# What's a few small bumps between friends?


E.J. Thoreson[1], J. Martin[2], and N.A. Burnham[1]

[1] Department of Physics, Worcester Polytechnic Institute, 100 Institute Road, Worcester, MA 01609-2280

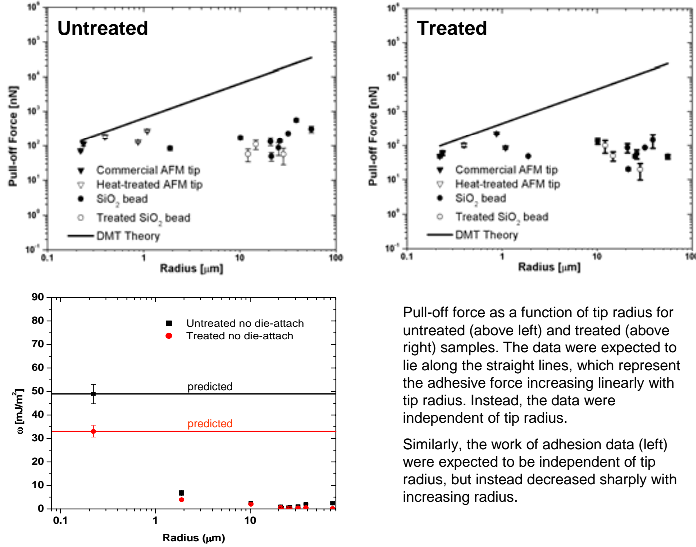
[2] Micromachined Products Division, Analog Devices Incorporated, Cambridge MA 02139-3556



## Abstract

The adhesive (pull-off) force was measured between differently sized AFM (Atomic-Force Microscope) tips of different roughness and smooth sample surfaces that had well-controlled material properties. The samples were untreated and treated unpatterned silicon die and the tip sizes ranged from 200 nm to 60 μm, a range that brackets typical feature sizes in MEMS. We observed that the uncorrected pull-off force was independent of the radius of the AFM tip, which was contrary to all continuum-mechanics model predictions. We calculated a simple correction due to the measured RMS (Root Mean Square) surface roughness of the AFM tips, which resulted in the expected dependence of the pull-off force on radius, but with higher than expected magnitudes. The presence of a few small asperities can greatly reduce the adhesive force.

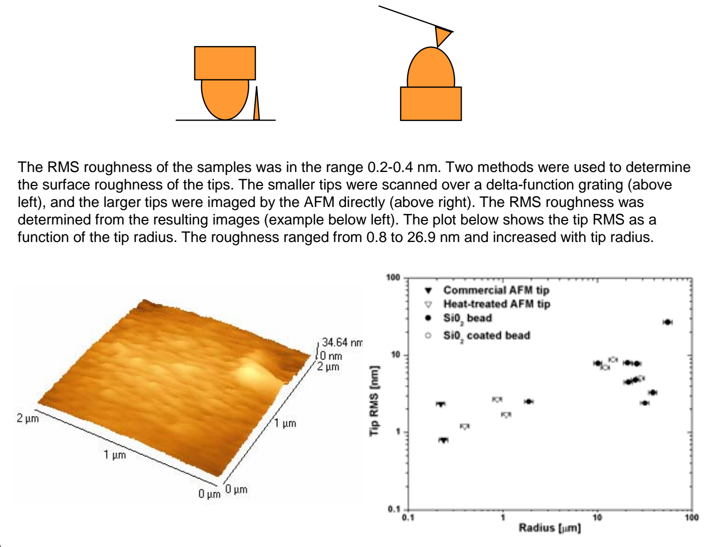

## Hypothesis and initial results




Pull-off force as a function of tip radius for untreated (above left) and treated (above right) samples. The data were expected to lie along the straight lines, which represent the adhesive force increasing linearly with tip radius. Instead, the data were independent of tip radius.

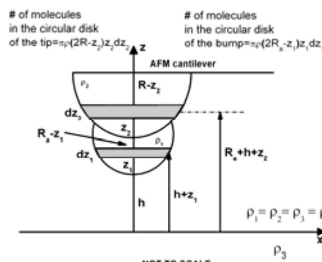
Similarly, the work of adhesion data (left) were expected to be independent of tip radius, but instead decreased sharply with increasing radius.

## Is the unexpected behavior due to roughness?




The RMS roughness of the samples was in the range 0.2-0.4 nm. Two methods were used to determine the surface roughness of the tips. The smaller tips were scanned over a delta-function grating (above left), and the larger tips were imaged by the AFM directly (above right). The RMS roughness was determined from the resulting images (example below left). The plot below shows the tip RMS as a function of the tip radius. The roughness ranged from 0.8 to 26.9 nm and increased with tip radius.

## A simple single-asperity model



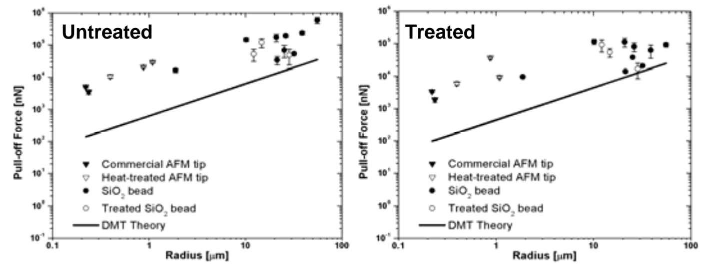

(1) Prediction:

$$F_{corrected}(R,R_a) = \frac{\left|F_{pull-off}\right|}{\left[\frac{(h_c+2R_a)h_c^3}{R(h_c+R_a)^3} - \frac{h_c}{R} + \frac{R_a}{R} + \frac{h_c^2}{(h_c+R_a)^2}\right]\left\{\left[1-\frac{3R}{2L}\tan\phi\right]\cos\phi\right\}}$$

(2) Keeping the largest terms:

$$F_{corrected}(R,R_a) = \frac{\left|F_{pull-off}\right|\sec\varphi}{\left[\frac{R_a}{R} + \left(\frac{h_c}{h_c+R_a}\right)^2\right]}$$

## Corrected results and conclusions




Corrected pull-off force (Eq.1) as a function of tip radius for the untreated (left) and treated (right) silicon oxide samples. The correction for the RMS surface roughness resulted in the expected dependence of the pull-off force on radius, but the magnitudes were higher than expected. Details of this work are given in [1] and [2]. Delrio et al. [3] found a similar sensitivity to small "asperities" in their study of micromachined surfaces. At the atomic scale, Luan and Robbins [4] found that atoms themselves act as "asperities".

Equation 2 on the left shows that physically there is a competition between the attraction of the asperities to the substrate and their role in separating the tip and sample. When the roughness is low, the asperities act to keep the tip and sample just slightly away from smooth, strong contact. When the roughness is large, the asperity-sample attraction dominates. The two contributions are equal when, e.g. if R = 10 um, $R_a$ = 6.5 nm ($h_c$ = 0.165 nm).

*The presence of a few small bumps on the tip can greatly reduce the measured adhesion. A model with a single representative asperity recovers the expected dependence of the force on the tip radius.*

## Materials and methods

- Adhesive (pull-off) force measured as the average value of the minimum in the retraction of 256 AFM force curves
- Seventeen tips of four different types ranging in radii from 200 nm to 60 um, a size range corresponding to typical MEMS contacts
- Samples were unpatterned silicon die, some treated with a few angstroms of diphenylsiloxane
- Cantilever stiffness and tip radii determined by methods described in [5] and [6]
- Geometric corrections due to angle of repose described in [7]
- Integration of expected force follows derivations given in [8]

## References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