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Self-Assembled Monolayers of Receptor Adsorbates on Gold: Preparation and Characterization

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In supramolecular chemistry, much of the work is inspired by possible applications.[1] We have exploited[2] host–guest interactions between macrocyclic receptor molecules and various guest species in selective membrane transport[3,4] and sensors based on chemically modified field effect transistors.[5] In these systems, crown ether- and calix[4]arene-based receptors are incorporated in thin polymeric membranes. Recently, we have shown that by electrical poling of thin films of neat tetranitrocalix[4]arene, highly ordered, stable materials could be obtained with promising second-order NLO properties.[6] One of the challenges of supramolecular chemistry is the development of new materials with well-defined properties based on specially designed properties of the molecular constituents. For the translation of the intrinsic properties of molecules into material properties, it is essential to have control over the molecular interactions and orientation in the material. An elegant strategy is the self-assembling of molecules in organized mono- and multilayers.[7,8] In this communication, we present the design and synthesis of resorcin[4]arene[9,10]-based receptor molecules containing four alkyl sulfide chains which self-assemble into stable, well-packed monolayers on gold substrates.

Organosulfur compounds bind strongly to gold surfaces, and several self-assembled monolayers of adsorbates consisting of a surface-active sulfur group, an alkyl chain, and a terminal functional group (OH, COOH) have been reported.[11-17] Only one example is known of an adsorbate containing a receptor cavity, i.e., heptakis(dodecyl sulfide) cyclodextrin adsorbate.[18] Although the compound was initially reported to form monolayers that discriminate between redox couples of different sizes, careful reexamination showed that the cyclodextrin cavity was not utilized; the redox reactions occurred via defects in the monolayer structure.[19] Such undesired interactions should be prevented by introducing a densely packed hydrocarbon layer between the gold substrate and the receptor moieties.

Resorcin[4]arenes (e.g., **4a–c**) are well suited for this purpose. In addition to the conelike cavity formed by the four resorcinol units, four points of attachment are available for alkyl chains at the methine linkages. These parallel chains are all oriented perpendicular with respect of the annulus of the macrocycle at a distance of 5 Å. By connecting four 11-thiaheneicosyl chains to the methine linkages, adsorbates are obtained that are able to form a well-packed monolayer. The sulfur atoms bind to the gold, forcing the terminal alkyl chains to loop back. The total lateral area of the alkyl chains in this conformation (ca. 160 Å^2) is slightly larger than the area of about 140 Å^2 occupied by the headgroup.

The synthetic strategy is shown in Scheme 1 and starts with the acid-catalyzed condensation of resorcinol and 10-undecylenic aldehyde, forming the cyclic tetramer **2** in the CCC conformation only. Subsequently, **2** was converted into the adsorbates **4a–c**. Treatment of **2** with bromochloromethane and sodium hydride in DMF yielded the rigid cavitand **3a**, methylation of **2** with methyl iodide and sodium hydride in DMF afforded the flexible octamethylate **3b**, and acylation with acetic acid anhydride and pyridine gave the octaacetate **3c**. Finally, selective addition of 1-decanethiol to the double bonds[20] of **3a–c** afforded the tetrasulfide adsorbates **4a–c**.[21]

Immersion of a polished gold disk electrode[22,23] in 1 mM solutions of the tetrasulfide adsorbates **4a–c** in dichloromethane for 16 h at room temperature yielded disordered submonolayers, as was concluded from the monolayer's inability to block the heterogeneous electron transfer between $Fe(CN)_6^{3-}$ in solution and the gold electrode.[24] However, the monolayer quality could be considerably improved by heating, and highly impervious monolayers were obtained by immersion of the gold substrate into an ethanol:chloroform (3:1 v/v) adsorbate solution at 60 °C for 13 h (see Figure 1; for monolayer characterization, see Table 1). The unique presence of a thermal activation barrier in the assembly process is attributed to the architecture of the adsorbate, having *four* flexible tethered surface-active groups with a high affinity for gold. When the adsorbate reaches the surface, it will not necessarily adsorb with all eight alkyl chains in the most densely packed, parallel orientation. At room temperature, the loose packing of the alkyl chains will be largely fixed by the strong sulfide–gold interaction, and kinetically disordered layers will be formed. At higher temperatures, however, the sulfide–gold interaction can be reversibly broken, and reorganization of the monolayer to an energetically more favorable structure with all alkyl chains oriented parallel can occur.[25] Adsorption sites that become vacant can now be filled by new adsorbates, resulting in a thermodynamically controlled, highly ordered structure with few defects.

These monolayers were also prepared on freshly evaporated gold substrates[26,27] and studied with a variety of surface analytical

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(1) *Crown compounds:towards future applications*; Cooper, S. R., Ed.; VCH Publishers: Weinheim, 1992.

(2) Van Dienst, E.; Iwema Bakker, W. I.; Engbersen, J. F. J.; Verboom, W.; Reinhoudt, D. N. *Pure Appl. Chem.* **1993**, *65*, 387–392.

(3) Van Straaten-Nijenhuis, W. F.; Van Doorn, A. R.; Reichwein, A. M.; de Jong, F.; Reinhoudt, D. N. *J. Org. Chem.* **1993**, *58*, 2265–2271.

(4) Nijenhuis, W. F.; Buitenhuis, E. G.; de Jong, F.; Südholter, E. J. R.; Reinhoudt, D. N. *J. Am. Chem. Soc.* **1991**, *113*, 7963–7968.

(5) Cobben, P. L. H. M.; Egberink, R. J. M.; Bomer, J. G.; Bergveld, P.; Verboom, W.; Reinhoudt, D. N. *J. Am. Chem. Soc.* **1992**, *114*, 10573–10582.

(6) Kelderman, E.; Derhaeg, L.; Heesink, G. J. T.; Verboom, W.; Engbersen, J. F. J.; Van Hulst, N. F.; Persoons, A.; Reinhoudt, D. N. *Angew. Chem., Int. Ed. Engl.* **1992**, *31*, 1075–1077.

(7) Katz, H. E.; Scheller, G.; Putvinski, T. J.; Schilling, M. L.; Wilson, W. L.; Chidsey, C. E. D. *Science* **1991**, *254*, 1485.

(8) Kakkar, A. K.; Yitzchaik, S.; Roscoe, S. B.; Kubota, F.; Allan, D. S.; Marks, T. J.; Lin, W.; Wong, G. K. *Langmuir* **1993**, *9*, 388–390.

(9) Official IUPAC name: 2,8,14,20-tetraalkylpentacyclo[19.3.1.1^{3,7}.1^{9,13}.1^{15,19}]octacosa-1(25),3,5,7(28),9,11,13(27),15,17,19(26),21,-23-dodecaene-4,6,10,12,16,18,22,24-octol.

(10) Högberg, A. G. S. *J. Am. Chem. Soc.* **1980**, *102*, 6046–6050.

(11) Ulman, A. *Ultrathin Organic Films*; Academic Press: Boston, 1991; and references cited therein.

(12) Dubois, L. H.; Nuzzo, R. G. *Annu. Rev. Phys. Chem.* **1992**, *43*, 437–463.

(13) Bain, C. D.; Whitesides, G. M. *Adv. Mater.* **1989**, *1*, 506–512.

(14) *Supramolecular architecture; Synthetic control in thin films and solids*; Bein, T., Ed.; ACS Symposium Series 499; American Chemical Society: Washington, DC, 1992; Chapter 2.

(15) Bain, C. D.; Troughton, E. B.; Tao, Y.-T.; Evall, J.; Whitesides, G. M.; Nuzzo, R. G. *J. Am. Chem. Soc.* **1989**, *111*, 321–325.

(16) Chidsey, C. E. D.; Loiacono, D. N. *Langmuir* **1990**, *6*, 682–691.

(17) Troughton, E. B.; Bain, C. D.; Whitesides, G. M.; Allara, D. L.; Porter, M. D. *Langmuir* **1988**, *4*, 365–385.

(18) Chung, C. Ph.D. Dissertation. Iowa State Univ., Ames, IA, 1990.

(19) Tamagaki, S.; Fukuda, K.; Sumita, H.; Tagaki, W. *Chem. Exp.* **1991**, *6*, 695–698.

(20) Masuda, Y.; Hoshi, M.; Nunokawa, Y.; Arase, A. *J. Chem. Soc., Chem. Commun.* **1991**, 1444–1445.

(21) All compounds were characterized by NMR, IR, and FAB-MS and gave satisfactory elemental analysis.

(22) Molten, pressed, and polished gold electrodes were cleaned by treatment with boiling sulfuric acid and electrochemical cycling until the well-known features of clean gold appeared.[23]

(23) Dalbera, J. P.; Hinnen, C.; Rousseau, A. *J. Phys., Colloq.* **1977**, *38*, C5–C185.

(24) SPS thickness measurements indicated that these assemblies are only 12–14 Å thick; furthermore the XPS spectrum showed signals of oxidized carbon and sulfur.

(25) Other processes like surface reorganization and desorption of adventitously adsorbed impurities will probably occur simultaneously.

(26) A 2000-Å gold substrate was resistively evaporated at 225 °C on freshly cleaved mica.

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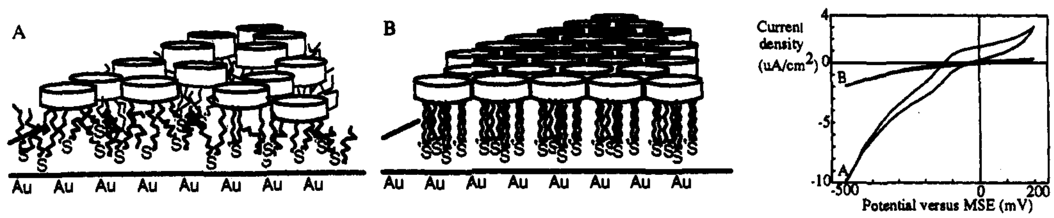
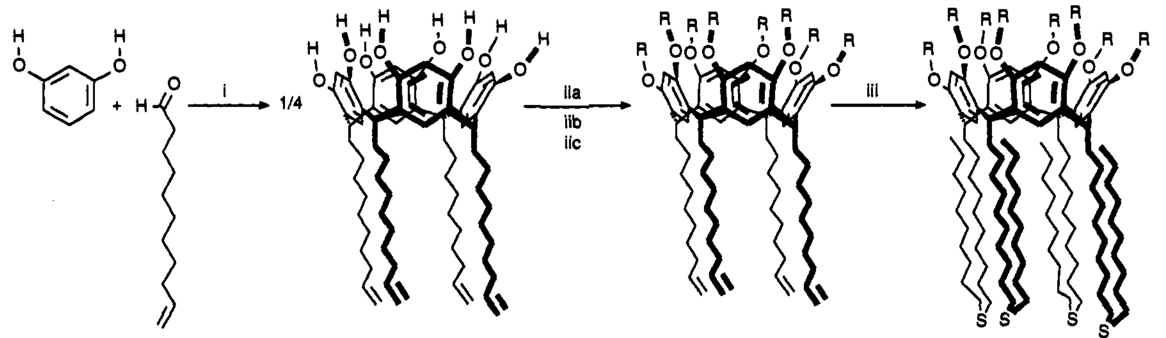


Figure 1. Monolayers of **4a** block the heterogeneous electron transfer between a gold electrode and a 1 mM $K_3Fe(CN)_6{}^{3-}$, 0.1 M K_2SO_4 electrolyte better when they are prepared at 60 °C in a 1 mM adsorbate solution (B), compared to room temperature prepared monolayers (A). This change is attributed to a monolayer reorganization, as is schematically depicted on the righthand side.

Scheme 1[a]



1

2

3a R,R = CH_2
3b R = CH_3
3c R = $C(O)CH_3$

4a R,R = CH_2
4b R = CH_3
4c R = $C(O)CH_3$

[a] (i) EtOH, HCl, 60°C, 16 h, 20%; (iia) $BrCH_2Cl$, NaH, DMF, 60°C, 72 h, 20%; (iib) CH_3I, NaH, DMF, 60°C, 48 h, 80%; (iic) Ac_2O, C_5H_5N, 100°C, 1 h, 60%; (iii) $H(CH_2)_{10}SH$, 9-BBN, THF, 16 h, 0°C -> room temperature, 75%.

Table 1. Monolayer Characterization

adsorbate	$\theta_a^{H_2O}$	$\theta_r^{H_2O}$, deg[a]	thickness, Å[b]	eff thickness, Å[c]
4a	105 ± 4	81 ± 2	22 ± 2	18 ± 2
4b	102 ± 2	74 ± 2	24 ± 2	18 ± 2
4c	99 ± 2	81 ± 2	22 ± 2	18 ± 2

[a] Sessile drop measurements, average of at least four different measurements. [b] The change in surface plasmon resonance angle was measured three times and averaged and used to calculate the thickness, assuming a refractive index of the monolayer of 1.50. [c] Effective thicknesses were calculated assuming a relative permittivity of the monolayer of 2.3.

techniques:[12] polarized infrared external reflectance spectroscopy (PIERS), X-ray photoelectron spectroscopy (XPS), surface plasmon spectroscopy (SPS), contact angle measurements, secondary ion mass spectroscopy (SIMS), and atomic force microscopy (AFM).

The PIERS spectra of the monolayers resemble the reported spectrum of didodecyl sulfide on gold,[17] with the asymmetrical and symmetrical stretch vibrations at 2925 and 2854 cm^{-1}, respectively, indicating the presence of gauche conformations in the alkyl chains. These undesired defects in the chain packing may result from the looped chain structure but can also imply a liquid-like packing.[28] The XPS spectra of the monolayers revealed signals originating from gold, carbon, oxygen, and sulfur.[29] The relatively strong O1s signal at 532 eV and the weak signal S2p at 163 eV indicate that the oxygen-rich headgroups reside near the outer interface and that the sulfur atoms are located near the gold surface. Contact angle measurements also indicate that the headgroups are located near the outer interface. The advancing contact angle with water was found to decrease with increasing polarity of the headgroup. The receding contact angle with water was found to reflect the rigidity of the headgroup. SPS thickness measurements[30] revealed that all three monolayers are 22–24 ± 2 Å thick, in good agreement with the 20–22 Å expected for a monolayer in which the alkyl chains are on the average perpendicularly oriented with respect to the surface. Effective thicknesses[31] of the monolayers, derived from capacitance measurements,[32] were found to be 18 ± 2 Å, indicating the impermeable nature of these assemblies toward electrolyte intrusion. AFM and SIMS measurements revealed that the monolayer-covered gold surfaces were different both from the uncovered substrates and from substrates that were covered with octadecanethiolate (a reference adsorbate).

In conclusion, resorcin[4]arenes derivatized with four flexible sulfide side chains self-assemble on gold at 60 °C, forming well-packed monolayers of which the outer interface consists of receptor sites only. The high density of receptor sites at the interface, the high stability of the film, and the complete passivation of the gold substrate render these assemblies very suitable for use as active layers of sensors. Studies on the use of these monolayers in mass-sensitive sensors are currently in progress.

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(27) Chidsey, C. E. D.; Loiacono, D. N.; Sleator, T.; Nakahara, S. *Surf. Sci.* **1988**, *200*, 45–66.

(28) Only weak headgroup-related vibrations could be observed, probably due to instrumental reasons.

(29) No sampling cooling was required, as was reported to be necessary for didodecyl sulfide monolayers.[17]

(30) In the thickness calculation, a refractive index of 1.50 was assumed.

(31) Porter, M. D.; Bright, T. B.; Allara, D. L.; Chidsey, C. E. D. *J. Am. Chem. Soc.* **1987**, *109*, 3559–3568.

(32) A relative permittivity of 2.3 was assumed in the effective thickness calculation.