COMMUNICATION www.rsc.org/chemcomm | ChemComm

Effective anion sensing based on the ability of copper to affect electron transport across self-assembled monolayers†

V. Ganesh, Maria Pilar Calatayud Sanz and Juan C. Mareque-Rivas*

Received (in Cambridge, UK) 21st August 2007, Accepted 14th September 2007
First published as an Advance Article on the web 1st October 2007
DOI: 10.1039/b712857f

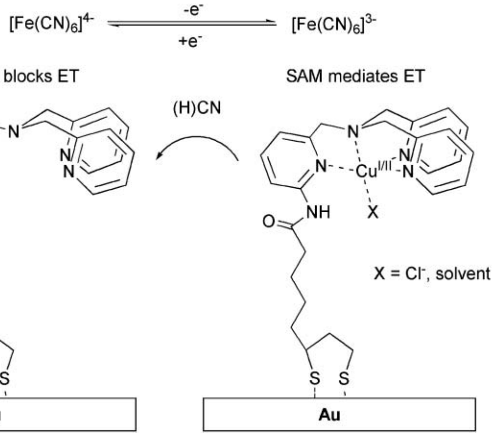
The ability of copper ions to affect the charge-transfer resistance of self-assembled monolayers (SAMs) of a tris-(2-pyridylmethyl)amine-based ligand on to gold electrodes is used to create a novel, sensitive and selective electrochemical cyanide sensor.

The development of sensors for anions in water has become an important target in supramolecular chemistry for biological and environmental reasons.[1,2] Strong and selective anion binding to the receptor component is challenging under physiological conditions, in part because most anions are highly solvated. Binding is even more difficult if the anion becomes protonated at physiological pH, and so looses its charge. Metal complexes and organic molecules with hydrogen bonding groups provide some of the most effective anion receptors created to date due to their ability to form strong coordination or hydrogen bonds with the anion.[2] In metal complex receptors the metal can act as a Lewis acid facilitating the deprotonation of the bound species,[3] and the shape can be designed to match that of the anion,[4] improving the binding affinity and selectivity. However, the overall efficiency of a sensor depends also on the sensitivity of the method reporting the presence of the analyte. As a consequence there are few sensors capable of detecting anions in the μM–nM concentration range in water and neutral pH, and these exploit the sensitivity provided by fluorescence spectroscopy.[5] Recent studies have proven that the use of self-assembled monolayers (SAMs) is an effective and convenient alternative strategy to detect cations in water due to the relative ease of preparation, fast response and pre-organisation of the receptor on the surface.[6] Anion sensing based on monolayers is, however, much rarer, and only a few recent studies have provided SAM-based sensors capable of detecting mM concentrations of important anions such as phosphates, acetate and fluoride in organic solvents[7a–c] and water.[7d,e]

The cyanide anion finds common industrial use in organic chemicals and polymers such as nitriles, nylon and acrylic plastics, fertilizer factories, precious metal mining and metal plating.[8] Due to the extreme toxicity of cyanide (0.5–3.5 mg per kg of body weight are lethal to humans), its concentration in drinking water cannot be greater than *ca.* 2 μM according to the World Health Organization.[9] Thus, there is a widespread need to develop effective cyanide sensors.[10] This is complicated in part because under physiological conditions cyanide ions exit as $HCN_{(g)}$[11] and common ions such as chloride can interfere with their detection. Cyanide reacts with copper ions to form very stable $[Cu(CN)_n]^{(n-1)-}$ species.[12] This property has been exploited to remove copper ions from a range of ligand environments.[13]

Recently, we and others have shown that in some SAMs capable of binding copper ions, these redox-active metal ions affect the kinetics of electron transfer (ET) to a negatively charged redox probe in solution.[14] Here, we have combined the ability of copper ions to affect electron transport across a SAM, with that of (H)CN to bind copper ions to create a novel, sensitive and selective electrochemical cyanide sensor (Scheme 1).

The monolayers were easily prepared by placing a clean gold electrode into a methanol solution of this copper complex (10 mM) and $NaBH_4$ as disulfide reducing agent for 16 h under a N_2 atmosphere.[14a] Initially, the ability of the SAM to detect different anions was investigated by cyclic voltammetry (CV). The CV studies were carried out in aqueous buffer containing HEPES (pH = 7.3) along with 1 mM $[Fe(CN)_6]^{3-}$, 1 mM $[Fe(CN)_6]^{4-}$ and 0.1 M NaCl as supporting electrolyte. The CV is consistent with a reversible behaviour for the $[Fe(CN)_6]^{3-/4-}$ redox couple due to the copper ions of the complex facilitating the ET across the molecular film (see Supplementary Information†).[14a] Upon addition of cyanide (1 mM) the shape of the CV indicates a somewhat less reversible redox behaviour due to less effective electron transport across the film (see Supplementary Information†). In contrast no changes were observed in the presence of other potentially interfering anions (1 mM) such as $H_2PO_4^-$, NO_3^-, AcO^- and F^-. However, this technique was not sensitive enough to detect environmentally relevant cyanide concentrations (1–100 μM).[8,9]



Scheme 1 SAM and cyanide sensing principle.

School of Chemistry, University of Edinburgh, Edinburgh, UK EH9 3JJ. E-mail: juan.mareque@ed.ac.uk; Fax: 0131 6504743; Tel: 0131 6504761

† Electronic supplementary information (ESI) available: details on experimental procedures and characterization data. See DOI: 10.1039/b712857f

To further explore the ability of the SAM to detect these anions, we used electrochemical impedance spectroscopy (EIS).[6,7*d,e*,15] The impedance (Nyquist) plots for the monolayer coated gold electrode and various cyanide concentrations are shown in Fig. 1. The charge-transfer resistance, R_{CT}, was determined by fitting the experimental data to an equivalent circuit based on Randle's circuit model [R(C(RW))]. This parameter reflects the charge-transfer resistance across the SAMs, and can be used to evaluate the rate of ET to the solution containing the redox probe.[14*a*,16] The SAM-modified gold electrode exhibits a R_{CT} value of 32 Ω cm^2 implying the metal-mediated ET across the molecular films. It can be observed from the impedance plots that the R_{CT} values increase as the cyanide concentrations increase. Clearly, EIS is much more effective than cyclic voltammetry for detecting small changes in charge-transfer resistance of SAMs. As a result, nanomolar concentrations of cyanide (detection limit is 1 nM) are clearly revealed by impedance plots even at pH 7.3 (Fig. 1).[17] To further explore the potential of the SAM as a cyanide sensor we have investigated the response of the monolayer to other biologically important and potentially interfering anions *viz*., $H_2PO_4^-$, NO_3^-, AcO^- and F^- using EIS in buffered aqueous solutions. Fig. 2 shows the comparison of impedance plots obtained for the several anions studied in this work. With the exception of cyanide, other anions did not change the charge-transfer resistance of the SAM even at a high concentration of 1 mM. This implies that the electrochemical response of this SAM is cyanide-selective.

The electrochemical response of the SAM on gold to cyanide in solution can arise from several processes, including one or several of the following: binding to the gold surface, binding to the L^1Cu complex and removal of copper from the SAM to form $[Cu(CN)_n]^{(n-1)-}$ species. To characterise this behaviour, we used X-ray photoelectron spectroscopy (XPS) and polarization-modulation reflection-absorption IR spectroscopy (PM-RAIRS).

XPS studies of the SAM-modified gold electrode showed peaks at 932.5 eV (Cu 2p3/2) and 952.3 eV (Cu 2p1/2) due to Cu^I centres. After immersion of the SAM into water solutions with increasing cyanide concentrations, the intensity of these peaks progressively decreased, suggesting that copper was removed from the film (Fig. 3). This result is consistent with previous studies in which CN^- ions have been shown to remove copper ions from a range of environments.[13] The stability constants of copper complexes of ligands similar to L^1 and of $[Cu(CN)_n]^{(n-1)-}$ species have been determined,[12,18] albeit in bulk water, and the values suggest that copper abstraction from L^1 is feasible. In fact, after addition of cyanide the ^{1}H NMR of the paramagnetic $[(L^1)CuCl]^+$ complex becomes indistinguishable from that of L^1. The inability of cyanide to completely remove the copper from the SAM is consistent with the EIS studies, which showed that R_{CT} values in the presence of CN^- ions are lower than for the SAM of the ligand alone. This may be due to limited access of $HCN_{(g)}$ to the copper ions of the SAM. PM-RAIRS studies showed that the bands observed for the adsorbed complex are similar to those of the solid material (see Supplementary Information†). The spectra obtained after addition of CN^- ions did not show any band in the 2100–2300 cm^{-1} range that could be assigned to a cyanide stretching frequency. Thus, it

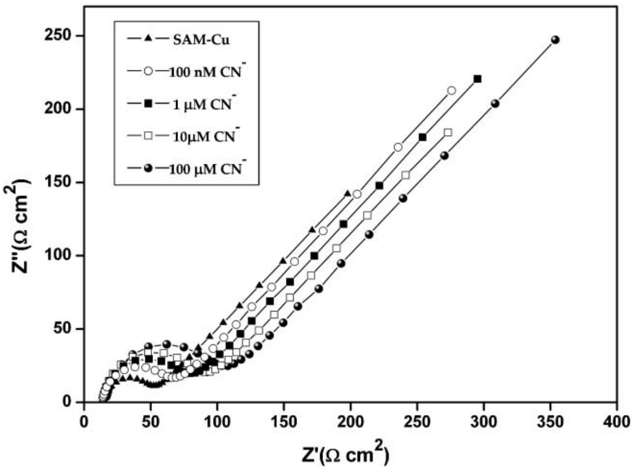


Fig. 1 Impedance (Nyquist) plots in 1 mM $[Fe(CN)_6]^{4-}$, 1 mM $[Fe(CN)_6]^{3-}$, 0.1 M NaCl and 100 mM HEPES (pH 7.3) at the monolayer-modified gold electrode in the absence and presence of increasing $[CN^-]$. T = 293 K.

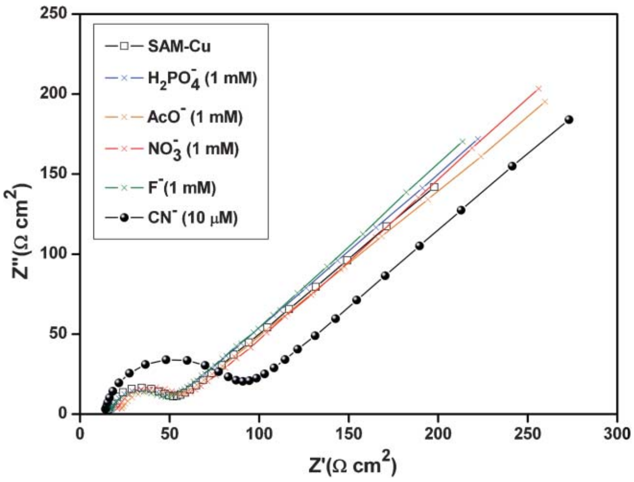


Fig. 2 Impedance (Nyquist) plots in 1 mM $[Fe(CN)_6]^{4-}$, 1 mM $[Fe(CN)_6]^{3-}$, 0.1 M NaCl and 100 mM HEPES (pH 7.3) at the monolayer-modified gold electrode in the absence and presence of different anions.

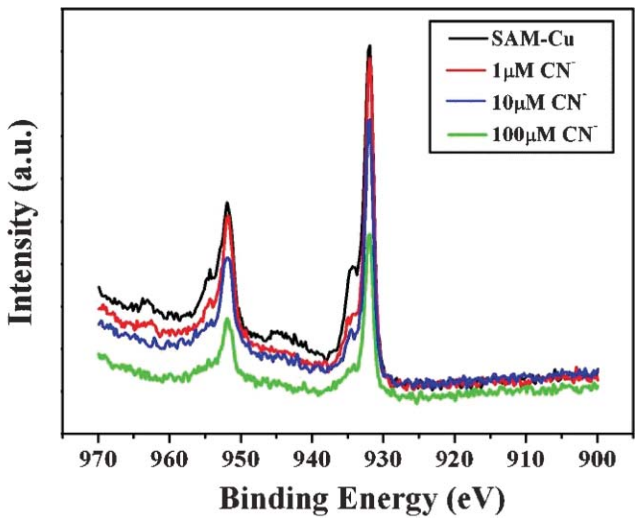


Fig. 3 Copper 2p X-ray photoelectron spectra of the SAM-modified gold surfaces before and after immersion into aqueous cyanide solutions.

seems unlikely that the electrochemical behavior is due to the formation of surface $[(L^1)CuCN]^{(+)}$ complexes or cyanide binding to the gold surface.

In summary, we have combined the ability of copper ions to affect the kinetics of electron transfer across a copper binding SAM to a negatively charged redox probe in solution with the ability of (H)CN to bind and remove copper ions to create a novel, sensitive and selective cyanide sensor that works under physiological conditions. This work shows for the first time that the recently found ability of metal ions to affect ET across SAMs can be exploited for sensing applications. Although the method is applied here for cyanide detection, it should be possible to apply it more widely for the detection of other anions and ion binding agents, including proteins, by using a suitable SAM and metal. Moreover, we believe that this and similar materials and methods can also be used to develop novel sensors based on gold nanoparticles and quantum dots.[19] We are continuing with the design of ligands and surface modification strategies for a range of sensory applications.

This work was funded by The Leverhulme Trust. We are grateful to Prof. L. J. Yellowlees for equipment and laboratory use. We acknowledge support from the EPSRC to purchase the XPS, and we thank Dr R. Brown (Edinburgh) and Dr T. E. Jones (St. Andrews) for helping with the XPS and PM-RAIRS studies respectively. We also thank Prof. V. Lakshminarayanan (Raman Research Institute, Bangalore, India) for providing evaporated gold samples.

Notes and references

1 Selected reviews: (*a*) P. D. Beer and P. A. Gale, *Angew. Chem., Int. Ed.*, 2001, **40**, 486; (*b*) J. L. Sessler and J. M. Davis, *Acc. Chem. Res.*, 2001, **34**, 989; (*c*) P. D. Beer and S. R. Bayly, *Top. Curr. Chem.*, 2005, **255**, 125–162; (*d*) F. P. Schmidtchen, *Top. Curr. Chem.*, 2005, **255**, 1–29.

2 Selected reviews: (*a*) Various authors in *Anion Coordination Chemistry II*, ed. P. A. Gale, *Coord. Chem. Rev.*, 2006, **250**, 2917–3244; (*b*) Various authors in *35 Years of Synthetic Anion Receptor Chemistry*, 1968–2003, ed. P. A. Gale, *Coord. Chem. Rev.*, 2003, **240**, 1–226; (*c*) S. O. Kang, A. R. Begum and K. Bowman-James, *Angew. Chem., Int. Ed.*, 2006, **45**, 7882; (*d*) J. Yoon, K. Sook, N. J. Singh and K. S. Kim, *Chem. Soc. Rev.*, 2006, **35**, 355.

3 J. C. Mareque Rivas, R. Prabaharan and R. Torres Martin de Rosales, *Chem. Commun.*, 2004, 76.

4 (*a*) S. L. Tobey, B. D. Jones and E. V. Anslyn, *J. Am. Chem. Soc.*, 2003, **125**, 4026; (*b*) B. P. Hay, T. K. Firman and B. A. Moyer, *J. Am. Chem. Soc.*, 2005, **127**, 1810.

5 (*a*) A. Ojida, Y. Mito-oka, K. Sada and I. Hamachi, *J. Am. Chem. Soc.*, 2004, **126**, 2454; (*b*) H. K. Cho, D. H. Lee and J.-I. Hong, *Chem. Commun.*, 2005, 1690; (*c*) H. N. Lee, Z. Xu, S. K. Kim, K. M. K. Swamy, Y. Kim, S.-I. Kim and J. Yoon, *J. Am. Chem. Soc.*, 2007, **129**, 3828; (*d*) D. H. Lee, S. Y. Kim and J.-I. Hong, *Angew. Chem., Int. Ed.*, 2004, **43**, 4777; (*e*) M. J. McDonough, A. J. Reynolds, W. Y. G. Lee and K. A. Jolliffe, *Chem. Commun.*, 2006, 2971.

6 S. Zhang, C. M. Cardona and L. Echegoyen, *Chem. Commun.*, 2006, 4461.

7 (*a*) P. D. Beer, J. J. Davis, D. A. Drillsma-Milgrom and F. Szemes, *Chem. Commun.*, 2002, 1716; (*b*) P. D. Beer, D. P. Cormode and J. J. Davis, *Chem. Commun.*, 2004, 414; (*c*) D. Astruc, M.-C. Daniel and J. Ruiz, *Chem. Commun.*, 2004, 2637; (*d*) S. Zhang and L. Echegoyen, *J. Am. Chem. Soc.*, 2005, **127**, 2006; (*e*) S. Zhang, A. Palkar and L. Echegoyen, *Langmuir*, 2006, **22**, 10732.

8 (*a*) C. O. Ikediobi and L. M. Latinwo, *Am. Environ. Lab.*, 1997, **9**, 20; (*b*) Ulmann's Encyclopedia of Industrial Chemistry, 6th edn., Wiley-VCH, New York, 1999; (*c*) G. C. Miller and C. A. Pritsos, *Cyanide: Social, Industrial and Economic Aspects*, Proceedings of the TMS Annual Meeting, 2001, The Minerals, Metals and Materials Society, Warrendale, PA, USA, 2001, pp. 73–81.

9 *Guidelines for Drinking-Water Quality*, World Health Organization, Geneva, 1996.

10 (*a*) P. Anzenbacher, Jr., D. S. Tyson, K. Jursikova and F. N. Castellano, *J. Am. Chem. Soc.*, 2002, **124**, 6232; (*b*) R. Badugu, J. R. Lakowicz and C. D. Geddes, *J. Am. Chem. Soc.*, 2005, **127**, 3635; (*c*) F. García, J. M. García, B. García-Acosta, R. Martínez-Mañez, F. Sancenon and J. Soto, *Chem. Commun.*, 2005, 2790; (*d*) W. J. Jin, M. T. Fernández-Argueelles, J. M. Costa-Fernández, R. Pereiro and A. Sanz-Medel, *Chem. Commun.*, 2005, 883; (*e*) Y. G. Timofeyenki, J. J. Rosentreter and S. Mayo, *Anal. Chem.*, 2007, **79**, 251.

11 The pK_a of $HCN_{(g)}$ is 9.21.

12 K. Kurmia, D. E. Giles, P. M. May, P. Singh and G. T. Hefter, *Talanta*, 1996, **43**, 2045.

13 (*a*) N. Solladie, J.-C. Chambron and J.-P. Savage, *J. Am. Chem. Soc.*, 1999, **121**, 3684; (*b*) N. Fujiwara, Y.-L. Liu, M. Takabashi and H. Kobayashi, *J. Electrochem. Soc.*, 2006, **153**, G394; (*c*) R. Rahimi and P. Hambright, *J. Porphyrins Phthalocyanines*, 1998, **2**, 493.

14 (*a*) V. Ganesh, M. P. Calatayud Sanz and J. C. Mareque-Rivas, *Chem. Commun.*, 2007, 804; (*b*) E. Soto, J. C. MacDonald, C. G. G. Cooper and W. G. McGimpsey, *J. Am. Chem. Soc.*, 2003, **125**, 2838; (*c*) X. Lu, M. Li, C. Yang, L. Zhang, Y. Li, L. Jiang, C. Liu and W. Hu, *Langmuir*, 2006, **22**, 3035.

15 (*a*) S. Flink, B. A. Boukamp, A. van der Berg, F. C. J. M. Van Veggel and D. N. Reinhoudt, *J. Am. Chem. Soc.*, 1998, **120**, 4652; (*b*) B. Colonna and L. Echegoyen, *Chem. Commun.*, 2001, 1104; (*c*) M. A. Herranz, B. Colonna and L. Echegoyen, *Proc. Natl. Acad. Sci. U. S. A.*, 2002, **99**, 5040; (*d*) R. K. Shervedani and S. A. Mozaffari, *Anal. Chem.*, 2006, **78**, 4957.

16 (*a*) H. O. Finklea, D. Zinder, J. Fedyk, E. Sabatini, Y. Gafni and I. Rubinstein, *Langmuir*, 1993, **9**, 3660; (*b*) V. Ganesh and V. Lakshminarayanan, *Langmuir*, 2006, **22**, 1561.

17 The changes, R^{C}_{CT}/R^{0}_{CT}, are reproducible within 5%, however, the magnitude of the change depends on the gold substrate used (R^{C}_{CT} charge-transfer resistance in the presence of $[CN^-] = c$, R^{0}_{CT} initial charge-transfer resistance).

18 E. A. Ambundo, M.-V. Deydier, A. J. Grall, N. Aguera-Vega, L. T. Dressel, T. H. Cooper, M. J. Heeg, L. A. Ochrymowycz and D. B. Rorabacher, *Inorg. Chem.*, 1999, **38**, 4233.

19 (*a*) J. J. Davis, *Chem. Commun.*, 2005, 3509; (*b*) G. Cooke, *Angew. Chem., Int. Ed.*, 2003, **42**, 4860; (*c*) U. Drechsler, B. Erdogan and V. Rotello, *Chem.–Eur. J.*, 2004, **10**, 5570; (*d*) b)X. Michalet, F. F. Pinaud, L. A. Bentolila, J. M. Tsay, S. Doose, J. J. Li, G. Sundaresan, A. M. Wu, S. S. Gambhir and S. Weiss, *Science*, 2005, **307**, 538.