

# Chemical Force Microscopy

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Chemical Force Microscopy (CFM), a variation of Atomic Force Microscopy (AFM), is a surface imaging technique which utilizes a tip that has been chemically modified.<sup>1</sup> AFM, developed in 1986 by Binnig et al., is capable of achieving piconewton sensitivity which allows it to probe intermolecular interactions and is capable of producing topographical images of surfaces with XY resolution of 2 to 10 nm and a Z resolution of 0.1 nm.<sup>2</sup> Different variations of AFM (Phase Imaging, Lateral Force Microscopy, and Magnetic Force Microscopy) are able to identify materials properties of a sample, such as elasticity, stiffness, friction, adhesion, and magnetism. In March 2007, AFM was shown to identify single atoms in a surface alloy of Si, Sn and Pb by Sugimoto et al.<sup>3</sup> CFM, however, allows one to probe intermolecular interactions between functional groups on both a probe and a sample surface.

Atomic Force Microscopy is a technique in which a small (~1-200 nm) tip probes a sample surface. The sample is moved in the x, y and z direction by a piezoelectric tube as it is scanned underneath a cantilever equipped with a probe tip (or the cantilever can be attached to a piezoelectric tube and scanned over a stationary surface, there are several variations of the setup). The most conventional means of detection utilizes the optical laser detection system.<sup>4</sup> A mirrored surface on the back of the cantilever deflects a laser to a four-panel position sensitive detector (Fig. 1). Adhesion forces between a tip surface and sample surface can be measured using chemically functionalized tips by recording the vertical deflection of a cantilever as it raster scans a sample. Image maps of the friction forces can also be acquired by monitoring the lateral forces of the cantilever. By investigating these forces using chemically modified tips on surfaces with known functional groups, a unique force value can be obtained for different systems. If these

forces are mapped simultaneously with topographical images of the same area, then the image contrasts of high and low forces would correspond to different functional groups on the surface, resulting in chemical imaging.<sup>1</sup>

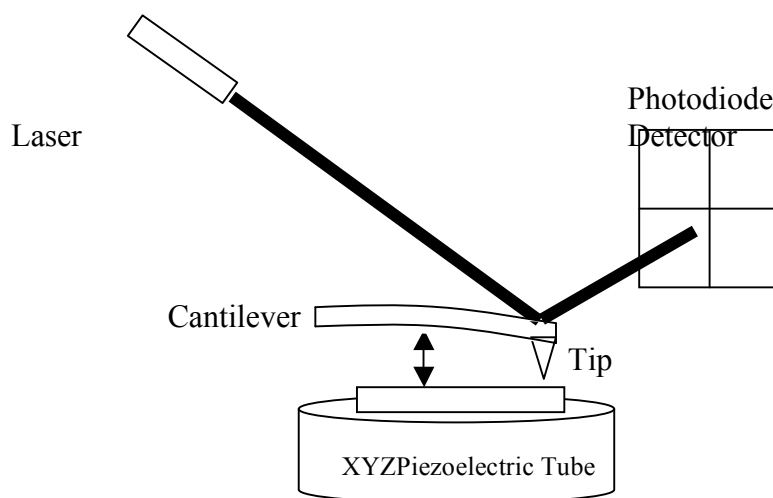


Figure 1. Schematic diagram of Atomic Force Microscope.

The first published results of chemical imaging by Chemical Force Microscopy were carried out by Frisbie et al.<sup>1</sup> who hypothesized that the friction force on a chemically functionalized tip is directly correlated to the tip-sample adhesive force. Force-displacement measurements as well as Lateral Force Microscopy were performed on lithographically patterned CH<sub>3</sub> and COOH surfaces using tips that had been modified with hydrophobic (CH<sub>3</sub>) and hydrophilic (COOH) functional groups. By recording the cantilever deflection as the sample approaches, touches, and is withdrawn from the tip, force versus cantilever displacement curves were obtained. The deflection of the cantilever was converted to adhesive force values allowing differentiation between functional groups. The resulting force-displacement curves (Fig. 2) confirmed expectations of interactions between the tip and the sample based on functional group

terminations. The adhesive force between the COOH terminated tip and COOH sample surface were greatest due to hydrogen bonding, while the adhesive force between the hydrophilic and hydrophobic tip-sample combinations were the weakest (Table 1).<sup>1</sup>

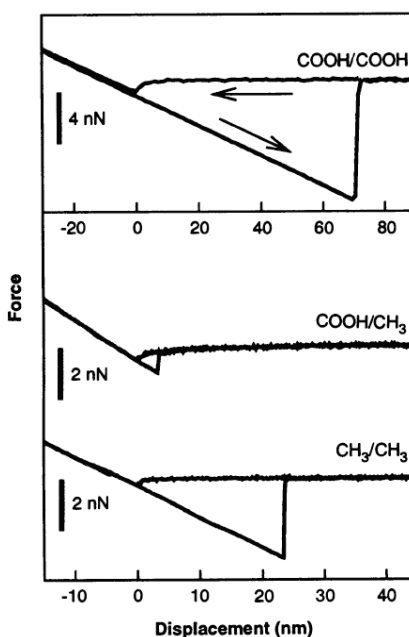


Figure 1. Force versus displacement curves of COOH/COOH, COOH/CH<sub>3</sub> and CH<sub>3</sub>/CH<sub>3</sub> tip-sample combinations.<sup>1</sup>

By being in constant contact while scanning a functionalized surface with a chemically modified tip and recording the lateral deflection of the tip, Frisbie et al. were able to spatially map the friction forces. Simultaneous topographic and friction force images were recorded, resulting in images with friction contrast. As expected, due to their structural similarity, functional group differentiation could not be achieved with topographic imaging using a CH<sub>3</sub> functionalized tip on lithographically patterned samples containing regions of CH<sub>3</sub> and COOH-terminated surface. However, lateral force scans

of the same area yielded images of high and low friction regions, corresponding to CH<sub>3</sub> and COOH areas of the surface, respectively (Fig. 3).<sup>1</sup>

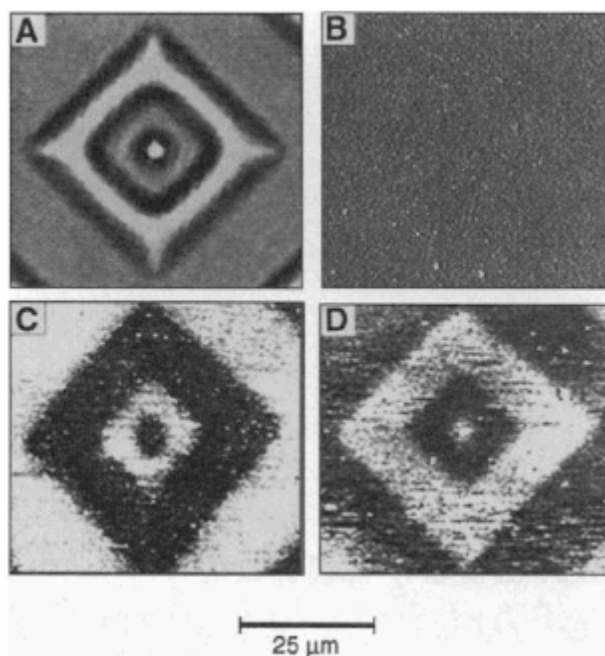


Fig 2. A) An optical condensation image of a sample patterned with CH<sub>3</sub> and COOH groups. The brighter area corresponds to condensed liquid H<sub>2</sub>O on COOH terminated regions. B) Force microscope image of sample topography of same surface pattern using a CH<sub>3</sub> terminated tip. C) Friction force image recorded simultaneously as B, with dark areas corresponding to lower friction force, and higher friction observed on CH<sub>3</sub> terminated regions of the sample. D) Similar region as in B and C, with a COOH terminated tip. High friction forces observed at COOH terminated regions of the sample B through D were imaged under ethanol with a load force of 4 nN and scan rate of 3 Hz.<sup>1</sup>

Vezenov et al. report that the JKR (Johnson, Kendall and Roberts) theory of adhesion mechanics is often applied to adhesion force studies and gives good predictions.<sup>5</sup> This theory states that there is finite contact area present between two solids under zero load force.<sup>6</sup> It can be used to calculate the number of molecular contacts that occur between the surfaces of the tip and the sample. For surfaces with the same terminal functional groups, the radius of the tip's contact area at the time that it is being pulled off of the surface,  $a$ , can be described using Equation 1.<sup>7</sup>

$$a = (3\pi\gamma R^2/K)^{1/3} \quad \text{Equation 1}$$

In Equation 1,  $\gamma$  is the free energy of the surface in equilibrium with vapor or solvent and  $R$  is the radius of the tip. The effective elastic modulus of the tip and sample,  $K = (2/3)[E/(1-\nu^2)]$ ,  $E$  is the Young modulus, and  $\nu$  is the Poisson ratio. By using Equation 1, it is estimated that there are 15 molecular contacts between a sharp tip (<50 nm) terminating in  $\text{CH}_3$  and sample surfaces terminating in  $\text{CH}_3$  when measured in ethanol. For tip-samples terminating in  $\text{COOH}$ , the number of molecular contacts is 25 when measured in ethanol. The authors suggest that individual molecular contacts could be achieved using ultra-sharp tips (<10 nm).<sup>7</sup> It is interesting to note that single molecular contacts were reported on studies of elongation and binding forces of individual DNA duplexes using tips with radii of 30-40 nm.<sup>8</sup>

Table 1. Adhesion forces of different tip-sample functional combinations, in nN. Obtained from at least 300 force-displacement curves for each combination.<sup>1</sup>

| Sample          | Tip         |                 |
|-----------------|-------------|-----------------|
|                 | COOH        | CH <sub>3</sub> |
| COOH            | 8.7 ± 3.2   | 0.85 ± 0.49     |
| CH <sub>3</sub> | 0.71 ± 0.35 | 2.7 ± 0.92      |

Since 1994, CFM studies have investigated the adhesive forces between several different functional group combinations such as  $-\text{CF}_3$ -- $\text{F}_3\text{C}$ -,  $-\text{CH}_2\text{OH}$ -- $\text{OHCH}_2$ -,  $-\text{CH}_2$ -- $\text{F}_3\text{C}$ - and  $-\text{COOH}$ -- $\text{OHCH}_2$ - (Table 2).<sup>7</sup> Noy et al. report adhesion forces for numerous tip-sample functional groups in a variety of liquids.<sup>7</sup> Interestingly, the initial trend of adhesive forces between hydrophilic groups being stronger than those of hydrophobic groups is observed with a few exceptions to the rule. When the functional group and the

liquid are immiscible (e.g. CH<sub>3</sub>-CH<sub>3</sub> in H<sub>2</sub>O) relatively high forces are observed (12.5-60 nN). When the liquid and functional groups are chemically alike (e.g. CH<sub>3</sub>-CH<sub>3</sub> in hexadecane), relatively low attractive forces are observed (0.07 nN) as well as some repulsive forces.<sup>7</sup>

Table 2. Adhesion forces of various tip-sample functional groups in liquid.<sup>7</sup>

| No. | Functional group pair (tip-surface)                                 | Monolayer, chain length                   | Medium   | Adhesion, (nN) | Tip radius, (nm)       | Ref |
|-----|---|---|--|----------------|------------------------|-----|
| 1   | CH <sub>3</sub> -CH <sub>3</sub>                                    | silane, C <sub>2</sub>                    | EtOH   | 0.4 ± 0.3      | 50                     | 9   |
| 2   | CH <sub>3</sub> -CH <sub>3</sub>                                    | silane, C <sub>9</sub>                    | EtOH   | 0.7 ± 0.6      | 50                     | 9   |
| 3   | CH <sub>3</sub> -CH <sub>3</sub>                                    | silane, C <sub>14</sub>                   | EtOH   | 2.4 ± 1.2      | 50                     | 9   |
| 4   | CH <sub>3</sub> -CH <sub>3</sub>                                    | silane, C <sub>18</sub>                   | EtOH   | 3.5 ± 2.3      | 50                     | 9   |
| 5   | CH <sub>3</sub> -CH <sub>3</sub>                                    | thiol, C <sub>18</sub>                    | EtOH   | 1.0 ± 0.4      | 60                     | 10  |
| 6   | CH <sub>3</sub> -CH <sub>3</sub>                                    | thiol, C <sub>12</sub>                    | EtOH   | 2.3 ± 1.1      | 30                     | 11  |
| 7   | CF <sub>3</sub> -CF <sub>3</sub>                                    | silane, C <sub>10</sub>                   | EtOH   | 15.4           | NR(20-40)              | 12  |
| 8   | CH <sub>3</sub> -CF <sub>3</sub> ; CF <sub>3</sub> -CH <sub>3</sub> | silane, C <sub>18</sub> , C <sub>10</sub> | EtOH   | repulsive      | NR(20-40)              | 12  |
| 9   | CH <sub>3</sub> -CH <sub>3</sub>                                    | silane, C <sub>18</sub>                   | CF <sub>3</sub> (CF <sub>2</sub> ) <sub>6</sub> CF <sub>3</sub>  | 52             | NR(20-40)              | 12  |
| 10  | CH <sub>3</sub> -CH <sub>3</sub>                                    | silane, C <sub>10</sub>                   | CH <sub>3</sub> (CH <sub>2</sub> ) <sub>6</sub> CH <sub>3</sub>  | 21             | NR(20-40)              | 12  |
| 11  | CH <sub>3</sub> -CH <sub>3</sub>                                    | thiol, C <sub>12</sub>                    | CH <sub>3</sub> (CH <sub>2</sub> ) <sub>14</sub> CH <sub>3</sub> | 0.07 ± 0.05    | 30                     | 11  |
| 12  | COOH-COOH   | thiol, C <sub>11</sub>                    | CH <sub>3</sub> (CH <sub>2</sub> ) <sub>14</sub> CH <sub>3</sub> | 0.11 ± 0.02    | 30                     | 11  |
| 13  | COOH-COOH   | thiol, C <sub>11</sub>                    | CH <sub>3</sub> (CH <sub>2</sub> ) <sub>4</sub> CH <sub>3</sub>  | 0.95 ± 0.26    | NR(20-40) <sup>a</sup> | 13  |
| 14  | COOH-CH <sub>3</sub>  | thiol, C <sub>11</sub> , C <sub>18</sub>  | EtOH   | 0.3 ± 0.2      | 60                     | 10  |
| 15  | COOH-COOH   | thiol, C <sub>11</sub>                    | EtOH   | 2.3 ± 0.8      | 60                     | 10  |
| 16  | COOH-COOH   | thiol, C <sub>11</sub>                    | EtOH   | 0.27 ± 0.04    | 30                     | 11  |
| 17  | COOH-COOH   | thiol, C <sub>11</sub>                    | PrOH   | 1.37 ± 0.26    | NR(20-40) <sup>a</sup> | 13  |
| 18  | CH <sub>2</sub> OH-CH <sub>2</sub> OH                               | thiol, C <sub>11</sub>                    | EtOH   | 0.18 ± 0.18    | 30                     | 11  |
| 19  | COOH-COOH   | thiol, C <sub>11</sub>                    | H <sub>2</sub> O, pH < 5 <sup>b</sup>                            | 2.80 ± 0.20    | NR(20-40) <sup>a</sup> | 13  |
| 20  | COOH-COOH   | thiol, C <sub>11</sub>                    | H <sub>2</sub> O, DI   | 7.0 ± 0.2      | 60                     | 14  |
| 21  | COOH-COOH   | thiol, C <sub>11</sub>                    | H <sub>2</sub> O, pH < 5 <sup>b</sup>                            | 2.3 ± 1.1      | 30                     | 11  |
| 22  | COOH-CH <sub>2</sub> OH   | thiol, C <sub>11</sub> , C <sub>11</sub>  | H <sub>2</sub> O <sup>b</sup>                                    | 1.1 ± 0.5      | 30                     | 14  |
| 23  | CH <sub>2</sub> OH-CH <sub>2</sub> OH                               | thiol, C <sub>11</sub>                    | H <sub>2</sub> O   | 1.0 ± 0.2      | 20                     | 14  |
| 24  | CH <sub>2</sub> OH-CH <sub>2</sub> OH                               | thiol, C <sub>11</sub>                    | H <sub>2</sub> O, DI   | 0.30 ± 0.05    | 30                     | 11  |
| 25  | CH <sub>3</sub> -CH <sub>3</sub>                                    | thiol, C <sub>18</sub>                    | H <sub>2</sub> O   | 60 ± 5         | 60                     | 14  |
| 26  | CH <sub>3</sub> -CH <sub>3</sub>                                    | thiol, C <sub>12</sub>                    | H <sub>2</sub> O   | 12.5 ± 4.4     | 30                     | 11  |

<sup>a</sup>Tips were coated with 50 nm of Au.

<sup>b</sup>Ionic strength IS = 0.01M

Whereas discrimination of terminating functional groups seem to have been the main focus of research involving Chemical Force Microscopy, results have been reported by Duwez et al. indicating that CFM can also distinguish between different anchoring

groups.<sup>15</sup> The adhesion forces of three different anchoring groups were investigated: octadecanethiol on gold, octadecyltrichlorosilane on silicon and octadecyltrimethoxysilane on silicon, all terminating with a methyl group. Adhesion forces were significantly different for each system, indicating that CFM has the ability to adequately distinguish between differing anchoring groups which terminate in the same functional group.<sup>15</sup>

Table 3. Adhesion forces of different tip-anchoring group combinations.<sup>15</sup>

| Monolayer  | Force (nN) |            |            |
|--|------------|------------|------------|
|  | Tip 1      | Tip 2      | Tip 3      |
| C <sub>18</sub> SH                                 | 22.9 ± 1.2 | 22.3 ± 1.1 | 23.8 ± 1.2 |
| C <sub>18</sub> SiCl                               | 18.2 ± 1.1 | 17.7 ± 1.2 | 19.1 ± 1.3 |
| C <sub>18</sub> Si(OCH <sub>3</sub> ) <sub>3</sub> | 15.6 ± 1.3 | 15.3 ± 1.1 | 16.5 ± 1.2 |

In 2000, Okabe et al. reported a new method, Pulsed-Forced-Mode Atomic Force Microscopy (PFM-AFM), in which topographical images of the surface and images of the adhesion force between the tip and the surface can be recorded simultaneously.<sup>16, 17</sup> This is different than images obtained from force friction images in that differences in the interactions are observed while the tip and the surface are detached. A sample on a piezoelectric scanner moves upward until contact with the tip is achieved. The scanner continues upward until a preset voltage,  $V_{diff}$ , is achieved ( $\sim 5$  nN). When  $V_{diff}$  has peaked, the scanner moves downward, detaching the tip from the surface. During this process, the tip is pulled down due to the adhesive force and an adhesive force map is obtained by measuring  $V_{adh}$ , which is the difference between  $V_{diff}$  right before being detached from the sample surface and  $V_{diff}$  observed when the tip is not in contact with the sample surface. An example of images of mixed SAMs obtained by PFM-AFM is shown in Figure 3. Samples were prepared on Au substrates by soaking in 1 mM

ethanolic solutions of 11- mercaptoundecanoic acid for 5 hours then soaking in a chloroform solution of 1 mM mercaptoundecanoic acid and 50  $\mu\text{M}$  1-octadecanethiol for 5 minutes. The samples were imaged using a  $\text{CH}_3$  functionalized tip. Images of a 11-mercaptoundecanoic acid SAM imaged with  $\text{CH}_3$  tip are shown in Figure 3. The PFM-AFM images of the mixed SAM (Figure 4) show discrimination between the major component of the SAM terminating in  $\text{COOH}$  and the octadecanethiol terminating in  $\text{CH}_3$ .<sup>17</sup>

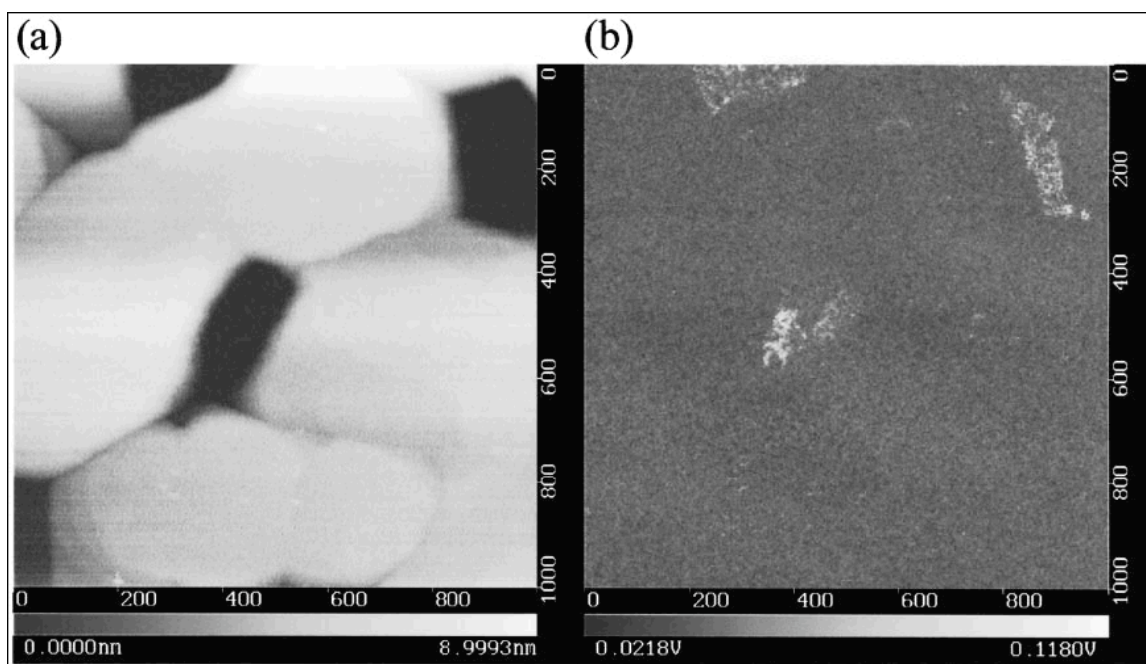


Figure 3. A)  $1000 \times 1000 \text{ nm}^2$  topographic image of 11-mercaptoundecanoic acid SAM and B) simultaneously acquired force map acquired with a  $\text{CH}_3$  terminated tip in water. Brighter regions correspond to larger adhesion forces.<sup>17</sup>

Most commercially available AFM tips are made of silicon or silicon nitride ( $\text{Si}_3\text{N}_4$ ) and can the radius of curvature range in size from 1-30 nm.<sup>18</sup> In Chemical Force Microscopy, the most common tip modification involves self-assembling monolayers (SAMs) of thiols on tips that have been coated with gold. This process involves coating

the tip with approximately 20-50 Å of chromium by thermal evaporation, followed by thermal evaporation of approximately 1000 Å of gold onto the tip. The tip is then soaked in dilute (0.1-3 mM) solution of thiol for approximately 2 hours.<sup>7, 19, 20</sup>

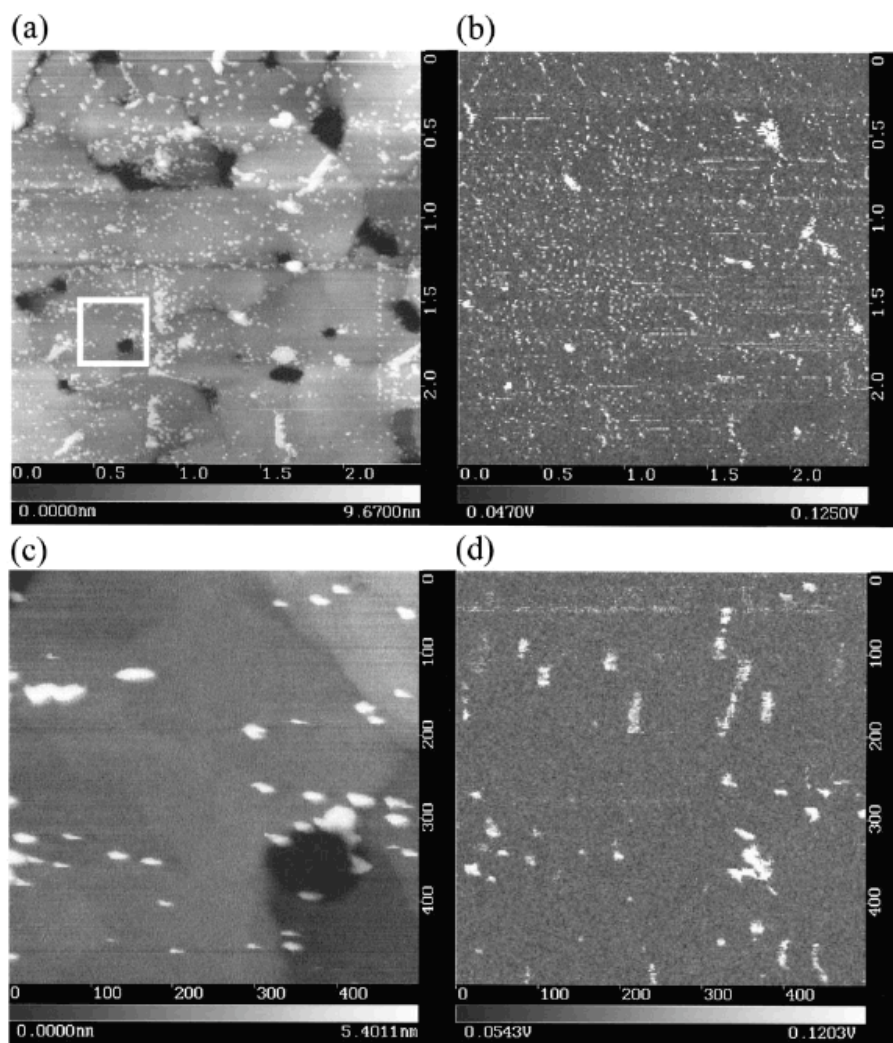


Figure 4. A) A 2500 x 2500 nm<sup>2</sup> topographic image of a mixed SAM and B) simultaneously acquired force map with a CH<sub>3</sub> terminated tip in water. C) A 500 x 500 nm<sup>2</sup> topographic image and D) simultaneously acquired force map of the area in the white lined box in A.<sup>17</sup>

Tips are also modified with organosilane adlayers. This process is more complicated than that of thiols on gold, requiring several cleaning and heating steps for the self assembling of the organosilanes onto the tip. Examples include 10-

undecyltrichlorosilane and 5-hexenyltrichlorosilane terminating in vinyl as well as hydroxyl groups.<sup>19,21</sup>

CFM is limited by numerous factors. The mechanical properties of the cantilever and tip are unique to Force Microscopy and can yield different results for cantilevers with differing resonant frequencies, lengths, spring constants as radii of curvature. The environment of the tip-sample interaction is an important factor in CFM.<sup>5</sup> Measurements and surface imaging can be performed in dry inert gas, but it is difficult to take into account the amount of adsorbed vapor on the tip or the surface.<sup>7</sup> Samples probed in ambient conditions are susceptible to water being adsorbed onto the surface, causing capillary forces to become the dominant interaction instead of the attractive force between the tip and the sample. The attractive capillary force can be as large as  $3.0 \times 10^{-7}$  N, which is 1-2 orders of magnitude higher than that of tip-sample interactions. The capillary problem can be overcome by either probing the surface in liquid or in a vacuum of up to  $5.0 \times 10^{-6}$  Torr.<sup>7,22</sup> However, adhesion force values can differ significantly for same tip-sample combinations that are probed in different conditions. For example, Frisbie et al. measured an adhesion force value of  $2.7 \pm 0.92$  nN (Table 1) for a  $\text{CH}_3\text{-CH}_3$  tip-sample combination in ethanol whereas Noy et al. reported in a review adhesion force values of  $60 \pm 5$  nN (Table 2) for the same tip-sample combination probed in water. Results can also vary significantly depending on monolayer chain length as well as the radius of the tip (Table 2). However, one advantage of CFM is that the functionalizing of the tips prevents degradation of the tip after several uses. Frisbie et al. reports that after 400 force curves, the average force dropped 15% with COOH terminated tip.<sup>1</sup>

The chemical modification of Atomic Force Microscopy tips has been successfully used to measure adhesion forces as well as friction forces of functionalized sample surfaces. It has been reported that the adhesion forces and the friction forces of tip-sample combinations are chemically specific and that chemical imaging can be achieved using both adhesion force and friction force imaging techniques. Studies have utilized CFM in investigations of DNA<sup>8</sup> as well as active enzymes<sup>23</sup> indicating that it is a valuable tool in investigating biological systems. CFM has also been shown to discriminate between enantiomers of chiral molecules, sometimes with better sensitivity than HPLC.<sup>24</sup> In 2005 Bottomley et al. utilized CFM with various ranges of functionalized tips to study the properties of Single-Walled Carbon Nanotubes for possible space applications.<sup>25</sup> Advances in Chemical Force Microscopy have led to Single Molecular Microscopy AFM, which also utilizes a functionalized tip. In a 2007 review, Dupres et al. reported several studies of single molecular level ligand-receptor forces.<sup>26</sup> From the examples given in this abstract, as well as the numerous studies found but were beyond the scope of this paper, it is suggestive that not only is CFM a viable enhancement of the chemical sensitivity of AFM but it is also a valuable analytical tool for the investigation of intermolecular forces of chemically interesting surfaces.

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