

Chemically-Sensitive Interfacial Force Microscopy: Contact Potential Measurements of Self-Assembling Monolayer Films

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We report contact potential difference (CPD) measurements of *n*-alkanethiol self-assembling monolayers (SAMs) adsorbed to Au substrates using an organomercaptan-modified Au probe. We perform experiments by applying a triangular-sweep voltage between the sample and probe while measuring the resulting electrostatic force. The interfacial force microscope permits us to keep the probe/sample distance rigidly fixed, which allows us to directly measure the electrostatic force at a constant interfacial separation. The CPD is determined by measuring the applied potential necessary to null the electric field and eliminate the interfacial force between the two surfaces. We show that CPD values obtained using Au probes modified with methyl-terminated SAMs are stable and reproducible, whereas identical unmodified probes yield highly variable data. Our experimentally determined CPD values are in qualitative agreement with calculated CPDs for several different ω -terminated SAMs.

We report contact potential difference (CPD) measurements of *n*-alkanethiol self-assembling monolayers (SAMs)^{1–3} adsorbed to Au substrates using an organomercaptan-modified Au probe. Our results demonstrate for the first time the feasibility and importance of controlling the chemical properties of force microscope probe surfaces. Moreover, control over the chemical characteristics of the probe provides a basis for distinguishing between chemically distinct surface features with nanometer resolution in force microscopy. We show that CPD values obtained using Au probes modified with methyl-terminated SAMs are stable and reproducible, whereas identical unmodified probes yield highly variable data. Our experimentally determined CPD values are in qualitative agreement with calculated CPDs for several different ω -terminated SAMs.

We have previously used the interfacial force microscope (IFM)⁴ to obtain detailed information about the mechanical properties of methyl-terminated *n*-alkanethiol SAMs adsorbed to Au substrates.^{5–8} In the present work, we use the IFM to determine local CPDs that arise between an organomercaptan-modified Au probe and various SAM-modified Au substrates (Scheme 1).⁹ The CPD is defined as the work function difference between these modified Au surfaces, which we view as tightly bound dipole sheets that shift the work functions of each modified Au surface.¹⁰ For example, the work function is increased relative to bare Au for dipoles having their negative end pointing away from the modified Au surface. We perform experiments by applying a triangular-sweep voltage between the sample and probe, which is held at ground, while measuring the resulting electrostatic force. Unless otherwise noted all CPD measurements were obtained in air. The force-feedback capability of the IFM is used to keep the probe/sample distance rigidly fixed, which allows us to directly measure the electrostatic force at a constant interfacial separation. The CPD is determined by measuring the applied potential necessary to null the electric field and eliminate the interfacial force between the two surfaces.¹¹

Figure 1 shows force vs substrate potential data obtained using a HS(CH₂)₁₁CH₃-modified Au probe. In these plots, negative forces are attractive, and the shape is parabolic since the electrostatic force is proportional to the square of the bias voltage.¹² The solid line represents a second-order polynomial fit of the

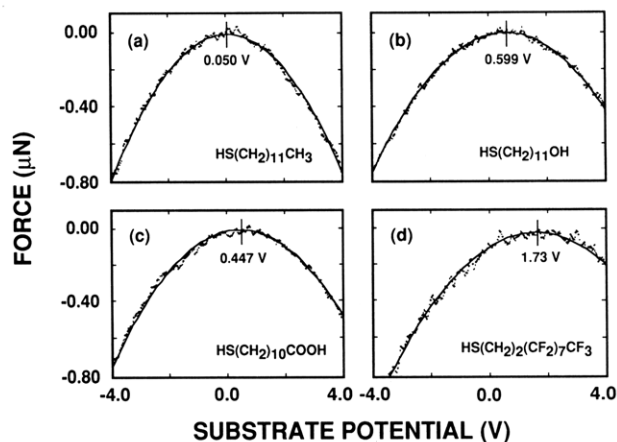
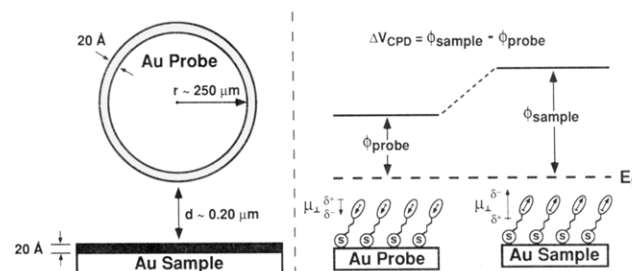


Figure 1. Interfacial force vs substrate potential curves between a spherical, HS(CH₂)₁₁CH₃-modified Au probe with a 250- μ m radius of curvature and organomercaptan-modified Au samples. The probe was held at ground while biasing the sample with a triangular-sweep voltage. Negative forces are attractive. The data points were fit with a second-order polynomial. Average standard deviations of curve fits were ~ 0.020 V. The CPD is determined at the applied potential at which the force goes through its minimum value. The data in this figure are typical of our results, but several such data sets were used to generate the average values given in Table 1.

SCHEME 1



data. In Figure 1a, the probe and the sample are both HS(CH₂)₁₁CH₃-modified Au substrates that should have identical work functions and the CPD should be zero. The measured CPD value of 0.050 V deviates slightly from zero, which is probably the result of differences in surface packing and coverage for each SAM-modified surface. By increasing the work function of the modified Au substrate with molecules having dipole moments of different magnitudes that point away from the surface, the applied

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TABLE 1: CPDs of SAM-Modified Au Substrates with Respect to HS(CH₂)₁₁CH₃-Modified Au Probes^a

SAM	exptl CPD (V)		calcd CPD (V)
	tip A	tip B	
HS(CH ₂) ₁₁ CH ₃	0.057 ± 0.021	0.010 ± 0.007	0.00
	0.008 ± 0.034 ^b	0.028 ± 0.030 ^b	
	0.050 ± 0.006 ^c	0.011 ± 0.022 ^c	
HS(CH ₂) ₁₁ OH	0.587 ± 0.041	0.567 ± 0.070	0.542
HS(CH ₂) ₁₀ COOH	0.533 ± 0.045	0.418 ± 0.157	1.69
HS(CH ₂) ₂ (CF ₂) ₇ CF ₃	1.68 ± 0.018	1.63 ± 0.032	1.91

^a All samples were prepared on Au/Ti/Si(100) unless noted. Other supporting substrates were ^bAu/Cr/Si(100) and ^csingle-crystal Au(111).

potential required to null the electric field becomes more positive. These CPD differences provide a basis for mapping the chemical characteristics of the surface.

Table 1 summarizes CPD results for each SAM relative to nominally identical HS(CH₂)₁₁CH₃-modified Au probes, tip A and tip B. The CPD data in this table represent an average of results obtained from several different locations on each substrate over a period of several weeks. The data show that *n*-alkanethiol-modified Au probes are both stable and reproducible. In contrast, experiments using either bare Au or W probes yield data that vary by several hundred millivolts for CPD measurements of the same samples. We also found that CPDs of methyl-terminated and perfluorinated substrates did not change appreciably over a one month period, whereas CPDs for hydroxyl- and carboxylic acid-terminated SAMs drifted substantially over the same period. For example, the CPD values for "aged" carboxylic acid-terminated surfaces shifted negative by several hundred millivolts relative to freshly prepared samples. Subsequent experiments performed in a system that was evacuated to 10⁻⁴ mmHg and then back-filled with N₂ usually gave CPDs close to the values obtained initially in air, but there was considerable variation in the results of these experiments. Clearly, the high-energy carboxylic acid-terminated SAM surfaces adsorb hydrocarbon contaminants, which decreases their work functions in a non-reproducible manner. In contrast, CPD values obtained for the low-surface energy methyl-terminated SAMs prepared in the evacuated and N₂-backfilled chamber were reproducible and essentially identical to values obtained in air.

The CPD estimates given in Table 1 are calculated in terms of the relative CPD shifts for each SAM terminal group, which are proportional to the electric dipole magnitude normal to the surface (μ_{\perp})

$$\Delta\text{CPD} = \mu_{\perp} / (\epsilon_0 A) \quad (1)$$

where ϵ_0 is the permittivity of free space and A is the area per molecule.¹⁰ We approximate μ_{\perp} using a vectorial addition method that relies on experimentally determined bond and group moments,¹³ along with previously published orientation and surface coverage data.^{14,15} Our calculation only considers the dipole of the SAM end groups, since Au/S interactions between the probe and sample cancel and C-H dipoles between adjacent methylene units also cancel since the molecules extend in an all-trans configuration. These approximations also hold for the perfluorinated SAM. The qualitative agreement between the calculated and measured values for HS(CH₂)₁₁CH₃, HS(CH₂)₁₁OH, and HS(CH₂)₂(CF₂)₇CF₃ monolayer films gives us confidence that we are measuring work function differences between the terminal groups of these SAMs.

The overestimated CPD value for the carboxylic acid-terminated SAM reflects uncertainty in our approximation of μ_{\perp} , which we estimate by assuming a 32° tilt angle and a 55° twist angle of the carbon backbone relative to the surface normal.¹⁴ We also assume that the carboxylic acid group is rigidly oriented and configured to minimize steric interactions between adjacent methylene groups. However, our calculation does not consider intermolecular hydrogen bonding, which occurs and affects the dipole magnitude and orientation.¹⁶ Our results indicate that

the net electric dipole of the carboxylic acid group is oriented at a larger angle relative to the surface normal as a result of these intermolecular interactions.

To determine the effect of different types of Au substrates on CPD data, we performed experiments with SAMs adsorbed on Au/Cr/Si(100), Au/Ti/Si(100), and single-crystal Au(111) surfaces. If appreciable amounts of either Cr or Ti diffuse to the Au surface, we would expect to observe a finite CPD relative to single-crystal Au(111), since the work function for both of these metals is at least 0.6 V less positive than Au.¹⁷ As shown in Table 1, the CPD data are not sensitive to the different Au adhesion layers, even though Cr and Ti are known to diffuse through Au.¹⁸ Although we do not fully understand this result at the present time, we speculate that the organomeraptans may complex and remove metal surface contaminants from the Au surface during self-assembly.¹⁹

To summarize, we have demonstrated that Au probes modified with methyl-terminated organomeraptan SAMs provide surfaces that are sufficiently stable and reproducible that they can be used to distinguish between different SAM terminal groups. By controlling the chemical properties of the probe surface, we are also able to estimate CPDs that are in qualitative agreement with experimentally measured values. Discrepancies that arise between calculated and measured CPD values reflect uncertainties in our approximation of μ_{\perp} . Our results demonstrate the importance of understanding the chemical properties of interfacial probes used for studying molecular interactions between two surfaces and provide a basis for imaging chemical inhomogeneities by force microscopy.⁹

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