Correspondence

Analysis of Self-Assembled Monolayers on Gold Surfaces Using Direct Analysis in Real Time Mass Spectrometry

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Mass spectrometry was performed on self-assembled monolayers (SAMs) of dodecanethiol on gold using the new direct analysis in real time (DART) ionization technique. Observed peaks for the SAMs included monomers, dimers, and trimers of the SAM molecules, with the dimer and trimer relative peak heights enhanced as compared to the spectra for neat dodecanethiol. The possibility that the observed peaks were due to residual (noncovalently bonded) material on the surface was tested by attempting to observe residual dodecanol. No peaks corresponding to dodecanol were observed. These results indicate that DART is an excellent ionization method for the direct and unambiguous mass analysis of chemical species in self-assembled monolayers.

The ability to modify certain surfaces with a single layer of molecules is of broad interest in many fields of chemical inquiry.1–3 The most common method involves the formation of self-assembled monolayers (SAMs) on gold surfaces from thiols. Lines of inquiry in SAMs on Au surfaces include investigations as modifiers to electrodes in electrochemical systems,4,5 as receptors to dodecanol were observed. These results indicate that DART is an excellent ionization method for the direct and unambiguous mass analysis of chemical species in self-assembled monolayers.

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with commercially available instruments. Laser ablation MS is another technique that has shown itself to be effective for molecular analysis of SAMs.

Other mass spectrometric methods have been reported with regard to SAMs, but provide indirect information regarding bound surface species, as determined from reaction products from the ionization.

We report here a novel application of an existing MS method that provides direct analysis of SAMs on gold surfaces. Specifically, we used the new direct analysis in real time (DART-TOF-MS) method for analyzing a SAM of dodecanethiol (DDSH) on a gold surface. The DART ionization method has shown itself to be easy to use, capable of analyzing almost any sample type, and is relatively inexpensive (~$200k). We chose DDSH as a test case because DDSH SAMs have been very well characterized. As described here, the DART-MS analysis allows unambiguous elucidation of the SAM species.

DART is a new ionization technique that was recently developed by Cody and Laramee. It is compatible with JEOL’s AccuTOF analyzer unit. The DART ion source utilizes helium plasma generated from a glow discharge via an electrode potential of 3500 V. The metastable (excited state) helium in turn ionizes water generating protonated water molecules (H_2O^+) and protonated water dimer ions (H_2O_2^+), the latter of which is often used to tune the DART ion source for optimal sensitivity. A sample placed in the stream of the He plasma will be ionized generally via protonation followed by desorption, and the resultant ions make their way through the intake orifice of the analyzer. A slightly offset second orifice (in the analyzer) ensures that only ions, focused by ion guide lenses, make it through to the analyzer and detector.

**EXPERIMENTAL SECTION**

Two methods were employed for the fabrication of gold substrates. For the first method, cleaved mica disks (Pelco International, Redding, CA) were sputter coated with gold in a Denton Vacuum, LLC (Moorestown, NJ) Desk III model sputter coater. These flat gold surfaces were also used for the contact angle measurements described below. Another convenient method for the fabrication of gold substrates used a technique similar to that described by Schneir et al.

Gold wire (99.99%, 0.20 mm, ultrahigh purity, Boggs Gases, Titusville, FL) was fed into a hydrogen flame (ultrahigh purity, Boggs Gases, Titusville, FL). By feeding several centimeters of the wire into the flame, a molten bead of gold, ~2 mm diameter, was formed. The gold substrates were then placed into ethanolic (USP grade, Pharmco Products, Inc., Brookfield, CT) solutions of 4–10 mM DDSH (Aldrich Inc., Milwaukee, WI), or equimolar solutions of DDSH and dodecanol (DDOH; Aldrich, Inc.) for >12 h. The samples were removed from the solutions, rinsed well (≥1 min) with ethanol, and placed into an ultrasonic cleaner, in ethanol, for ∼30 min.

For the MS analyses, the ion source temperature was set to 300 °C, with helium as the ionizing gas. The TOF-MS was set with a peak voltage of 1500 V, a reflectron voltage of 900 V, a pusher bias voltage of −0.52 V, and a detector voltage of 2500 V. These parameters were chosen because they have been found effective for the analyses of other organic compounds. Each sample was slowly moved into the ion stream about halfway between the ion source and the analyzer orifice, while looking for the response in the real time chronogram. The ionization completely strips the surface of the SAM, so each sample can be analyzed only once; additional attempts resulted in either a markedly decreased signal or no measurable signal. Thus, this technique is destructive to the SAM sample. Liquids were analyzed with a small glass rod (the closed end of a melting point tube) dipped into the solution and placed directly into the ionizing stream. Calibration was performed using liquid PEG600 (Tech Purity, Ultra, Kingstown, RI). Unless otherwise noted, all mass spectra were background corrected.

**RESULTS AND DISCUSSION**

Figure 1a shows the mass spectrum of neat DDSH. The primary peaks occur at m/z 203.1826 and 371.3706. By exact mass analysis, these peaks correspond to [DDSH]^+ (Figure 2a, m/z 203.1833) and a thioether dimer, [DDSSHD] (a result of a displacement reaction between DDSH and [DDSH]^+) (Figure 2b, m/z 371.3711), respectively.

Figure 1b shows the spectrum of a DDS–Au SAM. The primary peaks occur at m/z 201.1746, 403.3445, and 603.5090, corresponding to ionized thiol [DDS]^+ or [DD=SH]^+ (Figure 2c, d, m/z 201.1677), a disulfide dimer [DDSSHD]^+ (Figure 2e, m/z 403.3432), and a molecular trimer ([DD]_3S)_2^+ (Figure 2f, m/z 603.5031), respectively. All peaks are in agreement with predicted values (±7 mmu). Larger deviations are observed for the lower intensity peaks (m/z 201 and 603). We attribute the deviations to peak shape variability at these low signal levels, as well as the peaks’ locations at the extremes of the PEG calibration function.

One important difference between the results from the neat DDSH (Figure 1a) and the DDS–Au SAM (Figure 1b) is that the primary monomeric molecular peak occurs at m/z 203 for the neat sample, whereas it is observed at m/z 201 for the SAM, which is essentially M + 1 – H^+ cation. It is also common in the analysis of alcohols via DART to observe M + 1 – H_2O cation. See Supporting Information. This is quite possible since metastable He can also result in loss of an electron from the alcohol (instead of the water; see proposed ionization scheme below), and the RCH_2O^- (radical cation) can undergo a subsequent loss of a hydrogen atom followed by protonation giving RC=OH^+, a one-step oxidation (loss of H_2O) of an alcohol. This may also be occurring in the case of thiols, especially from the SAM, where they lack the original hydrogen of the thiol: RSH in place of RSH. Also, it is important to note that a m/z 201 peak is present in the neat DDSH spectrum, though in this case, the m/z 201 peak is diminished and is not the primary monomeric ion observed, as in the DDS–Au SAM spectrum.

Figure 3a shows a chronogram of the total ion signature versus time for the analyses. The periods of depressed ion count correspond to the periods that the gold samples were held in the ionization stream since the gold samples effectively block back-ground ions generated by the DART source. Figure 3b shows a
chronogram of the SAM analyses that tracks the $m/z$ 403 peak. The chronogram peaks occur at the same moments that the samples were introduced to the ion stream. These data indicate the DART-TOF-MS is able to observe ion species specifically from the samples, even though the total ion flux is decreased by the introduction of the samples.

One question is whether the observed mass spectra are the result of residual, physisorbed DDSH. Though the possibility of residual DDSH is remote since alkanethiol SAMs have been well characterized via residue-sensitive techniques (e.g., STM), we tested this possibility. The inherent differences between the spectra for the neat DDSH and the SAMs provide strong evidence indicating that the spectra are the result of SAMs rather than residual DDSH. Apart from the $m/z$ 201 monomer peak indicating the loss of H$_2$ relative to the primary monomeric peak in the spectrum from the neat DDSH (as discussed above), the appearance of strong dimer and trimer peaks in the SAM spectra provide convincing evidence that the ions originated from a covalently bound SAM; since the thiol ends of the SAM molecules are directed toward the surface, they are in proximity, thus increasing the likelihood that ionization will produce dimers and trimers. Indeed, the monomeric ion is suppressed for the SAM. The enhanced disulfide dimer peak ($m/z$ 403) observed for the SAMs is not unusual. Similar dimer ionic species from SAMs have been observed with other mass spectrometric methods; however, for SIMS, the dimer species include a bridging gold atom.

Figure 2. Proposed ions from DDSH and DDSAu. (a) The protonated thiol observed as the primary peak in the spectrum from the neat DDSH. (b) The thioether cation observed in the neat DDSH. Cation isomers that are indistinguishable via mass spectrometry. The $m/z$ 201 peak is present in the mass spectra for the neat DDSH as well as the SAM; however, it is significantly diminished in the former. (e, f) Disulfide dimer and trisulfide trimer cations observed in the mass spectra of the dodecanethiol SAMs.

Figure 1. (a) Mass spectrum of neat dodecanethiol. (b) Mass spectrum for a dodecanethiol SAM on gold.

The dimers observed here are likely not the result of excessive residual disulfide impurities in the original DDSH. The extent of the inevitable dimerization of DDSH forming DDS–SDS was analyzed by a direct NMR experiment; see Supporting Information. The commercial DDSH used was dissolved in DMSO-d$_6$ (from an ampule to minimize any dissolved oxygen), and the integration of the thiol proton italicized in DDSH at 2.22 ppm was 70% (0.703 instead of 1.000) of what it is supposed to be if there were no DDSSDD present. Exchangeable protons, such as RSH, generally integrate lower than regular C-H protons (usually about 0.9 instead of 1.0 for a single proton); therefore, we can fairly estimate that our DDSH is at least above 75% monomeric. In the process of fabricating SAMs, only DDSH reacts with the Au surface, and the remaining DDSSDD is rinsed off.

In order to test the possibility of noncovalently bound residual DDSH, we treated gold surfaces with an ethanolic solution of DDSH and DDOH. We analyzed the samples, looking for any residual DDOH. Pure DDOH generates a primary peak at m/z 169, corresponding to [DDOH + H$^+$ − H$_2$O]$^+$ (i.e., DD$^+$). Since the DART operates optimally at temperatures ranging from 250 to 350 °C, occasional loss of H$_2$O, i.e., (M + 1) − 18, is observed for alcohols. Although it is possible to observe dimers formed from 2M + H, in which the proton bridges across two atoms bearing an electron lone pair (e.g., N or O), trimers have only been observed in the analysis of SAMs. For the samples treated with the DDSH/DDOH solution, the m/z 169 peak was not observed, indicating that any residue is not detectable. Assuming that DDSH and DDOH have similar propensities for residue formation, these results indicate that the amount of residual DDSH (noncovalently bound) that might be expected for these surfaces is negligible.

A 1:1 mixture of neat DDSH and DDOH was subjected to DART analysis to observe whether there is a possibility of signal suppression from the preferential formation of either ion. A 1:1 molar mixture analyzed neat, as well as in MeOH solution, resulted in peaks at both m/z 169 (for DDOH + H$^+$ − H$_2$O) and 203 (for DDSH + H$^+$); see Supporting Information. In fact, the peaks resulting from DDOH were even more intense than those from DDSH. This experiment, in addition to the fact that when DDSH is on the SAM, i.e., DDSAu, it gives a m/z 201 peak for DDS$^+$ instead of m/z 203 for DDSH + H$^+$, eliminates any reasonable doubt concerning these data arising from the analysis of residual, noncovalently bound molecules.

It is not surprising that this ionization method is able to remove the SAM material from gold surfaces since a similar technique has been observed to be useful for lithography of SAMs on gold. In the reported studies, the surfaces were exposed to a metastable He atom beam that was masked. Where there was no mask, the SAMs were removed. Here we have utilized this same phenomenon for the analysis of the SAM molecules. Our observation that the ionization strips the SAM from the surface is consistent with these reported lithography methods. We performed a simple contact angle experiment to track the removal of the DDS–Au. We utilized gold films that had been grown on cleaved mica. The contact angle for Millipore water was 65° for the SAM, but before analysis by DART. After analysis by DART, the contact angle was 15°. These results are consistent with the removal of the SAM and with the gold surface being relatively clean after the analyses.

One interesting aspect of the mass spectra presented here is the relative lack of fragmentation. In general, only molecular ion peaks are observed. This is consistent with what is generally observed for DART-MS. While the lack of fragmentation can be convenient for the confirmation of the presence of a particular SAM species, fragmentation patterns can be useful for the identification of functional groups of unknown species. It should be kept in mind that the current work is a preliminary report. Fragmentation from these samples with the DART source may yet become possible as more variations in the experimental parameters are explored, e.g., a higher voltage at the analyzer orifice 1.

Scheme 1 shows proposed mechanisms of SAM ionization via the DART ion source. Note that the alkanethiols are depicted as attached to gold adatoms as has recently been reported. As described above, the DART source produces metastable excited He atoms that, when excited in air, can ionize water via a Penning mechanism to form a water radical cation (H_2O^+). Scheme 1a shows two possible mechanisms by which the SAM monomeric ions could be formed. Both mechanisms begin with the water radical cation removing an electron from the S of the SAM molecule, forming a surface-bound radical thiocation. The S–Au bond may then be broken via simple homolytic cleavage or via a rearrangement forming a protonated thioaldehyde. These isomers have identical exact mass values matching the m/z 201 peak observed in the SAM mass spectrum.

Scheme 1b shows a possible mechanism of the formation of the dimeric ions. In this scheme, the radical water cation reacts with water to form either the hydronium ion or associated ionic water clusters (i.e., the H_2O_2^+ peak is used in the DART to calibrate sensitivity, as mentioned above). The (H_2O)_m H^+ ion then protonates the S atom of a SAM molecule. Next, the Au–S bond is homolytically cleaved leaving a radical cation that forms a bond with an adjacent SAM sulfur atom. Finally, homolytic cleavage between the adjacent SAM sulfur and the Au surface releases the disulfide dimer cation with an exact mass matching the m/z 403 peak observed in the SAM mass spectrum. The formation of the trimeric ion could proceed in a manner similar to that of the dimeric ion.

CONCLUSIONS

These data clearly indicate that the DART ionization technique is able to directly analyze SAMs from the surfaces themselves. This is remarkable since the SAM is present at picomole levels. For reasons noted above, it is very unlikely that the mass spectra observed are due to residual material on the gold surfaces. As the DART technique becomes more popular, it should take its place among the available methods for SAM evaluation since it is relatively inexpensive, very easy to use, and requires little sample preparation.

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SUPPORTING INFORMATION AVAILABLE

Additional information as noted in text. This material is available free of charge via the Internet at http://pubs.acs.org.

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