

# Stress at the Solid–Liquid Interface of Self-Assembled Monolayers on Gold Investigated with a Nanomechanical Sensor

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The interfacial stress of self-assembled monolayers on Au exposed to buffers of various pH values and ionic strengths is measured as a function of the liquid environment. The method uses two thiol-modified Au-covered silicon cantilevers and a differential method to compensate for thermal and refractive index changes of the liquid environment. Increasing pH and ionic strength leads to a bending, i.e., a compressive stress, of a mercaptohexadecanoic acid-covered cantilever compared to a hexadecanethiol-covered reference cantilever. In addition, the interfacial stress is found to be highly dependent on the surface density of the ionizable mercaptohexadecanoic acid molecules when they are coadsorbed with hexadecanethiols on Au.

## Introduction

Mechanical stress at a solid–liquid interface occurs when either the physical or chemical properties of the surface change or when the liquid environment of the surface is altered, e.g., by solvents or buffers. Surfaces respond to such changes on their interface either by expanding (compressive stress) or by shrinking (tensile stress). Surface stress can originate from surface reconstructions<sup>1</sup> or from the interactions between a surface and adsorbates, e.g., during epitaxial growth<sup>1,2</sup> and in electrochemistry,<sup>3</sup> or it can result from the interactions between a surface and its environment. For the latter, biology provides an interesting analogy in how the curvature of cell membranes is influenced by the characteristics of the liquid medium. The shape of red blood cells, for example, is known to be dependent on the ionic strength and pH of a medium.<sup>4,5</sup>

Microfabricated Si cantilevers as used for atomic force microscopy (AFM) are sensitive sensors for surface stress. They have been used to monitor metal deposition on electrodes,<sup>6</sup> surface stress of solids in gas and liquids,<sup>7</sup> self-assembly of thiols,<sup>8</sup> and unspecific adsorption of proteins<sup>9,10</sup> as well as more recently to detect molecular recognition.<sup>11,12</sup> A cantilever for surface stress measurements consists of two chemically or physically different surfaces, so that reactions occurring preferentially on one side of the cantilever can change the surface stress on

that side, which causes the cantilever to bend. Si cantilevers homogeneously covered on one side with a thin gold layer provide such different surfaces and are therefore well suited for sensitive surface stress measurements. In this work, we take advantage of self-assembling monolayers on Au to derivatize such a Au-coated cantilever with hexadecanethiol (HS-(CH<sub>2</sub>)<sub>15</sub>-CH<sub>3</sub>, HDT) and another one with mercaptohexadecanoic acid (HS-(CH<sub>2</sub>)<sub>15</sub>-COOH, MHA). This results in two chemically well-defined surfaces that differ only by the functionality of their air–monolayer or liquid–monolayer interface.<sup>13,14</sup> Then, using one cantilever as a reference, the stress originating from the interaction between their specific coating and the liquid environment can be investigated in a very sensitive way.

## Experimental Section

Two cantilevers of an array of eight identical Si cantilevers (1 μm thick, 100 μm wide, 500 μm long, pitch 250 μm, spring constant 0.02 N/m, provided by the micro- and nanomechanics group at IBM Zurich Research Laboratory, Switzerland) were selected for derivatization and, hence, were the active parts of the array.<sup>10,11</sup> All cantilevers were homogeneously covered on one side with a 1-nm-thick layer of Ti and a 20-nm-thick layer of Au in an electron-beam (e-beam) evaporator. Two cantilevers of the array were introduced into two containers (typically for 15 min), each filled with 10 μL of a 1 mM solution of thiols in ethanol. With this simple method, one cantilever was functionalized with HDT, and the other with MHA or a mixture of HDT and MHA. Both molecules are known to form stable, well-ordered monolayers on Au.<sup>13</sup> The ratio of HDT to MHA in the monolayer on Au was checked by X-ray photoelectron spectroscopy (XPS) on identically prepared surfaces and was consistent with published work on adsorption isotherms of binary mixtures of alkanethiols on Au.<sup>15,16</sup> The packing density and conformations of the molecules in either type of monolayer are equivalent.<sup>13</sup> HDT and MHA monolayers on gold have, for example, nearly

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equivalent thicknesses ( $\sim 2.0$  nm) and molecular occupancies on the surface ( $\sim 0.21$  nm<sup>2</sup> per molecule).<sup>13</sup> Self-assembly resulted in a coverage of about  $10^{12}$  molecules per cantilever. The array was then carefully rinsed with 1 mL of ethanol, dried, and positioned in the liquid cell.

Two time-multiplexed vertical cavity surface emitting lasers (operated at 1 Hz, wavelength 760 nm, CSEM Zurich, Switzerland) and a position-sensitive detector (SiTek, Sweden) were used for beam deflection readout of the cantilever bending on the nanometer scale for two cantilevers.<sup>10,11</sup> All buffers were 0.1 M phosphate buffer solutions with  $4 < \text{pH} < 9$ . For pH 10 the buffer was adjusted with NaOH.<sup>17</sup>

The cantilevers were placed in a liquid cell with a volume of about 800  $\mu\text{L}$ . Buffer solutions were manually exchanged using a micropipet. The array was equilibrated until the drift of the differential signal was stable. Then, buffers with different pH or ion concentrations were injected and the bending signals of the two cantilevers were recorded simultaneously.

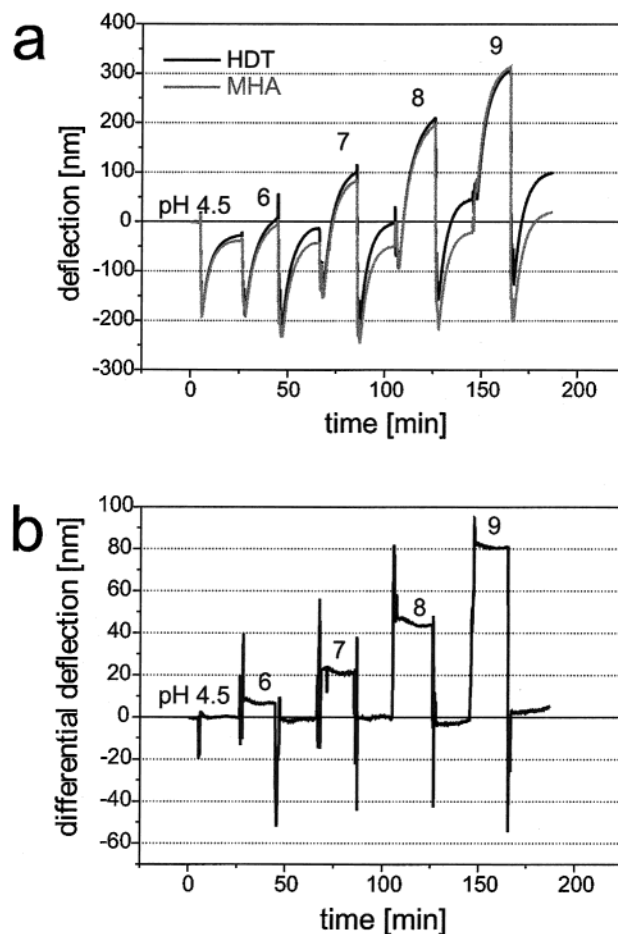
### Results and Discussion

Figure 1 shows deflection vs time traces of the cantilever responses on injection of buffer solution of various pH values. The absolute cantilever deflections as shown in Figure 1a always exhibited strong peaks due to the injection process as well as large signal changes and drifts due to refractive index and temperature differences between the injected buffer solution and the liquid in the cell. Consequently, the difference in deflection between the two cantilevers was recorded to eliminate such experimental artifacts on the deflection signal and to extract solely the signals originating from the various functionalities of the self-assembled monolayers. The differential deflection—the deflection of the MHA-covered cantilever minus the deflection of the HDT-covered reference cantilever—was always found to be stable shortly after injection of buffer solutions as shown in Figure 1b. The cantilever deflection always resumed its initial value when a pH 4.5 buffer solution was used to flush the cell before injecting the buffer solution with the next higher pH. This also demonstrates the reliability and reproducibility of our measurements.

As can be seen in Figure 1b the differential deflection clearly increases with increasing pH. These first results are summarized in the uppermost data set of Figure 2 showing the pH dependence of cantilever bending. From pH 4.5 to 10 the 100% MHA-covered cantilever bends up to 100 nm away from its functionalized surface compared to the HDT-covered cantilever. Such bending corresponds to a compressive surface stress change in the MHA monolayer of about 32 mN/m as calculated by Stoney's formula.<sup>18</sup> It also corresponds to an actuation force of up to 2 nN deflecting the cantilever.

It is clear from these results that the differential deflection depends on the pH changes of the buffer and the different functionality of the monolayers on the gold-coated cantilevers.<sup>19</sup> The deflection should originate from the different monolayer–liquid interfaces and depend on the chemical environment of these interfaces. HDT provides a monolayer with a largely unreactive and low-energy surface; we consequently expect that the differential signal reflects events occurring on the MHA-derivatized cantilever.

Organic carboxylic acids in solution have a  $\text{pK}_a$  value of  $\sim 5$ .<sup>20</sup> At  $\text{pH} < 5$  the majority of the carboxy groups is protonated and neutral, but at  $\text{pH} > 5$  they tend to



**Figure 1.** Changes in the interfacial stress between thiol-covered cantilevers and buffer solutions of various pH values as measured by the bending of the cantilevers. Every 20 min the liquid cell was purged with 6 mL of a buffer solution. Between every pH increase a buffer of pH 4.5 was injected to ensure identical initial conditions. (a) Absolute deflection vs time of a MHA- and a HDT-functionalized cantilever. (b) Corresponding differential signal of the deflection of the MHA-covered minus the deflection of the HDT-covered cantilever. The differential deflection increases to 80 nm with increasing pH and was reproducible within  $\pm 1.5$  nm for one array. This corresponds to a pH sensitivity of the method of at least 0.1 pH unit. Signals from different arrays differed within  $\pm 3$  nm in their response to buffers of identical pH.

deprotonate and become negatively charged ( $-\text{COO}^-$ ). Therefore, raising the pH is expected to increase the population of negatively charged groups in the MHA monolayer. The more deprotonated  $-\text{COO}^-$  groups present, the greater the lateral repulsive forces in the MHA monolayer. This bends the MHA-covered cantilever away from its charged surface and causes the observed compressive stress.

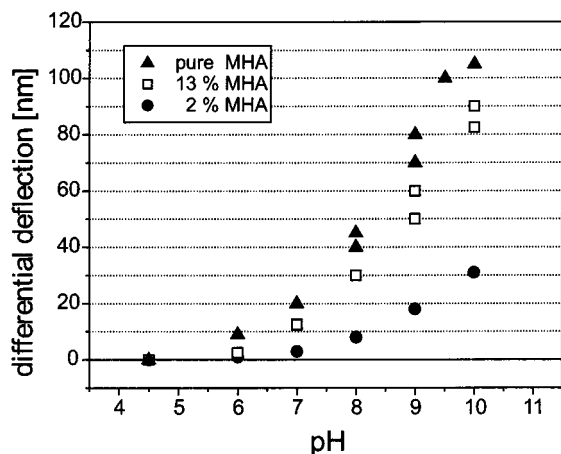
Interestingly, the differential deflection between MHA- and HDT-coated cantilevers is analogous to a titration curve: the signal variation is maximal between pH 8 and 9.5 but remains low at pH values below and above. Results from contact-angle titration of ionizable groups on surfaces indicated a strong divergence between the behavior of ionizable groups on surfaces with respect to the pH environment and the same groups carried by molecules in solution.<sup>21</sup> The close proximity of the acidic functions in a monolayer like MHA on gold shifts the observed surface  $\text{pK}_a$  to higher values (i) due to electrostatic

(17) The current design of the liquid cell made of plexiglass does not allow experiments with buffers of  $\text{pH} < 4$  or  $\text{pH} > 10$ .

(18) See for example: Miyatani, T.; Fujihira, M. *J. Appl. Phys.* **1997**, *11*, 7099.

(19) The influence of the stress possibly occurring over the Si/SiO<sub>2</sub> surfaces of the cantilevers is not considered here because it is canceled out by the differential measurements.

(20) *CRC Handbook of Chemistry and Physics 1999–2000*, 80th ed.; Lide, David R., Ed.-in-Chief; CRC Press: Boca Raton, FL, 1999.



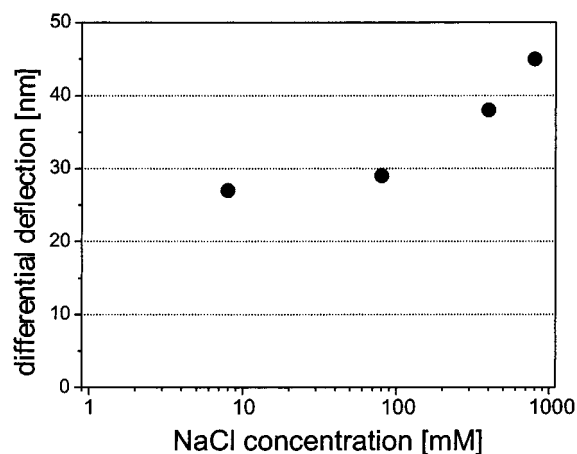
**Figure 2.** pH dependence of the differential deflection of cantilevers covered with various mixed MHA:HDT monolayers. The differential deflection increases with increasing pH and increasing MHA surface density. The total ionic strength of the buffers used in these experiments was kept constant.

interactions of neighboring protonated and deprotonated species and/or (ii) the accumulation of these functions over the low dielectric medium constituted by the alkyl chains of the molecules. Consequently, the more deprotonated species present at the surface, the more difficult the protonation of further acidic groups will be, even at higher pH.

We attribute the pH-dependent bending of the MHA-covered cantilever to the progressive deprotonation of acidic groups resulting in an electrostatic repulsion in the MHA monolayer. To verify this model we varied the number of MHA molecules on the cantilever surface in a defined way by preparing cantilevers with mixed MHA:HDT monolayers. Reducing the surface population of ionizable  $-\text{COOH}$  groups should also reduce the electrostatic repulsion in the monolayer at a given pH and hence reduce the bending of the cantilever during titration. An HDT-covered cantilever still served as a reference cantilever to extract the differential deflection. The data sets in Figure 2 demonstrate that the cantilever bending during titration decreases with decreasing percentage of MHA molecules on the cantilever surface as expected. It is worth noting that the bending of a mixed MHA:HDT-covered cantilever deviates significantly only from the bending of a 100% MHA-covered cantilever at MHA surface concentrations below 20%. This could indicate that during titration of the 100% MHA-covered cantilever, only a fraction of the acidic groups are deprotonated (which would be consistent with the effects of the close proximity of acidic groups reported above) or that pH-induced stress is not directly proportional to the mole fraction of MHA in the monolayer. All these findings support an electrostatic model of pH-dependent cantilever bending using buffers with fixed ionic strength.

The interaction between charged surface groups and a buffered solution was further explored in an experiment where the pH was kept constant but the ionic strength of the buffer (concentration of NaCl) was varied over 2 orders of magnitude. Figure 3 illustrates that the bending of an MHA-covered cantilever at fixed pH increases with increasing ionic concentration of the buffers.

This effect cannot be described by a simple electrostatic repulsion in the monolayer because the population of charged surface groups was kept constant. A screening of



**Figure 3.** Dependence of the differential deflection between a 2% MHA-covered cantilever and a HDT-covered cantilever on different NaCl concentrations. The pH of the buffers was kept constant at 8.7. The differential deflection increases with increasing ionic strength.

the charged groups by an increasing number of counterions should reduce the electrostatic repulsion in the monolayer and *decrease* the bending of the cantilever instead of increasing it. Because in this experiment only the properties of the liquid and not of the surface were modified, the origin of the bending has to be attributed to the structure of the liquid near the surface. This also involved entropic effects, which can be described by an electrostatic double layer, osmotic pressure, solvation, and hydration effects.<sup>22</sup>

A general description of the mechanical stress at a chargeable monolayer–liquid interface must therefore take into account the properties of the entire interface including electrostatic effects in the monolayer as well as entropic effects and the structure of the liquid several nanometers away from the surface.<sup>23,24</sup>

### Conclusion and Outlook

The buffer-induced bending of functionalized microfabricated cantilevers is a simple and direct method to investigate the properties of functional groups on a surface. It provides insight into the interaction of molecules within a monolayer of adsorbed molecules. Systems such as self-assembled monolayers of thiols and silanes, lipid layers or membranes, polymer brushes, or other monolayers can be investigated directly in terms of their mechanical properties and lateral interactions in a liquid environment. Further experiments should expand our initial findings and could, for example, use a larger range of pH, other thiol end groups, and a variety of buffers to enable a greater in-depth investigation of the underlying physics of stress at liquid–monolayer interfaces.

We think that alkanethiol-covered cantilevers could also be used as nanomechanical pH meters, e.g., for a lab-on-a-chip or in vivo sensors, and that derivatized cantilevers bent by interfacial stress could provide a new kind of actuation mechanism to move parts of microfabricated devices in a liquid environment.

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