

## Abstract

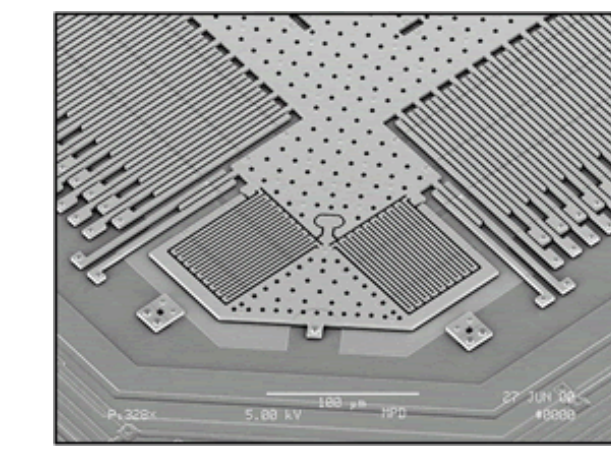
Surface roughness has a significant effect on adhesion. We used a single-asperity model to describe a smooth tip in contact with a rough surface and predicted that an optimal size of asperity will yield a minimum of adhesion. Experimentally, adhesive forces on silicon wafers with varying roughness were measured using AFM cantilevers with varying tip radii. It was found that minima do exist, and for all tip radii, the adhesion falls significantly for roughness greater than 1-2 nm and drops at higher roughness for larger tips. In addition to RMS roughness, the roughness exponent is another important parameter for the characterization of rough surfaces and its effect on adhesion was also investigated. We developed computer programs to simulate a set of fractal rough surfaces with differing roughness exponents. The adhesive forces between an AFM tip and the fractal surfaces were calculated and the adhesion was seen to decrease as the roughness exponent increases. This work should help minimize MEMS stiction (adhesion) and progress the understanding of nanoscale contact mechanics.

## Motivation

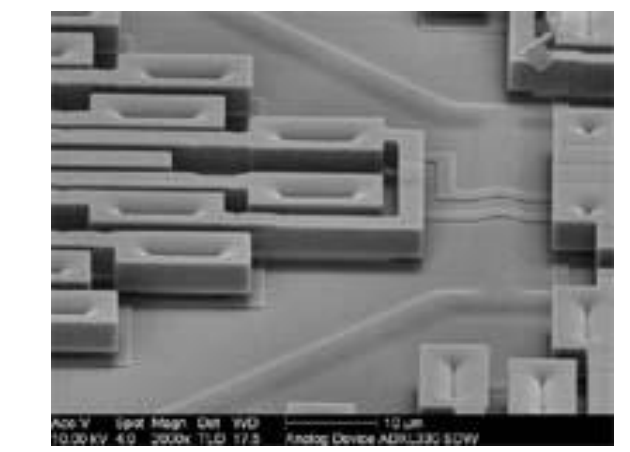
Stiction occurs when surface adhesion forces are higher than the mechanical restoring force of the microstructure and it is a notorious cause of malfunctioning in microelectromechanical systems (MEMS) due to their large surface area-to-volume ratio. To avoid in-use stiction, adhesion forces should be minimized. Although it is clear that roughness affects adhesion, a fundamental understanding of the role of nanoscale roughness in adhesion of the surfaces of modern micro-devices is still lacking.



Analog Devices' ADXL202 micro accelerometer



Microscope picture of the sensing beams



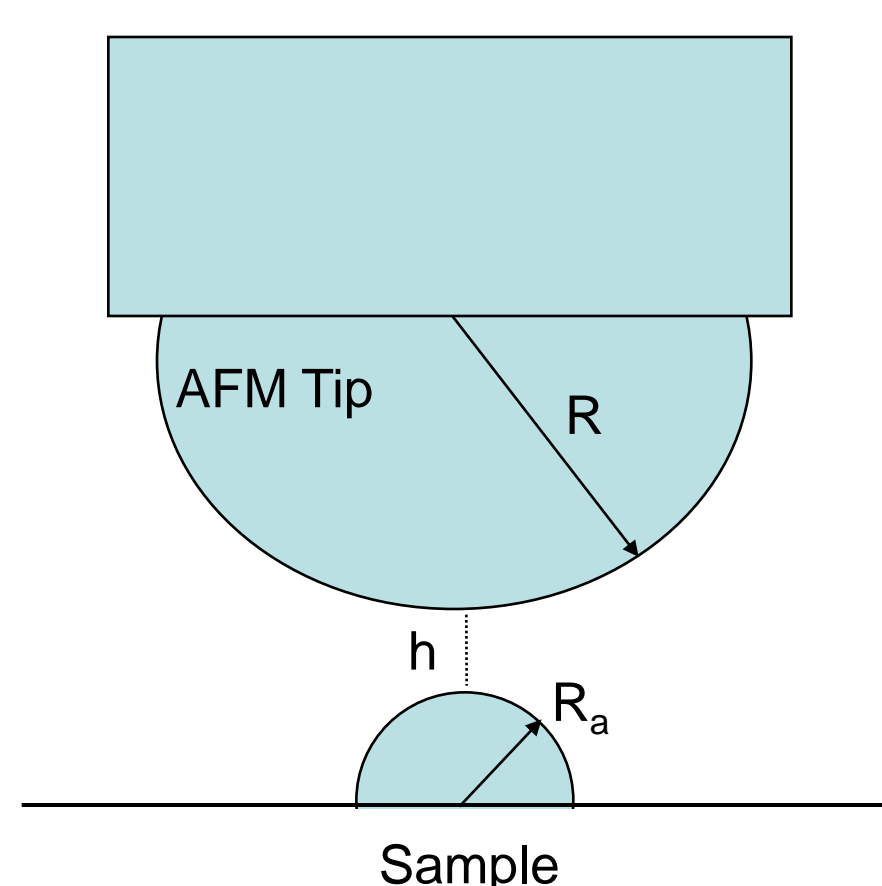
Capacitor Beams & Anchors

Can we understand how roughness affects adhesion in order to minimize stiction?

## I. Effect of RMS Roughness on Adhesion

### 1. Single asperity model

A single-asperity model was used to describe a smooth tip in contact with a rough surface and the total interaction force for all molecules interacting with the sample was obtained.[1]



$$F = 2\pi\omega R \left[ \frac{R_a}{R+R_a} + \left( \frac{h_c}{h_c+R_a} \right)^2 \right]$$

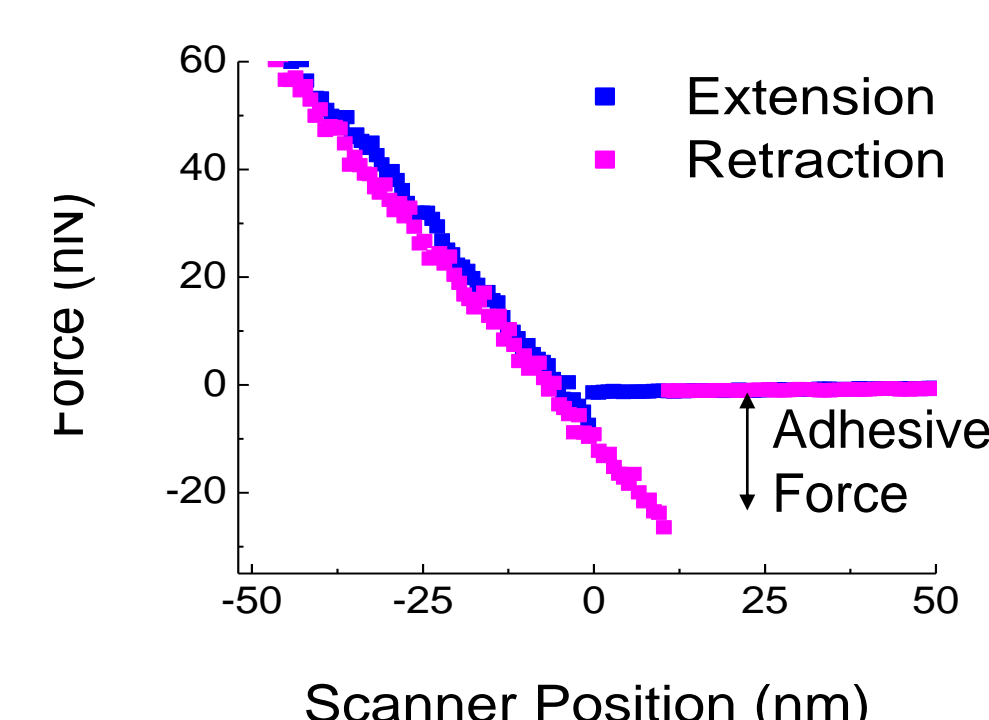
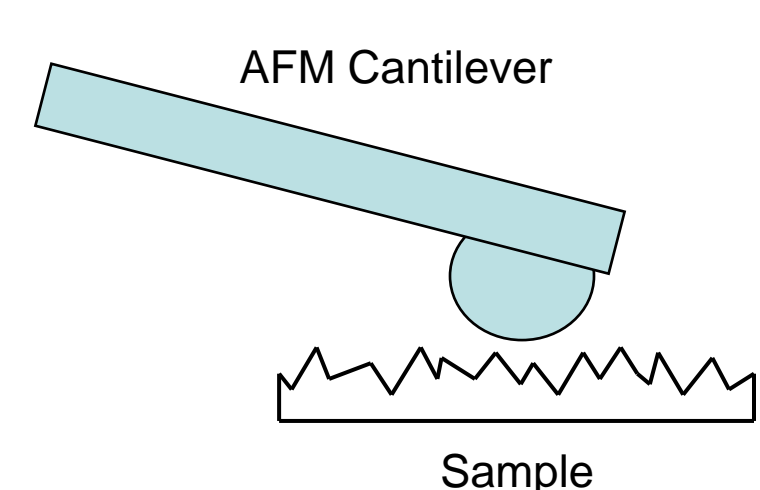
R: tip radius  
 $R_a$ : RMS roughness --- asperity radius  
 $h_c$ : separation at contact  
 $2\pi\omega R$ : the pull-off force for a smooth contact ( $R_a = 0$ )  
 Assumption:  $h_c \ll R$

- $R_a/(R+R_a)$  represents the asperity-other body interaction.  $[h_c/(h_c+R_a)]^2$  represents how the asperity plays a role in keeping the two major bodies apart.
- The first term dominates if asperities are large and the second term dominates if asperities are small.

F has a minimum for a given radius of tip if  $R_a^{\min} \cong (2h_c^2 R)^{1/3}$

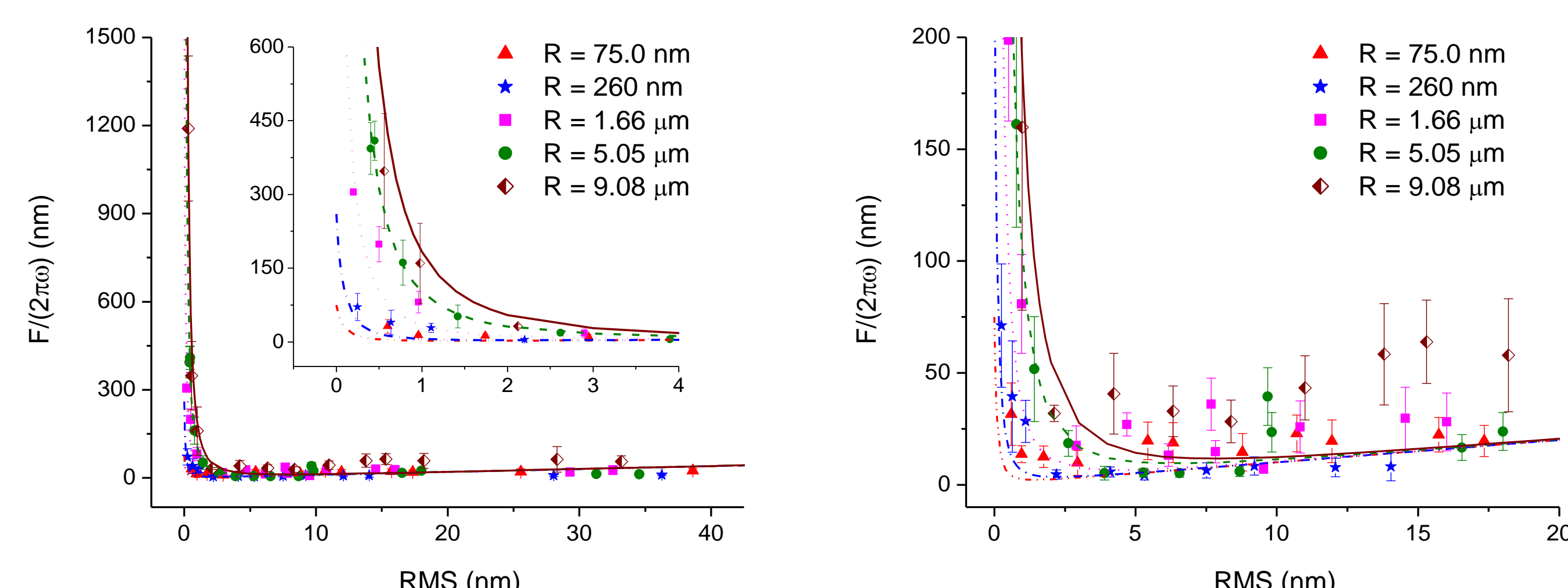
### 2. Adhesive force measurement

AFM cantilevers with varying tip radii (75.0 nm to 9.08  $\mu\text{m}$ ) were used to measure adhesive force on silicon wafers with varying roughness (0.2 nm to 39 nm).



### 3. Results

Plot and zoomed-in plot of measured adhesive force as a function of RMS roughness for varying tip radii R. The force is normalized by surface energy where  $\omega$  is the work of adhesion. The colored lines are corresponding predicted curves.



Roughness causes adhesion to fall; adhesion falls at higher roughness for larger tips; minima exist and depend on feature size. The adhesion between two surfaces can be minimized by tuning asperity height to feature size in MEMS devices.

## Summary

- For smooth surfaces, adhesion is directly proportional to feature size (not shown).
- Adhesion drops significantly for RMS roughness > 1-2 nm.
- Adhesion drops at higher RMS roughness for larger tips.
- The optimal roughness for minimum adhesion increases as the tip radius increases.
- Adhesion decreases as the roughness exponent increases.

## II. Effect of Roughness Exponent on Adhesion

### 1. Background

The present state of studies of roughness related to adhesion has been limited to the analysis of height fluctuations normal to the surface, which is assumed to be uncorrelated Gaussian, and one way to proceed beyond this limitation might be through self-affine fractal analysis [2-3]. In addition to the root-mean-square (RMS) roughness, the roughness exponent  $\alpha$ , which shows how "wiggly" the local surface is, and the lateral correlation length  $\xi$ , which is the "wavelength" of surface fluctuations, are also required to completely describe a fractal rough surface.

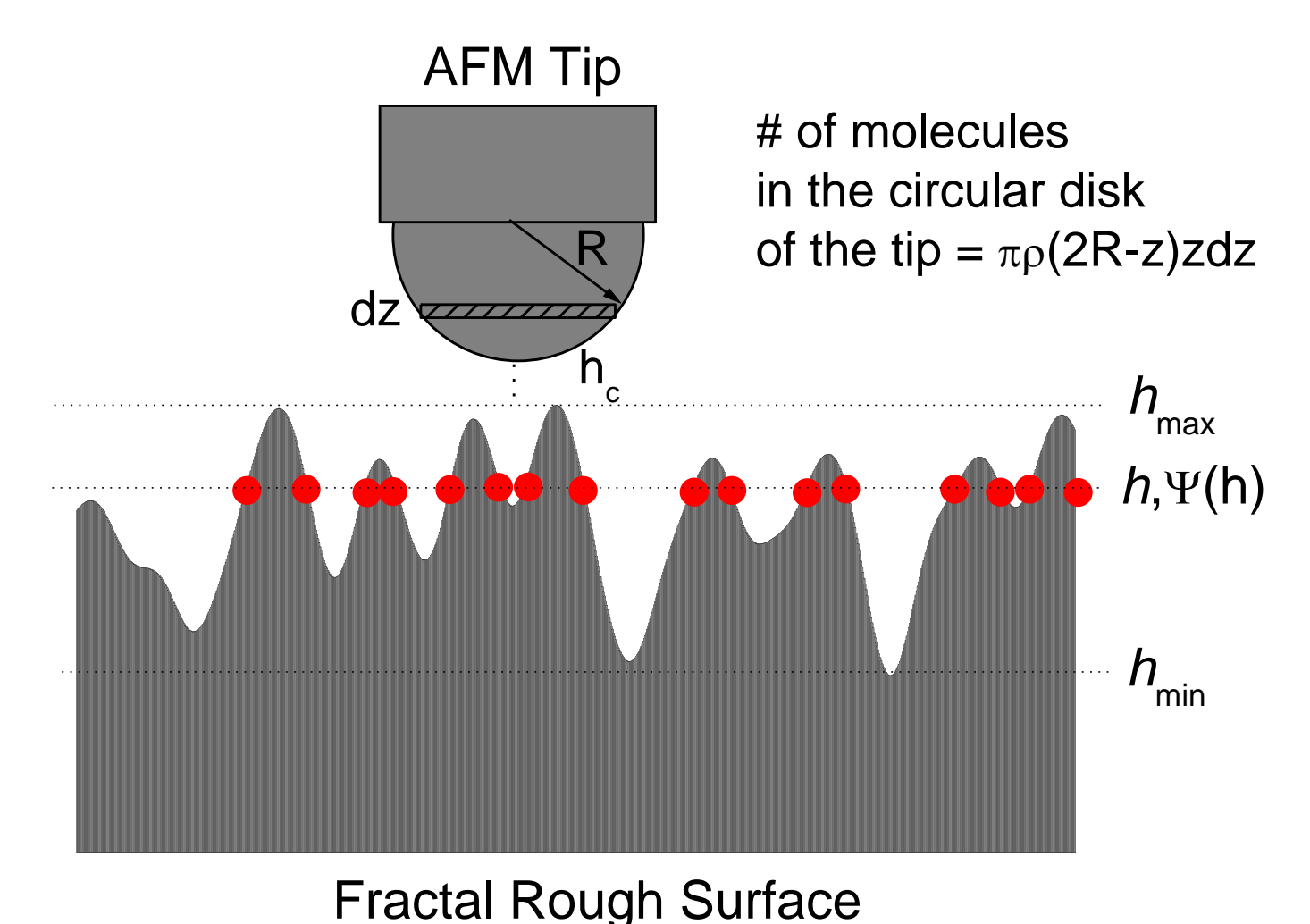
### 2. Fractal surface generation and adhesion calculations

A set of fractal rough surfaces with differing  $\alpha$  was generated by computational simulation and their probabilities  $\Psi(h)$  of the surface height h were calculated.

The interaction force between a molecule and a rough surface is [4]:

$$f(D) = \int_{h_{\min}}^{h_{\max}} \frac{\pi C \rho}{(D + h_{\max} - h)^4} \Psi(h) dh$$

D: distance between the molecule and the surface  
 $\rho$ : number density of molecules  
 C: coefficient of the molecule-molecule pair potential.  
 $D + h_{\max} - h$ : vertical distance between the molecule and the surface points which has the height of h.

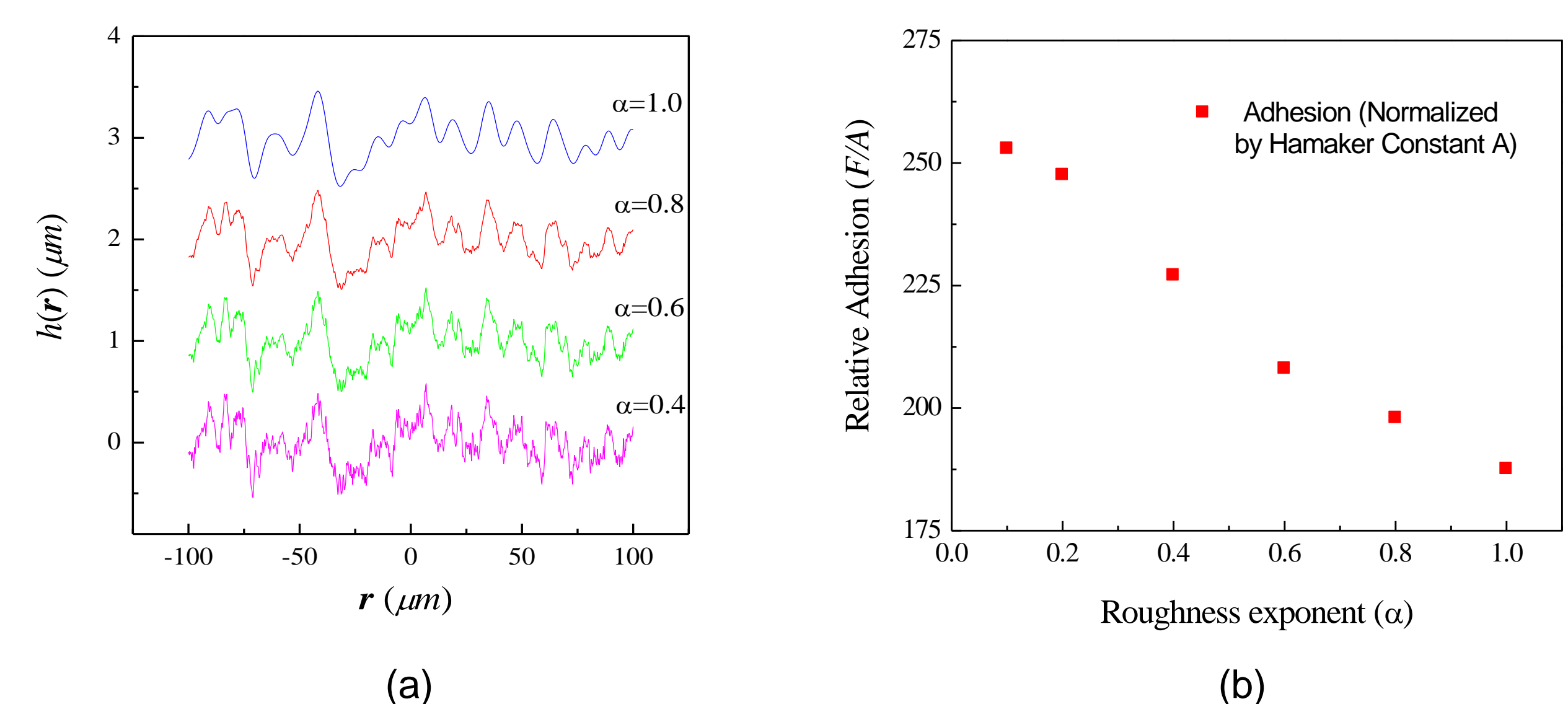


The interaction force between a spherical AFM tip and a rough surface can thus be obtained by integrating the forces between all the molecules in the tip and the rough surface:

$$F = \int_0^R f(z + h_c) \pi \rho (2R - z) z dz$$

### 3. Results

(a) The cross section of the simulated rough surfaces with the same RMS roughness  $\sigma$  and lateral correlation length  $\xi$  but different roughness exponent  $\alpha$ ; (b) Plot of adhesion as a function of roughness exponent. Adhesion was normalized by Hamaker constant A.



The calculations reveal that the adhesion decreases as the roughness exponent increases. The adhesion between two surfaces can be minimized by reducing the "local roughness" of the device surfaces.

## Acknowledgement

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## References

- [1] D.-L. Liu, J. Martin, and N.A. Burnham, *Appl. Phys. Lett.* **91**, 043107 (2007).
- [2] A.-L. Barabasi and H.E. Stanley, *Fractal concepts in surface growth*, Cambridge University Press, New York (1995).
- [3] T.S. Chow, *Phys. Rev. Lett.* **86**, 4592 (2001).
- [4] K. L. Johnson, *Contact mechanics*, Cambridge University Press (1985).