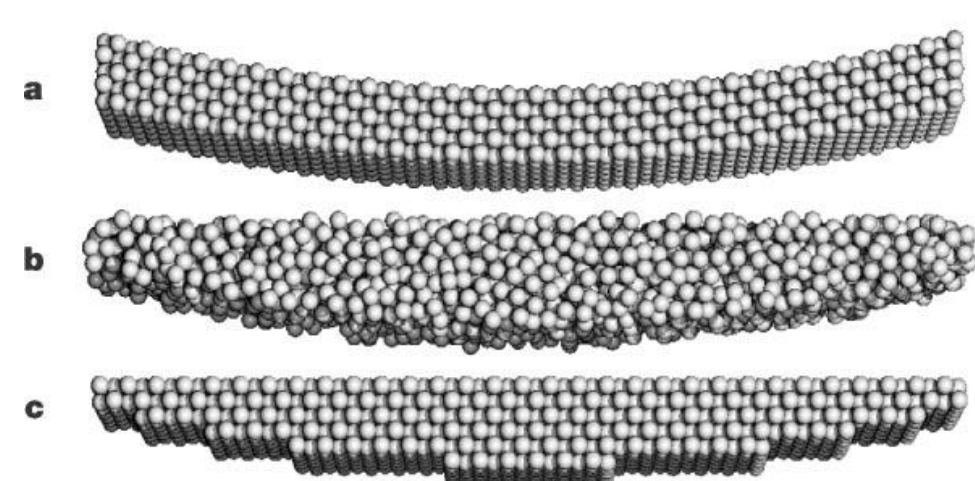


## Abstract

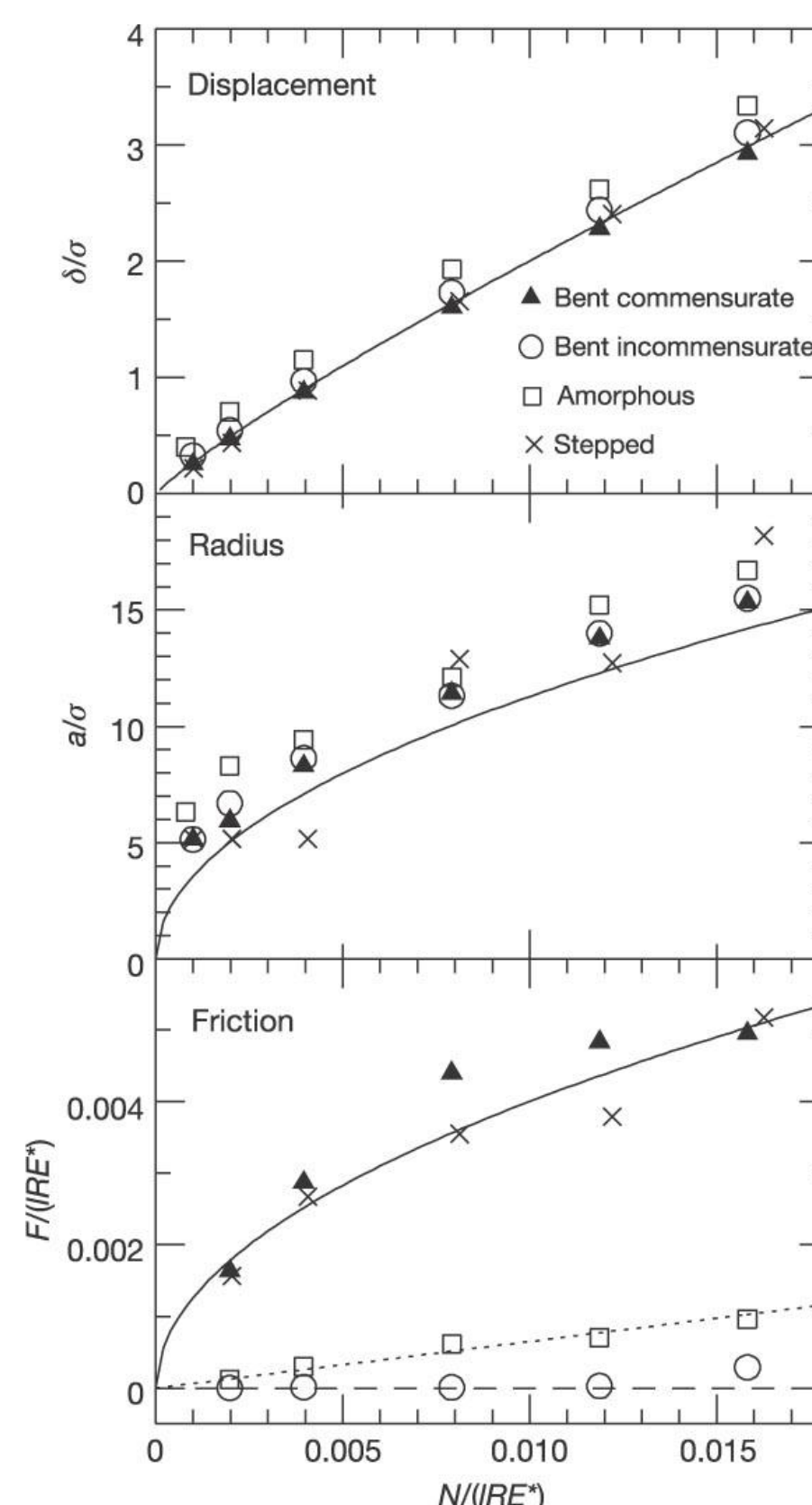
Differing views on the effect of surface roughness on adhesion have appeared in the literature recently. Molecular dynamics has been used to simulate the contact of two surfaces and found that atomic-scale roughness can have a large influence on adhesion, causing the breakdown of continuum mechanics models [1]. An experimental study showed that roughness can determine the adhesion in nanometer contacts and indicated that continuum mechanics still works down to nanometer length scales [2]. In this work, we use a single-asperity model to describe a smooth tip in contact with a rough surface and predict that there is an optimal size of asperity that will yield a minimum of adhesion. Experimentally, adhesive forces on silicon wafers with varying roughness from 0.2 nm to 39 nm were measured using AFM (atomic force microscope) cantilevers with varying tip radii from 75.0 nm to 9.08 μm. It is found that for all tip radii, the adhesion falls significantly for roughness greater than 1-2 nm and drops at higher roughness for larger tips. Minimum adhesion was observed as expected in the 1-10 nm range and the optimal roughness for minimum adhesion increases as the tip radius increases, which is consistent with the predictions. The work presented here should help minimize stiction for future MEMS devices and progress the understanding of adhesion between the atomic- and macro-scale.

## Motivation

Luan *et al.* [1] studied the atomic contact between surfaces and used molecular dynamics simulations to test the limits of contact mechanics. They found that the atomic-scale surface roughness produced by discrete atoms leads to dramatic deviations from continuum theory. As shown in the figure on the right, contact areas and stresses may be changed by a factor of two, whereas friction and lateral contact stiffness change by an order of magnitude.



Cylindrical surfaces with different atomic-scale roughness. Three models:  
a. Bending a crystalline slab  
b. Cutting an amorphous solid  
c. Crystalline solid



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

## Single Asperity Model

A few asperities determine the work of adhesion in nanometer contacts ---- single asperity model [2]

Using the single asperity model, the total interaction force for all molecules interacting with the sample is approximately:

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

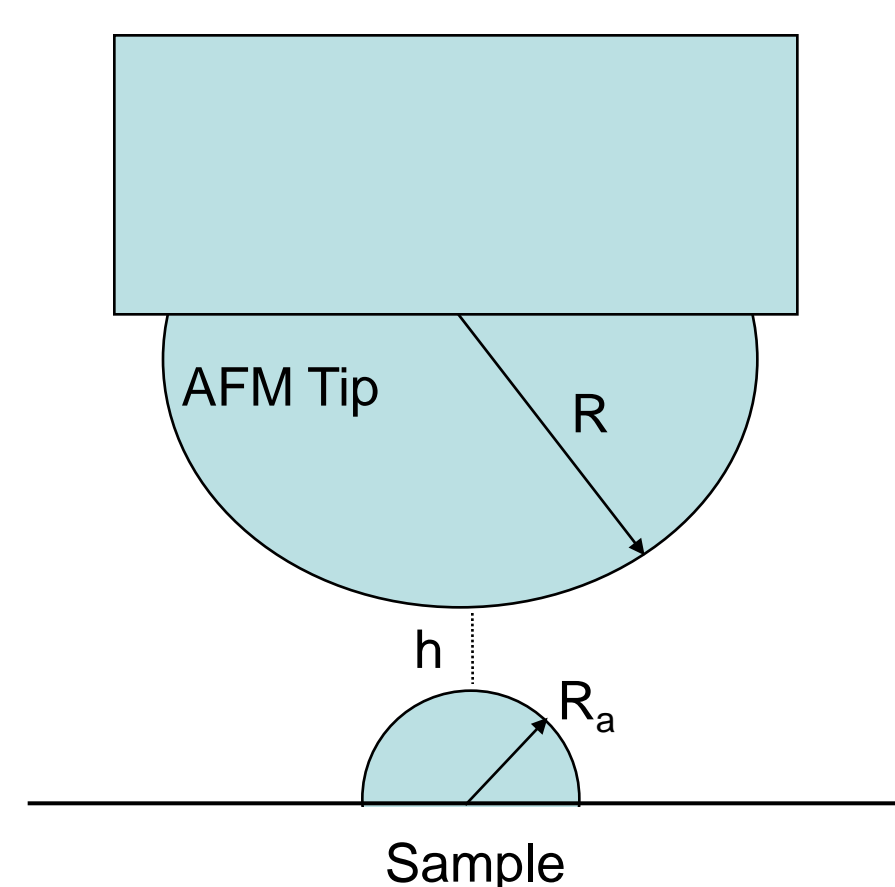
R: tip radius;  $R_a$ : roughness --- asperity radius;  $h_c$ : separation at contact  
 $2\pi\omega R$ : the pull-off force for a smooth contact ( $R_a = 0$ ); assumption  $h_c \ll R$

- $R_a/(R+R_a)$  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.

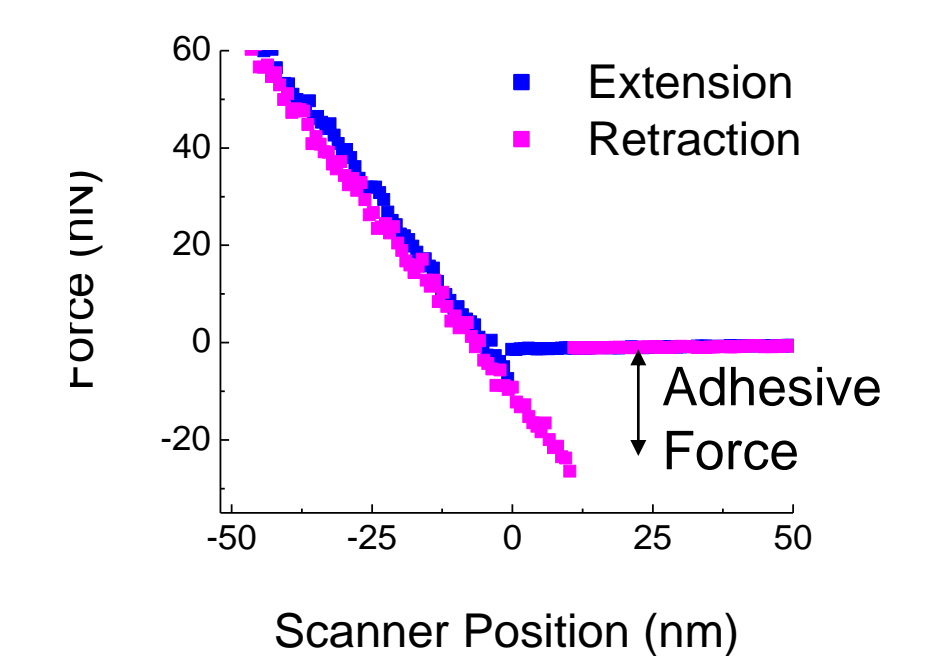
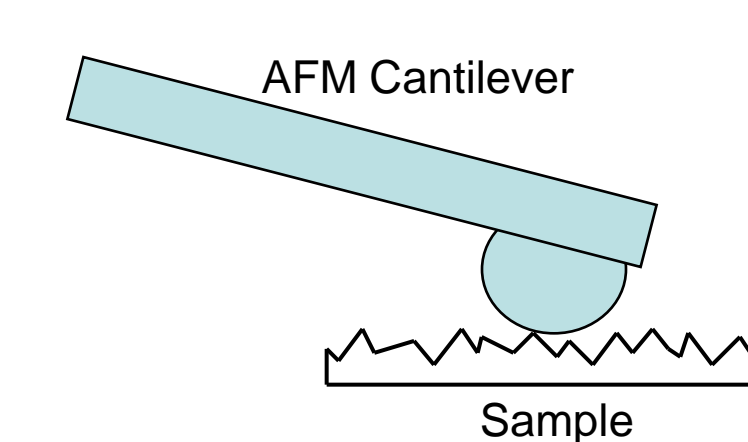
$F$  has a minimum for a given radius of tip if

$$R_a^{\min} \cong (2h_c^2 R)^{1/3}$$

R: tip radius;  $R_a$ : roughness --- asperity radius;  $h_c$ : separation at contact



## Adhesive Force Measurement



AFM cantilevers with varying tip sizes are used to measure adhesive force on silicon wafers with varying roughness.

## Experimental Details

- 4 types of AFM cantilevers used in the experiment

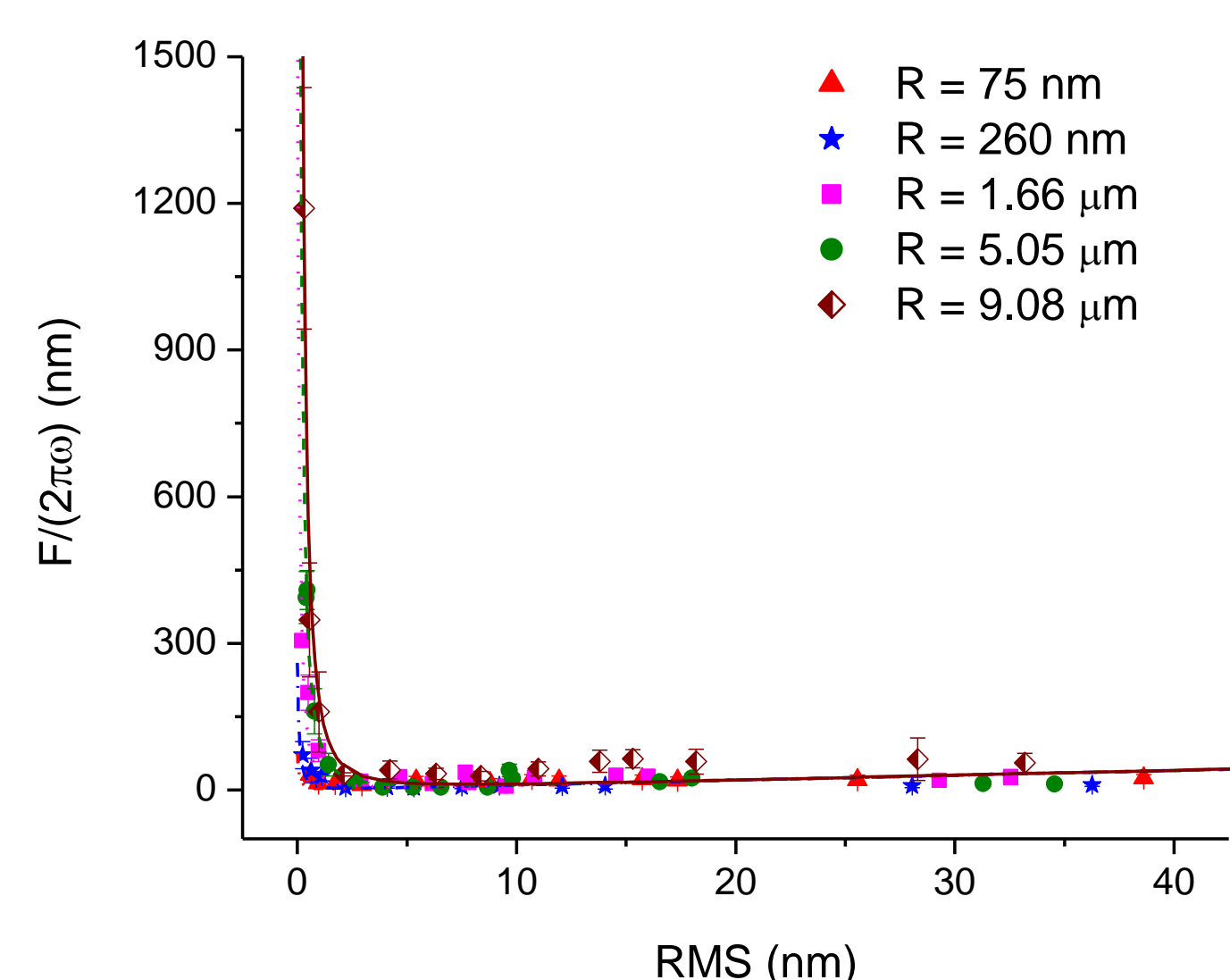
AFM tips	Tip Radius	Tip Roughness
New commercial AFM tips	75.0 nm	1.21 nm
Used commercial AFM tips	260 nm	1.70 nm
Heat-treated AFM tips	1.66 μm	1.96 nm
Bead-attached AFM tips	5.05 μm	0.78 nm
	9.08 μm	0.81 nm

\* All these AFM tips can be considered to be relatively smooth.

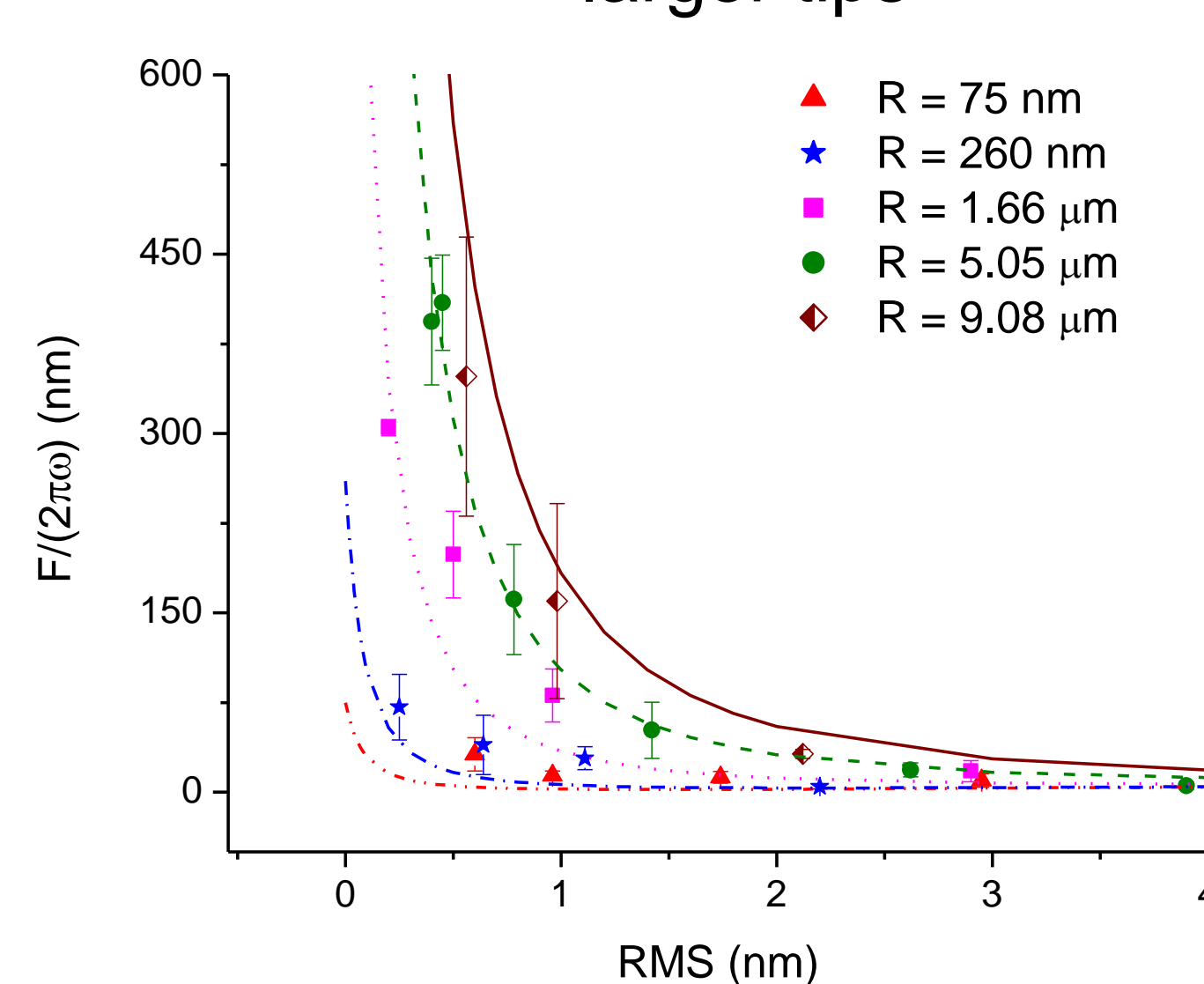
- Roughness of measured silicon wafers ranges from 0.2 nm to 39 nm.

## Results

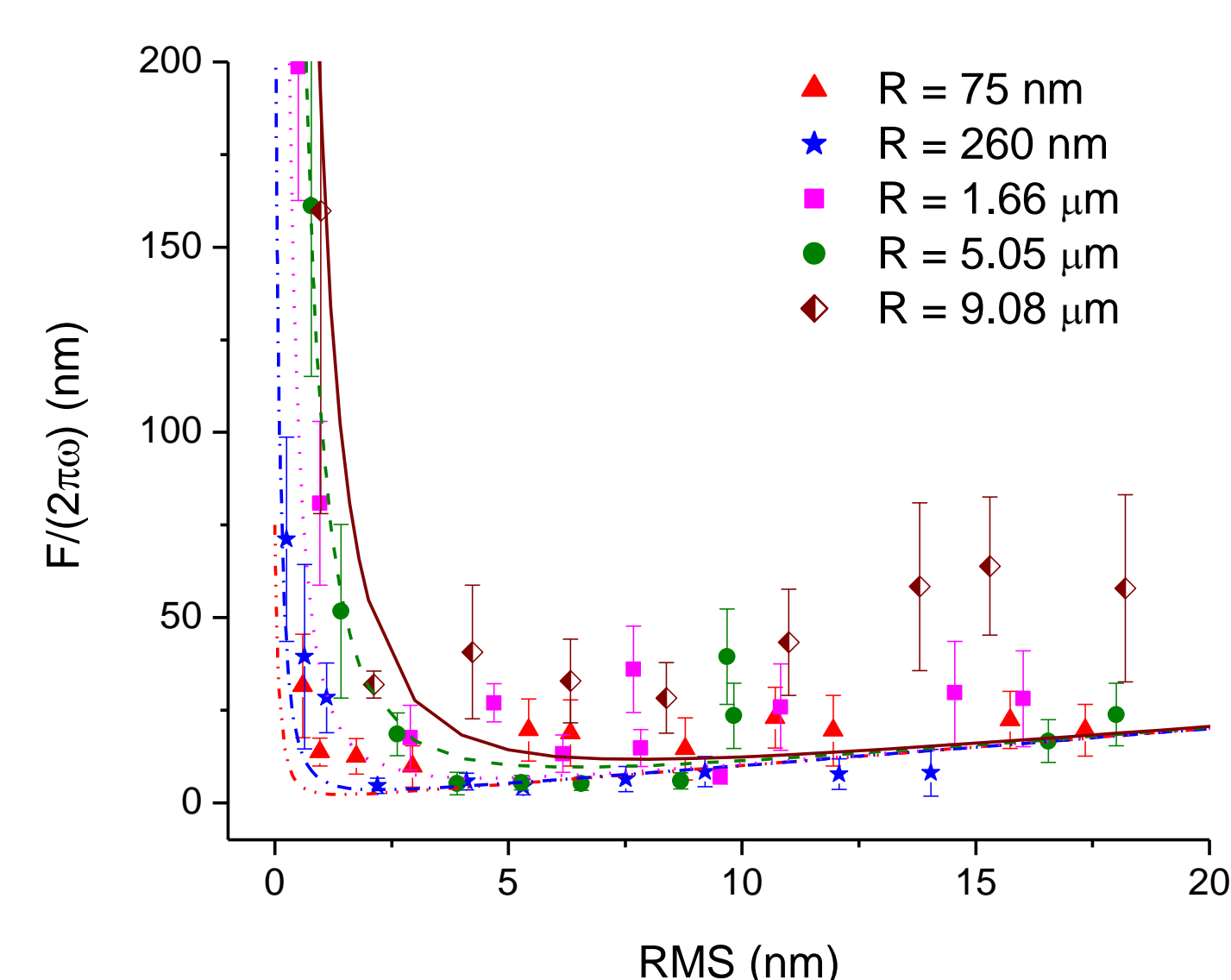
### Roughness causes adhesion to fall



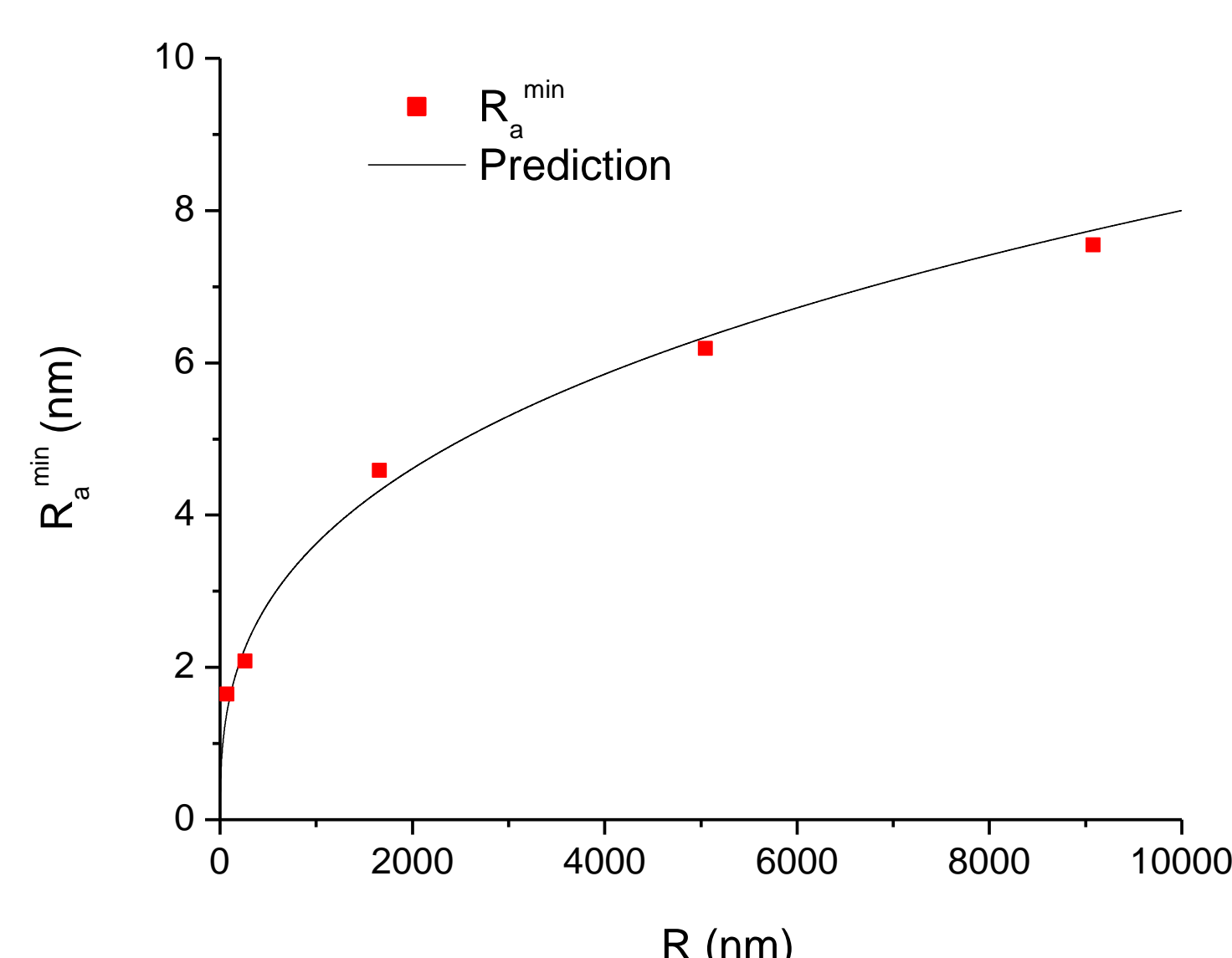
### Adhesion falls at higher roughness for larger tips



### Minima exist and depend on feature size

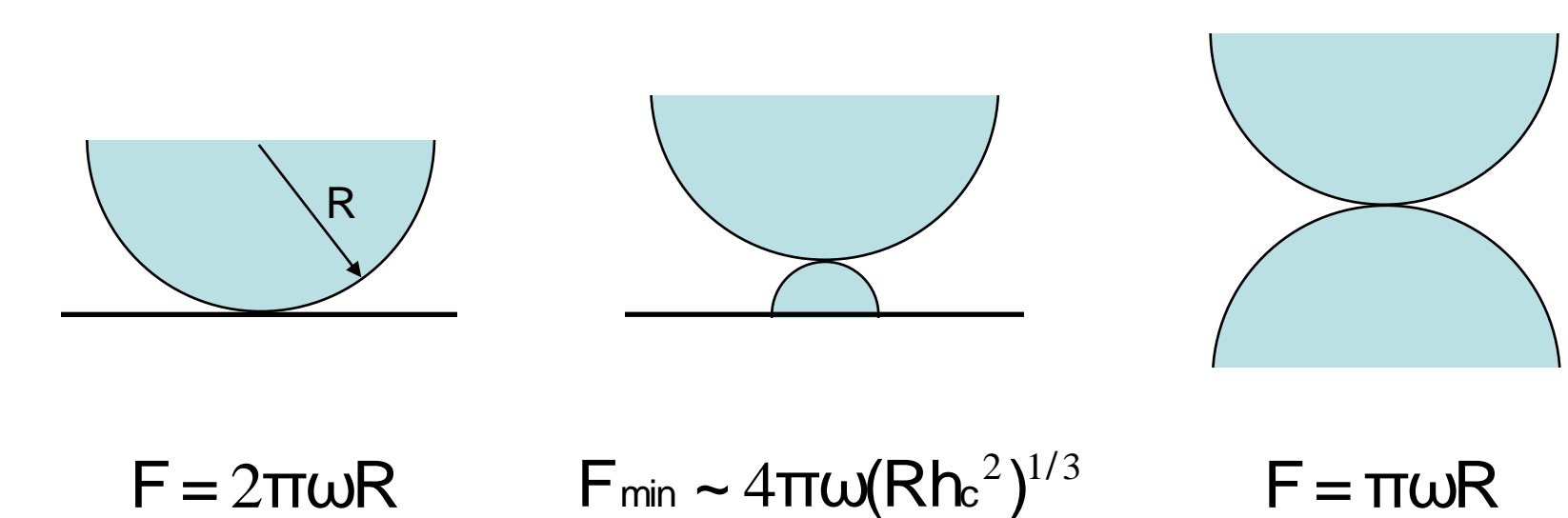


### $R_a^{\min}$ vs. tip radius curve



\* The scattered points are experimental data. The colored lines are the corresponding predicted curves. The force is divided by  $2\pi\omega$ , which is the normalization for surface energy.  $R_a^{\min}$  is obtained from the fitting curves for each tip radius.

## Discussion



Although the data are noisy, the model seems to hold. Asperities act to separate tip and sample when they are small, and contribute to adhesion when they are big. The minimum adhesion depends on the size of the tip.

## Summary

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

## References

- [1] B. Luan and M.O. Robbins, *Nature* **435**, 929-932 (2005).
- [2] E.J. Thoreson, J. Martin, N.A. Burnham, *J. Colloid Interface Sci.* **298**, 94-101 (2006).