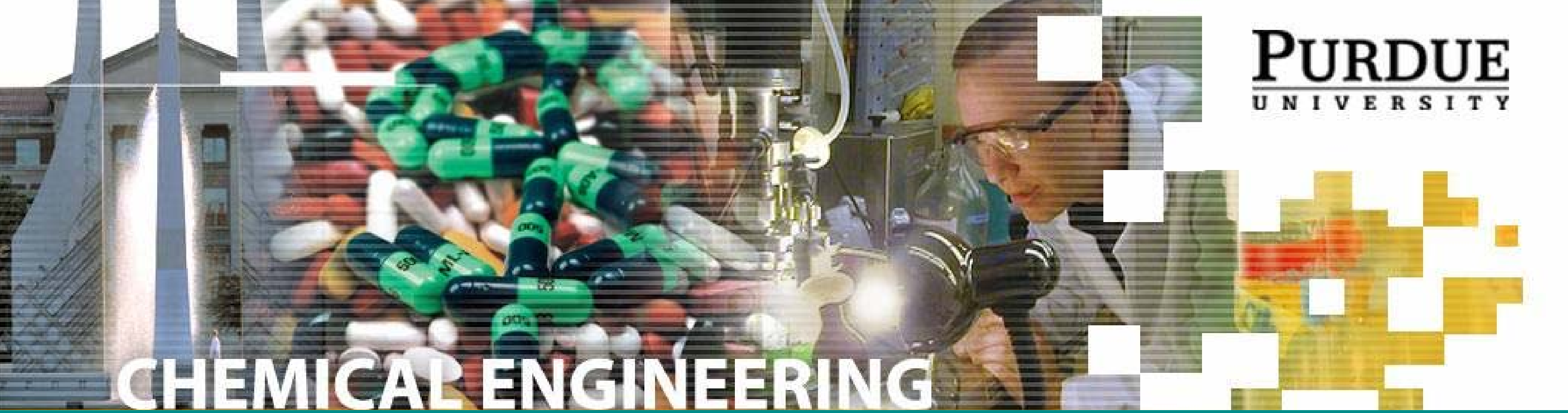


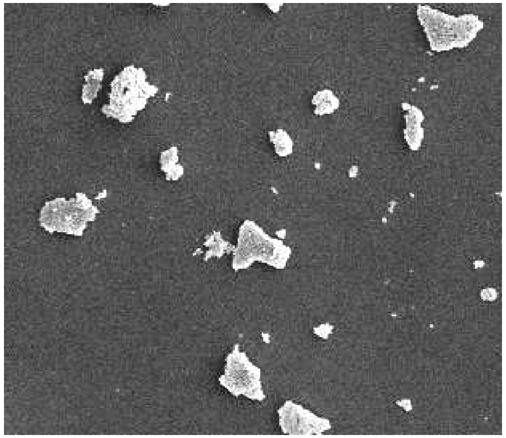
A Theoretical and Experimental Study of Surface Forces in Adhesion of Particles to Thin Films

Ravi Jaiswal, Caitlin Kilroy, Gautam Kumar
Prof. Stephen Beaudoin

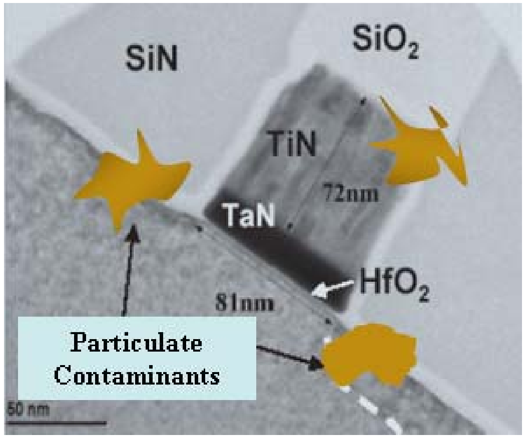
Applications

- Surface forces play a decisive role in many surface-/interfacial processes
  - Colloidal/emulsion stability
    - ✓ Relevant to pharmaceutical, food and coating industries
  - Surface modification of thin films or substrates **to promote or reduce adhesion**
    - ✓ biosensors, oil recovery, cleaning of micron-/nano-scale contaminants

- Our focus: Microelectronic manufacturing

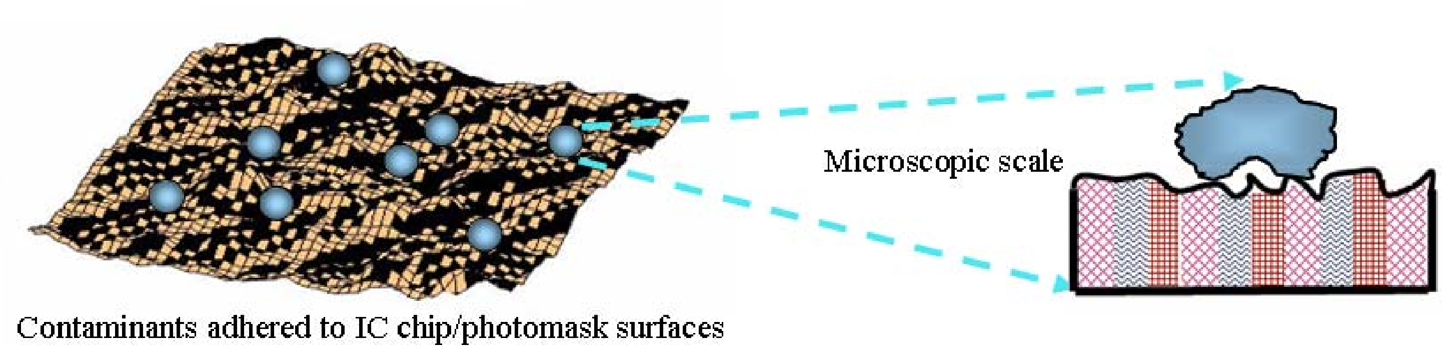


Wafer cleaning

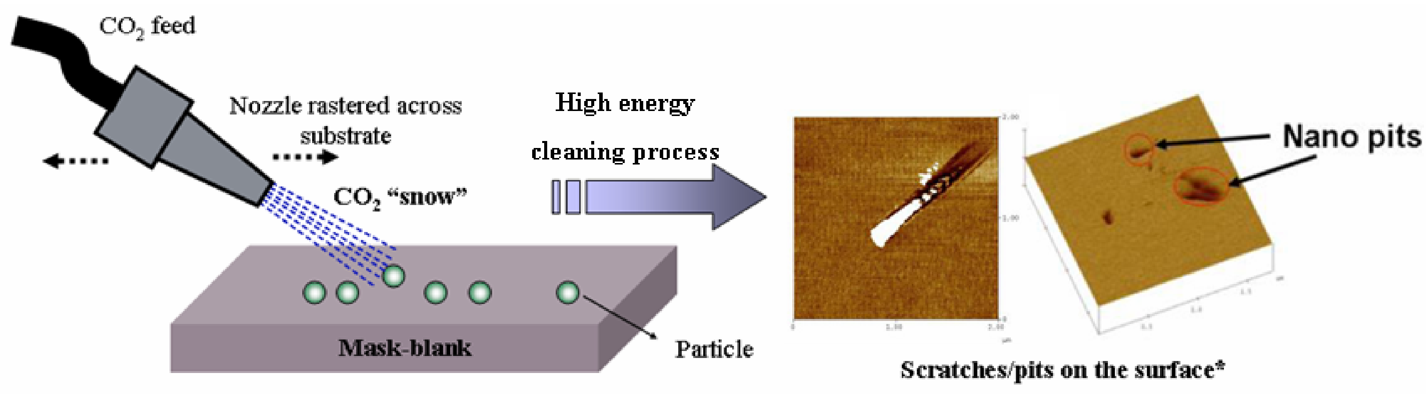


Integrated circuits (IC) chip- or Photomask- cleaning

Motivation/Objective



- **Contaminants**
  - Rough
  - Irregular
- **Substrate**
  - Rough
  - Inhomogeneous
  - Fragile

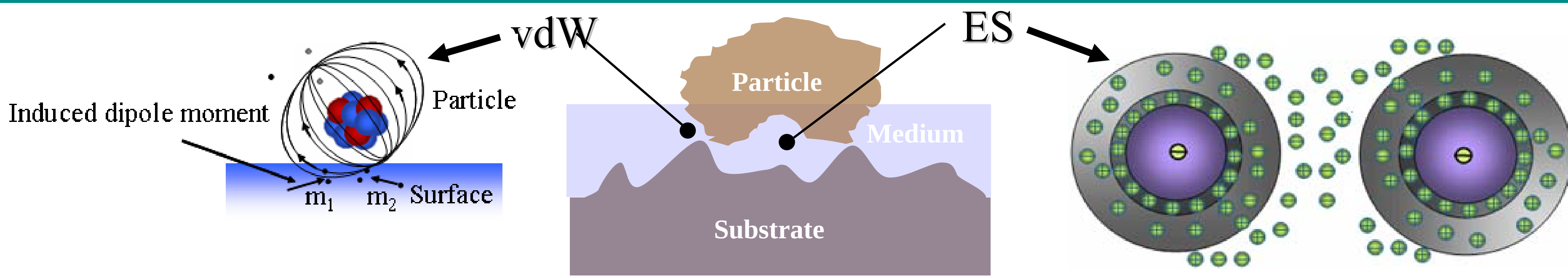


- High energy cleaning processes cause surface damage

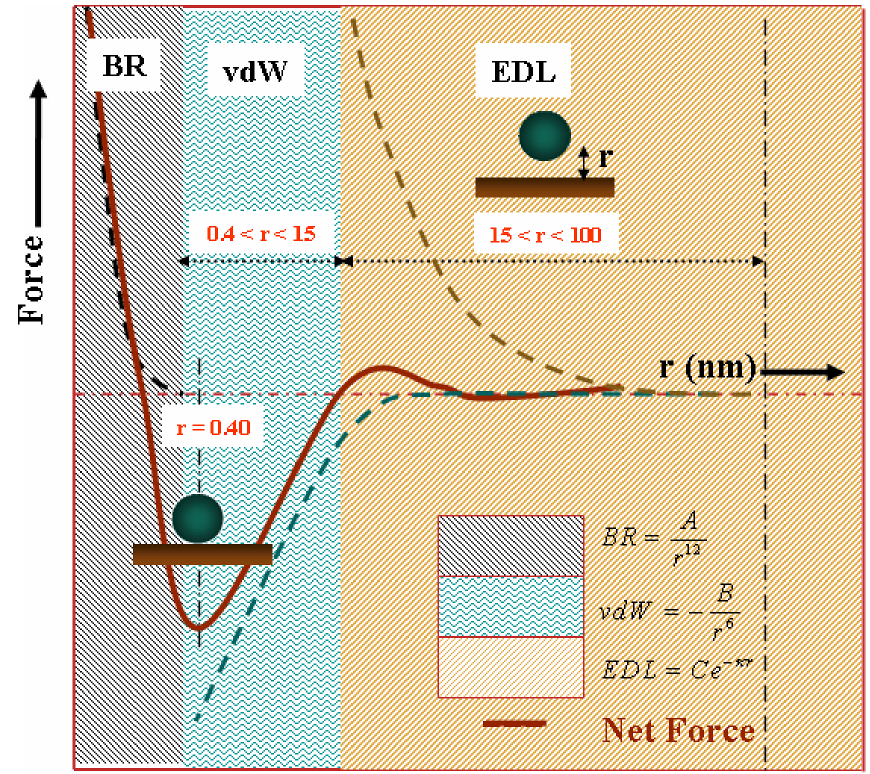
- **Challenge**
  - 99.99% cleaning efficiency **without surface damage or film-loss**
    - ✓ Contaminants as small as 7nm
- **Need**
  - Detail understanding of particle (µm- to nm- sized) adhesion in these systems
  - Estimation of **required removal force** window
  - Optimal cleaning process parameters

Particle Adhesion: Theory, Experiments and Modeling Approach

Fundamental Forces in Particle Adhesion



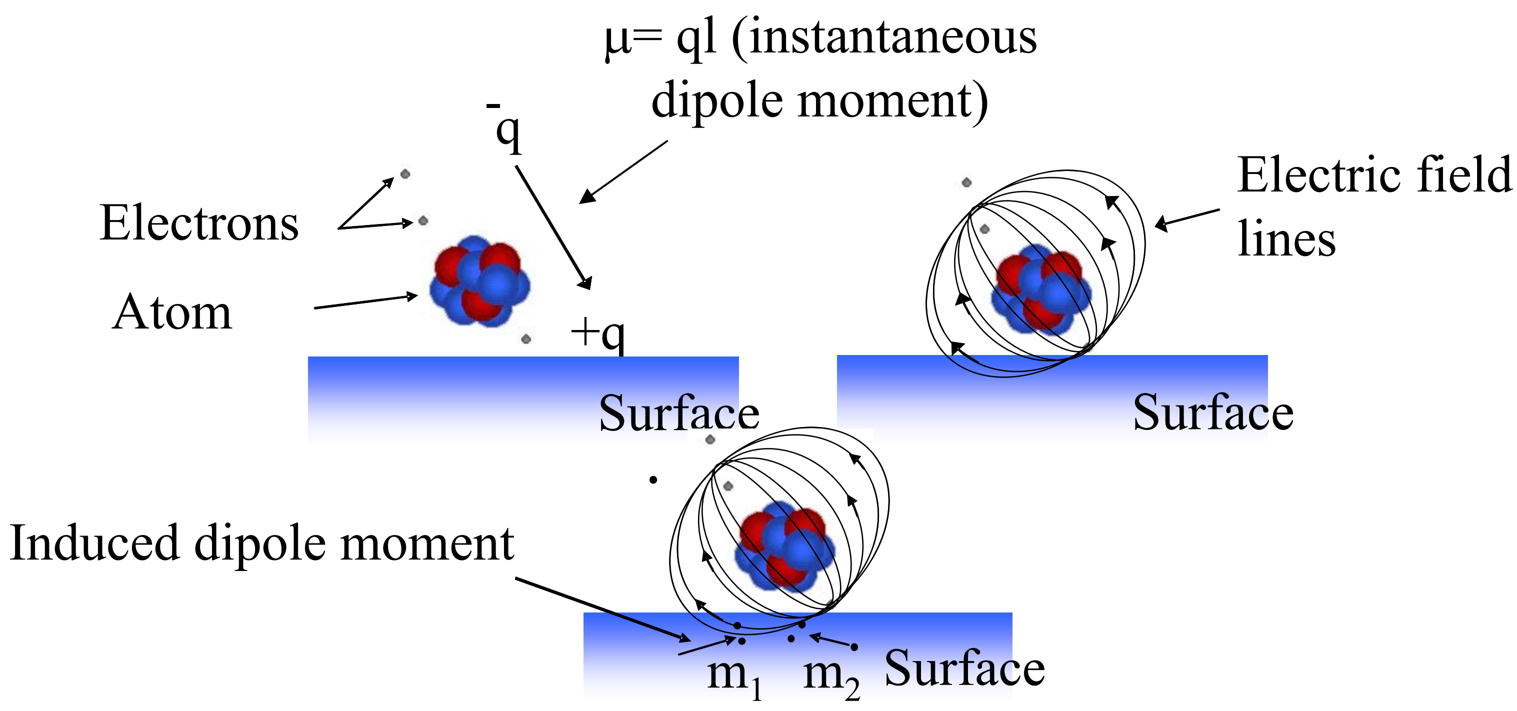
- **van der Waals (vdW)**
  - Interactions between dipoles (and/or induced dipoles)
- **Electrostatic (ES)**
  - Columbic or double layer
- Steric Force
- Hydrophobic Force
- Chemical Bonds



✓ vdW and ES forces are the major contributors in adhesion

✓ In fact, vdW force is the most dominating force in close-contact

van der Waals (vdW) Force

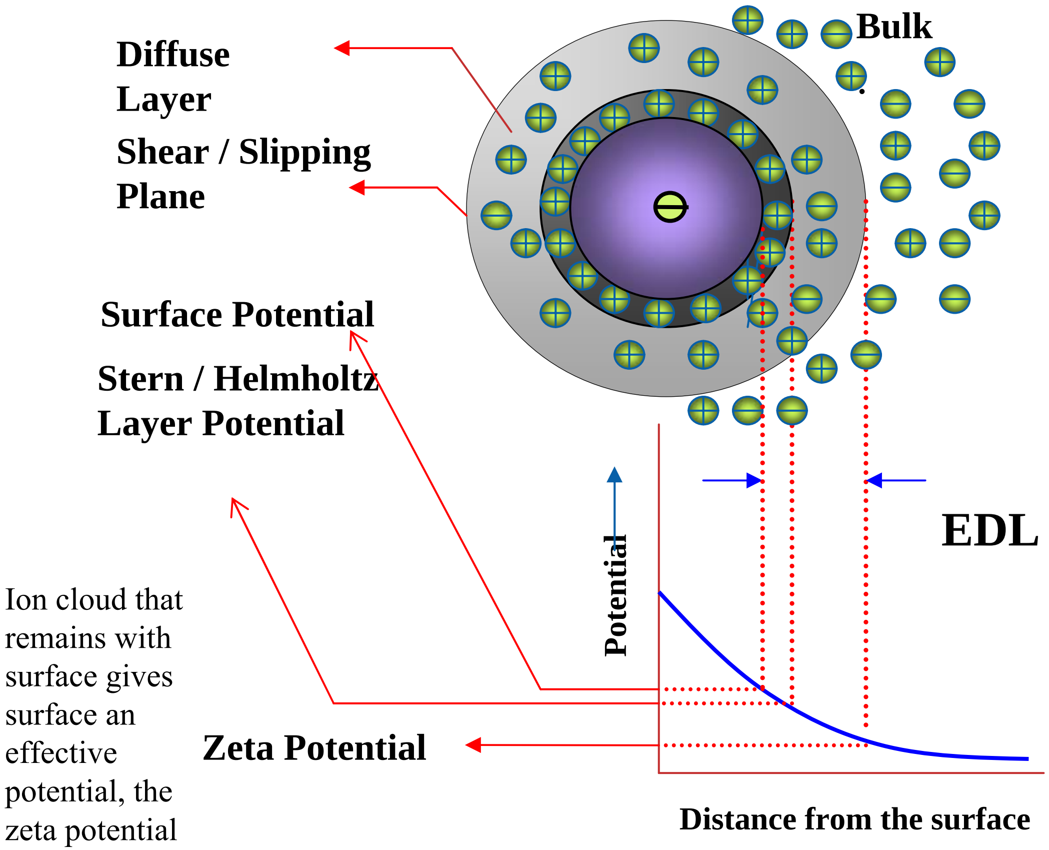


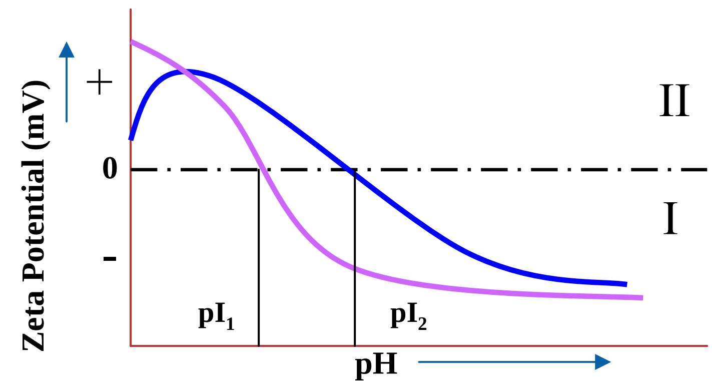
- vdW forces are always present
- Interactions between dipoles in particle, solution (if present) and surface

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

induced-permanent permanent-permanent induced-induced

Electrostatic (ES) Force





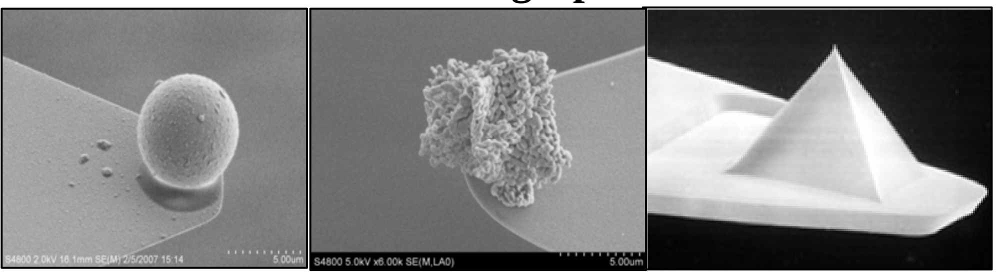
The thickness of EDL depends on the solution and the surface of interest, typically 10s to 100s of nm

- **In air, a particle and surface out of contact have fixed potentials**
- **In solution, a particle and surface attract counter-ion clouds and form double layers**

Approach: Experimental

Sample preparation

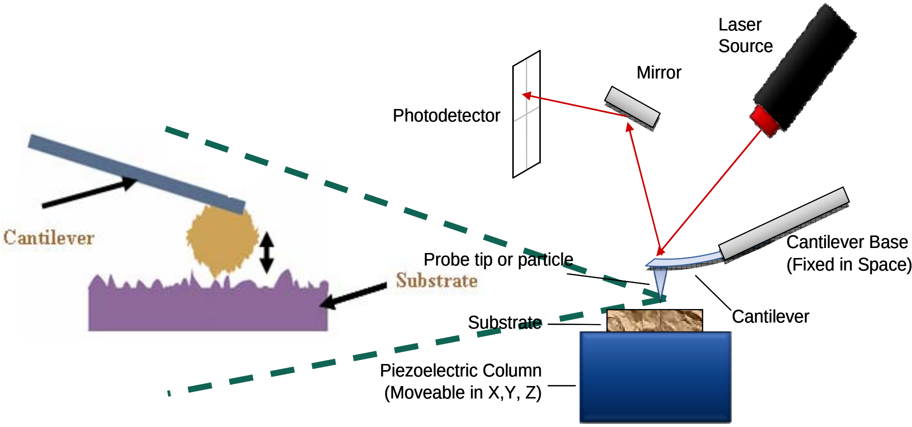
FESEM micrographs



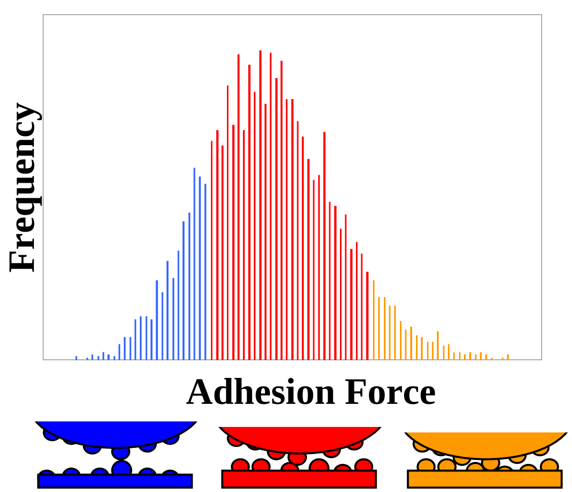
Micron-scale SiO_2 and Al_2O_3 particle

Nano- scale Si_3N_4 AFM-probe

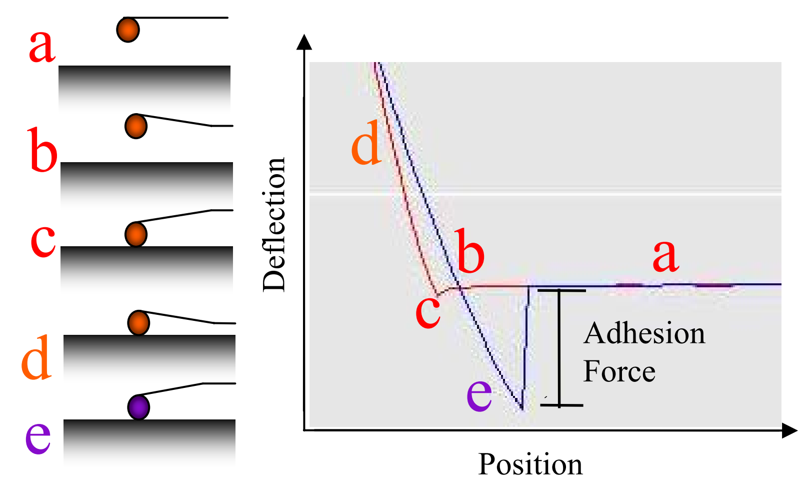
AFM force measurement



Distribution of forces

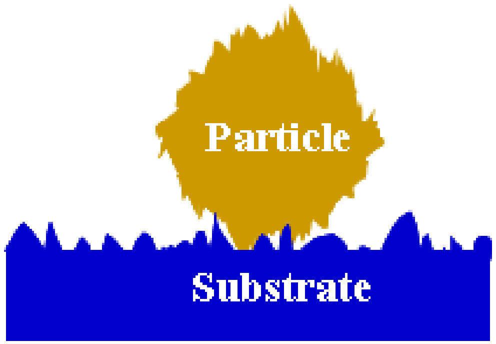


Typical AFM force curve



✓Surface heterogeneity leads to a distribution of adhesion forces

Approach: Theoretical



- Unusual geometry
- Random surface morphology
- Chemical heterogeneity

Model Inputs
Identify key parameters that control adhesion force and quantify their effects

Model Prediction
Distribution of forces

Model Validation
Compare model prediction with experimental measurement

Needs:

- Geometry

- Surface morphology

- Surface composition

Needs:

- Computational approach

Net predicted force:

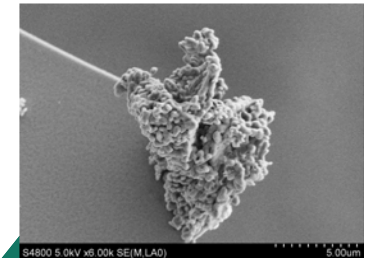
$$F_{Adhesion} = F_{vdW} + F_{ES}$$

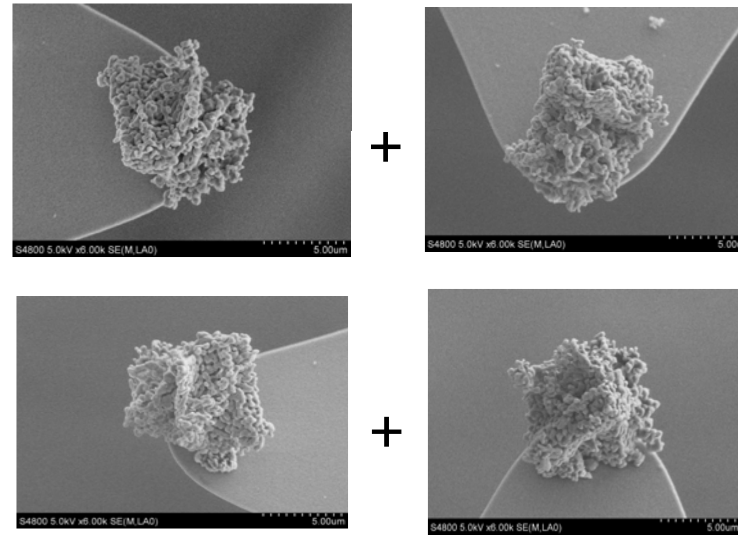
Modeling Approach

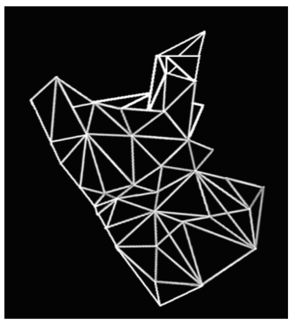
- **Surface Characterization- Geometry**

  - **Geometry**

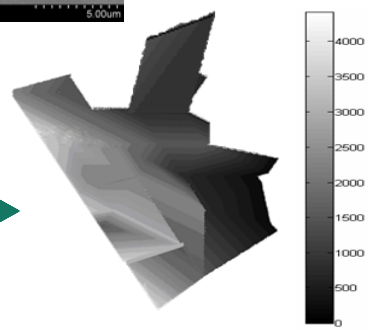
    - Irregular







PhotoModeler wire-mesh (Top-projection)



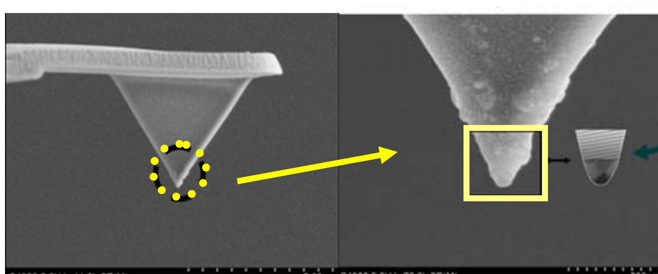
Top-view of the constructed surface

(Height data are in nanometer)

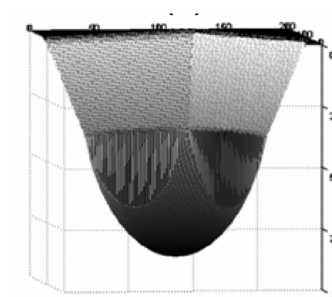
FESEM micrographs of Al_2O_3

  - **Geometry**

    - Regular



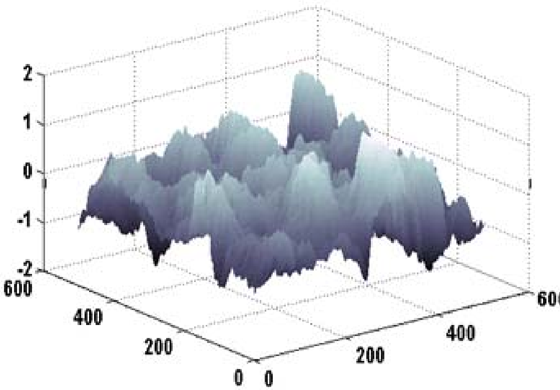
Si_3N_4 Nanosize pyramidal tip **Zoomed-In view: ROC ~ 75nm**



Modeled tip

Modeling Approach

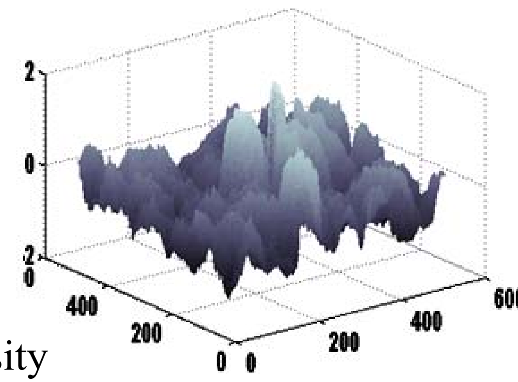
- **Surface Characterization- Roughness**



AFM scan of Chrome surface

- FFT
- Extract Fourier coefficients

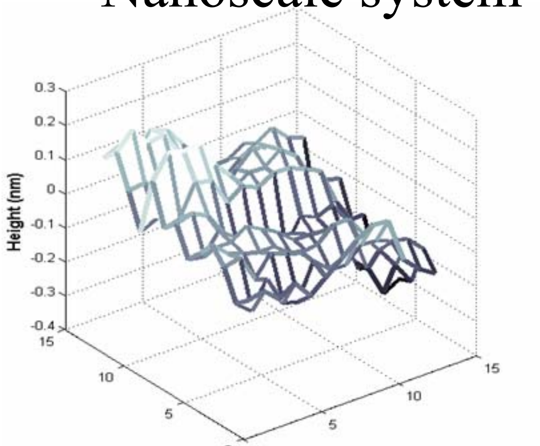
- Addition of random phase angle
- Inverse Fourier
- Multiple roughnesses, same spectrum density



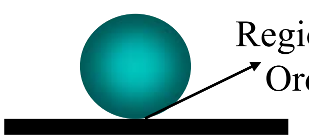
FFT generated Chrome roughness
(With random phase shift)

$$z_{x,y} = \sum_{k=0}^{M-1}\sum_{l=0}^{N-1} Z_{k,l}\, e^{i2\pi\left[\varphi_{k,l} + \frac{kx}{m} + \frac{ly}{n}\right]}$$

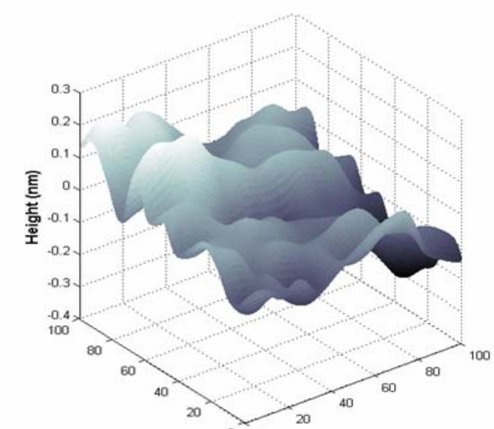
- Nanoscale system



AFM scan at small area



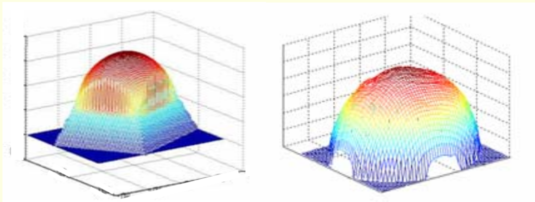
Fourier Interpolation



Highly resolved surface roughness

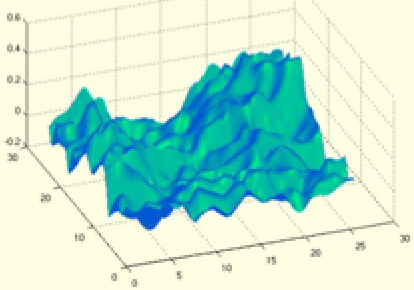
Modeling Approach

Geometry



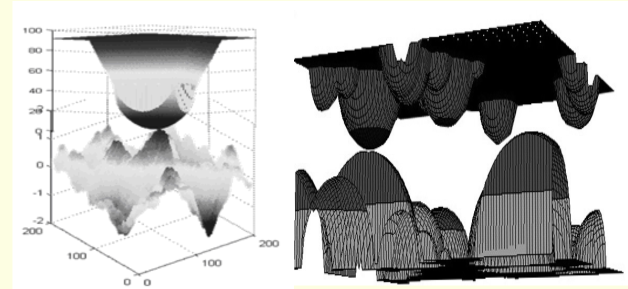
+

Surface morphology



Contact Surfaces

Generate mathematical surface representations

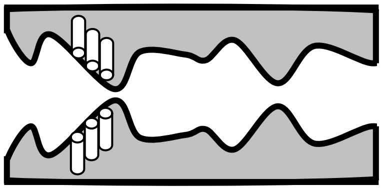


Contact area determination

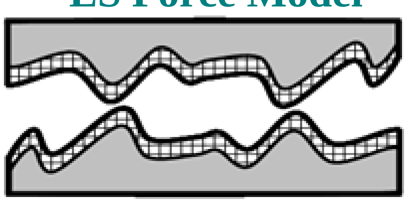
Force Calculation

(Computational Approach)

vdW Force Model



ES Force Model

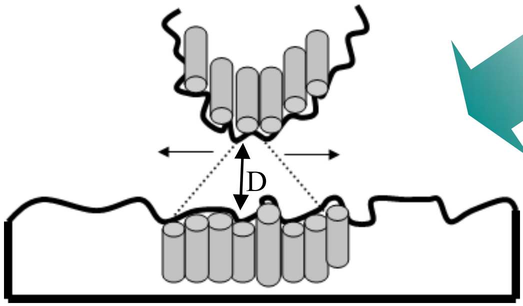


F_{vdW} F_{ES}

Removal Force Statistics ↔ **AFM Measurements**

van der Waals (vdW) and Electrostatic (ES) Force Model Description

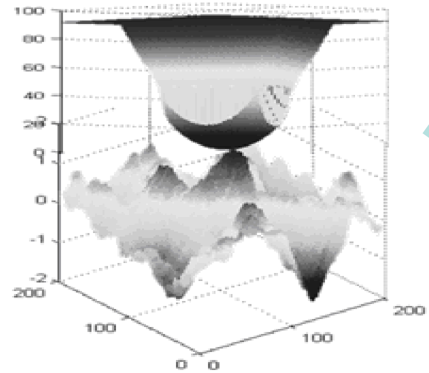
vdW



$$F_{1j} = C\frac{\partial}{\partial D}\iiint d\forall_j \iiint \frac{d\forall_1}{r'^6}$$

$$F = \sum_i \sum_j F_{ij}$$

Point-by-point additivity



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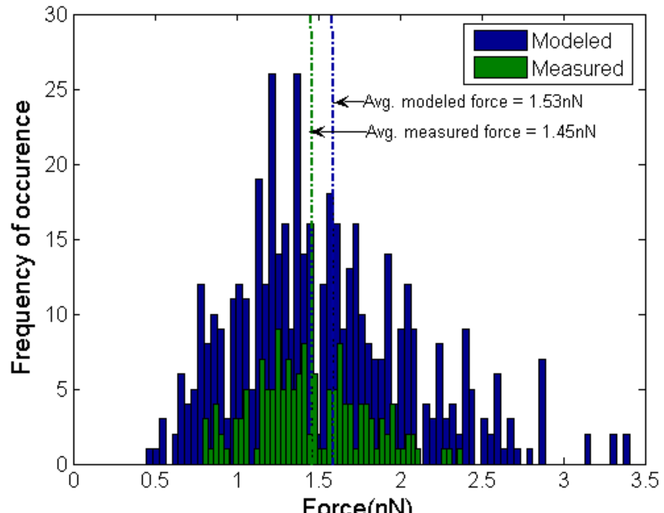
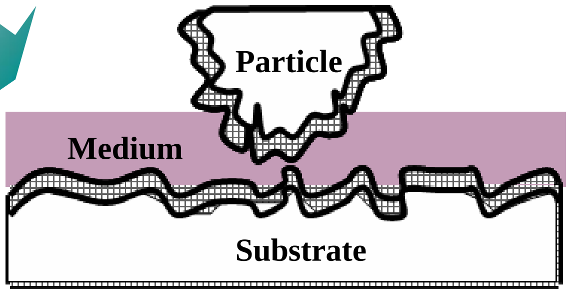
Si_3N_4 on TaN in Aqueous NH_4OH



ES



Double Layer

$\nabla^2\psi = k^2\psi$ Poisson-Boltzmann Eq.

$$k = \sqrt{\frac{e^2 \sum_i z_i^2 n_{i0}}{\varepsilon_0 \varepsilon_r K_B T}}$$ Reciprocal Debye length

Constant potential boundary conditions

Columbic

$$F_{el} = \left(\frac{1}{4\pi\varepsilon}\right)\left(\frac{q^2 R(D+R)}{((D^2+2RD)^2)^2}\right)$$

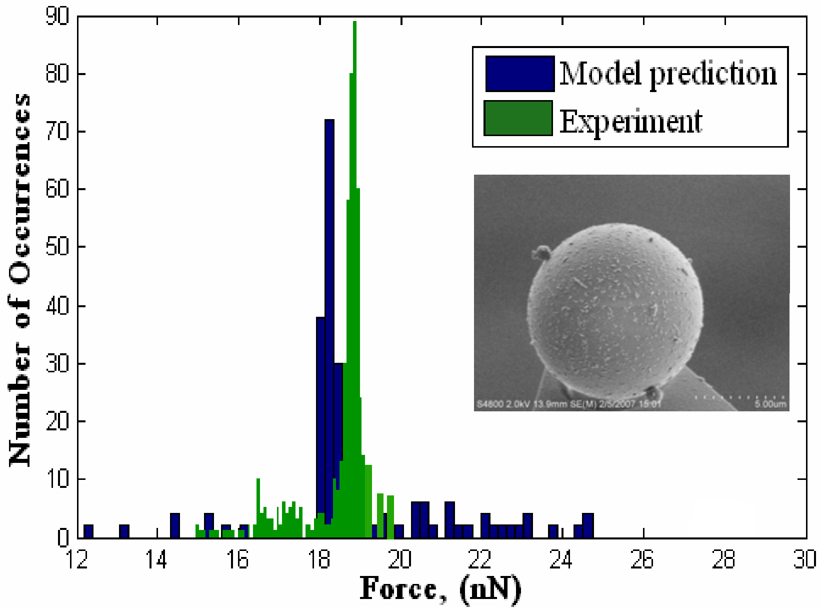
$$F_{Adhesion} = F_{vdW} + F_{ES}$$

Adhesion in Micron-Scale Particulate-Substrate System

- Particle geometry and particle and substrate roughness were measured and modeled

Regular geometry

Silica particle (~3μm) on TaON in air

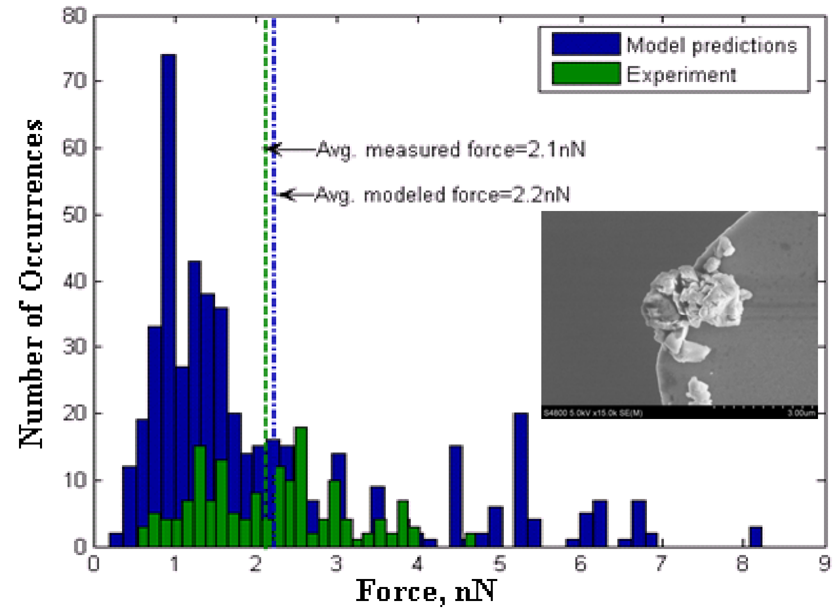


$F_{, av\text{-}Measured}$: 18.2 nN

$F_{, av\text{-}Predicted}$: 19.1 nN

Irregular geometry

Silicon nitride particle (~4μm) on TaON in DI water



$F_{, av\text{-}Measured}$: 2.1 nN

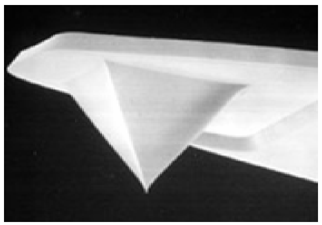
$F_{, av\text{-}Predicted}$: 2.2 nN

- Range of predicted force is wider than measured
  - ✓ Measured forces are in the range of model predictions

Adhesion in Nano-Scale Body-Substrate System

- Silicon nitride AFM probe on silicon dioxide surface in air and DI water
  - Tip ROC ~ 50nm

Si_3N_4



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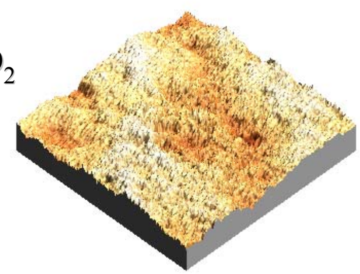
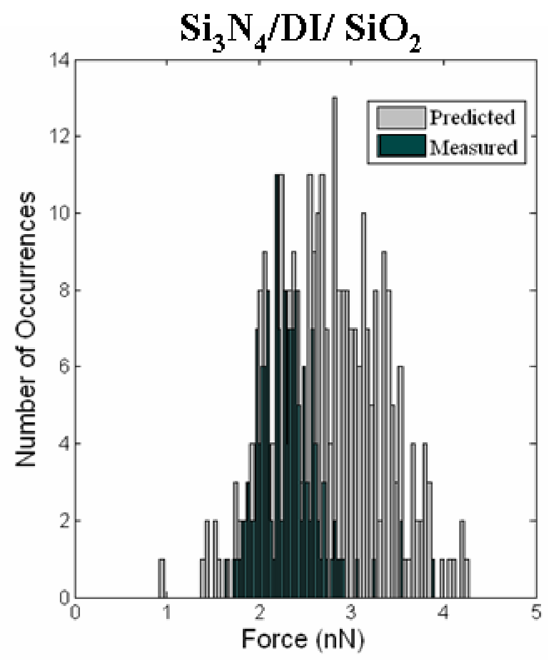
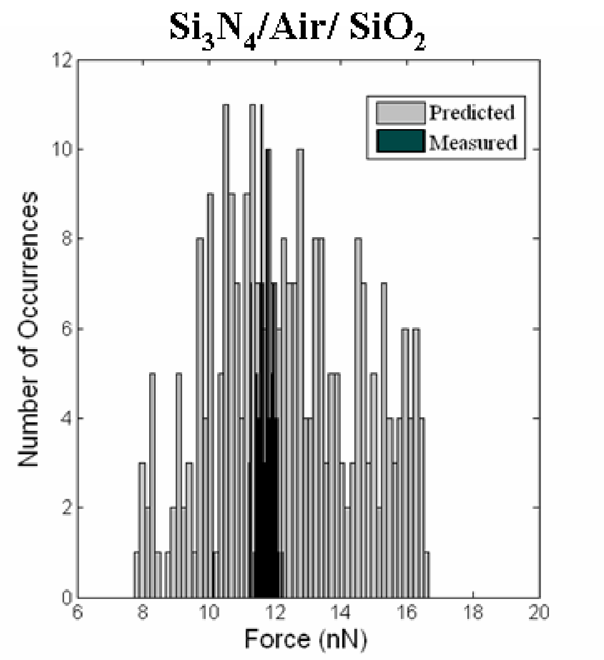
SiO_2





$F_{, av\text{-}Measured}$: 2.32 nN

$F_{, av\text{-}Predicted}$: 2.75 nN



$F_{, av\text{-}Measured}$: 11.67 nN

$F_{, av\text{-}Predicted}$: 12.47 nN

✓ Adhesion model is capable of predicting the adhesion forces for systems as small as few 10's of nm

✓ DI water screens the net adhesion force (vdW force)

Conclusions

- **Adhesion forces for most of the microelectronic systems can be described by considering only vdW and ES interactions**

- **Continuum approximation based adhesion model can describe the adhesion force for systems of sizes down to few 10’s of nm**

Acknowledgement

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