# Self-Assembled Monolayers on Gold Generated from Alkanethiols with the Structure RNHCOCH<sub>2</sub>SH

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This paper outlines a general synthetic route to alkanethiols useful in forming self-assembled monolavers (SAMs) starting from amines, RNH<sub>2</sub>, and converting them, via α-chloroamides RNHCOCH<sub>2</sub>Cl, to thiols having the structure RNHCOCH<sub>2</sub>SH. The wettabilities restimated from contact angles of water and hexadecane) and the thicknesses (as measured by ellipsometry and X-ray photoelectron spectroscopy. XPS) of SAMs having an amide moiety eta to Au/thiolate were similar to those of SAMs of alkanethiols with similar backbone length on gold. The internal amide group present in SAMs prepared from CF<sub>3</sub>CH<sub>2</sub>-NHCOCH<sub>2</sub>SH increases their stability against desorption of exchange with hexadecanethiol in ethanol relative to SAMs from  $CF_3(CH_2)_3$ SH. The desorption of SAMs from  $CF_3(CH_2)_3$ SH was first order in the alkanethiolate and had a half-life of ~2 h at 10<sup>-9</sup> Torr; SAMs from  $CF_3(CH_2)_3$ SH, by contrast, showed no loss after 48 h at  $\sim 10^{-9}$  Torr. The rate of exchange of a SAM from CF<sub>3</sub>CH<sub>2</sub>NHCOCH<sub>2</sub>SH with hexadecanethiol in ethanol was  $10^2 - 10^3$  times slower than the SAMs from  $CH_3(CH_2)_3SH$  or from  $CF_3(CH_2)_3 - 10^3$  times slower than the state of the s SH. The susceptibility of a SAM prepared from a short-chain alkanethiol (e.g., CH<sub>3</sub>(CH<sub>2</sub>)<sub>3</sub>SH or CF<sub>3</sub>-CH<sub>2</sub>NHCOCH<sub>2</sub>SH) to damage by UV was 10 times greater than that observed for a SAM prepared from hexadecanethiol (as measured by XPS). UV damage of SAMs derived from CF<sub>3</sub>CH<sub>2</sub>NHCOCH<sub>2</sub>SH, followed by protection of the UV-damaged SAM by replacement with hexadecanethiol and etching, gave gold patterns with minimum feature sizes of  $5 \mu$ m; these sizes were limited by the lithographic procedure used and do not reflect the true edge resolution of this photolithographic method.

## Introduction

This paper outlines a general synthetic route to alkanethiols useful in forming self-assembled monolayers (SAMs) on gold starting from structurally complex amines,  $RNH_2$  (eq 1). This work had three objectives. First, we

$$\begin{array}{c} \operatorname{RNH}_2 \to \operatorname{RNHCOCH}_2 \operatorname{Cl} \to \\ \mathbf{1} & \mathbf{2} \\ \operatorname{RNHCOCH}_2 \operatorname{SCOCH}_3 \to \operatorname{RNHCOCH}_2 \operatorname{SH} \ (1) \\ \mathbf{3} & \mathbf{4} \end{array}$$

wished to develop a general procedure by which a common class of functionalized organic molecules could be converted to thiols suitable for incorporation into SAMs. The direct introduction of thiols into many organic groups (e.g., by  $S_N 2$  reaction or by free radical addition to an olefin) can be problematic, and a straightforward sequence that modified an existing functional group seemed more general. We chose the amine group as the basis for our work. The great majority of the work on SAMs of alkanethiolates  $(RS^{-})$  on gold has used the structure  $HS(CH_2)_nX$ ;<sup>1-8</sup> greater structural variations in R would increase the breadth of the field.<sup>9-13</sup> Second, we wished to determine if an amide moiety  $\beta$  to the thiol group would stabilize SAMs by forming hydrogen bonds (Figure 1). We chose the susceptibility of short-chain thiols on gold toward exchange with long-chain alkanethiols  $(CH_3(CH_2)_{15}SH)$ in solution as a primary measure of stability. Third, we wished to explore if the amide moiety  $\beta$  to the gold/thiolate bond of SAMs would undergo photocleavage or would affect the rate of photooxidation of thiolates to sulfonates. Increased photosensitivity would increase the utility of SAMs in UV lithography. Although SAMs of unfunctionized alkanethiolates on gold have been used in UV lithographic procedures, the rate of the relevant reaction-the photooxidation of RS<sup>-</sup> to RSO<sub>3</sub><sup>-</sup>-is too slow to be convenient. A modest enhancement of the photo-

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**Figure 1.** A hypothetical model of a SAM of alkanethiolates with amide moieties  $\beta$  to the thiol groups. Interchain hydrogen bonds form among the amide groups.

cross-section might lead to a useful technology for lithographic patterning.

Patterning SAMs of alkanethiolates on gold surfaces can be accomplished by microcontact printing  $(\mu CP)$ ,<sup>14,15</sup> microwriting,16 and micromachining.17 SAMs of longchain alkanethiolates protect gold from etching by CN  $\,/$ O<sub>2</sub>,<sup>16</sup> and techniques for forming patterns of SAMs on the gold surface, combined with a CN  $/O_2$  etch. provide a procedure for patterning gold.<sup>16</sup> UV-induced photooxidation of SAMs has been studied by Hemminger and used by him and others as the basis for photolithography with SAMs.<sup>18</sup> <sup>21</sup> Alkanesulfonates resulting from photooxidation of SAMs on gold were detected by static secondary ion mass spectroscopy (SSIMS)<sup>21</sup> and laser-induced desorption-coupled Fourier transform mass spectroscopy (LID-FTMS),<sup>18,19</sup> and oxidized sulfur species have been detected by X-ray photoelectron spectroscopy (XPS).<sup>22</sup> Alkanesulfonates formed by photooxidation are only weakly bound to gold and are thus easily removed from its surface. Selective damage of the SAM resulted from selective illumination, but edge resolution and feature size are currently substantially poorer than can be achieved by  $\mu$ CP.

Here we show that a SAM prepared from CF<sub>3</sub>CH<sub>2</sub>-NHCOCH<sub>2</sub>SH exhibits a significantly enhanced stability against thermal desorption (in vacuo) or exchange with hexadecanethiol (in ethanol); a monolayer formed from  $CH_3CH_2CH_2CH_2SH \ is \ less \ stable \ under \ similar \ conditions.$ These data indicate that the internal amide group present in SAMs derived from CF<sub>3</sub>CH<sub>2</sub>NHCOCH<sub>2</sub>SH increases their stability. SAMs from long-chain alkanethiolates also require relatively longer exposures to UV than do SAMs from shorter chain alkanethiols to give clean etching by  $CN^{-}/O_{2}$ : the effective rate of UV damage of a SAM prepared from CF<sub>3</sub>CH<sub>2</sub>NHCOCH<sub>2</sub>SH is 10 times greater than that of a SAM prepared from hexadecanethiol; SAMs prepared from  $CF_3\dot{C}H_2\dot{N}HCOCH_2SH$  may thus be suitable for fabricating patterned gold features (which in turn can serve as chemically robust resists for other types of processing) by UV lithography.

#### **Results and Discussion**

Synthesis of Thiols. The synthesis of thiols 4a-g demonstrates a general synthetic route for the formation

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of  $\omega$ -substituted alkanethiols from a range of organic structures containing amine groups. Reactions of amines 1a-g with chloroacetyl chloride vielded 2a-g, respectively (Scheme 1); these amines were chosen in part to represent a range of organic structural types. Substitution of the chloride of 2a-g by thioacetic acid resulted in the thioacetates **3a**-g. These, on hydrolysis, gave the thiols 4a-g, respectively (Scheme 1).<sup>23</sup> In the case of compound 3e (with the structure CH<sub>3</sub>OCO(CH<sub>2</sub>)<sub>11</sub>NHCOCH<sub>2</sub>-SCOCH<sub>3</sub>), method B rather than method C was chosen to ensure the conversion of the COOCH<sub>3</sub> group to the COOH group. The stirring of a suspension of compound 3e in 1 N NaOH solution for 24 h resulted in the hydrolysis of both COOCH<sub>3</sub> and SCOCH<sub>3</sub> groups to the desired product **4e** with the structure HOOC( $CH_2$ )<sub>11</sub>NHCOCH SH. The reactions proceeded rapidly and in high vield, although in some cases protection of other functional groups present in the molecule was necessary. Commercial availability of a large number of primary and secondary amines and the ease with which amines can be introduced into a range of structures make this method of formation of thiols particularly convenient.

### **Characterization of Monolayers**

Wettability with Water and Hexadecane. The wettabilities of SAMs derived from 4a-g on gold (1000)



Å) were determined by measuring the advancing and receding contact angles,  $\theta_a$  and  $\theta_r$ , of water (H<sub>2</sub>O) and hexadecane (HD), respectively (Table 1).

Acetic acid was added to ethanolic solutions of thiols  $4\mathbf{a}-\mathbf{g}$  to minimize the formation of disulfides by basecatalyzed oxidation of the thiolates and thus to facilitate comparison of the resulting SAMs, although disulfides of

<sup>(23)</sup> This route has been used in the conversion of *N.N*'-dimethylhydrazine to *N,N*'-dimethyl-*N,N*'-bis(mercaptoacetyl)hydrazine. Singh, R.; Whitesides, G. M. J. Org. Chem. **1991**, *56*, 2332–2337.

		Scheme 1					
R-NH <sub>2</sub>	CICH2COCI, NEt3,		2 eq. CH <sub>3</sub> COSH 1.5 eq. NEt <sub>3</sub> , CH <sub>2</sub> Cl <sub>2</sub> or THF, 0 °C, r.t.				
	CH <sub>2</sub> Cl <sub>2</sub> or MeOH, 0 °C, r.t.				R-NHCOCH <sub>2</sub> SCOCH <sub>3</sub>		OCH3
1a R = C 1b R = H 1c R = C 1d R = C 1f R = C 1g R =	$H_{3}(CH_{2})_{11}$ $O(CH_{2})_{11}$ $F_{3}CH_{2}$ $IO \longrightarrow CH_{2}CH_{2}$ $HO$ $CH_{3}OOC(CH_{2})_{11}$ $H_{3}C CH_{2}$ $H_{3}C CH_{2}$ $H_{3}C CH_{2}$ $H_{3}C CH_{3}$ $H CH_{3}$ $Method A:$	2a 85 % 2b 78 % 2c 46 % 2d 78 % 2e 92 % 2f 85 % 2g 87 %	ħ		3a 3b 3c 3d 3e 3f 3g	85 % 52 % 77 % 88 % 96 % 96 % 92 %	
	or Method B:	1. 1N NaOH(aq), Ar, r.t. 2. HCl(aq)	, 24 h;	4a method 4b method	3 A, 91 %	(66 % fi	rom <b>1a</b> ) rom <b>1b</b> )
	or Method C.	1. NaOMe, MeOH, Ar, r 2. HCliagy	t. 12 h	4c method 4d method 4e method 4f method 4g method	1 A, 72 % 1 A, 94 % 1 B, 94 % 1 C, 89 % 1 A, 72 %	(26 % fr (65 % fr (83 % fr (73 % fr (58 % fr	rom 1c) rom 1d) rom 1e) rom 1f) rom 1g)

Table 1.	Contact Angles of Water (H <sub>2</sub> O)	and Hexadecane	(HD) on SAMs and	Thickness o	f SAMs I	Determined	by
		Ellipsometry	and XPS				·

			contact angles (deg)				
			$H_2O$		D	thickness of SAM (Å)	
SAM prepared from	[AcOH] <sup>a</sup> mM	$\theta_{\rm a}$	$\theta_{r}$	$\theta_{\rm a}$	$\theta_{r}$	by ellipsometry <sup>b</sup>	by XPS <sup>b,c</sup>
$CH_3(CH_2)_{11}NHCOCH_2SH(4a)$	0	117	101	47	34		
	0.06	116	102	46	32	21	21
$CH_3(CH_2)_{15}SH$	0	118	105	48	35	$20^d$	$20^e$
	0.06	117	106	46	35		
$CH_3(CH_2)_{17}SH$	0	118	106	48	37	$23^d$	
	0.06	118	106	49	38		
$HO(CH_2)_{11}NHCOCH_2SH (4b)$	0	20	8	· 10	· 10	21	21
	0.06	18	8	· 10	· 10		
$HO(CH_2)_{16}SH$	0	22	10	× 10	+10	20	
	0.06	22	10	< 10	< 10		
$CF_3CH_2NHCOCH_2SH(4c)$	0.06	99	75	55	< 10	4	9
$CF_3(CH_2)_3SH$	0	88	64	17	<10	4	6
HO-CH2CH2-NHCOCH2SH (4d)	0.06	14	9	< 10	<10		18
НО							
$HOOC(CH_2)_{11}NHCOCH_2SH(4e)$	0	16	<10	< 10	<10		25
$HOOC(CH_2)_{15}SH$	0	<10	<10	<10	<10	$23^d$	
ON-{}-NHCOCH₂SH ( <b>4f</b> )	0.06	59	44	15	<10		15
H <sub>3</sub> C CH <sub>2</sub> -NHCOCH <sub>2</sub> SH (4g)	0.06	104	95	14	<10		15

H<sub>3</sub>C CH<sub>3</sub>

н́сн₃

<sup>*a*</sup> [AcOH] is the concentration of acetic acid in the solution used for the formation of SAMs. <sup>*b*</sup> A vacancy in this column means that the thickness was not determined. <sup>*c*</sup> The thickness of other SAMs was calculated from the Au(4f) signal in XPS using the thickness of SAM of hexadecanethiol as a standard (see Experimental Section). <sup>*d*</sup> Reference 3. <sup>*e*</sup> Assigned to be 20 Å. <sup>*f*</sup> Reference 25.

these thiols form SAMs on gold that are similar to those formed from the thiols. Oxidative formation of disulfides occurs primarily by oxidation of the thiolate anion.<sup>23</sup> Since RNHCOCH<sub>2</sub>SH (pK<sub>a</sub>~8) is significantly more acidic than alkanethiols RCH<sub>2</sub>CH<sub>2</sub>SH (pK<sub>a</sub>~10), spontaneous oxidation of compounds **4a**-**g** by O<sub>2</sub> is relatively rapid in neutral media;<sup>23,24</sup> oxidation of these thiols is, however, slower in acidic media. The wetting properties of SAMs prepared from ethanolic solutions of thiols containing acetic acid  $(\sim 0.06 \text{ M})$  were similar to those prepared from solutions without acetic acid. The presence of the acetic acid thus did not noticeably alter either the rate of the formation or the properties of the SAMs.

The wettability of monolayers prepared from thiols

<sup>(24)</sup> Singh, R.; Whitesides, G. M. Sulfur Containing Functional Groups; Supplement S; John Wiley & Sons: New York, 1994; p 633. (25) Biebuyck, H. A.; Whitesides, G. M. Langmuir **1993**, 9, 1766– 1770.



**Figure 2.** Polarized infrared external reflectance spectrum of a SAM from CH<sub>3</sub>(CH<sub>2</sub>)<sub>11</sub>NHCOCH<sub>2</sub>SH.

containing the amide moiety were comparable to those prepared from alkanethiols with the same nominal backbone structures, although there were significant differences in the hysteresis between the advancing and receding contact angles. SAMs of **4a**, for example, showed a slightly larger hysteresis between the advancing and receding contact angles (a few degrees) of either water or hexadecane than did SAMs from hexadecanethiol and octadecanethiol.

**Determination of the Thickness of SAMs.** The thicknesses of SAMs containing the HSCH<sub>2</sub>CONH group were determined by ellipsometry and XPS; these data are presented in Table 1. The thicknesses of SAMs having an amide moiety  $\beta$  to Au/thiolate are similar to those of related SAMs lacking this moiety. These data suggest that the formation of the monolayer proceeds by bonding of sulfur to the gold substrate in a manner analogous to that for simpler alkanethiol adsorbates.

Polarized Infrared External Reflectance Spectroscopy (PIERS) of SAMs from 4a. Contact angles and ellipsometry establish that many of the SAMs derived from the adsorbates detailed in Scheme 1 have wetting properties and mass coverages comparable to those of structurally related SAMs that lack the amide group in the head group region. This observation suggests that those SAMs that have long alkyl chains *might* organize themselves with the same  $(\sqrt{3} \times \sqrt{3})R30^\circ$  periodicity that characterizes SAMs derived from structurally unsubstituted *n*-alkanethiols.<sup>26</sup> This notion was tested by examining the polarized infrared external reflectance spectrum (PIERS) of the SAM derived from 4a. The data in the C–H stretching region, shown here in Figure 2a, clearly establish that the organizations of the hydrocarbon chain is unlike that found in an n-alkanethiolate SAM. The most striking suggestion of this difference comes from an analysis of the intensities, line shapes, and peak positions of the methylene  $(CH_2)$  stretching vibrations. For a  $C_{11}$ chain, closest-packed on a (  $\sqrt{3}\times\sqrt{3})R30^\circ$  overlayer lattice, we expect that the antisymmetric  $(d^{-})$  and symmetric  $(d^{+})$ CH<sub>2</sub> stretching vibrations would be at least a factor of 4 more intense than those seen here. The very strong methyl stretching bands, together with the mass coverages

independently measured by XPS and ellipsometry, compel the conclusion that the factor influencing the intensities of the  $CH_2$  high-frequency modes is not a substantially diminished mass coverage of adsorbate 4a relative to that of an *n*-alkanethiol SAM. We believe that the character of these spectra is most consistent with a "chain-melting" model.

It is well-known that the d<sup>+</sup> and d<sup>-</sup> band intensities of the bulk *n*-alkanes are very sensitive to the phase state in which they are measured. The phase I to phase II (rotator) transition of orthorhombic *n*-alkane crystals is accompanied by a significant decrease in the oscillator strengths of the CH stretching and other low-frequency modes; factors of 2–3 have been noted between the crystalline and the melt states as well.<sup>27</sup> The spectra of **4a** shown in Figure 2a are consistent with the intensities one might expect to see for disorganized chains. Additional conformation is obtained from the position of the d<sup>-</sup> band (~2922 cm<sup>-1</sup>); this very high value suggests that *gauche* conformations are heavily weighted in the structure of these SAMs.

The conformational disordering of the alkyl chain in a SAM of 4a is, at first glance, most unexpected given the results obtained by PIERS studies of numerous long-chain thiol derivatives The logical inference is that interactions at the head group, presumably conformational and/or packing restrictions for the hydrogen bending interactions of the aniste melety, are responsible. The spectrum then set the annue measured set of spectrum operations recorded between 1985 and 2005 nm. Figure 2b provides addrects infirm at in it misinfluence. The immant band seen in this spectrum appears at 1995 cm. This band is only consistent with an assignment to the and le II band of a trave conformer of a secondary amile. The amide I band predominantly (=0 strutening is very weak. appearing as a broad unresolved feature at 1650 cm<sup>-1</sup>. The amide III mode expected for a trans conformer is seen at  $\sim$ 1310 cm<sup>-1</sup>. The assignments of the remainder of the bands are uncertain but presumably comprise the other bending and skeletal modes expected in this range for 4a.

The line shape and intensity distribution of the amide II band provide perhaps the best insights into the nature of these SAMs. As noted above, the presence of this intense band, and absence of any mode in the 1450 cm<sup>-1</sup> region, is only consistent with a largely (if not entirely) *trans* conformation of the amide.

No other conformations of this group are possible. The intensity/frequency distribution also suggests that the chains are largely hydrogen bonded in the SAM; from the line shape, it would seem that some (albeit a much smaller population of) non-hydrogen-bonded segments may also be present.

The amide II band involves torsional motions of both the N-H and C-N moieties. This coupling in the *trans* form leads directly to the splitting responsible for the amide III band.<sup>25</sup> Hydrogen bonding in solution and in the solid state shift, but do not eliminate, these bands. Hydrogen bonding typically is reflected in a band centered at ~1550-1560 cm<sup>-1</sup> for an amide of this structure. This band, in a non-hydrogen-bonded state, would appear at ~1510 cm<sup>-1</sup>. The spectrum in Figure 2a thus reveals conclusively that most segments are hydrogen bonded in the SAM of **4a**. This band is asymmetric, however; the low-frequency side shows a pronounced, nonhomogenous contribution to the line shape. We therefore conclude that

<sup>(26)</sup> The polycrystalline gold substrates used in this study exhibit a preferred (111) orientation. SAMs of *n*-alkanethiols adopt a commensurate overlayer structure on Au(111), with a single chain spacing consistent with a ( $\sqrt{3} \times \sqrt{3}$ )R30° organization.

<sup>(27)</sup> Snyder, R. G.; Maroncelli, M.; Strauss, H. L.; Hallmark, V. M. J. Phys. Chem. **1986**, 90, 5623.

<sup>(28)</sup> See discussion and references cited in Bellamy, L. J. *The Infrared Spectra of Complex Molecules*; Chapman and Hall: New York, Volume 1, pp 231–262.



Figure 3. Space-filling models showing (side on) two molecules of **4a** in an all-trans conformation spaced at 5.1 Å and oriented (left) vertically along a hypothetical surface normal vector and (right) canted by 18° from this vector along the nearest neighbor direction. The N-H···O contact shown on the right corresponds to a N-O distance of 2.8 Å.

a small fraction of the segments must experience different types of chain-chain interactions.

The most important feature that emerges from the data in Figure 2b is the orientation of the chain that must exist to accommodate (1) the trans conformation of the amide and (2) the complex chain organizations that must accompany this interchain H-bonding. The model structures shown in Figure 3 adopt the conventions necessary to make this analysis.

We start our analysis from a vantage based on literature precedents. Given its importance to the tertiary structure of proteins, the hydrogen-bonding characteristics of the amide group have been the subject of considerable study. The structures of many systems, both in solution and the solid state, have been characterized and reported in the literature. The more important features of the current understanding of these interactions remain very much the same as those elegantly described by Pauling in an overview written more than 30 years ago.29 The amide group adopts a similar hydrogen-bonded arrangement in almost all unstrained systems. The preferred N-H-O bond angle is zero degrees. The torsional barrier associated with a distortion from linearity is modest (> 0.1-0.2 kcal/ mol). The N-O bond distances for the amide N-H-O hydrogen bond tend to fall in a narrow range around 2.8 А.

If we use these insights to guide an organizational model of the structure formed by 4a on Au, an interesting result is obtained. A linear hydrogen bond can only be formed if a significant perturbation of the packing of the SAM occurs-one which distorts both the chain packing and the typical  $(\sqrt{3} \times \sqrt{3})R30^\circ$  S overlayer structure presumed to characterize most thiol monolayers on Au. For simplicity of discussion, we assume that the chains are present in a hexagonal overlayer related to the  $(\sqrt{3} \times \sqrt{3})R30^{\circ}$ structure. As shown in Figure 3, the linear hydrogen bond in such a lattice can only be obtained by a tilt of the molecule in the nearest neighbor direction (seen here side on for two chains). In order for a chain tilt in this direction to yield a linear hydrogen bond and an N-O bond distance of 2.8 Å, the S–S spacing must increase to 5.1 Å (from 4.98 Å); for this structure, the chain tilt cannot exceed

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 ${\sim}18^{\circ}$  (as compared to the  ${\sim}24{-}28^{\circ}$  chain tilt found for the n-alkanethiol SAMs on Au). As the space-filling model clearly demonstrates, there is no simple arrangement of an *all-trans* chain that will densely pack within these constraints.

The model shown in Figure 3 is but one of several possible arrangements that yield a linear hydrogen bond of the proper length. The arrangement shown is one that we favor strongly, for several reasons. First, this simple arrangement minimizes the cross-sectional projection of the head group on the Au surface and thus allows a dense chain structure. Second, this orientation allows the construction of long hydrogen-bonded chains and thus allows this attractive interaction to be easily maximized. Third, the trans arrangement at the head group accounts well for the significant projection of the amide II transition moment along the surface normal direction and, thus, for the negligible intensity seen for the amide I, C=O stretching mode. Fourth, the model provides a simple arrangement that yields interchain hydrogen bonding of a sort consistent with the rather typical values of the vibrational frequencies seen for the amide group in these SAMs. The model does require, however, that conformational changes from an all-trans arrangement of the polymethylene chain (shown in the figure) must occur to maximize the attractive interactions of the chains. This maximization can only be accomplished by relaxing the chains via trans-gauche isomerism. In this regard, the structure shown adequately explains both the low intensity of the d<sup>+</sup> and d<sup>-</sup> modes and the high values of these vibrational frequencies as compared to an ordered alkane phase (the "average" chain tilt is less than that of the normal thiol SAM structure, and the gauche conformer density is relatively high).

Taken together, the simplest interpretation of the data suggests that a modest expansion  $({\sim}3\%)$  of the sulfur lattice constant is likely obtained for these SAMs and that the organization of the chains is altered as a result. It is therefore likely that the overlayer structure would be incommensurate with respect to the Au lattice spacing. This arrangement would also make it very difficult to accommodate a S-S dimerization as has been recently proposed to occur for n-alkanethiol SAMs on Au.<sup>30</sup> We should also point out that were the hydrogen-bonding arrangement to involve the long linear chains, as the data tend to suggest, this hydrogen bonding could not be accommodated within the type of superlattice present in the n-alkanethiol systems.<sup>31</sup>

Finally, we note that many of the qualitative aspects of the data presented here are reminiscent of the results of a study of an amide-containing SAM capped by a long perfluorinated chain that appeared while this paper was under review.<sup>13</sup> The quantitative aspects show some differences, however. We think these differences are entirely consistent with the relatively larger size of the perfluoro side chain and the packing constraints that this difference in size would impose on the organization of the SAM.

The Amide Moiety Stabilizes Short-Chain Thiolates against Thermal Desorption. The stability of SAMs toward isothermal desorption in ultrahigh vacuum  $(\sim 10^{-9} \text{ Torr})$  at ambient temperature  $(\sim 300 \text{ K})$  was investigated by monitoring their composition using XPS. SAMs derived from 4,4,4-trifluorobutanethiol and its disulfide were unstable toward desorption in high vacuum  $(\sim 10^{-9} \text{ Torr})$ . Molecules desorbed from the gold surface,

<sup>(30)</sup> Fenter, P.; Eberhardt, A.; Eisenberger, P. Science 1994, 266, 1216 - 1218

<sup>(29)</sup> Pauling, L. The Nature of the Chemical Bond, 3rd ed.; Cornell University Press: Ithaca, NY 1960; pp 498-503.

<sup>(31)</sup> Camillone, C. E. D.; Chidsey, P.; Eisenberger, P.; Fenter, J.; Li, K. S.; Liang, Y.-G. Liu; Scoles, G. J. J. Chem. Phys. 1993, 99, 744-747.



Figure 4. Amide linkages stabilizing short-chain alkanethiolates against desorption in high vacuum ( $\sim 10^{-9}$  Torr). SAMs were prepared from thiols or disulfides with the molecular formulas indicated on the plot. Desorption of the thiolates was monitored using the F(1s) signal measured by XPS.  $I_{\rm F}(t=0)$  is the F(1s) signal from the freshly prepared SAM in each case studied.  $I_{\rm F}(t)$  is the residual fluorine signal in the SAM after a time t spent in high vacuum.

presumably as disulfides, although we did not identify the desorbing species. This desorption was not caused by the X-rays or by secondary electrons emitted from the substrate:  $^{32}$  no F(1s) or S(2p) signal (  $\leq 0.1\%$  F, and  $\leq 1\%$ S) was detected after the samples remained in ultrahigh vacuum for 24 h; the same results were obtained even when limited or no X-ray analyses were made at short times of exposure to vacuum. A small residual C(1s) signal remained that was similar in binding energy, peak shape, and intensity to that observed for adventitious contaminants present in the chamber and adsorbed onto the surface of the gold after argon sputtering of its surface.<sup>3</sup>

The kinetics of the isothermal desorption of SAMs of 4,4,4-trifluorobutanethiol, determined from the decrease in intensity of the F(1s) signal in XPS, was found to be first order in the coverage of the alkanethiolate. and the measured half-life of the desorption at 300 K was  $\sim 2$  h (Figure 4). SAMs derived from  $CF_3(CH_2)_3SS(CH_2)_3CF_3$ desorbed at rates similar to SAMs derived from  $CF_3(CH_2)_3$ -SH; this observation is compatible with the conclusion that thiols and disulfides adsorb on gold and form similar species.<sup>25</sup> The fluorinated component of SAMs formed from  $CF_3(CH_2)_3SS(CH_2)_{16}OH$  desorbed much more slowly than the alkanethiolate species in SAMs from  $CF_3(CH_2)_3$ -SH(Figure 4). We presume that the increased interaction with the hexadecyl chain present in SAMs derived from the unsymmetrical disulfide accounts for this difference in stability.

SAMs from **4c** on gold, in contrast, showed no change in the F(1s) signal after being left in ultrahigh vacuum for 48 h (Figure 4). Interchain H-bonding of the amide moiety of 4c probably provides an additional energy barrier (as high as 5 kcal/mol)<sup>34</sup> and may explain the substantially increased stability of this SAM compared to the SAM of 4,4,4-trifluorobutanethiol.

The thermal lability of the SAM of CF<sub>3</sub>(CH<sub>2</sub>)<sub>3</sub>SH at 300 K is most unusual. SAMs from CH<sub>3</sub>SSCH<sub>3</sub>, when formed in ultrahigh vacuum (UHV), are completely stable at 300 K over periods of many days. The measured heat of desorption (as  $CH_3SSCH_3$ ) is ~32 kcal/mol.<sup>35,36</sup> In the present instance, if we model the desorption kinetics as

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Figure 5. The amide moiety stabilizing SAMs derived from short-chain thiols (\*) against exchange with hexadecanethiol in ethanol. The amide moiety, however, had a less noticeable effect on the rate of exchange of long-chain thiolates (#) on gold with CF<sub>3</sub>CONH(CH<sub>2</sub>)<sub>11</sub>SH in ethanol. The inset plots the data for the rate of exchange of the short-chain thiolates in SAMs with hexadecanethiol in ethanol up to 1 h. These experiments were carried out in weighing bottles wrapped with aluminum foil to exclude the possible effect of light. The percent exchange of SAMs of thiolates on gold with thiols in ethanol was monitored by XPS (see Experimental Section).

being an apparent first-order process and assume an initial coverage  $\sim 4.6 \times 10^{14}$  molecules/cm<sup>2</sup> and a pre-exponential factor  $\sim 10^{13}$  s<sup>-1</sup>, we calculate that the activation energy for desorption is 24 kcal/mol. This value would represent a substantial perturbation due to the neighboring group interactions of the CF groups. The situation is only aggravated when one assumes a more reasonable secondorder rate law Due to the considerable uncertainty as to what would constitute a proper choice of A in this case, a more complete analysis is not possible on the basis of these data alone

A SAM Prepared from CF<sub>3</sub>CH<sub>2</sub>NHCOCH<sub>2</sub>SH 4c Is More Stable against Exchange with Hexadecanethiol in Ethanol Than SAMs Prepared from Either CH<sub>3</sub>(CH<sub>2</sub>)<sub>3</sub>SH or CF<sub>3</sub>(CH<sub>2</sub>)<sub>3</sub>SH. SAMs prepared from 4c, butanethiol, and 4,4,4-trifluorobutanethiol on gold were allowed to exchange with hexadecanethiol (5 mM) in ethanol. The rates of exchange of SAMs prepared from 4c and SAMs prepared from 4,4,4-trifluorobutanethiol were calculated from the F(1s) signal measured by XPS after correction for the attenuation of this signal due to changes in the thickness of the monolayer following exchange (see the Experimental Section for a description of the methods used in this calculation). The rate of exchange of SAMs prepared from butanethiol was calculated from the C(1s) signal after correction for its attenuation (see Experimental Section). The rate of exchange of SAMs prepared from 4c was  $10^2 - 10^3$  times slower than that of the SAMs prepared from butanethiol or from 4.4.4-trifluorobutanethiol (Figure 5). Exchange experiments carried out in weighing bottles, wrapped with aluminum foil and kept in the dark to exclude the possible effects of light, were compared to exchange experiments carried out in weighing bottles from which ambient light was not excluded. The rates in light or dark were indistinguishable.<sup>37</sup> Ambient light did not therefore contribute to the rate of exchange observed under our experimental conditions.

The relative stability of SAMs prepared from 4c toward exchange is probably due to the amide group  $\beta$  to the gold/thiolate: intermolecular hydrogen bonding, or changes in bond strength of the gold/thiolate bond, may increase

<sup>(32)</sup> Graham, R. L.; Bain, C. D.; Biebuyck, H. A.; Laibinis, P. E.; Whitesides, G. M. J. Phys. Chem. **1993**, *97*, 9456-9464.

<sup>(33)</sup> Samples left in high vacuum for 24 h could be rederivatized by dipping the samples into a 5 mM ethanolic solution of CF<sub>3</sub>CONH(CH<sub>2</sub>)<sub>11</sub>-SH for 5 min to give SAMs of CF<sub>3</sub>CONH(CH<sub>2</sub>)<sub>11</sub>S/Au. (34) Doig, A. J.; Dudley H. W. J. Am. Chem. Soc. **1992**, 114, 338-

<sup>343.</sup> 

<sup>(35)</sup> Nuzzo, R. G.; Zegarski, B. R.; Dubois, L. H. J. Am. Chem. Soc. 1987, 109, 733-740.

<sup>(36)</sup> Nuzzo, R. G. J. Chem. Phys. 1993, 98, 678-688.

 $<sup>(\</sup>mathbf{37})$  The glass of the container may screen light of the wavelength required for the photodamage of monolayers.

### SAMs on Gold from Alkanethiols

the stability of **4c**. In order to distinguish the effect of  $pK_{\downarrow}$  on the S-Au bond strength, we measured the rate of exchange of a SAM prepared from thioacetic acid with hexadecanethiol in solution. Thioacetic acid has a  $pK_a$  of  $\sim 3$ . Although this value is 5 orders of magnitude lower than the pKa of **4c**, SAMs prepared from thioacetic acid exchanged with hexadecanethiol in ethanol at rates similar to SAMs prepared from propanethiol.

The stability of the SAM prepared from **4c** with respect to thermal desorption and exchange was compared with that of trifluorobutanethiol since trifluorobutanethiol can be synthesized readily from commercially available starting materials. The stability of SAMs prepared from trifluorobutanethiol is comparable to that of those from butanethiol, although trifluorobutanethiol has a larger molecular weight and larger dipolar interactions.

The Rate of Exchange of a SAM Prepared from  $CH_3(CH_2)_{11}CONHCH_2SH$  4a with  $CF_3CONH(CH_2)_{11}SH$  in Solution Was Comparable to That of a SAM Prepared from Hexadecanethiol. SAMs prepared from 4a and hexadecanethiol on gold were allowed to exchange with  $CF_3CONH(CH_2)_{11}SH$  (5 mM) in ethanol and in heptane. The rates of exchange of the SAMs with  $CF_3CONH(CH_2)_{11}SH$  were calculated from the intensity of the F(1s) signal (see Experimental Section). The rates of exchange of the SAMs from 4a and hexadecanethiol with  $CF_3CONH(CH_2)_{11}SH$  in ethanol were similar to those in heptane (see Experimental Section), although only results of exchange in ethanol are shown in Figure 5.

SAMs formed from long-chain alkanethiols exchange more slowly than SAMs formed from short-chain alkanethiols (Figure 5). The effect of the amide group on the rate of exchange of a SAM prepared from 4a was therefore less noticeable than that for SAMs formed from **4c** on the time scale used for these experiments. The rate of exchange of the SAMs with thiols in ethanol may be dependent on the chain length, the  $pK_{a}$ , the presence of functional groups, and the solubility of the thiols in ethanol. SAMs prepared from the short-chain thiols. (butanethiol, 4.4.4-trifluorobutanethiol, and 4c, were allowed to exchange with hexadecanethiol in ethanol. while SAMs prepared from long-chain thiols 4a and hexadecanethiols) were allowed to exchange with  $CF_3$ - $CONH(CH_2)_{11}SH$  in ethanol. The rate of exchange of SAMs with hexadecanethiols in ethanol cannot be directly comparable with those with  $CF_3CONH(CH_2)_{11}SH$  in ethanol although their rates of exchange are plotted on the same graph for convenience.

SAMs of 4c Were Unstable in the Atmosphere of the Laboratory. A monolayer of thiol 4c was unstable to oxidation of its sulfur under ambient conditions (room temperature and pressure and standard laboratory lighting), but this SAM was stable when kept in the dark, as shown by XPS (see Experimental Section). The thiolate in monolayers was 35% and 86% oxidized after 1 and 5 h, respectively, in the atmosphere of the laboratory. The thiolate was oxidized (presumably to a sulfonate) as indicated by the increase in the intensity of XPS S(2p) signal at 168 eV.<sup>19,22</sup> Sulfonates do not form stable monolayers on gold.<sup>35</sup> The percentage of sulfur remaining in the SAM was similar to the amount of residual nitrogen (within the limits of experimental error): this result suggested that light does not induce cleavage of the amide bond but does induce oxidation of the thiolate to sulfonate. This result provides the most direct evidence that the chain organization may be important in protecting the thiolate moiety of SAMs from atmospheric oxidation.



**Figure 6.** The dependence of the rate of damage of a SAM by UV on its thickness and composition. The rates of damage of SAMs prepared from **4c** or 4,4,4-trifluorobutanethiol by UV were determined directly by measuring F(1s) signals of the SAMs by XPS. SAMs derived from **4a** or hexadecanethiol, after exposure to UV and washing, were dipped into a 5 mM solution of CF<sub>3</sub>CONH(CH<sub>2</sub>)<sub>11</sub>SH in ethanol for 5 min. The rates of damage of SAMs prepared from **4a** and hexadecanethiol were determined from the fluorine content, measured by XPS, of these SAMs.

The Rate of UV-Induced Damage of SAMs Depends on the Thickness and the Composition of the Monolayer. UV damage experiments were performed with the SAMs prepared from 4a, 4c, 4.4.4-trifluorobutanethiol, and hexadecanethiol on gold. Different samples were placed side by side, 5 mm under the immersion well of the UV lamp, to ensure that all samples were damaged under similar conditions. After exposure to UV light, samples were washed with ethanol, water, and heptane to remove the oxidized sulfur species. Rates of damage of SAMs prepared from short-chain thiols (e.g., 4c) or 4,4,4trifluorobutanethiol by UV were determined directly from the fluorine content, measured by XPS, of these SAMs. SAMs derived from long-chain thiols (e.g., 4a) or hexadecanethiol, on gold were dipped into a 5 mM solution of  $CF_3CONH(CH_2)_{11}SH$  in ethanol for 5 min after these samples were exposed to UV and washed. Rates of damage of SAMs prepared from 4a or hexadecanethiol were then determined from the fluorine content, measured by XPS, of these SAMs. This procedure provided a reproducible and sensitive method for determining the extent of their oxidation.

All four SAMs were stable when kept in the dark. No photodamage of the SAMs was observed after the SAMs were exposed to UV for 2 h in a nitrogen atmosphere. An oxidant was therefore necessary, but not sufficient, to cause oxidation at the rates observed in these experiments. Light (probably UV, although the wavelength sensitivity remains unknown) is also required for the oxidation of sulfur in SAMs.

SAMs prepared from **4c** and 4,4,4-trifluorobutanethiol were damaged by UV at similar rates, suggesting no discernible effect of the amide group on the rate of oxidation of thiolate to sulfonate for these short chains (Figure 6). SAMs prepared from long-chain thiols (hexadecanethiol and 4a) were damaged more slowly (by ~10 times) than SAMs formed from short-chain thiols (Figure 6). The alkyl chains of the long-chain thiols probably provide a barrier to penetration of these SAMs by oxygen and therefore retard photooxidation of thiolates in these SAMs. SAMs on copper or silver protect the metal from oxidation, and the rate of oxidation of Ag or Cu depends inversely on the thickness of the SAM.<sup>22</sup> Since the thickness of the SAM prepared from **4a** is comparable to that for a SAM prepared from hexadecanethiol, we infer from Figure 6 that the rate of UV-induced oxidation of SAMs from long-chain thiols is dependent on the composition of the monolayer.

UV Lithography Using SAMs Prepared from 4c. Figure 7 demonstrates a strategy for the formation of gold

<sup>(38)</sup> Chadwick, J. E.; Myles, D. C.; Garrell, R. L. J. Am. Chem. Soc. **1993**, *115*, 10364–10365.



Figure 7. Schematic illustration of the procedure used to pattern gold using UV lithography of SAMs followed by a CN  $O_2$  etch.



**Figure 8.** Scanning electron microscopy (SEM) image of a gold pattern prepared by photopatterning of a SAM from **4c** on gold, using a copper grid (line width of about  $60 \,\mu$ m) as a mask, followed by protection of the gold in the region exposed to UV by hexadecanethiol and subsequent etching of the gold under the SAM prepared from **4c** in masked regions of the SAM.

features. This method uses three properties of SAMs from 4c: (1) these SAMs can be damaged faster (~10×) than SAMs prepared from hexadecanethiol. (2) These SAMs slowly exchange with thiols in solution(~10<sup>2</sup>-10<sup>3</sup>×), relative to SAMs from short-chain (four carbons or less) alkanethiols. (3) SAMs formed from 4c do not block the CN<sup>-/</sup>O<sub>2</sub> etch. Figure 8 shows that UV damage of SAMs prepared from 4c, followed by protection of the UV damaged area by hexadecanethiol, and etching away the gold in regions masked from UV light (where SAM from 4c remained) gave gold patterns. The resolution of this process (5 µm) was limited by shadowing effects due to the mask and does not provide a measure of the edge resolution that might be obtained in another experiment.

### Conclusions

We have developed a general synthetic route to alkanethiols useful in forming self-assembled monolayers (SAMs) starting from amines, RNH<sub>2</sub>, and conversion via  $\alpha$ -chloroamides RNHCOCH<sub>2</sub>Cl to thiols RNHCOCH<sub>2</sub>SH. in overall yields in the range 30-80%. The wettabilities (obtained by measuring the contact angles of water and hexadecane) and the thicknesses (as measured by ellipsometry and X-ray photoelectron spectroscopy of SAMs having an amide moiety  $\beta$  to Au/thiolate were similar to those of SAMs of alkanethiols with similar backbone length on gold although their chain organizations, as inferred from vibrational spectroscopy, appear to differ in detail. The interchain H-bonding of the amide moiety of the  ${
m SAM}$ derived from CF<sub>3</sub>CH<sub>2</sub>NHCOCH<sub>2</sub>SH, 4c, seemed to provide additional stabilization; this SAM was significantly more stable than the SAMs from butanethiol or 4,4,4-trifluorobutanethiol against desorption in high vacuum (  $\sim 10^{-9}$ Torr) or exchange with hexadecanethiol in ethanol. SAMs from long-chain alkanethiolates required longer exposure to UV than SAMs from short-chain thiols to accumulate sufficient damage to give clean etching by CN /O<sub>2</sub>. SAMs from 4c may have applications in the fabrication of patterned features by UV lithography: UV damage of SAMs from 4c, followed by protection of the UV damaged area by hexadecanethiol, and etching away the gold in regions masked from UV light where a SAM from 4c remained gave gold patterns

# **Experimental Section**

General. Di vaget, was removed from absolute ethanol before use by subbling a stream. If argon through it for 20 min. Hexadecane: Aldri 1, 94 — was percolated twice through activated, neutral alumina: EM Science . Water was deionized and distilled in a glass and Teffor, apparatus.

16-Mercaptohexadecanol.<sup>-</sup> N- 11-mercaptoundecyl)trifluoroacetamide,<sup>32</sup> trifluorobutanethiol, and the mixed disulfide of 4,4,4trifluorobutanethiol and 16-mercaptohexadecanol<sup>25</sup> were available from previous studies. All chemicals were reagent grade and used as received unless otherwise stated. E. Merck silica gel (Kieselgel 60, 230-400 mesh) was used for liquid column chromatography. Melting points are uncorrected. <sup>4</sup>H and <sup>43</sup>C NMR spectra were obtained on a Bruker AM-400 spectrometer. Chemical shift values are reported in ppm using known chemical shifts of solvent peaks as references.

11-Aminoundecanol (1b). Compound 1b was prepared in two steps from 11-bromo-1-undecanol. 11-Bromoundecanol (6.30 g, 24.0 mmol) was dissolved in 45 mL of *N*,*N*-dimethylformamide. After the addition of 2.4 g (36 mmol) of sodium azide, the mixture was heated to 80 °C for 2 days. The reaction mixture was cooled to room temperature, and 50 mL of water was added to dissolve the salts. The solution was extracted twice with diethyl ether. The combined ethereal layer was washed several times with water and dried with magnesium sulfate. The solvent was removed in vacuo to give 4.95 g (23.2 mmol, 97%) of a vellow oil of 11-azido-1-undecanol. <sup>3</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  1.2-1.4 (overlapping resonance, 14H), 1.45-1.6 (overlapping resonance, 4H), 3.21 (t, J = 7.0 Hz, 2H), 3.56 (t, J = 5.9 Hz, 2H); <sup>13</sup>C NMR (100 MHz,  $CDCl_3$ )  $\delta$  25.60, 26.54, 28.67, 28.99, 29.28, 29.30, 29.41, 32.58, 51.31, 62.66; IR  $vN \equiv N$  (CHCl<sub>3</sub>) 2099 cm<sup>-1</sup>. HRMS-EI (M + H<sup>-</sup>) calcd for C<sub>13</sub>H<sub>24</sub>N<sub>3</sub>O m/z 214.1919, found m/z 214.1932.

11-Azido-1-undecanol (3.88 g, 18.18 mmol) was suspended in 10 mL of tetrahydrofuran (THF) in a round-bottomed flask. The solution was cooled in an ice bath. Borane--tetrahydrofuran complex in THF (1.0 M, 60 mL, 60 mmol) was added slowly to the solution. The ice bath was removed after 30 min, and the solution was heated at reflux for 24 h. The solution was allowed to cool, and the reaction was quenched with methanol. The solvent was evaporated *in vacuo*. The white solid obtained was dissolved in 3% sulfuric acid in ethanol (200 mL), and the solution was refluxed overnight. The solution was neutralized slowly with saturated sodium carbonate solution. Ethanol was evaporated *in vacuo*. Compound **1b** precipitated as a white solid from the aqueous solution and was separated by filtration and washed several times with water. The solid was recrystallized with hexane to give 2.83 g (15.1 mmol, 83%) of **1b**: mp 70–71 °C; <sup>1</sup>H NMR (400 MHz, CD<sub>3</sub>OD)  $\partial$  1.2–1.4 (overlapping resonance, 14H), 1.4–1.55 (overlapping resonance, 4H), 2.61 (t, *J* = 7.1 Hz, 2H), 3.53 (t, *J* = 6.8 Hz, 2H); <sup>13</sup>C NMR (100 MHz, CD<sub>3</sub>OD)  $\partial$  26.96, 28.06, 30.62, 30.65, 30.70, 30.73, 30.76, 33.68, 33.83, 42.58, 63.00. HRMS-CI (M + H<sup>+</sup>) calcd for C<sub>11</sub>H<sub>26</sub>NO *m/z* 188.2014, found *m/z* 188.2008.

Methyl 12-Aminododecanoate (1e). 12-Aminododecanoic acid (4.0 g, 19 mmol) was added to a solution of 25 mL of methanol, 250 mL of toluene, and 1 mL of concentrated sulfuric acid. The mixture was heated at reflux for 20 h. Water resulting from the esterification was collected with a Dean-Stark receiver. Solvent was evaporated in vacuo. The white solid obtained was dissolved in 300 mL of dichloromethane. The organic solution was washed with 1 N NaOH ( $2 \times 50$  mL) and brine (50 mL) and dried with anhydrous magnesium sulfate. Evaporation of solvent gave 3.81 g(16.6 mmol, 89%) of **le** as a white solid: mp 38-40 °C; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ 1.2-1.35 (overlapping resonance, 14H), 1.35-1.45 (m, 2H), 1.5-1.6 (m, 2H), 2.0 (br), 2.27 (t, J = 7.6 Hz, 2H),  $2.67 (t, J = 7.0 \text{ Hz}, 2\text{H}), 3.63 (s, 3\text{H}); {}^{13}\text{C} \text{ NMR} (100 \text{ MHz}, \text{CDCl}_3)$  $\delta$  24.89, 26.83, 29.09, 29.18, 29.36, 29.42, 29.47, 29.54, 33.26, 34.04, 41.95, 51.34, 174.21. HRMS-EI (M<sup>+)</sup> calcd for C<sub>1</sub>(H<sub>17</sub>NO) m/z 229.2042, found m/z 229.2033.

2-Chloro-N-dodecylacetamide (2a). Dodecylamine 1a 3.45 g, 18.6 mmol) was dissolved in 30 mL of dichloromethane, and 3 mL (22 mmol) of triethylamine was added. The solution was cooled in an ice bath, and 2.2 mL (28 mmol) of chloroacetyl chloride was added slowly. The solution was stirred at room temperature for 30 min, during which time a solid precipitated slowly. Dichloromethane was added to the mixture until all of the solids dissolved. The solution was washed twice with saturated sodium carbonate solution and once with water. The organic layer was dried with magnesium sulfate. The solvent was removed by evaporation in vacuo to give 5.70 g of a light yellow solid. The product was recrystallized from hexane to give a total of 4.12 g (15.7 mmol, 85%) of **2a** as a white solid: mp 53-54 °C; <sup>1</sup>H NMR  $(400 \text{ MHz}, \text{CDCl}_3) \delta 0.88 (t, J = 6.7 \text{ Hz}, 3\text{H}), 1.2 - 1.4 (overlapping)$ resonance, 18H), 1.50-1.60 (m, 2H), 3.29 (t, J = 7.0 Hz, 1H), 3.31(t, J = 7.0 Hz, 1H), 4.05 (s, 2H), 6.57 (br, 1H); <sup>13</sup>C NMR (100) MHz, CDCl<sub>3</sub>) & 14.08, 22.65, 26.79, 29.20, 29.30, 29.46, 29.52, 29.59, 31.87, 39.87, 42.67, 165.66. HRMS-FAB (M - H -) calcd for C14H29ClNO m/z 262.1938, found m/z 262.1924

2-Chloro-N-(11-hydroxyundecyl)acetamide (2b). Compound 1b(1.99 g, 10.6 mmol) was dissolved in 50 mL of methanol. The solution was cooled in an ice bath. Triethylamine 6 mL. 43 mmol) and chloroacetyl chloride (3.6 mL, 45 mmol) were added slowly to the solution of 1b over 3 h. The ice bath was removed, and the solution was stirred at room temperature for an additional hour. The solvent was evaporated in vacuo. The light yellow solid obtained was dissolved in chloroform (200 mL). The solution was washed with brine  $(3 \times 50 \text{ mL})$ , the organic fraction was dried with anhydrous magnesium sulfate, and the solvent was removed by evaporation in vacuo. The solid obtained was purified by chromatography with ethvl acetate/hexane (v/v = 40:60) on silica gel. A total of 2.19 g (8.3 mmol, 78%) of 2b was obtained as a white solid: mp 68–69 °C; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$ 1.2-1.4 (overlapping resonance, 14H), 1.5-1.6 (overlapping resonance, 4H), 3.28 (t, J = 7.2 Hz, 1H), 3.30 (t, J = 7.2 Hz, 1H),  $3.62 (t, J = 6.6 Hz, 2H), 4.04 (s, 2H), 6.59 (br, 1H); {}^{13}C NMR (100)$ MHz, CDCl<sub>3</sub>) & 25.70, 26.76, 29.15, 29.27, 29.35, 29.40, 29.49, 32.76, 39.87, 42.66, 62.99, 96.09, 165.70. HRMS-FAB (M + H<sup>+</sup>) calcd for C13H27ClNO2 264.1730, found 264.1732. Anal. Calcd for C<sub>13</sub>H<sub>26</sub>ClNO<sub>2</sub>: C, 59.19; H, 9.93; N, 5.31. Found: C, 59.32; H, 9.87; N, 5.24.

**2-Chloro-***N***·**(**2**,**2**,**2**-trifluoroethyl)acetamide (2c). 2,2,2-Trifluoroethylamine **1c** (1.91 g, 19.3 mmol) in 20 mL of chloroform was cooled in an ice bath. Triethylamine (4.0 mL, 29 mmol) was added, followed by 3.1 mL (39 mmol) of chloroacetyl chloride. The ice bath was removed after 30 min, and the solution was stirred at room temperature for 2 h. The solvent was evaporated to give a brown solid. The desired product **2c** was purified by chromatography on silica gel (ethyl acetate/hexane, v/v = 30:70) to give 1.56 g (8.9 mmol, 46%) of a white solid: mp 50–51 °C; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  3.95 (q, J = 8.9 Hz, 1H), 3.96 (q, J = 8.9 Hz, 1H), 4.11 (s, 2H), 6.98 (br, 1H); <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>)  $\delta$  40.90 (q, J = 35 Hz), 42.25 (s), 123.69 (q, J = 276 Hz), 166.43 (s). HRMS-EI (M<sup>+</sup>) calcd for C<sub>4</sub>H<sub>5</sub>F<sub>3</sub>ClNO *m/z* 175.0012, found *m/z* 175.0018.

**2-Chloro-***N*-(**2-(3,4-dihydroxyphenyl)ethyl)acetamide** (**2d**). Acetamide **2d** was prepared from 2-(3,4-dihydroxyphenyl)ethylamine hydrochloride (the hydrochloride of **1d**) according to the procedure described for acetamide **2b**. The hydrochloride of **1d** (5.05 g, 26 mmol) gave 4.66 g (20 mmol, 78%) of **2d**, after purification by chromatography on silica gel (ethyl acetate/ hexane, v/v = 50:50), as a white solid: mp 94–96 °C; <sup>1</sup>H NMR (400 MHz, CD<sub>3</sub>OD)  $\partial$  2.64 (t, J = 7.2 Hz, 2H), 3.37 (t, J = 7.2 Hz, 2H), 3.40 (s, 2H), 6.52 (dd, J = 8.0, 1.6 Hz, 1H), 6.64 (d, J = 1.6Hz, 1H); 6.67 (d, J = 8.0 Hz, 1H); <sup>13</sup>C NMR (100 MHz, CD<sub>3</sub>OD)  $\partial$  35.65, 42.63, 43.13, 116.38, 116.84, 121.05, 131.71, 144.82, 146.26, 169.13. HRMS-CI (M + NH<sub>4</sub>) calcd for C<sub>10</sub>H<sub>16</sub>ClN<sub>2</sub>O<sub>3</sub> m/z 247.0849, found m/z 247.0837. Anal. Calcd for C<sub>10</sub>H<sub>12</sub>-ClNO<sub>3</sub>: C, 52.30; H, 5.27; N, 6.10. Found: C, 52.10; H, 5.19; N, 6.02.

**Methyl (2-Chloroacetamido)dodecanoate (2e).** Compound **2e** was prepared from **1e** (1.47 g, 6.49 mmol) according to the procedure described for acetamide **2a**. The desired product **2e** was purified by chromatography on silica gel (ethyl acetate/hexane, v/v = 30:70) to give 1.81 g (20 mmol, 92%) of a white solid imp 59 (60 C) (H NMR (400 MHz, CDCL))  $\delta$  1.2 - 1.4 cover.apping resonance, 14H), 1.45 (1.55 (m, 2H), 1.55 (1.65 (m, 2H), 1.25 (1.65

**2-Chloro-***N*-(**4**-(**4-morpholiny**])**benzy**])**acetamide** (2f). Compound **2f** was prepared from **1f** (5.01 g, 28 mmol) according to the procedure described for acetamide **2a**. The desired product **2f** was purified by chromatography on silica gel (ethyl acetate/ hexane, v/v = 50:50) to give 6.05 g (23.8 mmol, 85%) of a white solid: mp 157–158 °C; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  3.13 (t, *J* = 4.8 Hz, 4H), 3.86 (t, *J* = 4.8 Hz, 4H), 4.17 (s, 2H), 6.89 (d, *J* = 8.8 Hz, 2H), 7.43 (d, *J* = 8.8 Hz, 2H), 8.15 (br, 1H); <sup>13</sup>C NMR (100 MHz, CDCl  $\rightarrow \delta$  42.82, 49.49, 66.79, 116.13, 121.63, 129.19, 148.85, 163.57 HRMS-E1 · M · calcd for C<sub>10</sub>H<sub>10</sub>ClN<sub>2</sub>O<sub>4</sub> *m*/z 254.0822, found *m*  $\approx$  254.0828.

2-Chloro-N-dehydroabietylacetamide (2g). Compound 2g was prepared from dehvdroabietylamine acetate (the acetate of 1g) according to the procedure described for acetamide 2a. Dehydroabietylamine acetate (Aldrich, 85%) was recrystallized from hexane before use. The acetate (2.96 g, 8.57 mmol) gave 3.10 g (2.69 mmol, 87%) of 2g, after purification by chromatography on silica gel (ethyl acetate/hexane, v/v = 30.70), as a white solid: mp 48-49 °C; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) & 0.98 (s, 3H), 1.24 (s, 3H),1.25 (d, J = 6.4 Hz, 6H), 1.26–1.35 (overlapping resonance, 1H), 1.35-1.5 (overlapping resonance, 3H), 1.65-1.95 (overlapping resonance, 4H), 2.32 (d, J = 12.8 Hz, 1H), 2.8 - 12.8 Hz, 2H), 2H, 3.0 (overlapping resonance, 3H), 3.17 (dd, J = 6.4, 13.2 Hz, 1H),  $3.30 \,(dd, J = 6.4, 13.2 \,Hz, 1H), 4.07 \,(s, 2H), 6.67 \,(br, 1H), 6.92$ (s, 1H), 7.02 (dd, J = 1.6, 8 Hz, 1H), 7.19 (d, J = 8 Hz, 1H); <sup>13</sup>C NMR(100 MHz, CDCl<sub>3</sub>) & 18.54, 18.57, 19.05, 23.89, 23.92, 25.36, 30.31, 33.37, 36.16, 37.43, 37.48, 38.24, 42.83, 45.64, 50.25, 123.88, 124.15, 126.91, 134.61, 145.61, 146.90, 165.74. HRMS-FAB (M + Na<sup>+</sup>) calcd for C<sub>22</sub>H<sub>32</sub>ClNONa *m/z* 384.2070, found *m/z* 384.2074.

**N-Dodecyl-2-(thioacetyl)acetamide (3a).** Triethylamine (1.3 mL, 9.5 mmol) and thioacetic acid (1.1 mL, 13 mmol) were mixed with cooling in an ice bath. The solution was stirred for about 5 min under argon. Compound **2a** (1.93 g, 7.37 mmol) dissolved in 7 mL of dichloromethane was added slowly to the above solution. The solution was stirred for another 40 min during which a white solid precipitated out slowly. After about 30 mL of dichloromethane was added to dissolve the solution was washed twice with brine. The organic layer was dried with magnesium sulfate, and the solvent was removed by evaporation *in vacuo*. The pale yellow solid obtained was purified by chromatography on silica gel with ethyl acetate/hexane (v/v

= 25:75). Product **3a** (1.88 g, 6.24 mmol, 85%) was obtained as a white solid: mp 66–67 °C; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  0.88 (t, J = 6.6 Hz, 3H), 1.2–1.4 (overlapping resonance, 18H), 1.4–1.5 (m, 2H), 2.41 (s, 3H), 3.20 (t, J = 7.2 Hz, 1H), 3.22 (t, J = 7.2 Hz, 1H), 3.51 (s, 2H), 6.15 (br, 1H); <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>)  $\delta$  14.06, 22.63, 26.74, 29.18, 29.29, 29.47, 29.51, 29.56, 30.20, 31.85, 33.03, 39.83, 167.92, 195.87. HRMS-FAB (M + H<sup>+</sup>) calcd for C<sub>16</sub>H<sub>32</sub>NO<sub>2</sub>S m/z 302.2154, found m/z 302.2136. Anal. Calcd for C<sub>16</sub>H<sub>31</sub>NO<sub>2</sub>S: C, 63.74; H, 10.36; N, 4.65. Found: C, 63.65; H, 10.25; N, 4.58.

General Synthesis of (Thioacetyl)acetamides 3b-3g. Compounds 3b, 3c, and 3e-g were prepared by a procedure similar to that described for 3a. The desired products were obtained as white solids. For 3d, tetrahydrofuran was used as solvent for the reaction, and the desired product 3d was obtained as a light yellow oil.

**N-(11-Hydroxyundecyl)-2-(thioacetyl)acetamide (3b).** mp 83–84 °C; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  1.2–1.4 (overlapping resonance, 14 H), 1.4–1.5 (m, 2H), 1.5–1.6 (m, 2H), 2.41 (s, 3H). 3.20 (t, J = 7.2 Hz, 1H), 3.21 (t, J = 7.2 Hz, 1H), 3.51 (s, 2H). 3.64 (t, J = 6.6 Hz, 2H), 6.17 (br, 1H); <sup>13</sup>C NMR (100 MHz, CDCl,  $\delta$  25.68, 26.71, 29.14, 29.29, 29.34, 29.38, 29.48, 30.23, 32.76, 33.05, 39.84, 63.02, 167.98, 195.94. HRMS-FAB (M + Na + calcd for C<sub>15</sub>H<sub>29</sub>NO<sub>3</sub>SNa *m/z* 326.1766, found *m/z* 326.1769. Anal. Calcd for C<sub>15</sub>H<sub>29</sub>NO<sub>3</sub>S: C, 59.37; H, 9.63; N, 4.62. Found: C, 59.40; H, 9.66; N, 4.62.

**N-(2,2,2-Trifluoroethyl)-2-(thioacetyl)acetamide (3c).** mp 86–88 °C; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  2.43 (s, 3H), 3.57 (s, 2H), 3.87 (q, J = 8.9 Hz, 1H), 3.89 (q, J = 8.9 Hz, 1H), 6.60 (br, 1H); <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>)  $\delta$  30.08 (s), 32.65 (s), 40.89 (q, J = 35 Hz), 123.84 (q, J = 276 Hz), 168.72, 196.08. HRMS-EI (M<sup>+</sup>) calcd for C<sub>6</sub>H<sub>8</sub>F<sub>3</sub>NO<sub>2</sub>S *m/z* 215.0228, found *m/z* 215.0240.

*N*-(2-(3,4-Dihydroxyphenyl)ethyl)-2-(thioacetyl)acetamide (3d). <sup>1</sup>H NMR (400 MHz, CD<sub>3</sub>OD)  $\delta$  2.33 (s, 3H), 2.60 (t, J = 7.6 Hz, 2H), 3.32 (t, J = 7.6 Hz, 2H), 3.55 (s, 2H), 6.49 (d, J = 8.0 Hz, 1H), 6.61 (s, 1H), 6.67 (d, J = 8.0 Hz, 1H); <sup>13</sup>C NMR (100 MHz, CD<sub>3</sub>OD)  $\delta$  30.00, 33.59, 35.63, 42.58, 116.38, 116.88, 121.05, 131.81, 144.76, 146.21, 170.49, 196.05. HRMS-EI M<sup>++</sup> calcd for C<sub>12</sub>H<sub>15</sub>NO<sub>4</sub>S *m/z* 269.0722, found *m/z* 269.0718.

**Methyl 12-(2-(Thioacetyl)acetamido)dodecanoate (3e).** mp 69–71 °C; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  1.2–1.35 (overlapping resonance, 14H), 1.4–1.5 (m, 2H), 1.55–1.65 (m, 2H), 2.30 (t, *J* = 7.6 Hz, 2H), 2.40 (s, 3H), 3.20 (t, *J* = 7.2 Hz, 1H), 3.21 (t, *J* = 6.8 Hz, 1H), 3.51 (s, 2H), 3.66 (s, 3H), 6.17 (br, 1H); <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>)  $\delta$  24.94, 26.76, 29.12, 29.19, 29.21, 29.34, 29.38, 29.45, 30.24, 33.07, 34.10, 39.87, 51.42, 167.97, 174.30, 195.93. HRMS-FAB (M + Na<sup>+</sup>) calcd for C<sub>17</sub>H<sub>31</sub>NO<sub>4</sub>SNa *m/z* 368.1872, found *m/z* 368.1881. Anal. Calcd for C<sub>17</sub>H<sub>31</sub>NO<sub>4</sub>S: C, 59.10; H, 9.04; N, 4.05. Found: C, 59.05; H, 9.12; N, 4.00.

*N*-(4-(4-Morpholinyl)benzyl)-2-(thioacetyl)acetamide (3f). mp 170−171 °C; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\partial$  2.43 (s, 3H). 3.10 (t, *J* = 4.8 Hz, 4H), 3.64 (s, 2H), 3.85 (t, *J* = 4.8 Hz, 4H). 6.85 (d, *J* = 8.8 Hz, 2H), 7.39 (d, *J* = 8.8 Hz, 2H), 8.03 (br, 1H); <sup>15</sup>C NMR (100 MHz, CDCl<sub>3</sub>)  $\partial$  30.22, 34.07, 49.71, 66.80, 116.21, 121.25, 130.37, 148.33, 165.99, 196.72. HRMS-EI (M<sup>+</sup>) calcd for C<sub>14</sub>H<sub>18</sub>N<sub>2</sub>O<sub>3</sub>S *m*/z 294.1038, found *m*/z 294.1027.

**N-Dehydroabietyl-2-(thioacetyl)acetamide (3g).** mp 40–41 °C; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  0.91 (s, 3H), 1.20 (s, 3H), 1.21 (d, J = 6.8 Hz, 6H), 1.25 – 1.4 (overlapping resonance, 4H), 1.6–1.9 (overlapping resonance, 4H), 1.95 (s, 3H), 2.28 (d, J = 12.8 Hz, 1H), 2.81 (h, J = 6.8 Hz, 1H), 2.85–2.95 (overlapping resonance, 3H), 3.31 (dd, J = 7.2, 14 Hz, 1H), 3.39 (d, J = 14 Hz, 1H), 3.50 (d, J = 14 Hz, 1H), 6.33 (br, 1H), 6.89 (d, J = 1.2 Hz, 1H), 6.96 (dd, J = 1.2, 8 Hz, 1H), 7.14 (d, J = 8Hz, 1H); <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>)  $\delta$  18.57, 18.80, 18.84, 23.95, 23.99, 24.99, 29.49, 29.85, 33.02, 33.43, 36.10, 37.22, 37.68, 38.46, 44.44, 49.51, 123.64, 124.08, 126.87, 134.84, 145.62, 147.22, 168.31, 196.72. HRMS-FAB (M + Na<sup>+</sup>) calcd for C<sub>24</sub>H<sub>35</sub>NO<sub>2</sub>SNa *m/z* 424.2286, found *m/z* 424.2294.

**N-Dodecyl-2-mercaptoacetamide (4a).** Compound **3a** (1.20 g, 3.98 mmol) was dissolved in 30 mL of methanol. An aqueous solution of HCl (38%, 6 mL) was added to the solution. The solution was stirred under argon for 12 h. After the evaporation of methanol *in vacuo*, the aqueous solution was

extracted three times with dichloromethane. The combined organic layer was dried with magnesium sulfate. Evaporation of solvent gave 0.94 g (3.6 mmol, 91%) of thiol 4a as a white solid: mp 48–50 °C; <sup>1</sup>H NMR (400 MHz, CDCL,  $\partial$  0.88 (t, J = 7.0 Hz, 3H), 1.2–1.4 (overlapping resonance, 18H), 1.48–1.58 (m, 2H), 1.84 (t, J = 9.2 Hz, 1H), 3.24 (d, J = 9.2 Hz, 2H), 3.27 (t, J = 7.0 Hz, 1H), 3.28 (t, J = 7.0 Hz, 1H), 6.68 (br. 1H); <sup>1</sup>C NMR (100 MHz, CDCl<sub>3</sub>)  $\partial$  14.05, 22.62, 26.83, 28.26, 29.21, 29.27, 29.35, 29.46, 29.50, 29.56, 31.84, 39.91, 168.97. HRMS-FAB (M = H<sup>+</sup>) calcd for C<sub>14</sub>H<sub>29</sub>NOS: C, 64.81; H, 11.27; N, 5.40. Found: C, 65.09; H, 11.10; N, 5.52.

*N*-(11-Hydroxyundecyl)-2-mercaptoacetamide (4b). Thiol 4b was prepared from 3b (0.100 g, 0.30 mmol) according to the procedure described for thiol 4a. Thiol 4b (0.061 g, 0.23 mmol, 77%) was obtained as a white solid: mp 64−65 °C; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\partial$  1.25−1.4 (overlapping resonance, 14H), 1.5−1.6 (overlapping resonance, 4H), 1.84 (t, *J* = 9.0 Hz, 1H), 3.24 (d, *J* = 9.0 Hz, 2H), 3.27 (t, *J* = 6.7 Hz, 1H), 3.29 (t, *J* = 6.7 Hz, 1H), 3.64 (t, *J* = 6.6 Hz, 2H), 6.69 (br, 1H); <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>)  $\partial$  25.70, 26.83, 28.29, 29.18, 29.35, 29.41, 29.49, 32.77, 39.98, 63.05, 169.06. HRMS-FAB (M + H<sup>+</sup>) calcd for C<sub>13</sub>H<sub>28</sub>NO<sub>2</sub>S *m/z* 262.1841, found *m/z* 262.1829.

*N*-(2,2,2-Trifluoroethyl)-2-mercaptoacetamide (4c). Thiol 4c was prepared from 3c (0.11 g, 0.51 mmol) according to the procedure described for thiol 4a. Thiol 4c (0.064 g, 0.37 mmol, 72%) was obtained as a thick slurry which turned to a white solid on cooling to 5 °C. <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  1.92 (t, J = 9.2 Hz, 1H), 3.33 (d, J = 9.2 Hz, 2H), 3.95 (q, J = 8.9 Hz, 1H), 3.96 (q, J = 8.9 Hz, 1H), 7.02 (br, 1H); <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>)  $\delta$  28.08 (s), 41.05 (q, J = 35 Hz), 123.88 (q, J = 278 Hz), 169.40 (s). HRMS-EI (M<sup>+</sup>) calcd for C<sub>4</sub> H<sub>6</sub> F<sub>3</sub> NOS *m*/*z* 173.0122, found *m*/*z* 173.0116.

**N**-(2-(3,4-Dihydroxyphenyl)ethyl)-2-mercaptoacetamide (4d). Thiol 4d was prepared from 3d (0.15 g, 0.56 mmol) according to the procedure described for thiol 4a. Thiol 4d (0.12 g, 0.53 mmol, 94 e was obtained as a light yellow oil. <sup>1</sup>H NMR 400 MHz, CD (D)  $\rightarrow$  2.64 t, J = 7.6 Hz, 2H), 3.11 (s, 2H), 3.34 t, J = 7.6 Hz, 2H, 6.52 dd, J = 6.7, 2.0 Hz, 1H), 6.64 (d, J =2.0 Hz, 1H, 6.67 d, J = 6.7 Hz, 1H); <sup>5</sup>C NMR (100 MHz, CDCl<sub>3</sub>)  $\delta$  27.66, 35.30, 42.78, 116.31, 116.78, 120.96, 131.43, 144.62, 146.02, 174.69. HRMS-EI (M<sup>+</sup>) calcd for C<sub>10</sub>H<sub>13</sub>NO<sub>3</sub>S *m*/z 227.0616, found *m*/z 227.0607.

12-(2-Mercaptoacetamido)dodecanoic acid (4e). Ester 3e (0.21 g, 0.59 mmol) was suspended in 20 mL of 1N NaOH. The white suspension was stirred at room temperature under nitrogen for 24 h to give a colorless solution. The solution was acidified with a 38% aqueous solution of HCl. The white solid precipitate was filtered and dissolved in dichloromethane. The solution was  ${\it dried\,with\,anhydrous\,magnesium\,sulfate.}\ Evaporation\,of\,solvent$ gave 0.16 g (0.55 mmol. 94%) of thiol 5 as a white solid: mp 75-76 °C; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  1.25–1.4 (overlapping resonance, 14H), 1.5 · 1.6 (m, 2H), 1.6 – 1.7 (m, 2H), 1.87 (t, J = 9.2 Hz, 1H), 2.34 · , J = 7.6 Hz, 2H), 3.26 (d, J = 9.2 Hz, 2H),  $3.28 (t, J = 7.6 Hz, 2H, 6.78 (br, 1H); {}^{13}C NMR (100 MHz, CDCl_3)$ o 24.68, 26.79, 28 30, 28.94, 29.07, 29.15, 29.24, 29.31, 29.34, 29.36, 33.93, 40.02, 169.31, 178.72. HRMS-FAB (M + Na<sup>+</sup>) calcd for  $C_{14}H_{27}NO_3SNa m/z$  312.1609, found m/z 312.1612. Anal. Calcd for C14H3 NOS: C, 64.81; H, 11.27; N, 5.40. Found: C, 65.09; H, 11.10; N, 5.52. Anal. Calcd for  $C_{14}H_{27}NO_3S$ : C, 58.10; H, 9.40; N, 4.84 Found: C, 58.11; H, 9.50; N, 4.80.

**2-Mercapto-V-(4-(4-morpholinyl)benzyl)acetamide (4f).** Compound **3f** (0.16 g, 0.54 mmol) and sodium methoxide (0.03 g, 0.54 mmol) were dissolved in 5 mL of methanol and stirred at room temperature under argon for 12 h. The solution was acidified to pH 4 with 38% aqueous solution of HCl. The solvent was evaporated, and 5 mL of water was added to dissolve the inorganic salt. The undissolved solid was filtered, washed with water, and dried *in vacuo* to give 0.091 g (0.36 mmol, 72%) of thiol **4f** as a white solid: mp 230 °C (decomp); <sup>1</sup>H NMR (400 MHz, DMSO-*d*<sub>6</sub>)  $\delta$  3.18 (t, *J* = 8.0 Hz, 1H), 3.33 (d, *J* = 8.0 Hz, 2H), 3.47 (br, 4H), 4.03 (br, 4H), 7.70 (br, 2H), 7.74 (s, 1H), 7.76 (s, 1H), 10.85 (br, 1H); <sup>13</sup>C NMR (100 MHz, DMSO-*d*<sub>6</sub>)  $\delta$  28.21, 53.34, 63.85, 119.87, 119.98, 120.97, 138.58, 169.09. HRMS-EI (M<sup>+</sup>) calcd for C<sub>12</sub>H<sub>16</sub>N<sub>2</sub>O<sub>2</sub>S *m/z* 252.0933, found *m/z* 252.0937.

**N-Dehydroabietyl-2-mercaptoacetamide (4g).** Thiol **4g** was prepared from **3g** (0.11 g, 0.27 mmol) according to the

Table 2.	X-ray	Photoelectro	n Spectroscopic	Data	of SAMs
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	XPS binding energy (eV)								
SAM prepared from	$\overline{F(1s)}$	O(1s)	N(1s)	C(1s)	S(2p <sup>3/2)</sup>	$S(2p^{1/2})$	$Au(4f^{7/2})$	$Au(4f^{5/2})$	
$CH_3(CH_2)_{11}NHCOCH_2SH(4a)$		531	399	287, 285	164	162	88	84	
$HO(CH_2)_{11}NHCOCH_2SH (\mathbf{4b})$		533, 531	400	287, 285	164	162	88	84	
$CF_3CH_2NHCOCH_2SH(4c)$	688	531	400	292, 287, 286, 284	164	162	88	84	
$CF_3(CH_2)_3SH$	687			292, 284	163	161	88	84	
HO $\leftarrow$ CH <sub>2</sub> CH <sub>2</sub> -NHCOCH <sub>2</sub> SH (4d)		533, 531	399	287, 285, 284	163	162	88	84	
HOOC(CH <sub>2</sub> ) <sub>11</sub> NHCOCH <sub>2</sub> SH ( <b>4e</b> )		533, 532	399	285	163	162	88	84	
		532, 530	399	287, 286, 285, 284	163	162	87	84	
H <sub>3</sub> C CH <sub>2</sub> -NHCOCH <sub>2</sub> SH ( <b>4</b> g)		531	399	287, 284	163	162	88	84	

procedure described for thiol **4a**. Thiol **4g** (0.088 g, 0.24 mmol, 89%) was obtained as a white solid: mp 105–107 °C; <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  0.96 (s, 3H), 1.22 (s, 3H), 1.22 (d, J = 6.8 Hz, 6H), 1.25–1.55 (overlapping resonance, 4H), 1.65–1.95 (overlapping resonance, 5H), 2.29 (d, J = 12.4 Hz, 1H), 2.75–3.0 (overlapping resonance, 3H), 3.15 (dd, J = 6.4, 13.6 Hz, 1H), 3.25–3.35 (overlapping resonance, 3H), 6.85 (br, 1H), 6.89 (d, J = 1.6 Hz, 1H), 7.00 (dd, J = 1.6, 8 Hz, 1H), 7.17 (d, J = 8 Hz, 1H); <sup>13</sup>C NMR (100 MHz, CDCl<sub>3</sub>)  $\delta$  18.52, 19.14, 23.93, 25.32, 26.65, 30.11, 33.40, 36.27, 37.51, 37.84, 38.17, 45.85, 51.72, 123.93, 124.16, 126.90, 134.46, 145.71, 146.80, 173.26. HRMS-FAB (M + H<sup>+</sup>) calcd for C<sub>22</sub>H<sub>34</sub>NOS *m*/*z* 360.2361, found *m*/*z* 360.2370.

**Preparation of Substrates.** Gold films supported on silicon wafers were prepared by electron-beam evaporation of ~10 Å of titanium (Aldrich, 99.99%), used to promote adhesion of the gold to SiO<sub>2</sub>, followed immediately (~1 s) by evaporation of ~1000 Å of high-purity gold (Materials Research Corp., Orangebury, NY, 99.9999%) onto single crystal silicon(100) test wafers (Silicon Sense: Nashua, NH; 100 mm diameter, ~500  $\mu$ m thick). The metals were evaporated at a rate of 3 Å/s onto substrates at ~20 °C.

Formation of SAMs. Adsorption on gold of thiols from their solution in ethanol was performed according to the procedure published previously. Except that 0.06 mM acetic acid was added. unless stated otherwise, to the solutions of thiols 4a-g to minimize the formation of disulfide.

Characterization of SAMs. Contact angles were measured on a Rame-Hart Model 100 goniometer at room temperature and ambient humidity. Advancing and receding contact angles were measured on each side of at least 3 drops of each liquid on the SAMs; data reported represent the average of these measurements. A Micro-Electrapette syringe (Matrix Technologies, Lowell, MA) was used for dispensing or removing the liquids onto or from the SAMs. Ellipsometric measurements were made using a Rudolf Research Type 43603-200E ellipsometer equipped with a He–Ne laser ( $\lambda = 6328$  Å) at an incident angle of 70°. Values of thickness were calculated using a program written by Wasserman.<sup>39</sup> The procedures for contact angles and ellipsometric measurements were described previously.<sup>3</sup> X-ray photoelectron spectroscopy (XPS) was performed with an Surface Science Instruments X-100 spectrometer. Detection was performed with a concentric hemispherical analyzer operating in fixed analyzer transmission mode and a multichannel detector: the angle between the sample and detector was  $36.5^{\circ}$ . The area of the sample illuminated by X-rays was  $\sim 600 \text{ nm}^2$ , and the acquisition time of the sample was  $\sim 50$  min for high-resolution analysis (Table 2). No compensating flood gun was used in this study since all samples were conducting and grounded to the spectrometer. The thicknesses of SAMs derived from 4a-g were

#### Table 3. Exchange of SAMs Prepared from 4a or from Hexadecanethiol with 5 mM Solution of CF<sub>3</sub>CONH(CH<sub>2</sub>)<sub>11</sub>SH in Heptane

SAM prepared from	% exchange after 3 days	で exchange after 10 days
CH_CHNHCOCH_SH+ <b>4a</b> CH_CHSH	4) ±5) 8 ±5)	$\frac{21(\pm5)}{23(\pm5)}$

calculated from the XPS intensities of the Au(4f  $^{\rm 2})$  peak of the samples using the relationship described in eq 2:40

$$Au_d = Au_{d=0}(e^{-d/(\lambda_{Au}\sin\theta)})$$
(2)

where  $\operatorname{Au}_d$  and  $\operatorname{Au}_{d=0}$  are the intensities of the  $\operatorname{Au}(4f^{7/2})$  peak due to a SAM of thickness *d* and bare gold, respectively;  $\lambda_{\operatorname{Au}}$  (equal to 42 Å)<sup>40</sup> is the inelastic mean free path of the  $\operatorname{Au}(4f^{7/2})$ photoelectron;  $\theta$  (equal to 36.5°) is the angle between the analyzer and the sample – The value  $\operatorname{Au}_{d=0}$  was determined using eq 2 for a SAM derived from hexadecanethiol, which has a thickness (*d*) of 20 A. as a standard.

**Exchange with Thiols in Solution.** The exchange of SAMs prepared from butanethiol or **4c** with hexadecanethiol was followed by dipping the SAMs in a 5 mM ethanolic solution of hexadecanethiol in a weighing bottle kept in the dark. After a fixed time, the sample was removed from the vial and washed with 10 mL of ethanol, 10 mL of water, and 10 mL of heptane. The percentage exchange of SAM prepared from butanethiol (C4SH) with hexadecanethiol (C16SH) was obtained from the surface composition ( $\chi_n =$  mole fraction of component n) of the mixed SAM after exchange (eq 3).

$$\% \text{ exchange} = \chi_{\text{C16SH}} \times 100\% \tag{3}$$

To evaluate the surface composition  $(\chi_n)$ , we assumed that the thickness (d) of a SAM composed of the two thiolates was the simple weighted average of the thicknesses of SAMs derived from the individual thiols (eq 4).<sup>41</sup>

$$d = (\chi_{C4SH}d_{C4SH}) + (\chi_{C16H}d_{C16SH})$$
(4)

Equation 4 assumes that the packing density of the SAM does not change with surface composition. The surface composition was determined by comparing the thickness of the mixed SAM

<sup>(39)</sup> Wasserman, S. R.; Whitesides, G. M.; Tidswell, I. M.; Ocko, B. M.; Pershan, P. S.; Axe, J. D. J. Am. Chem. Soc. **1989**, 111, 5852-5861.

<sup>(40)</sup> Bain, C. D.; Whitesides, G. M. J. Phys. Chem. 1989, 93, 1670-1673.

<sup>(41)</sup> Laibinis, P.; Fox, M. A.; Folkers, J. P.; Whitesides, G. M. Langmuir 1991, 7, 3167-3173.

 Table 4. Data from XPS of a SAM from 4c That Show That This SAM Is Unstable under Standard Laboratory

 Conditions but Is Stable When Kept in the Dark

exposure		F(1s)	N(1s)	$S(2n)^b$	$S(2n^{3/2})^{c}$	$S(2n^{1/2})^{c}$	
$light^a$	time (h)	687.8 eV	399.7  eV	168.0 eV	163.6 eV	162.2 eV	% oxidation <sup>d</sup>
as prepared		100	100	0	100	100	0
no	1	97	100	0	100	100	0
yes	1	61	70	$0^{\rm e}$	65	65	35
no	5	97	100	0	98	98	0
yes	5	29	46	$29^{e}$	14	14	86

<sup>*a*</sup> Standard laboratory lighting. <sup>*b*</sup> The observed peak is the combined  $S(2p^{1/2})$  and  $S(2p^{3/2})$  peaks of sulfonates (RSO<sub>3</sub>) which are unresolved for this weak signal. <sup>*c*</sup> S(2p) peak of gold thiolates. <sup>*d*</sup> Calculated as (100 -  $I_{S(2p^{1/2})}$ ).  $I_{S(2p^{1/2})}$  is the normalized intensity of the  $S(2p^{1/2})$  peaks of the thiolate remained. <sup>*c*</sup> Sulfonates do not form stable monolayers on gold.<sup>38</sup>

to the thickness of SAMs derived from the individual components (eq  $\,5).^{41}$ 

$$\chi_{\rm C16SH} = \frac{d - d_{\rm C4SH}}{d_{\rm C16SH} - d_{\rm C4SH}}$$
(5)

The thickness of each SAM was calculated from the XPS intensity of its C(1s) peak using eq 6:

$$C_d = C_{\infty} \left(1 - e^{-d/(\lambda_c \sin \theta)}\right) \tag{6}$$

where  $C_d$  and  $C_{\infty}$  are the intensities of the C(1s) peak due to a monolayer of thickness d and an infinitely thick layer of hydrocarbon respectively;  $\lambda_{\rm C}$  (equal to 35 Å)<sup>40</sup> is the inelastic mean free path of the C(1s) photoelectron.  $C_{\infty}$  was determined from a SAM derived from hexadecanethiol (d = 20 Å)<sup>3</sup> using eq 6.

The percentage exchange of SAMs derived from **4c** or 4.4.4-trifluorobutanethiol with hexadecanethiol was obtained from the surface composition  $(\chi_n = \text{mole fraction of component } n \cdot \text{of the mixed SAM obtained after exchange } (eq 3)$ . The exchange of hexadecanethiol with SAMs derived from **4c** or 4.4.4-trifluorobutanethiol resulted in a decrease in the mole fraction of the fluorinated component on the surface and an increase in the thickness of the monolayer that attenuated the F(1s) signal. To determine the surface composition  $\chi_n$  of the SAMs after exchange, we monitored the F(1s) signal (*I*) and corrected this signal for attenuation:

$$I = (1 - \chi_{\rm C16SH}) I_{\rm F} \left( e^{-\Delta/(\lambda_{\rm F} \sin \theta)} \right)$$
(7)

where  $I_{\rm F}$  is the intensity of the F(1s) peak of SAMs prepared from **4c** (or 4,4,4-trifluorobutanethiol);  $\lambda_{\rm F}$  (equal to 27 A)<sup>46</sup> is the inelastic mean free path of the F(1s) photoelectron;  $\Delta$  is the increase in the thickness of the monolayer resulting from exchange (eq 8). The value  $d_{\rm F}$  is the thickness of a SAM derived from **4c** (or 4,4,4-trifluorobutanethiol).

$$\Delta = \chi_{\rm C16SH} (d_{\rm C16SH} - d_{\rm F}) \tag{8}$$

Exchange of SAMs prepared from **4a** or from hexadecanethiol with  $CF_3CONH(CH_2)_{11}SH$  was performed by dipping these SAMs in a 5 mM ethanolic solution of  $CF_3CONH(CH_2)_{11}SH$  for a fixed time. The amount of exchange was determined by comparison of the F(1s) signal of the mixed SAM ( $I_{mix}$ ) obtained after exchange with the intensity ( $I_{std}$ ) for a SAM derived from  $CF_3CONH(CH_2)_{11}$ -SH:

% exchange = 
$$\frac{I_{\text{mix}}}{I_{\text{std}}} \times 100\%$$
 (9)

The exchange of SAMs prepared from 4a or from hexadecanethiol with CF<sub>3</sub>CONH(CH<sub>2</sub>)<sub>11</sub>SH in heptane was performed using the same procedure described for the exchange experiments performed in ethanol (Table 3).

SAMs from 4c Are Unstable in the Atmosphere of Laboratory. SAMs from 4c were left under ambient conditions (room temperature and pressure and standard laboratory lighting) for a fixed time. After photodamage, the SAMs were not washed with water or any solvents, and the composition of these monolayers was analyzed immediately by XPS (Table 4). The amount of photooxidation of sulfur in these SAMs was determined by comparison of the XPS intensity of the  $S(2p^{3/2})$  and the  $S(2p^{1/2})$ signal, at 163.6 eV and 162.2 eV, respectively, of SAMs before and after their exposure to light.

**UV-Induced Damage of SAMs.** UV damage of SAMs was induced by a Canrad-Hanovia 450 W medium pressure mercury vapor lamp (type 7825-34 from ACE Glass) that was water cooled (type 7854B from ACE Glass). The UV damage experiments were performed with substrates lying side by side, at about 5 mm under the immersion well of the UV lamp, to ensure that SAMs were damaged under similar conditions. After UV-induced damage, the samples of SAMs prepared from **4a** or from hexadecanethiol were dipped into a 5 mM ethanolic solution of CF<sub>3</sub>CONH(CH<sub>2</sub>)<sub>11</sub>SH for 5 min and then analyzed by XPS. The percentage of damage was calculated from the F(1s) signal of the mixed SAM obtained  $L_{\rm ex}$  compared with that of a SAM prepared from CF CONH CH<sub>2</sub> wSH  $L_{\rm ext}$ , eq 10:

$$\bar{e} \text{ damage} = \frac{I_{\text{mix}}}{I_{\text{std}}} \times 100\%$$
 (10)

The percentage of damage of SAMs derived from 4c or from 4,4,4-trifluorobutanethiol was determined by monitoring the decrease in the F(1s) peak (*I*) of the SAMs after its exposure to UV for a fixed time t (eq 11).

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$$G \text{ damage} = \frac{(I_{t=0} - I_t)}{I_{t=0}} \times 100\%$$
 (11)

UV Lithography Using SAMs from 4c. Photopatterning of SAMs from 4c used a copper grid G075 (Bio-rad) placed in contact with the SAM as a mask. Lines on the grid were  $60 \mu m$ wide and  $20 \mu m$  thick. The sample was placed 2 cm below the UV lamp. The mask was removed after UV-induced damage of the SAM of 4c and dipped into a 5 mM solution of hexadecanethiol for 2 min. The etching was performed using a 1 M KOH/0.1 M KCN solution saturated with oxygen.

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