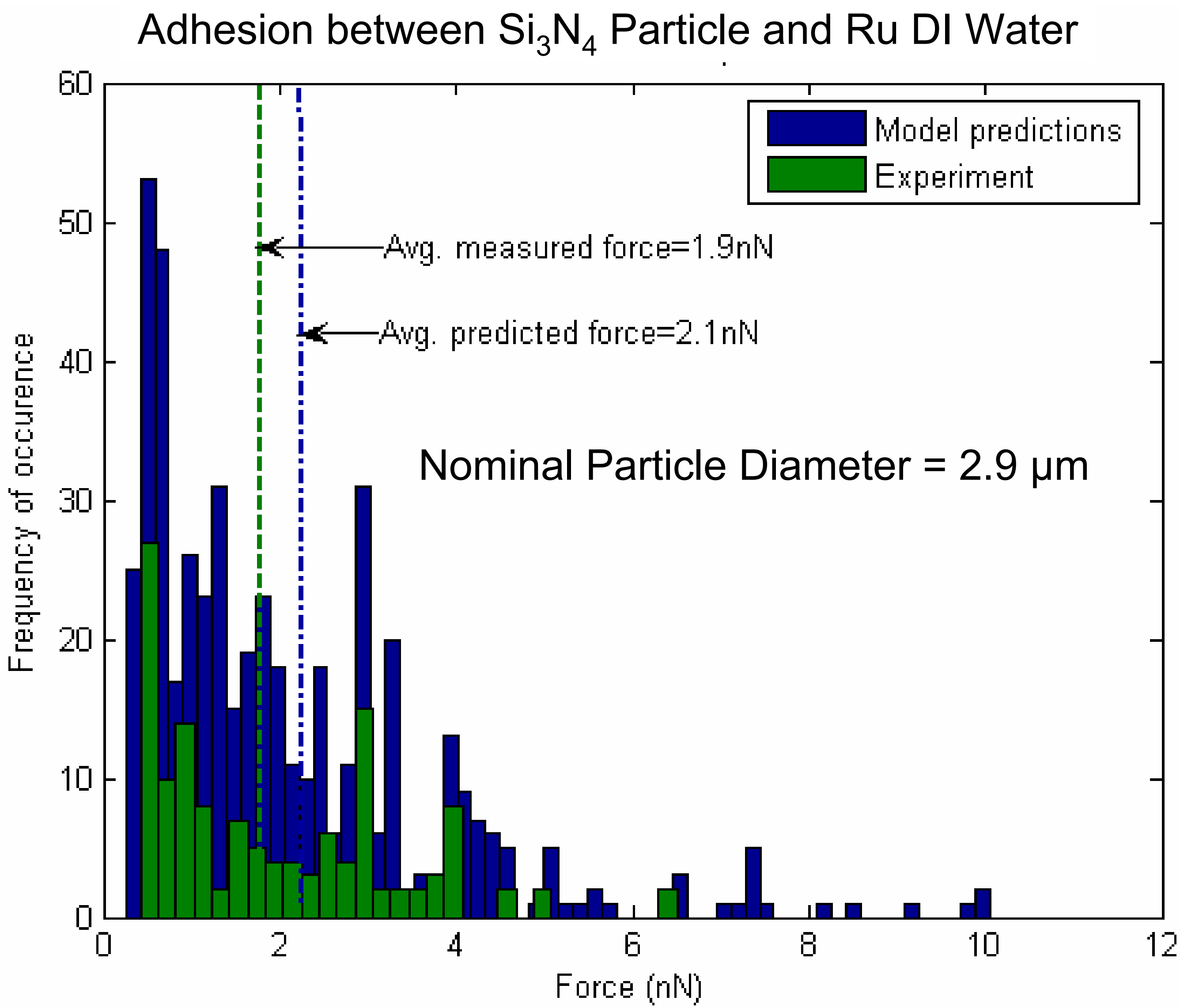
Adhesion between Si_3N_4 Particle and Quartz in DI Water



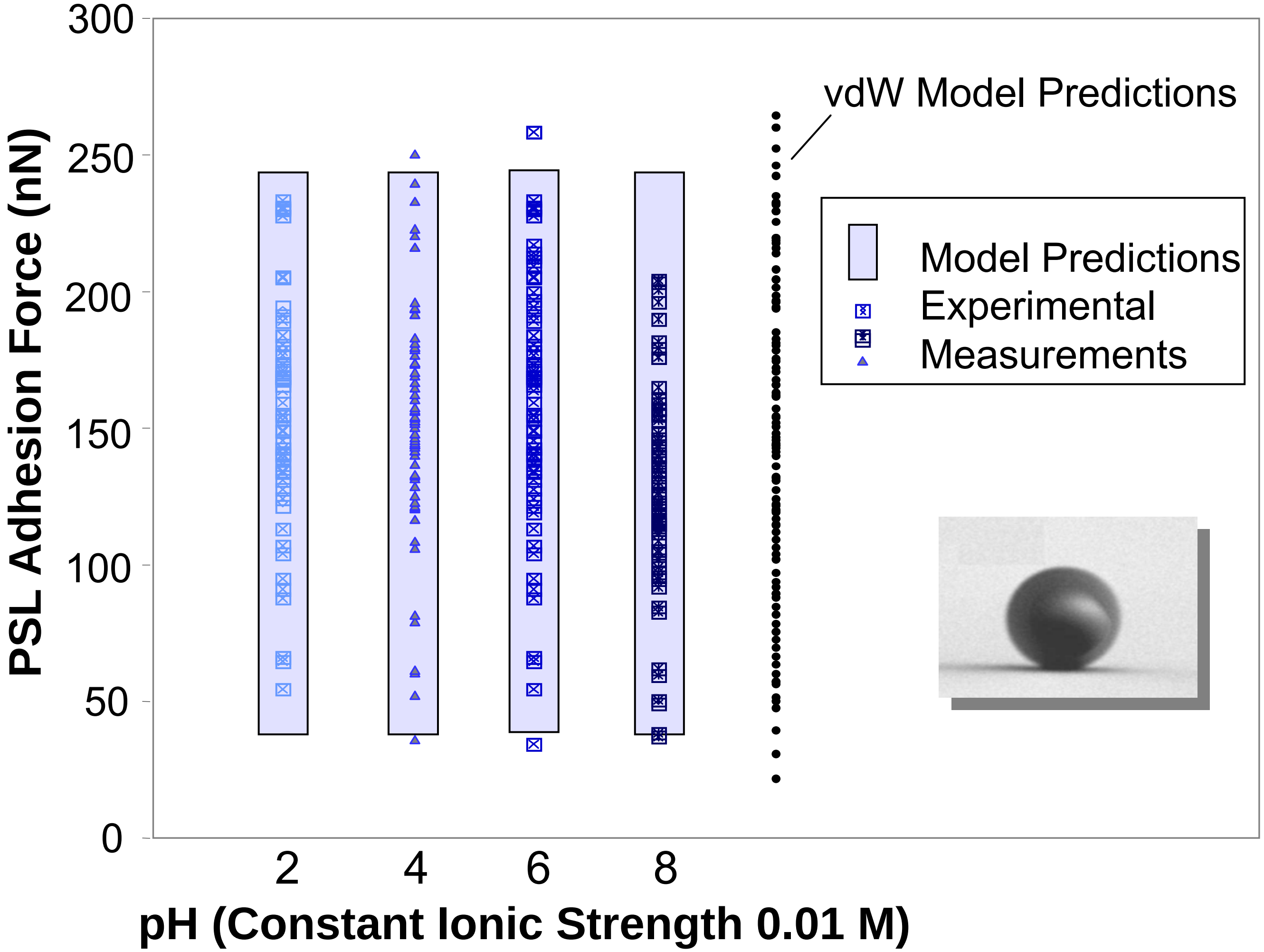
Force Distributions: Multiple Contacts IV



Force Distributions: Multiple Contacts V

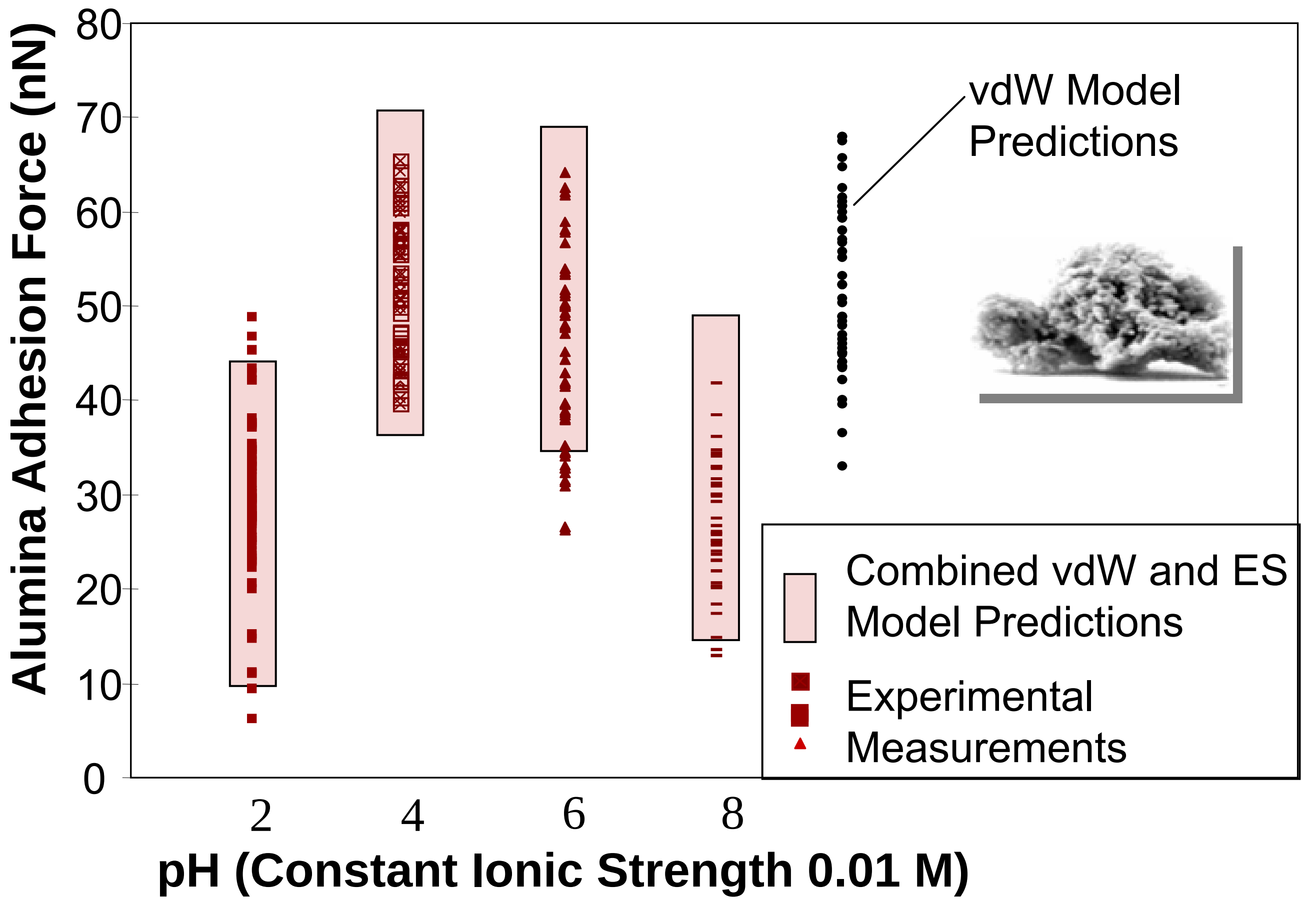


PSL Interactions with SiO_2



- 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

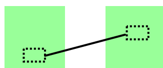


- Electrostatic interactions do affect the adhesion force, which varies with pH
- Large area between particle and wafer out of contact
- Small contact area

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

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

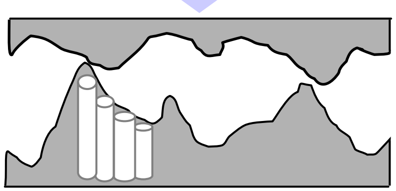
+

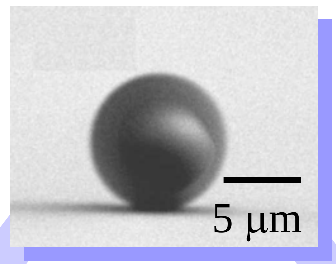
$$F = \frac{-A}{6h}\frac{R_1R_2}{R_1+R_2}$$

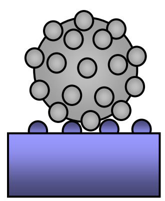
+

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

Computational Solutions







Combination of ideal shapes

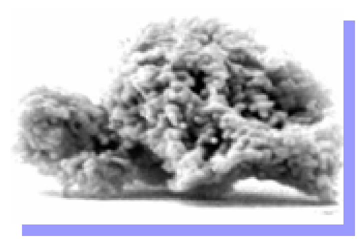
sphere-plate

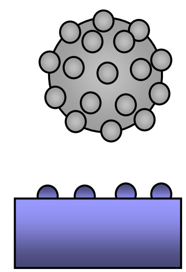
+

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

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

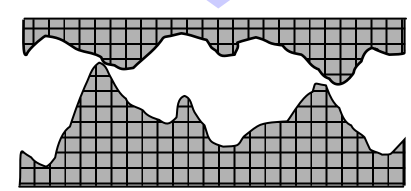
+

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

+

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

Computational Solutions



van der Waals (vdW) Force Model

Model Inputs
Identify key properties that control van der Waals force and quantify their effects

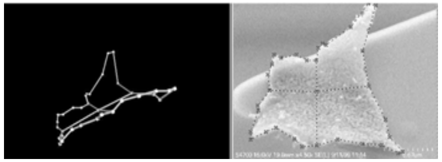
→

Model Prediction
Distribution of forces

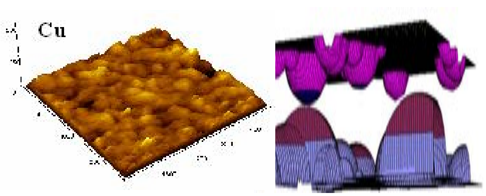
↔

Model Validation
Compare model prediction with experimental measurement

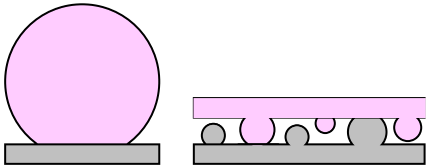
Composition



Geometry

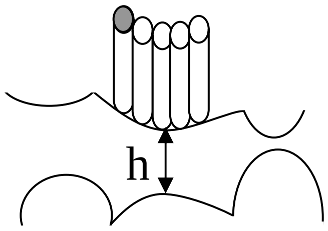


Morphology



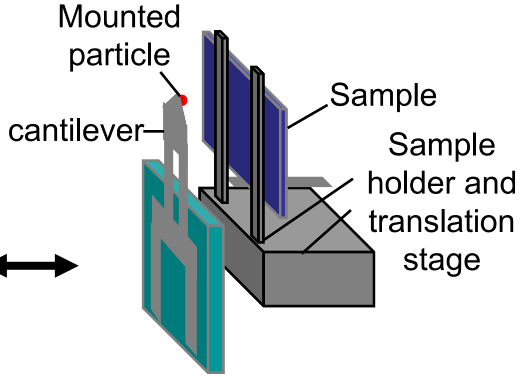
Deformation

→



van der Waals Model (Integrate vdW force over volume elements)

↔



AFM Force Measurements

Calculation of Electrostatic Forces

1.) Find ψ, q, ρ

Reduce equation to a system of algebraic equations

$$\nabla^2\psi = \kappa^2\psi \qquad \psi = \psi_0 \text{ on } \Gamma_1 \qquad q_0 = \partial u_0 / \partial n \text{ on } \Gamma_2$$

Weighted Residuals

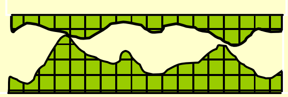
$$\psi = \alpha_1\phi_1 + \alpha_2\phi_2 + \ldots \qquad q - q_0 \neq 0 \quad \text{on } \Gamma_1$$

$$w = \beta_1\psi_1 + \beta_2\psi_2 + \ldots. \qquad \psi - \psi_0 \neq 0 \quad \text{on } \Gamma_2$$

$$\psi_j = \int \psi^* q_0 d\Gamma - \int q^* \psi_0 d\Gamma \qquad \psi^* = \frac{1}{4\pi r} e^{-\kappa r}$$

$$c_j \psi_{0j} = \int \psi^* q_0 d\Gamma - \int q^* \psi_0 d\Gamma \qquad q^* = \nabla \psi^* \cdot \mathbf{n}_\alpha$$

Apply to Discretized Boundary



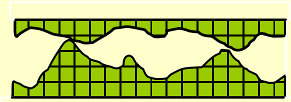
$$\psi_j = \sum_{i=1}^{N}\left(\int_{\Gamma_i} \psi^* d\Gamma_i\right) q_{0i} - \sum_{i=1}^{N}\left(\int_{\Gamma_i} q^*\right)\psi_{0i} \qquad \frac{1}{2}\psi_{0j} = \sum_{i=1}^{N}\left(\int_{\Gamma_i} \psi^* d\Gamma_i\right) q_{0i} - \sum_{i=1}^{N}\left(\int_{\Gamma_i} q^*\right)\psi_{0i}$$

Solve with quadrature

2.) Calculate force

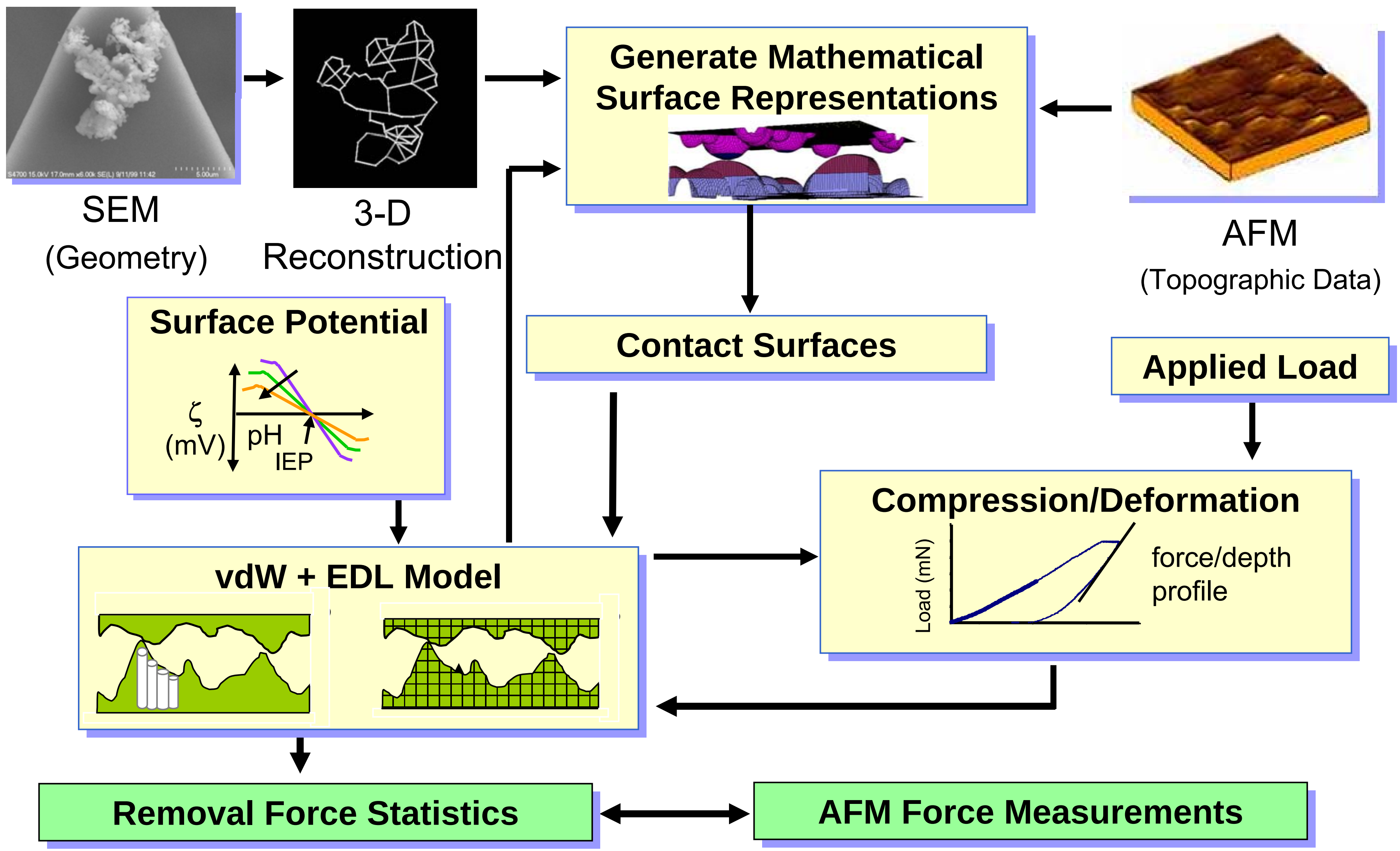
$$\frac{F}{Area} = -\frac{\sigma^2}{2\varepsilon_0\varepsilon_r} + kT\sum_i \left(c_i^*(0) - c_{io}^*\right)$$

Integrate over surfaces

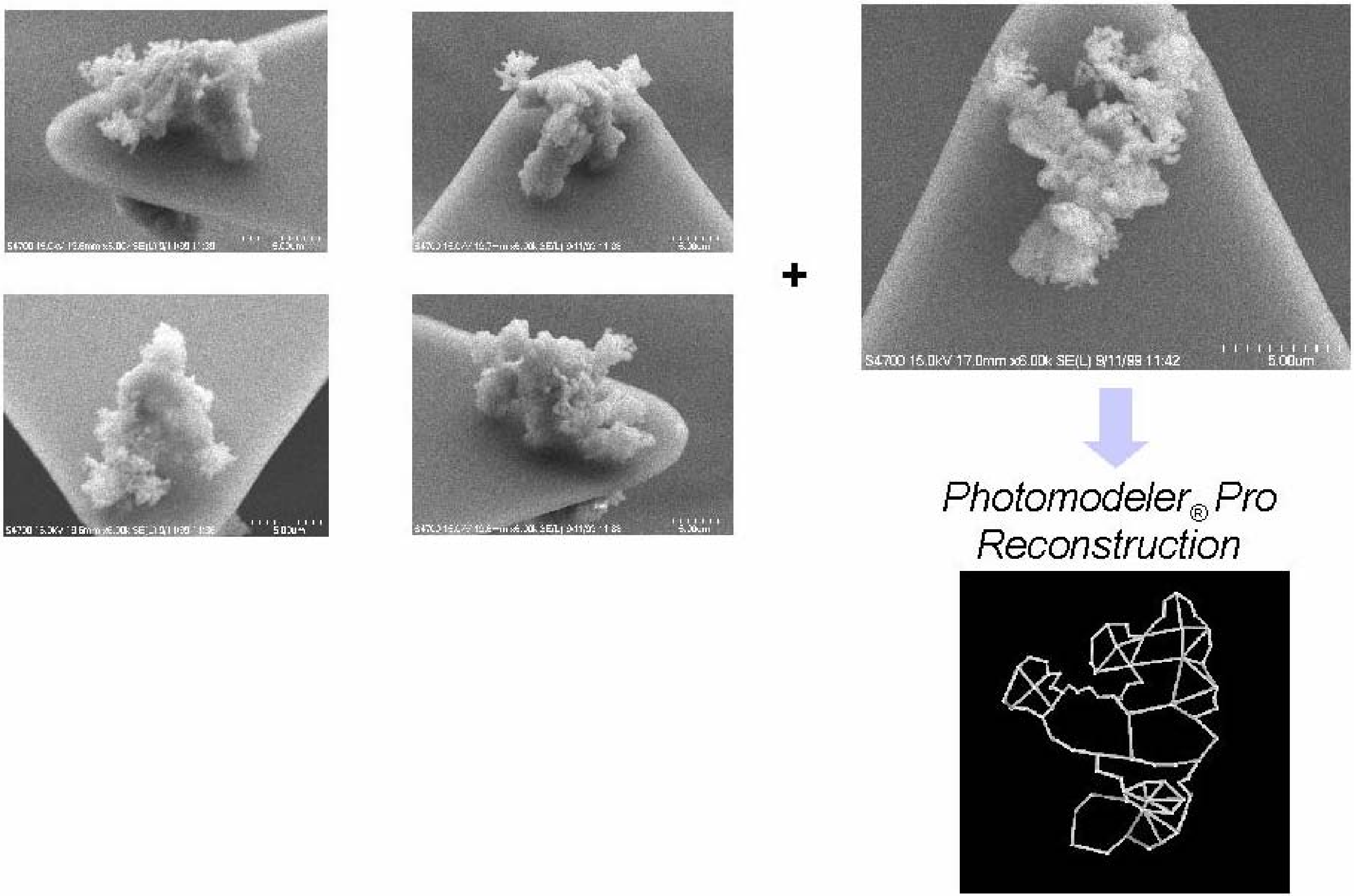


$$F = \sum\left[-\frac{\sigma^2}{2\varepsilon_0\varepsilon_r} + kT\sum_i \left(c_i^*(0) - c_{io}^*\right) * Area\right]$$

Combined vdW, ES Interaction Models

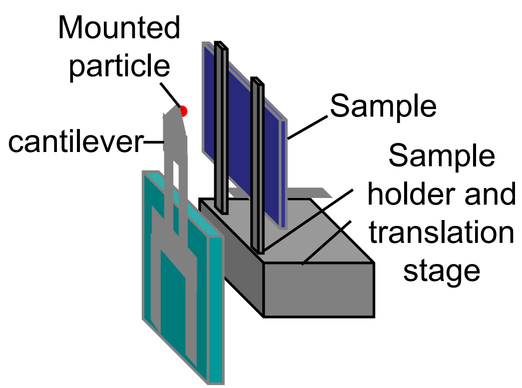


Geometric Models

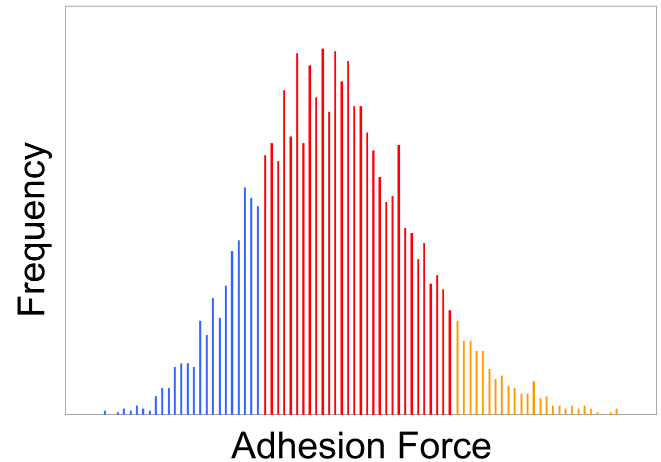


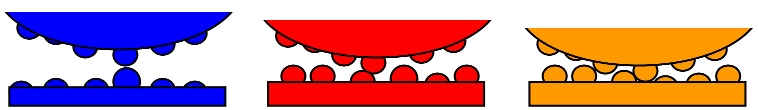
Particle Adhesion Measurements

AFM Schematic



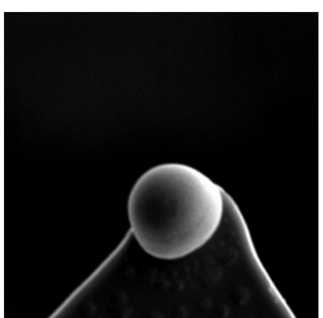
Distribution of Forces



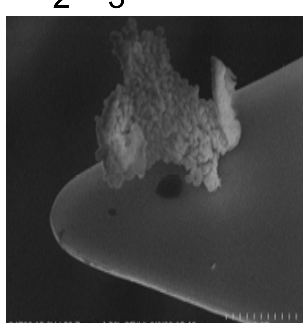


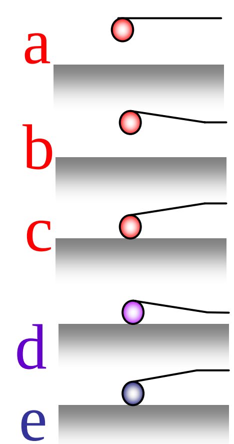
Particles Mounted on AFM Cantilevers

PSL Particle

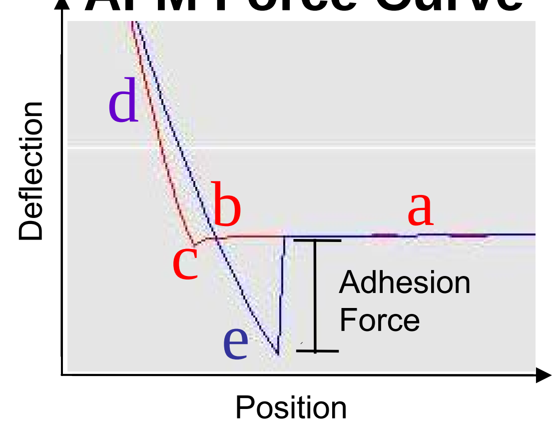


Al_2O_3 Particle

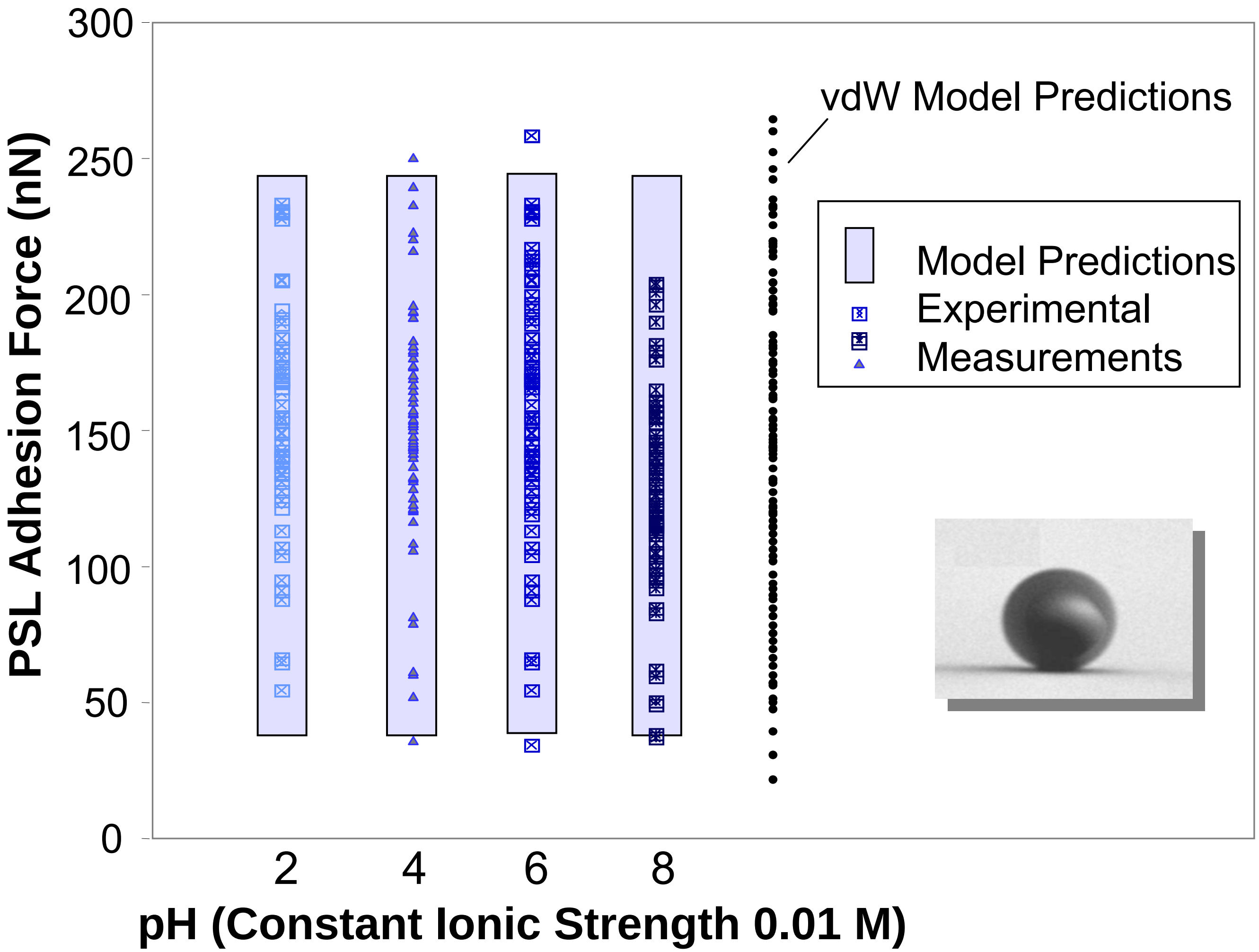




AFM Force Curve

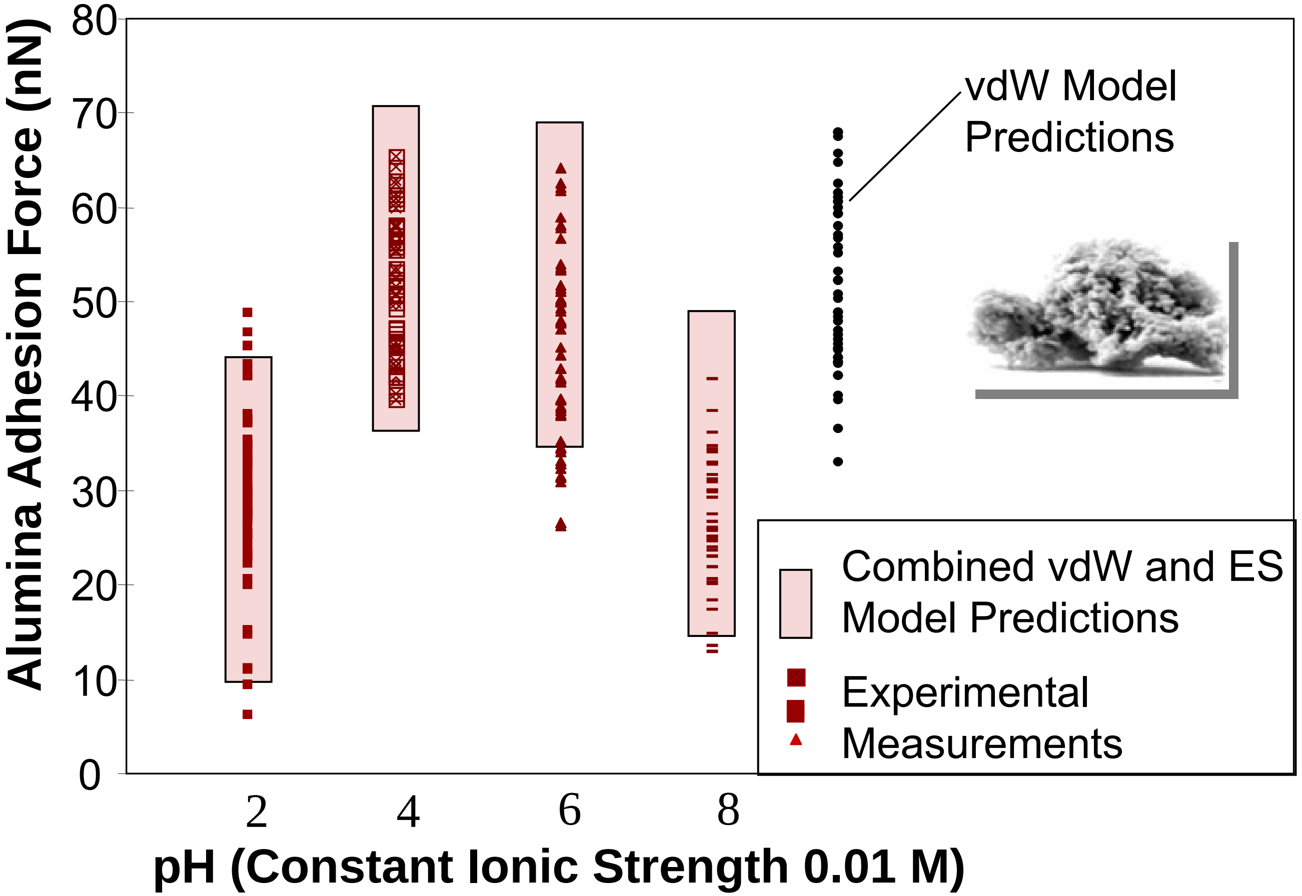


PSL Interactions with SiO_2



- 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

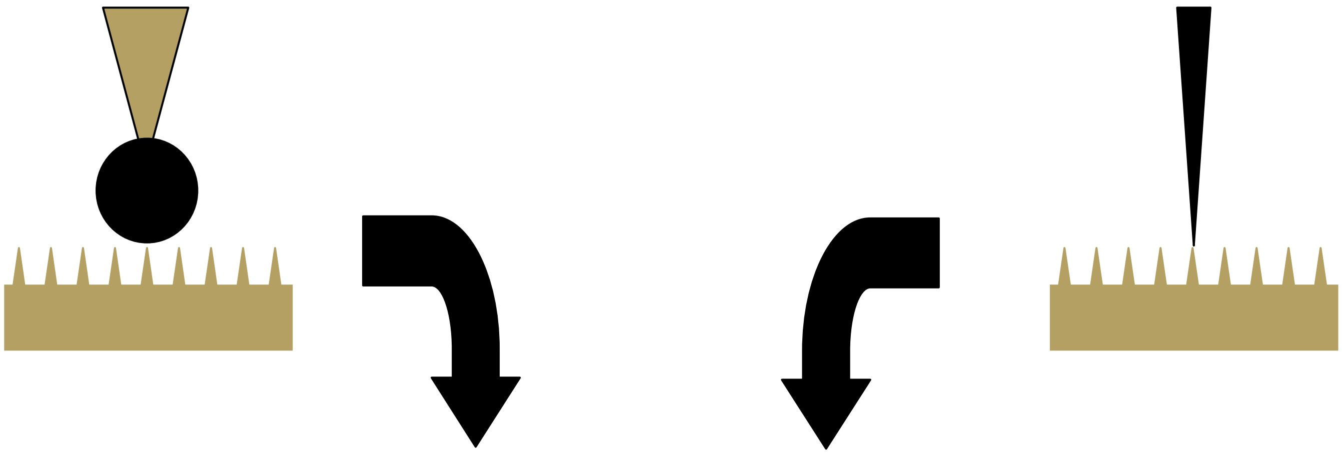


- Electrostatic interactions do affect the adhesion force, which varies with pH
- Large area between particle and wafer out of contact
- Small contact area

Nanoscale Adhesion Approach

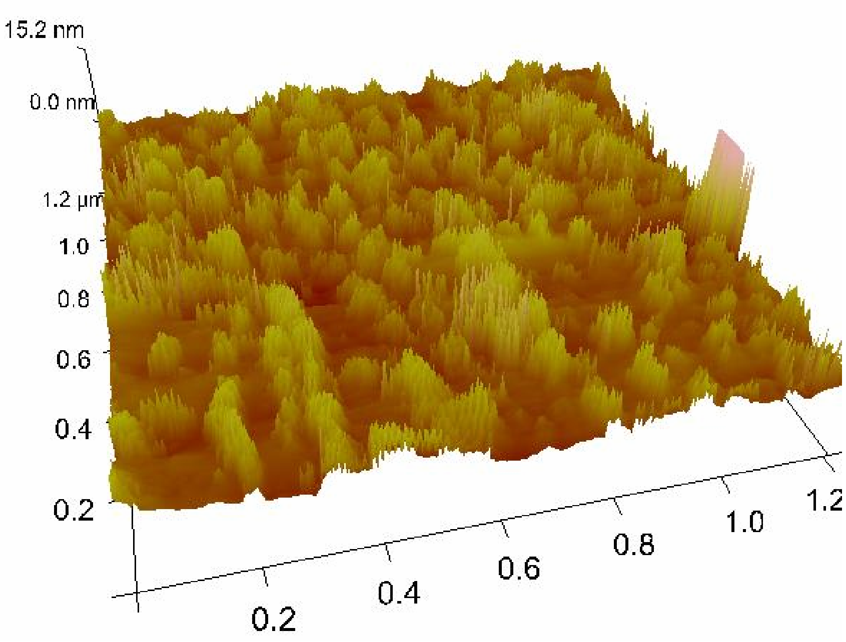
- Measure, model micron-scale adhesion
- Extract vdW, ES constants

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

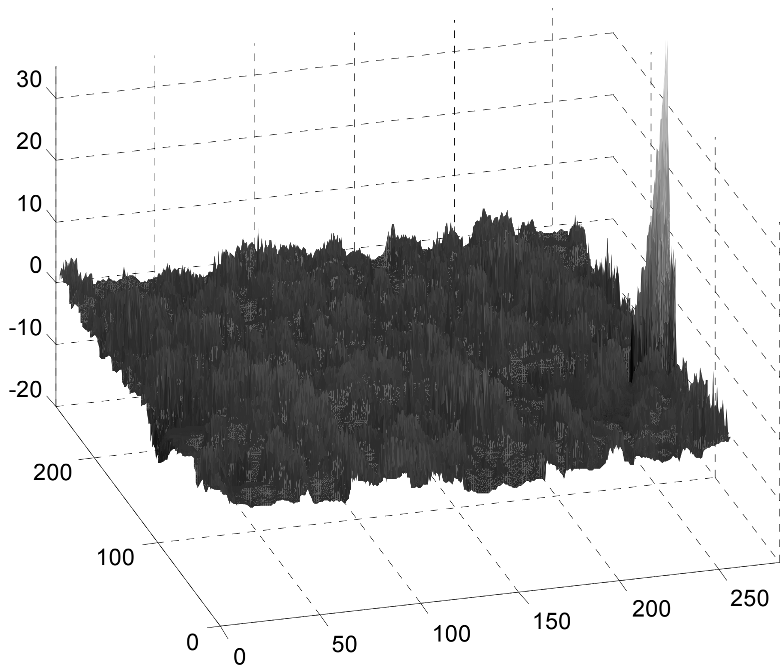


- Can measure nano-scale adhesion
- Can model roughness and geometry effects
- Can predict nano-scale adhesion

Silicon Dioxide Surface

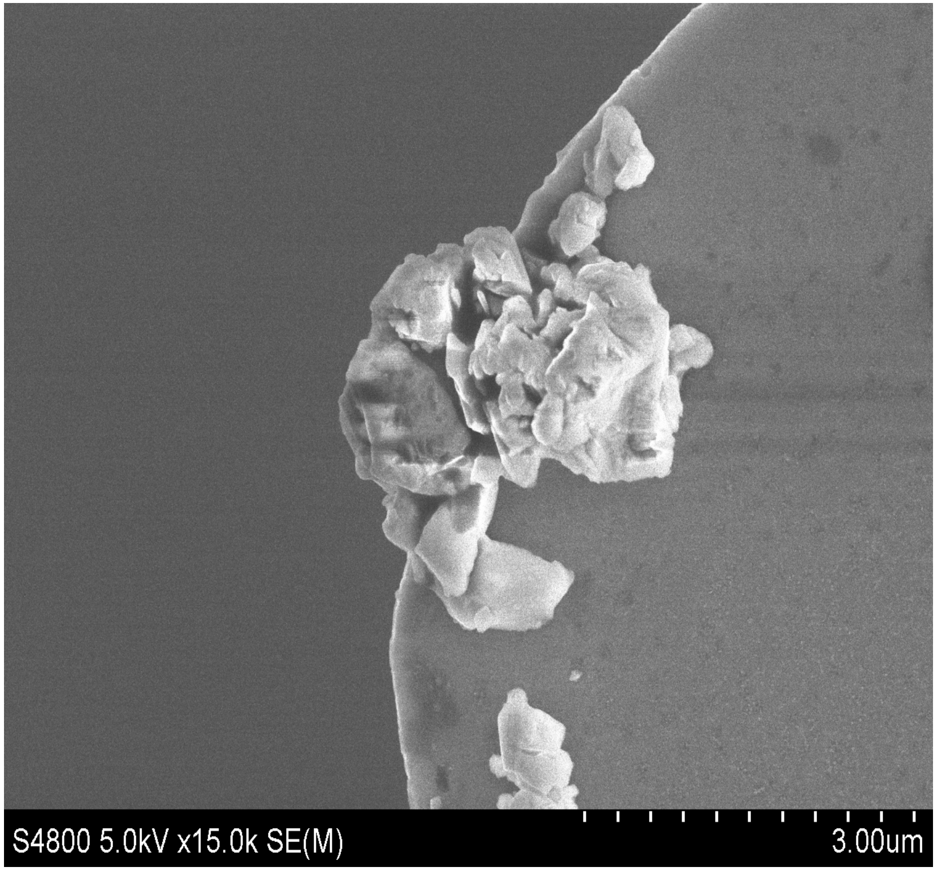


AFM Image

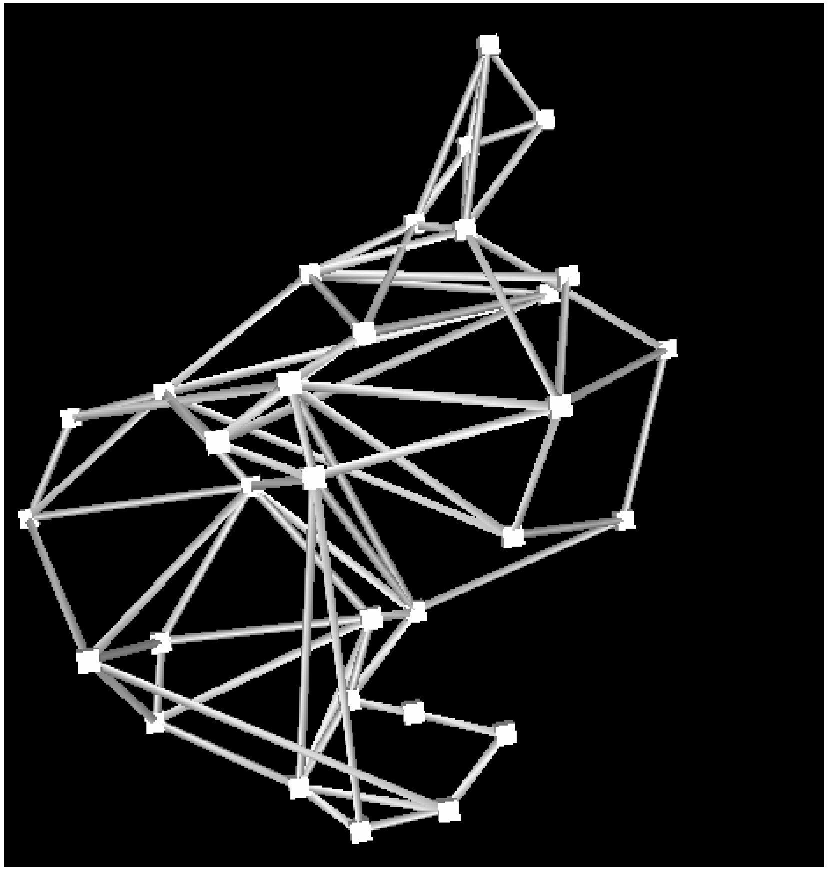


FFT model Regeneration

Silicon Nitride Particle: Micron-Scale

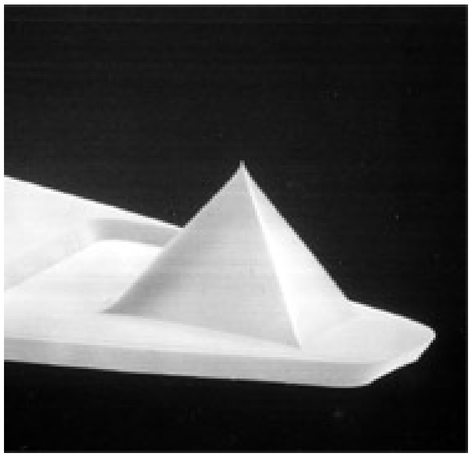


FESEM image of a Si_3N_4 particle mounted on an AFM cantilever



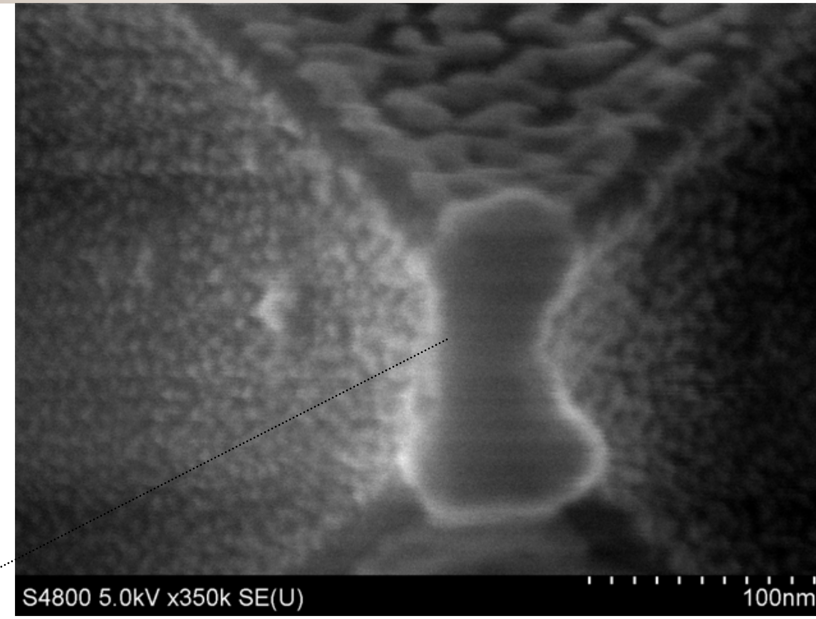
Photomodeler Pro® model for the nitride particle

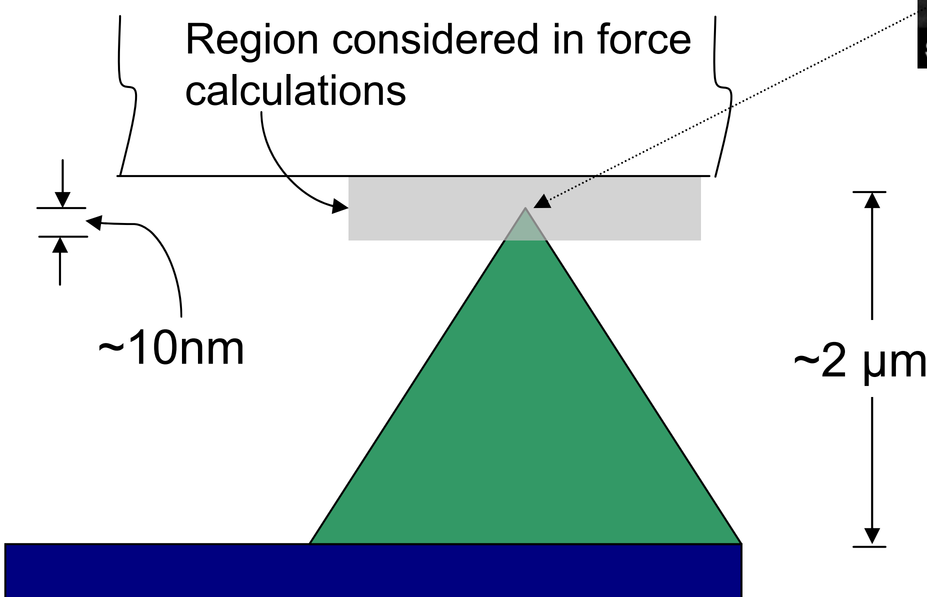
Silicon Nitride Cantilevers: Nanoscale



Sharpened silicon nitride probe

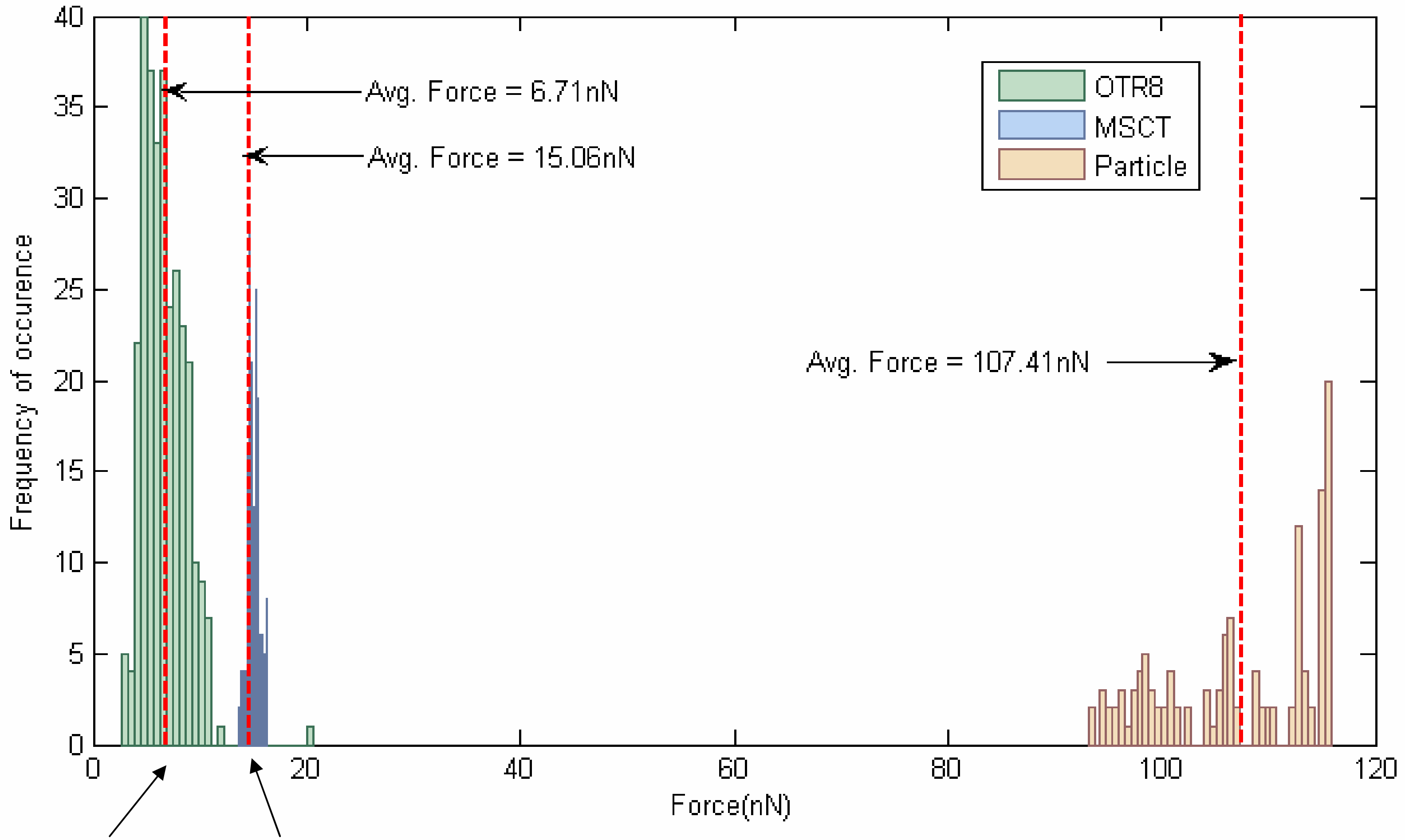
Max ROC ~ 40nm





Geometry considered in modeling the force between nanoscale cantilevers and substrates

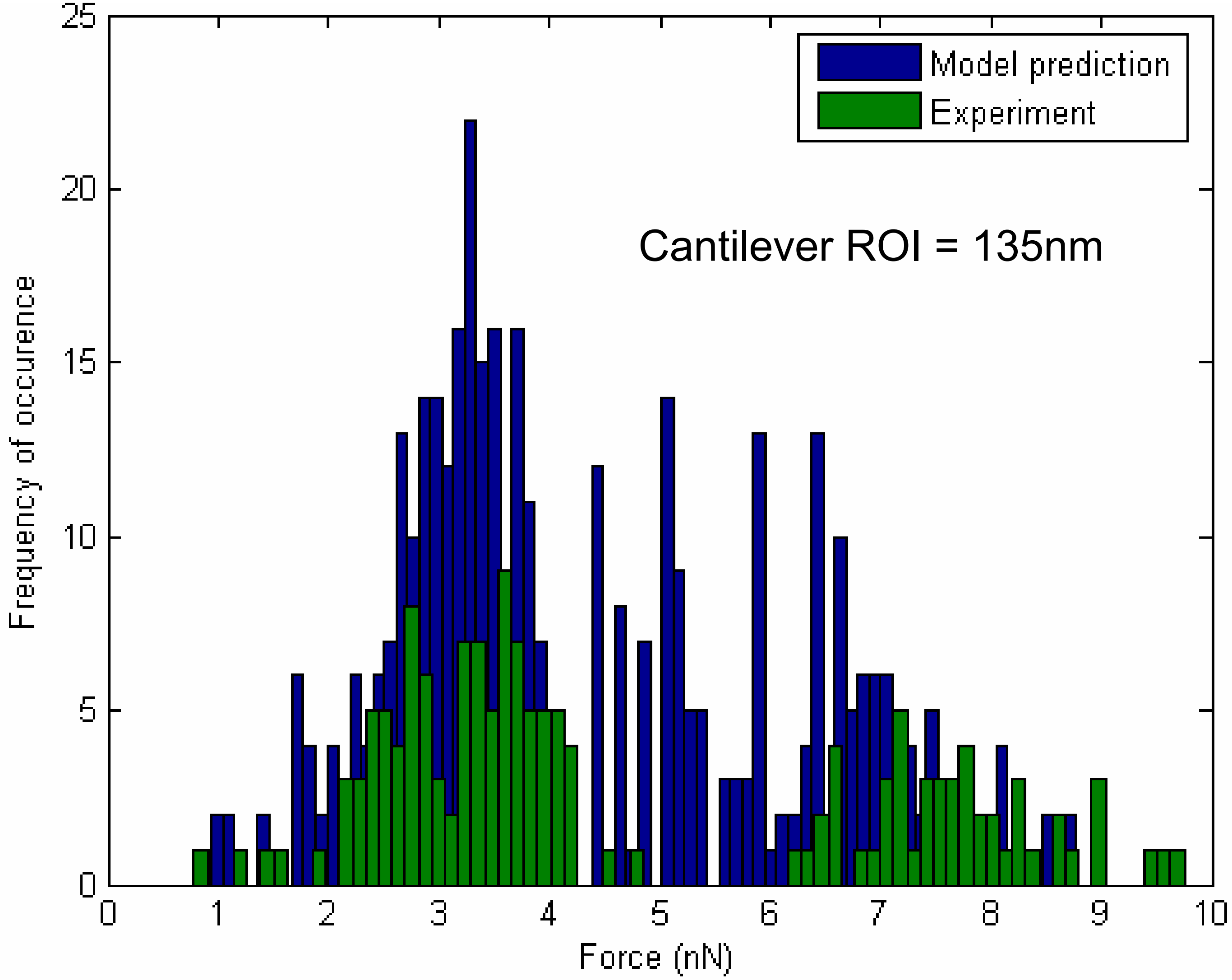
Silicon Nitride Adhesion to Silicon Dioxide in Air



Tip ROC=12nm Tip ROC=36nm

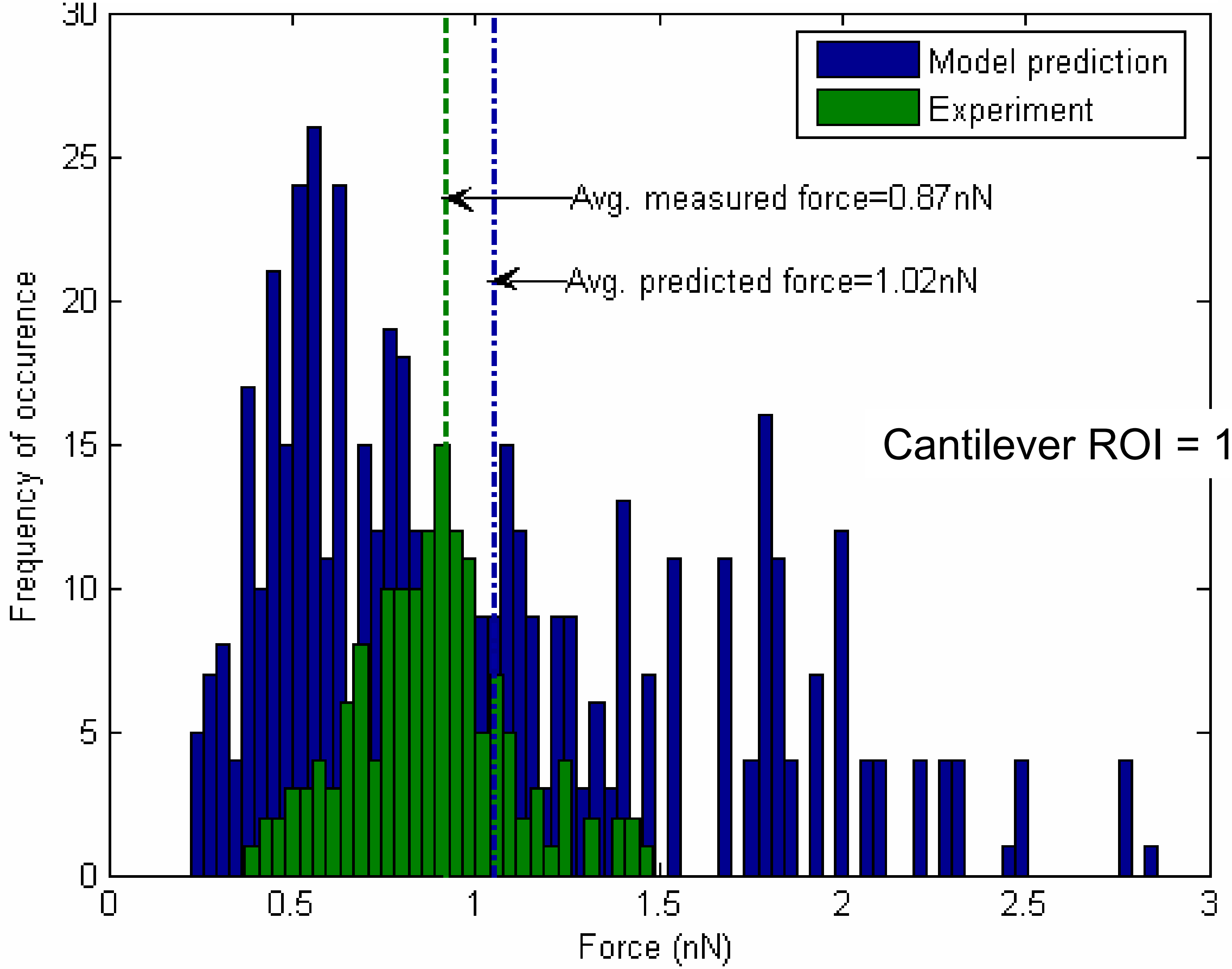
Force Distributions: Multiple Contacts I

Adhesion between Si_3N_4 Cantilever and TEOS-Sourced Oxide in DI Water



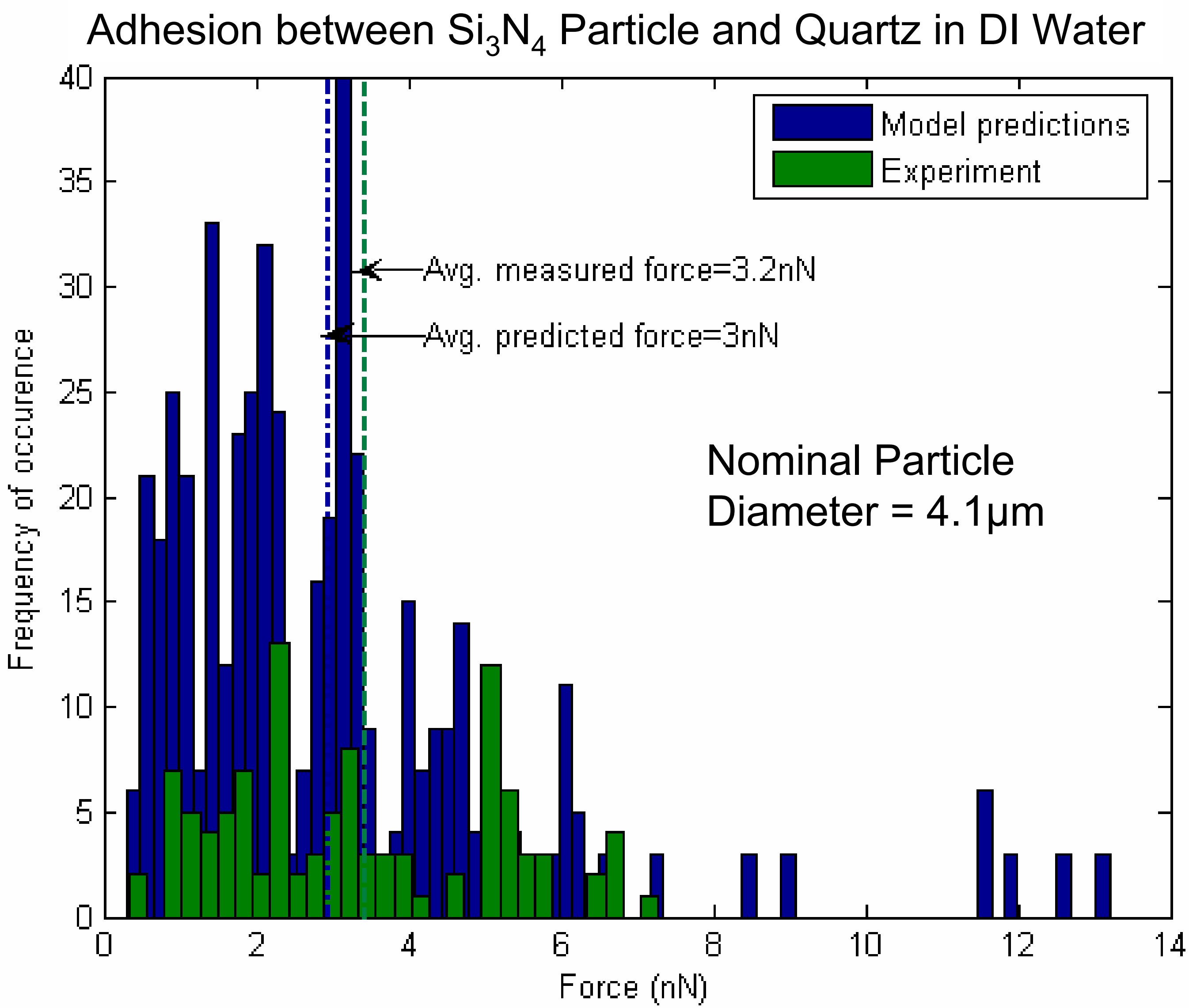
Force Distributions: Multiple Contacts II

Adhesion between Si_3N_4 Cantilever and Quartz in DI Water



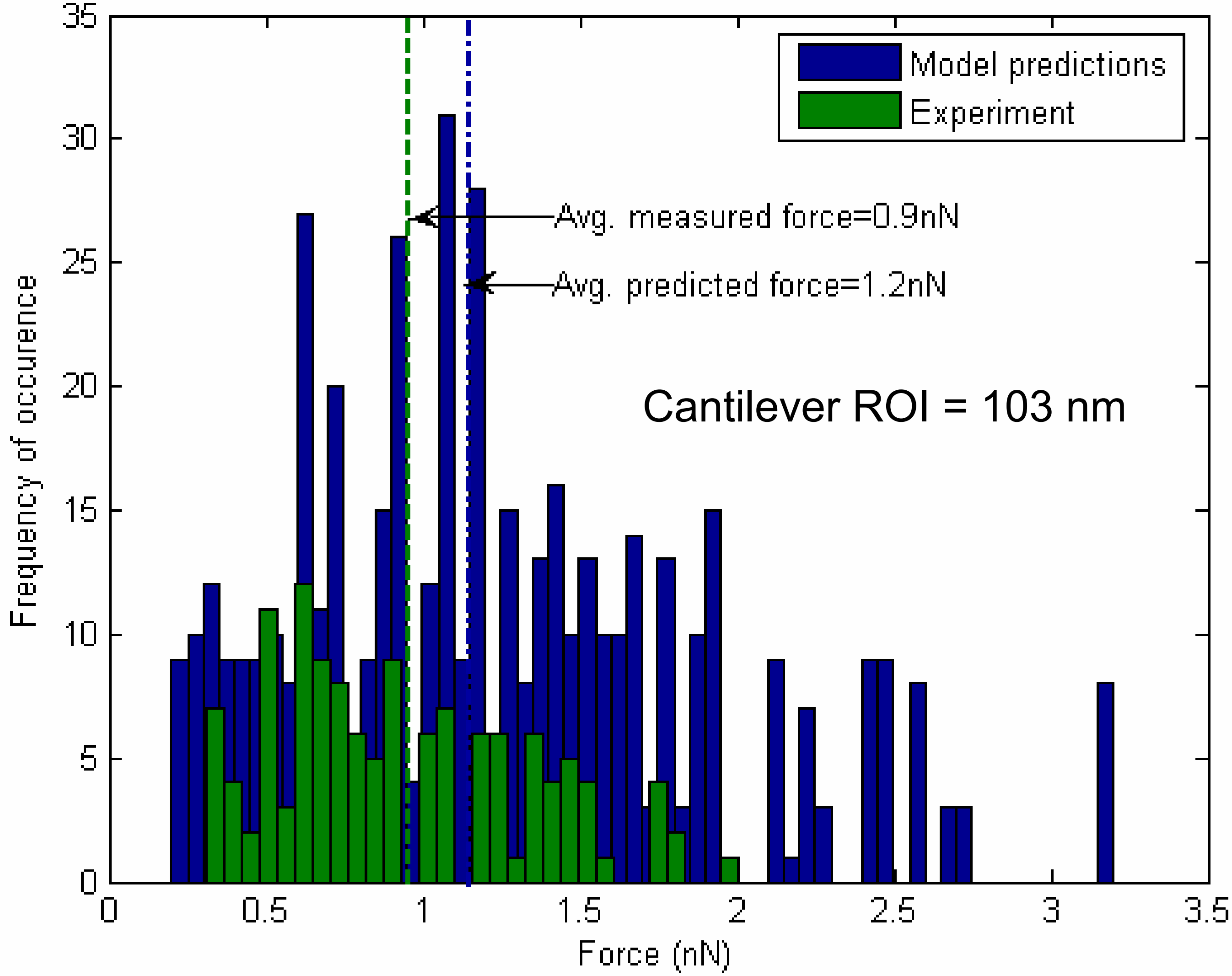
Cantilever ROI = 110 nm

Force Distributions: Multiple Contacts III

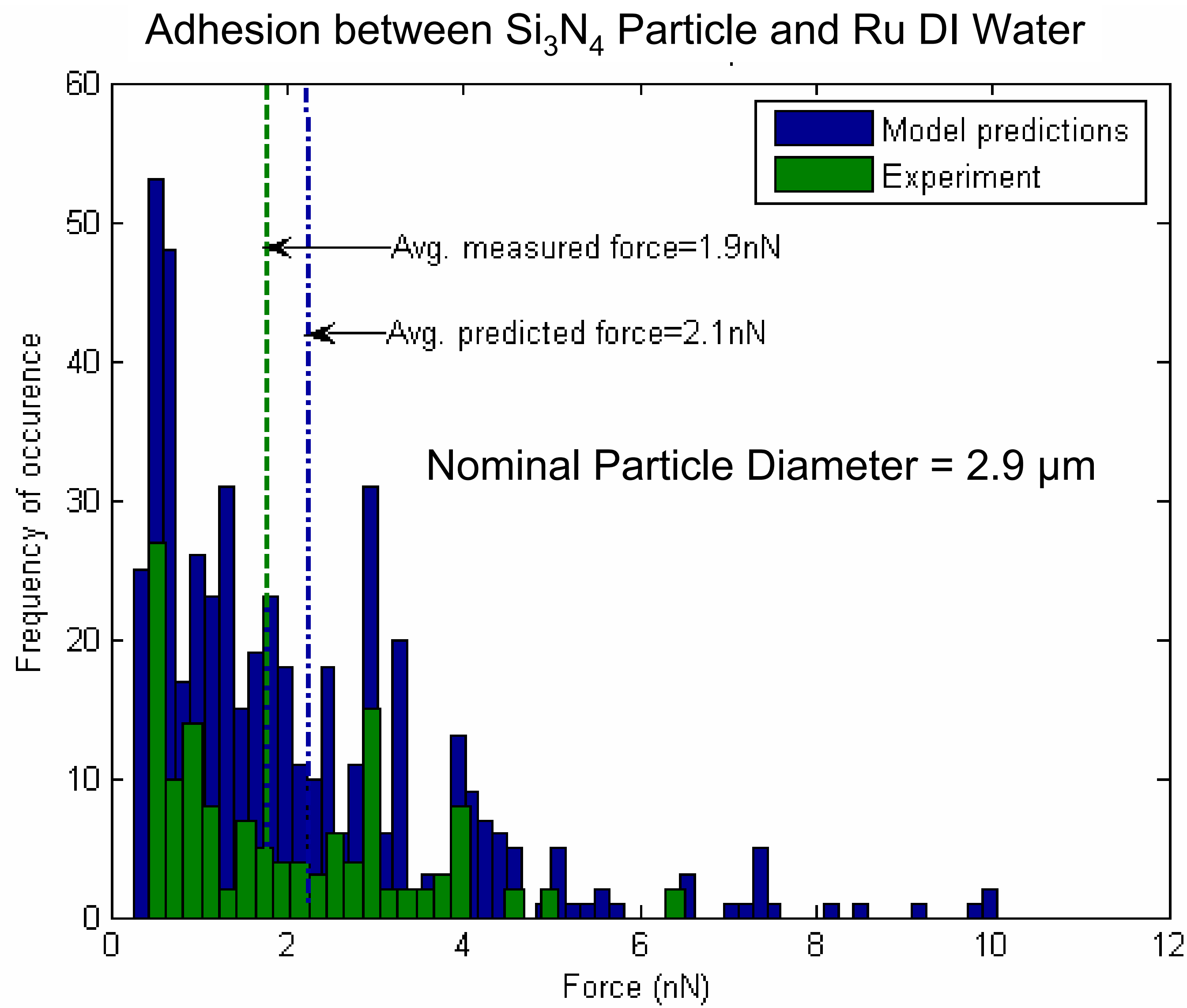


Force Distributions: Multiple Contacts IV

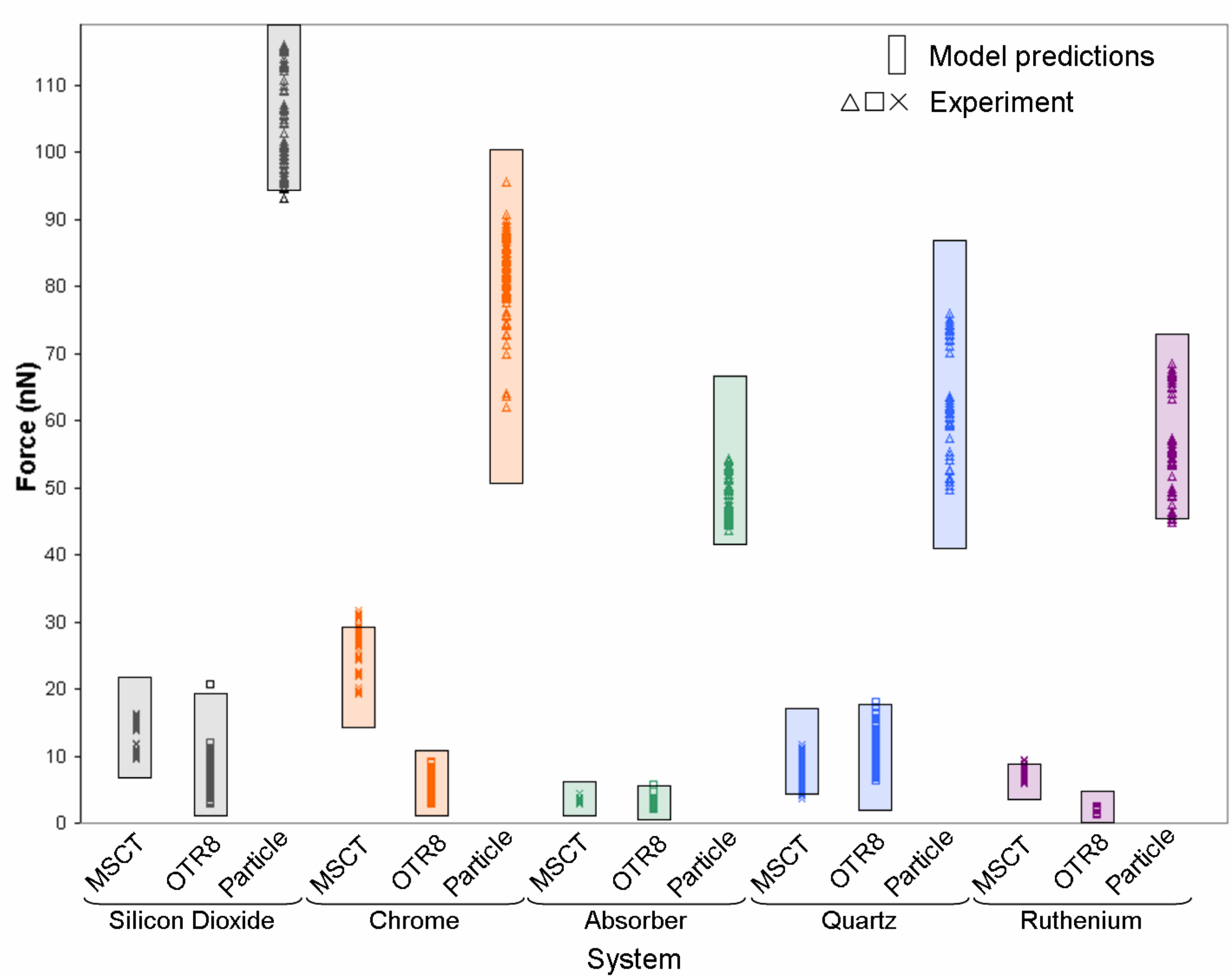
Adhesion between Si_3N_4 Cantilever and Ru in DI Water



Force Distributions: Multiple Contacts V



Micron-Nanoscale Adhesion in Air



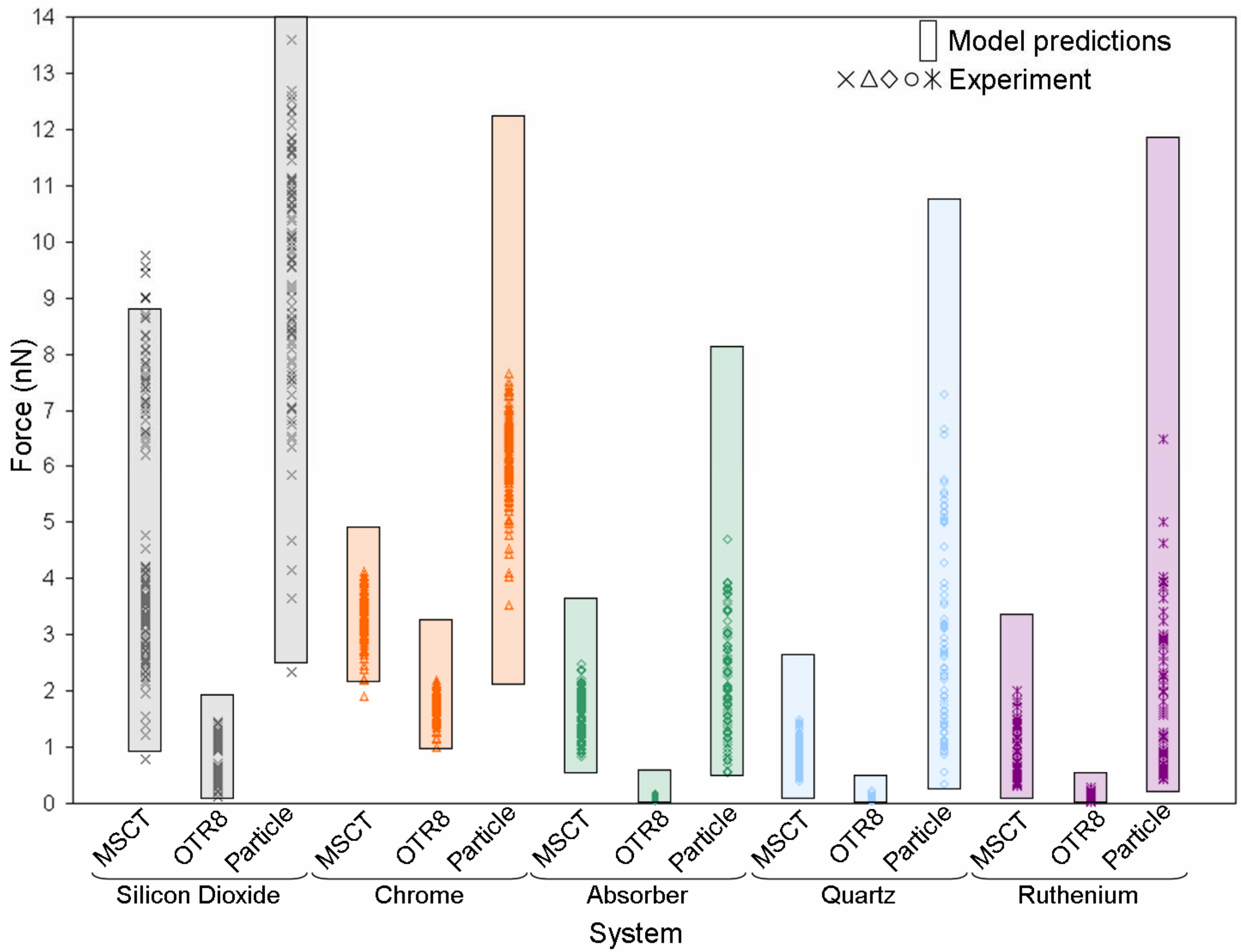
<u>ROIs (nm)</u>

MSCT: 110

OTR8: 35

Particle: 3.5 (μm)

Micron-Nanoscale Adhesion in H_2O



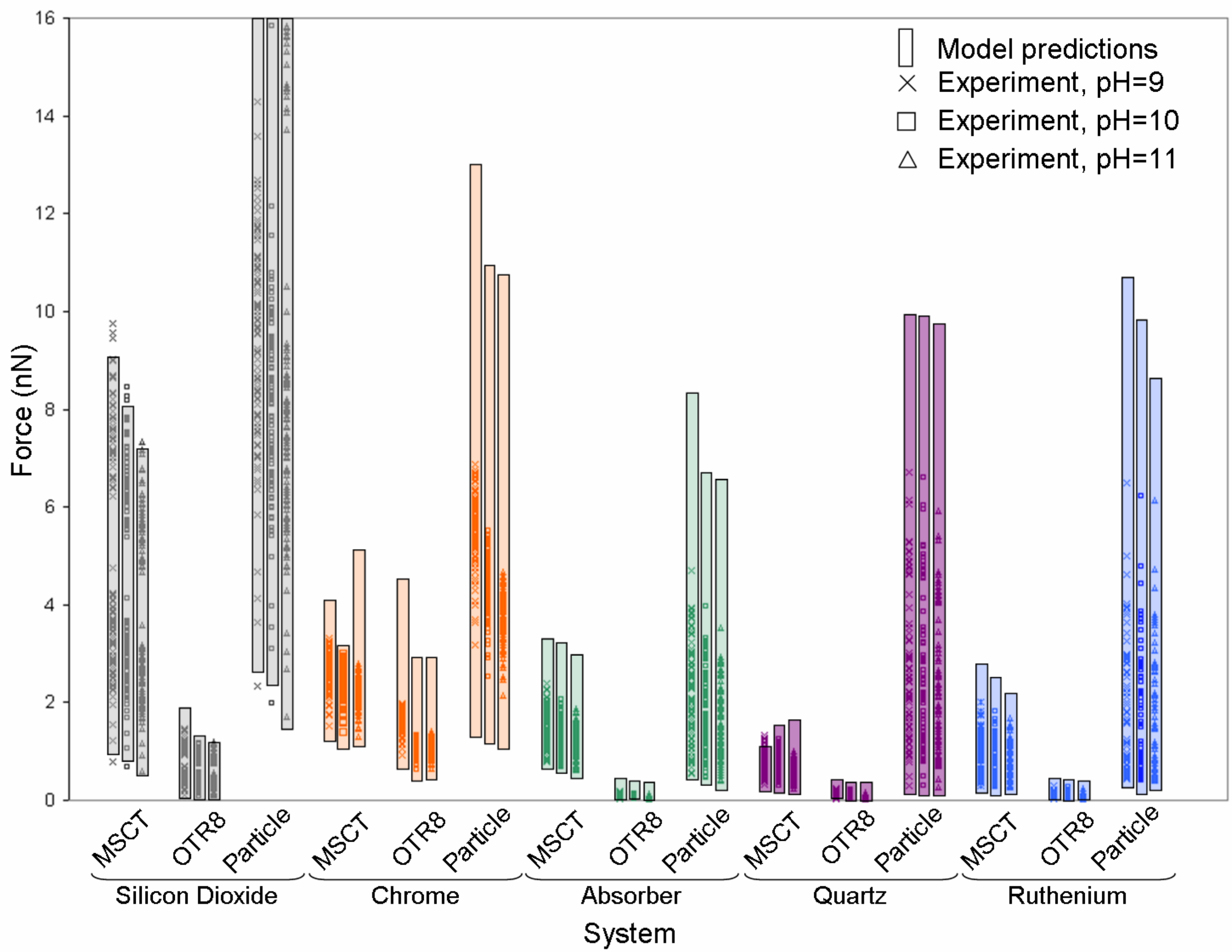
ROIs (nm)

MSCT: 125

OTR8: 25

Particle: 2.9 (μm)

Micron-Nanoscale Adhesion in NH_4OH



ROIs (nm)

MSCT: 90

OTR8: 40

Particle: 3.2 (μm)

Academic 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

Industrial Conclusions

- Nano-scale particle adhesion not significantly influenced by composition of aqueous medium
  - Electrostatic effects not significant
- Adhesion of wet particles to wet substrates much lower than adhesion of dry particles to dry substrates
- Nanoparticle adhesion forces generally less than 5-10 nN

Acknowledgements

- Financial support
  - National Science Foundation
    - CAREER grant (CTS-9984620)
  - NSF/SRC ERC for Environmentally-Benign Semiconductor Manufacturing
  - State of Indiana 21st Century Fund
  - Intel
  - Praxair Microelectronics
- SEZ America
- Stefan Myhajlenko
  - Arizona State University Center for Solid State Electronics Research
- Ann Gelb
  - Arizona State University Mathematics