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Synthesis of new SAM-forming ferrocene derivatives and their interfacial properties on gold

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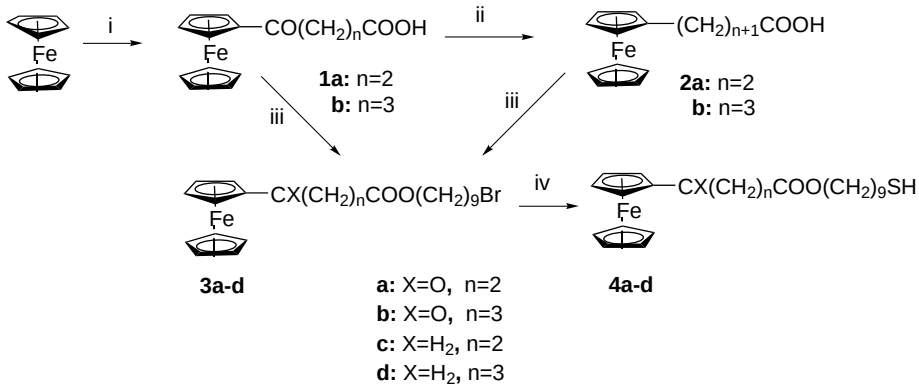
Abstract—We report the synthesis of ferrocene-terminated (C_{12}–C_{13})-alkylthiols containing an ester group removed from the ferrocene ring by 3-4 carbon atoms. The basic redox properties and some structural features of the self-assembled monolayers formed by these compounds on gold were studied by cyclic voltammetry and surface-enhanced Raman spectroscopy. The monolayers of 9-mercaptanonyl-4′-ferrocenyl butanoate (**4c**) and -5′-ferrocenyl pentanoate (**4d**) demonstrated exclusive stability.

Supramolecular structures that might undergo redox conversions are relevant to molecular (bio)sensors and other electronic devices of the future.[1] Examples of such systems in this diverse field of research include redox-active self-assembled monolayers (SAMs), redox-modulated recognition sensors, redox-switchable membranes, etc. Commonly used organic molecules for SAMs include various derivatives containing a mercapto group. Ferrocene (Fc)-terminated alkanethiols occupy a highly important place in the field of SAM-forming substances because of their potential applications in electrochemical (bio)sensors, heterogeneous catalysis, etc.[2] A considerable number of Fc derivatives have been synthesized, and the formation processes of SAMs have been studied.[3] It has been shown that the redox properties of a Fc group in such 2D systems depend both on the length and molecular structure of the chain. For instance, introduction of an ester group with a considerable dipole moment into the chain may perturb the monolayer packing, and the interfacial orientation of the redox-active moiety due to the dipole–dipole interactions.[4] However, as far as we know,



Scheme 1. *Reagents and conditions*: (i) acylation with succinic or glutaric anhydride in presence of $AlCl_3$ (65–70%); (ii) amalgamated Zn with $HgCl_2$ and HCl in methanol solution (70%); (iii) 9-bromononanol in benzene (93–95%); (iv) thiocarbamide in dry acetone (65–82%).

Keywords: ferrocene derivatives; synthesis; self-assembled monolayers; gold; electrochemistry; surface-enhanced Raman spectroscopy.
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Fc-terminated alkylthiols containing an ester group somewhere in the middle of the C_{12}–C_{13} chain have not been synthesized or investigated.

Considering the foregoing, we synthesized a number of ferrocenoyl and ferrocenyl derivatives containing a 9-mercaptanonylalkanoate group. The synthetic steps are presented in Scheme 1. Ferrocenoyl-3-propanoic and 4-butanoic acids (**1a**,**b**) were prepared via Friedel–Crafts acylation of Fc with the corresponding acid anhydride by adapting a reported procedure.[5] Subsequent Clemensen reduction of the carbonyl group led to the formation of the ferrocenyl carboxylic acids **2a**,**b**. Esterification of these acids with 9-bromononanol afforded compounds **3a**–**d**.[6] Finally, the Fc-terminated mercapto derivatives **4a**–**d** were obtained by the conversion of the bromide substituent into a mercapto group with thiocarbamide. This transformation required elaboration of the reaction conditions since the usual procedures employ ethanol and potassium hydroxide in ethanol for the decomposition of isothiouronium salts. In our case, these reaction conditions could not be used due to the presence of the ester group. We succeeded in obtaining compounds **4a**–**d** in good yields by using thiocarbamide in acetone and conducting the decomposition of the isothiouronium salt in a water/chloroform heterogeneous phase containing $Na_2S_2O_5$.[7] Structures of the derivatives **4a**–**d** were confirmed by analytical methods.[8]

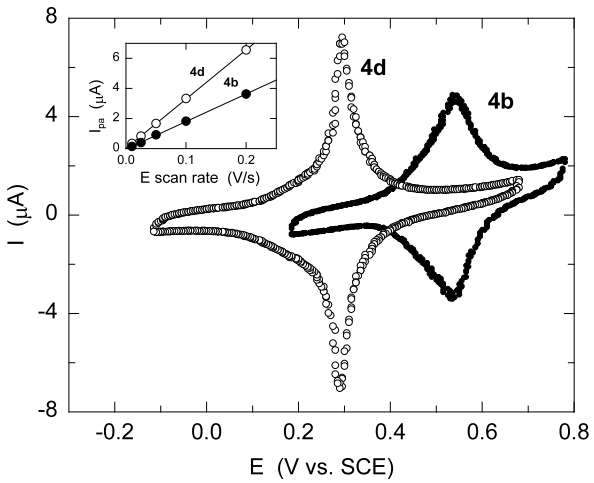

Figure 1. Cyclic voltammetric curves of the gold electrode modified by compound **4b** (filled circles) and **4d** (open circles), recorded in 1.0 M $NaClO_4$ solution at 25°C and an E scan rate of 0.2 V/s. Insert shows the dependence of the anodic peak current (I_{pa}) on the E scan rate.

Table 1. Basic electrochemical and interfacial characteristics of **4a**–**d** SAMs on gold (1.0 M $NaClO_4$, 25°C, mean values are given $\pm$S.D.)

Compound **4**	$E^{\circ\prime}$ (mV versus SCE)	k_s (s^{-1})	Γ (10^{-10} mol/cm^2)
a	561±3	177±36	4.0±0.3
b	529±10	325±31	4.7±0.4
c	324±2	274±32	4.6±0.4
d	292±6	124±16	4.6±0.4

Following the synthesis, basic self-assembling, electrochemical and structural features of the monolayers formed by compounds **4a**–**d** on gold were studied by cyclic voltammetry (CV) and surface-enhanced Raman spectroscopy (SERS).

For electrochemical experiments, monolayers were obtained via self-assembly of the compounds for 20 h from 0.1 mM ethanolic solutions on a pre-treated polycrystalline Au surface. The surface pre-treatment was accomplished by polishing with 0.05 μm alumina slurry, rinsing with water and ethanol, cleaning for 5 min in an ultrasonic bath (surface dipped in water/ethanol, 1:1 v/v), and electrochemical etching in 0.1 M H_2SO_4 by the potential (E) cycling between 0.4 and 1.6 V (versus saturated calomel electrode, SCE) for 25 min at a E scan rate of 0.1 V/s. In anaerobic 1.0 M $NaClO_4$ at 25°C, the CV curves of the SAMs exhibited clearly expressed oxidation–reduction peaks of the $Fc^+/Fc°$ couple (Fig. 1). These curves served to determine the formal redox potentials ($E^{\circ\prime}$), heterogeneous electron-transfer rate constants (k_s), and surface concentrations (Γ) of compounds **4a**–**d** in the monolayers (Table 1). The values of Γ are in good agreement with those to be expected for a hexagonally close-packed assembly, i.e. 4.4×10^{-10} mol/cm^2, based on a calculation assuming the accepted 0.66 nm diameter for the Fc group and a smooth Au surface.

In an effort to study a well-known degradation of the Fc-terminated monolayers in aqueous media,[9] a decrease of the electrochemically determined Γ after a particular time of E cycling over the E scan range from $E^{\circ\prime}$–250 to $E^{\circ\prime}$+250 mV was taken to be a measure of the monolayer stability. Thus, for compounds **4a** and **4b**, Γ decreased by 50% after ca. 54 and 71 min, respectively. On the other hand, no detectable decrease in Γ of compounds **4c** and **4d** was observed over continuous E cycling for 10 h. The latter results indicate the exceptional stability of the SAMs **4c** and **4d** in the $NaClO_4$ solution.

Another interfacial feature of the monolayers **4b** and **4d** was derived from the electrochemical experiments performed at relatively low E scan rates. The slope of the CV peak current (I_p) versus E scan rate reflects the interaction between attached molecules (Fig. 1, insert). From this slope the interaction parameters were calculated.[10] For compounds **4b** and **4d**, the obtained interaction parameters were of opposite signs, -0.5×10^{10} and 0.1×10^{10} cm^2/mol, respectively, indicating repulsion between the Fc centres in the monolayer **4b**, and the dominant attraction between the redox-active groups in the monolayer **4d**. It might be speculated that, in the case of compound **4b**, the presence of a C=O group close to the Fc ring prevents the effective neutralization of Fc^+ by counterions, resulting in repulsion between attached molecules. By contrast, a positive interaction parameter for the monolayer **4d** is an indication of strong ion pairing between Fc^+ and ClO_4^-.

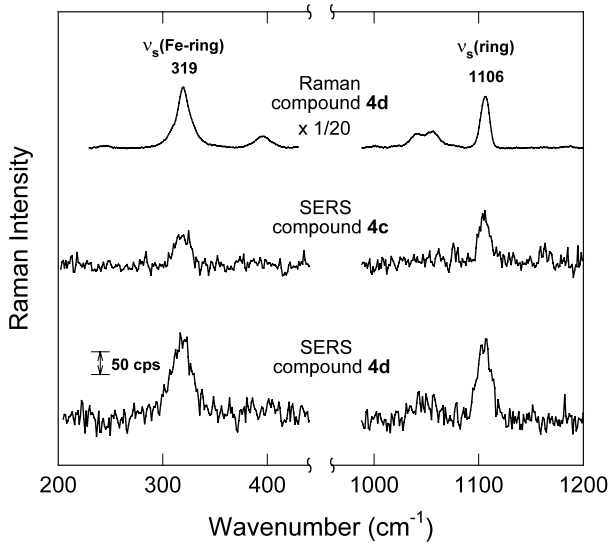

Figure 2. Comparison of the 632.8 nm-excited Raman and SERS spectra of compounds **4c** and **4d** in the low-frequency (200–440 cm^{-1}) and middle-frequency (960–1200 cm^{-1}) ranges. Raman spectrum is obtained from 1 M compound **4d** in CCl_4 (solvent spectrum is subtracted). SERS spectra are recorded in a 0.1 M $NaClO_4$ solution at −0.1 V (versus SCE). Integration time was 16 s and laser power at the sample, 15 mW.

The structure of the most stable monolayers **4c** and **4d** was probed by SERS. For SERS measurements, the Au surface was electrochemically roughened in 0.1 M KCl solution by scanning E 21 times from −0.3 to 1.2 V at 0.5 V/s with holds of 1.5 and 30 s at the positive and negative E limits, respectively.[11] Fig. 2 shows that the relative intensity of the two well-defined modes located at 319 and 1106 cm^{-1} in the SERS spectra depends on the alkyl chain length. The low-frequency peak was assigned to the symmetric stretching vibration of the Fe-ring bonding, while the band at 1106 cm^{-1} was attributed to the symmetric stretching motion of the Fc ring.[12] The main changes in the polarizability ellipsoid (PE) for those two modes occur in perpendicular directions. Therefore, according to the SERS selection rules,[13] modes containing high perpendicular to surface PE components are preferentially enhanced. The ratio of integrated intensities $A[\nu_s(\text{Fe-ring})]/A[\nu_s(\text{ring})]$ decreases in the following order: 2.5 (solution, compound **4d**)>1.7 (SERS, compound **4d**)>0.8 (SERS, compound **4c**). This result indicates that the orientation of the planes of the Fc rings with respect to the surface normal is slightly lower than 45° in the case of monolayer **4d**, whereas for monolayer **4c** the angle decreases considerably. Thus, reduction of the alkyl chain length by one methylene unit causes observable interfacial reorientation of the Fc moiety.

A more detailed study of the interfacial structure, electron-transfer and (bio)electrocatalytic properties of the SAMs presented in this work will be reported elsewhere.

References

1. Crooks, R. M.; Ricco, A. J. *Acc. Chem. Res.* **1998**, *31*, 219–227.
2. (a) Carr, J. D.; Lambert, L.; Hibbs, D. E.; Hursthouse, M. B.; Malik, K. M. A.; Tucker, J. H. R. *Chem. Commun.* **1997**, 1649–1650; (b) Carr, J. D.; Coles, S. J.; Hassan, W. W.; Hursthouse, M. B.; Malik, K. M. A.; Tucker, J. H. R. *J. Chem. Soc., Dalton Trans.* **1999**, 57–62; (c) Lahav, M.; Katz, E.; Willner, I. *Electroanalysis* **1998**, *10*, 1159–1162; (d) Razumas, V.; Kulys, J.; Knichel, M.; Wiemhöfer, H.-D.; Göpel, W. *Electroanalysis* **1993**, *5*, 399–404.
3. (a) Sumner, J. J.; Creager, S. E. *J. Am. Chem. Soc.* **2000**, *122*, 11914–11920; (b) Sumner, J. J.; Weber, K. S.; Hockett, L. A.; Creager, S. E. *J. Phys. Chem. B* **2000**, *104*, 7449–7454; (c) Sek, S.; Misicka, A.; Bilewicz, R. *J. Phys. Chem. B* **2000**, *104*, 5399–5402; (d) Yu, C. J.; Chong, Y.; Kayyem, J. F.; Gozin, M. *J. Org. Chem.* **1999**, *64*, 2070–2079; (e) Gallardo, B. S.; Gupta, V. K.; Eagerton, F. D.; Jong, L. I.; Craig, V. S.; Shah, R. R.; Abbott, N. L. *Science* **1999**, *283*, 57–60; (f) Casado, C. M.; Cuadrado, I.; Alonso, B.; Moran, M.; Losada, J. *J. Electroanal. Chem.* **1999**, *463*, 87–92; (g) Beulen, M. W. J.; van Veggel, F. C. J. M.; Reinhoudt, D. N. *Chem. Commun.* **1999**, 503–504; (h) Clot, O.; Wolf, M. O. *Langmuir* **1999**, *15*, 8549–8551; (i) Butkus, E.; Tauraite, D.; Barauskas, J.; Talaikyte, Z.; Razumas, V. *J. Chem. Res. (S)* **1998**, 722–723.
4. Ulman, A. *Chem. Rev.* **1996**, *96*, 1533–1554.
5. Rinehart, Jr., K. L.; Curby, Jr., R. J.; Sokol, P. E. *J. Am. Chem. Soc.* **1957**, *79*, 3420–3423.
6. **General procedure for the esterification of 1–2a,b**: In a flask with a Dean–Stark head a solution of the corresponding Fc carboxylic acid (1.0 mmol), 9-bromononanol (1.0 mmol) and *p*-toluenesulfonic acid (1.0 mmol) in benzene (15 ml) was refluxed for 5 h under an argon atmosphere. The reaction mixture was filtrated and the solvent was evaporated under reduced pressure. The residue was purified by column chromatography with methylene chloride.
   Selected data for new compounds: **3a** (reddish oil, yield 0.46 g, 95%), ^{1}H NMR δ (ppm): 1.0–2.05 (14H, m), 2.67 (2H, m), 3.05 (2H, m), 3.4 (2H, t), 4.15 (2H, t), 4.25 (5H, s), 4.5–4.8 (4H, m); **3b** (orange crystals, mp 47–49°C, yield 0.48 g, 95%), ^{1}H NMR δ (ppm): 1.0–2.0 (14H, m), 2.05 (2H, m), 2.4 (2H, m), 2.8 (2H, m), 3.4 (2H, t), 4.1 (2H, t), 4.2 (5H, s), 4.5–4.8 (4H, m); **3c** (yellow crystals, mp 39–42°C, yield 0.45 g, 94%), ^{1}H NMR δ (ppm): 1.0–2.05 (16H, m), 2.2–2.5 (4H, m), 3.4 (2H, t), 3.9–4.2 (11H, m); **3d** (yellow oil, yield 0.45 g, 93%), ^{1}H NMR δ (ppm): 1.1–2.1 (18H, m), 2.3 (4H, m), 3.4 (2H, t), 3.9–4.2 (11H, m).
7. **General procedure**. Bromononyl ester **3a–d** (1.0 mmol) and thiocarbamide (4.0 mmol) in dry acetone were refluxed for 48 h under argon. The solvent was evaporated in vacuo, and, upon addition of $CHCl_3$ (40 ml), water (20 ml) and $Na_2S_2O_5$ (1.8 mmol), the mixture was vigorously stirred and refluxed for 3 h. The organic layer was separated, washed with water (2×), dried over $MgSO_4$ and concentrated in vacuo. The residue was purified by column chromatography using hexane/ethyl acetate (3:1 v/v).

8. Selected data for new compounds: **4a** (orange oil, yield 0.36 g, 82%), ^{1}H NMR δ (ppm): 1.2–1.9 (14H, m), 1.4 (1H, s), 2.5 (2H, t), 2.7 (2H, m), 3.1 (2H, m), 4.1 (2H, t, *J* 6.5 Hz), 4.25 (5H, s), 4.5–4.8 (4H, m); **4b** (orange oil, yield 0.36 g, 79%), ^{1}H NMR δ (ppm): 1.1–2.0 (14H, m), 1.4 (1H, s), 2.1 (2H, m), 2.4 (4H, m), 2.8 (2H, m), 4.1 (2H, t, *J* 6.5 Hz), 4.2 (5H, s), 4.5–4.8 (4H, m); **4c** (yellow oil, yield 0.33 g, 78%), ^{1}H NMR δ (ppm): 1.2–2.0 (16H, m), 1.4 (1H, s), 2.2–2.6 (6H, t, *J* 6.5 Hz), 3.9–4.2 (11H, m); **4d** (yellow oil, yield 0.29 g, 65%), ^{1}H NMR δ (ppm): 1.2–2.0 (18H, m), 1.4 (1H, s), 2.3 (4H, m), 2.6 (2H, t, *J* 6.5 Hz), 3.9–4.2 (11H, m).
9. Finklea, H. O. In *Electroanalytical Chemistry*; Bard, A. J.; Rubinstein, I., Eds.; Marcel Dekker: New York, 1996; pp. 108–335.
10. (a) Brown, A. P.; Anson, F. C. *Anal. Chem.* **1977**, *49*, 1589–1595; (b) Ju, H.; Leech, D. *Phys. Chem. Chem. Phys.* **1999**, *1*, 1549–1554.
11. Gao, P.; Gosztola, D.; Leung, L.-W. H.; Weaver, M. J. *J. Electroanal. Chem.* **1987**, *233*, 211–222.
12. Diana, E.; Rossetti, R.; Stanhellini, P. L.; Kettle, S. F. A. *Inorg. Chem.* **1997**, *36*, 382–391.
13. Creighton, J. A. In *Spectroscopy of Surfaces*; Clark, R. H. J.; Hester, R. E., Eds.; Wiley: New York, 1988; pp. 37–89.