Highly Sensitive Aluminium(III) Ion Sensor Based on a Self-assembled Monolayer on a Gold Nanoparticles Modified Screen-printed Carbon Electrode

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A new approach for the development of a highly sensitive aluminium(III) ion sensor via the preconcentration of aluminium(III) ion with a self-assembled monolayer on a gold nanoparticles modified screen-printed carbon electrode and current mediation by potassium ferricyanide redox behavior during aluminium(III) ion binding has been attempted. A monolayer of mercaptosuccinic acid served as an effective complexation ligand for the preconcentration of trace aluminium; this led to an enhancement of aluminium(III) ion capture and thus improved the sensitivity of the sensor with a detection limit of down to the ppb level. Under the optimum experimental conditions, the sensor exhibited a wide linear dynamic range from 0.041 to 12.4 μM. The lower detection limit of the developed sensor was 0.037 μM (8.90 ppb) using a 10 min preconcentration time. The sensor showed excellent selectivity towards aluminium(III) ion over other interference ions.

Keywords Aluminium(III), gold nanoparticles, self-assembly monolayer, screen-printed electrode

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Introduction

Over the past decades, the toxicity of aluminium in the environment and its effect on human healthcare far beyond concern due to its relatively low bioavailability. However, recently many biomedical studies demonstrated that several neurological disorders, such as Alzheimer’s disease, Parkinson’s disease, dialysis encephalopathy, anaemia and cancers are closely associated to the presence of aluminium.1-7 Apart from that, high concentrations of aluminium in the environment exert destructive effects towards aquatic organisms and plants.8 The contamination of natural water by this metal has been accelerated by the phenomenon of acid rain as well as human activities.9,10 Thus, the urge to develop a sensitive, accurate and fast respond sensing device for the detection of trace amounts of aluminium in the environment and biological matrices is of great importance.

In recent years, electrochemical measurements for the speciation of aluminium have been extensively studied due to its simplicity and high sensitivity. Nevertheless, any direct electrochemical determination of aluminium is difficult, since the reduction potential of the metal ion is extremely negative (about −1.75 V vs. SCE) and suffers interference from hydrogen ion.11-14 An alternative way to conduct the electroanalysis of aluminium ion was through indirect electrochemical determination using electroactive aluminium chelators.15-19 Chemically modified electrodes with the adsorption of dyes, such as pyrocatechol violet and alizarin, have been widely exploited for voltammetry determinations of aluminium. The first dye chemically modified electrode for aluminium(III) determination was developed in 1991 by Downard et al.,11 where alizarin was adsorbed onto the surface of a high-density graphite electrode through dip-coating process. Chen et al.19 then fabricated a pyrocatechol violet chemically modified electrode by adsorption of the dye onto the surface of a pyrolytic graphite electrode. Most recently, Tang et al.20 have employed a graphene modified glassy carbon electrode for the detection of aluminium in biological samples using alizarin as an electroactive ligand. The principle of the detection was based on the adsorptive accumulation of Al-alizarin complexes on the electrode surface. Although a chemically modified electrode offers advantages such as good selectivity, sensitivity and simple instrumentation,11,17 yet the electroactive ligands were being physically adsorbed onto the electrode surface, where the leaching of ligands is a major problem. A reagentless aluminium(III) sensor was constructed by entrapping alizarin red S in sol-gel film on the surface of a glassy carbon electrode.13 Nonetheless, the sensor encountered the same problem as most of the chemically modified electrodes.

The application of a self-assembled monolayers (SAMs) technique in the construction of sensors and biosensors has attracted considerable attention in recent years since they provide advantages, such as ease of preparation, great stability, reproducibility, versatility and the possibility of incorporating...
different chemical functionalities to produce highly molecular order of monolayers.\textsuperscript{20} SAMs-modified planar gold electrodes are widely used in the fabrication of metal ions sensors and biosensors since they exhibited excellent sensitivity and selectivity.\textsuperscript{20-25} Nonetheless, a majority of solid-state metal ions sensors fabricated from a planar gold electrode were costly in terms of commercialization. Increased demand for developing simple, accurate and rapid devices for the \textit{in situ} analysis of metal ions have made screen-printing electrodes as a primary choice in the construction of sensors and biosensors. Screen-printing electrodes offer advantages, like simple instrument design, easy to carry and miniature as compared to conventional planar electrodes.\textsuperscript{26,27}

Metal nanoparticles exhibit unique physiochemical properties due to their minute size, large surface area, excellent conductivity and good biocompatibility. The modification of electrode surfaces with metal nanomaterials has been proposed as an appealing approach for enhancing the conductivity, electron transfer process and analytical sensitivity as well as selectivity.\textsuperscript{23,25} Gold nanoparticles are the most widely used nanomaterials in the fabrication of sensing devices. Gold nanoparticles provide a large surface area that greatly increases the amount of organothiol being assembled onto their surface, and further enhance the structure and stability of the self-assembly monolayer.\textsuperscript{28} On top of that, the assembled organothiol on gold nanoparticles presents a three-dimensional monolayer system that exhibits excellent catalytic and electrocatalytic properties as compared to the two-dimensional monolayer on a planar gold electrode.\textsuperscript{28-30} A study from Zhang and Oyama\textsuperscript{29} demonstrated that the three-dimensional monolayer of mercaptopropionic acid self-assembled on gold nanoparticle arrays boosts the electron transfer between small biomolecules and the electrode. Determination of trace copper(II) ion using a self-assembled monolayer of 3-mercaptopropionic acid on a gold nanoparticles modified glassy carbon electrode exhibited a lower detection limit of 0.0032 ppb.\textsuperscript{30}

We have reported an copper(II) ion biosensor based on a three-dimensional monolayer of L-cysteine on a gold nanoparticles modified screen-printed carbon electrode, together with a preliminary application to aluminium(III) ion. The sensor demonstrated a lower detection limit of 8 ppb which showed a comparable electrochemical performance to a copper(II) sensor based on a self-assembled monolayer of L-cysteine on planar gold electrode.\textsuperscript{31} Thus, in the present study, an aluminium(III) ion sensor was fabricated based on a three-dimensional monolayer of a mercaptosuccinic acid gold nanoparticles modified screen-printed carbon electrode. The dicarboxylic acid terminated monolayer serves as an efficient aluminium(III) ion chelator; electrochemical detection of the target ion was based on the a reversible reaction of potassium ferricyanide. The anodic peak potential of potassium ferricyanide increases proportionately with the concentration of aluminium. The phenomenon of an under potential deposition of copper on the surface of gold nanoparticles was observed in our previous work. The occurrence of an under potential deposition of copper showed great impact on the application of the developed copper(II) sensor for real sample analysis. Since aluminium is an non-electroactive metal, the phenomenon of an under potential deposition of aluminium on the surface of gold nanoparticles will not occur.

A reagentless sensor was achieved through the immobilization of potassium ferricyanide in polyvinyl alcohol membrane on the area above the self-assembled monolayer of mercaptosuccinic acid on a gold nanoparticles modified electrode active surface. The novel approach for the quantitative analysis of aluminium in this work is based on the fact that aluminium is a good electrical conductor, where the anodic peak current of potassium ferricyanide is enhanced with an increased amount of aluminium being captured by the ligand. This work presented a simple, accurate and rapid sensing device for the \textit{in situ} detection of aluminium.

**Experimental**

**Reagents and chemicals**

Gold(III) chloride trihydrate (HAuCl$_3$·3H$_2$O) and mercaptosuccinic acid were purchased from Aldrich. Trisodium citrate dihydrate, ethanol, sodium acetate, acetate acid, copper(II) chloride, sodium chloride, aluminium chloride, iron(III) chloride, potassium chloride, lead(II) chloride and nitric acid were obtained from Sigma. However, manganese(II) chloride tetrahydrate, magnesium chloride, calcium chloride, potassium ferricyanide, polyvinyl alcohol and chromium(III) chloride hexahydrate were from Merck. All aqueous solutions were prepared by using deionized water (18.2M resistivity) from a Millipore water system. A 40 mM acetate buffer solution (pH 3.6) was prepared by mixing an appropriate volume of a sodium acetate solution with acetic acid. A metal ions stock solution was prepared in an acetate buffer solution. All glassware was soaked in 6 M HNO$_3$ for 24 h and then carefully rinsed with deionized water so as to avoid any metal contamination. The screen-printed carbon paste electrodes were purchased from Scrint Technologies Sdn Bhd (Malaysia).

**Synthesis of gold nanoparticles**

Gold nanoparticles (AuNPs) were synthesized by adding an appropriate amount of sodium citrates to a HAuCl$_3$·3H$_2$O aqueous solution near boiling. The concentration of the synthesized gold colloidal solution was approximately 17 nM.\textsuperscript{22}

**Sensor fabrication**

An appropriate volume of gold colloids was drop-coated onto the surface of the carbon-paste electrode region and allowed to dry at room temperature overnight. The gold nanoparticles modified screen-printed carbon electrode was immersed in an ethanolic solution containing 5 mM of mercaptosuccinic acid for 15 h followed by washing with deionized water.

The formation of a three-dimensional monolayer of mercaptosuccinic acid on a gold nanoparticles modified screen-printed electrode was achieved as outlined in Fig. 1. An appropriate volume of a 1% polyvinyl alcohol (PVA) solution containing 10 mM of potassium ferricyanide was then drop-coated at the area above the carbon-paste electrode (Fig. 1) where mercaptosuccinic acid and gold nanoparticles has been deposited earlier and dried at room temperature overnight.

**Instrumentation**

Voltammetric measurements were performed using an AUTOLAB PG 12 (AUT 71681) Potentiostat/Galvanostat in a three-electrode electrochemical system with a gold nanoparticles modified screen-printed carbon electrode and a mercaptosuccinic acid gold nanoparticles modified screen-printed carbon electrode as the working electrode, a platinum counter electrode and an Ag/AgCl reference electrode. Cyclic voltammetry of a gold nanoparticles modified screen-printed carbon electrode was carried out in 5 mL of 0.5 M H$_2$SO$_4$ as a supporting electrolyte at room temperature. The detection of aluminium(III) ion by a mercaptosuccinic acid gold nanoparticles modified screen-printed carbon electrode was performed by the accumulation of
aluminium ions at a modified electrode at an open circuit by incubating the electrode in 10 mL of a stirred aqueous solution of aluminium chloride in a 40 mM sodium acetate buffer (pH 3.6) for 10 min. The modified electrode was then removed from the target ion solution and rinsed thoroughly with deionized water before being transferred to an aqueous solution containing 40 mM sodium acetate buffer and 0.5 M KCl for electrochemical measurements.

The selectivity of the mercaptosuccinic acid gold nanoparticles modified screen-printed carbon electrode towards Al\(^{3+}\) was carried out with ratios of Al\(^{3+}\) to interfering ions of 1:0.1, 1:1 and 1:10. The interferent metal ions under investigation were Na\(^+\), K\(^+\), Mg\(^{2+}\), Ca\(^{2+}\), Cu\(^{2+}\), Pb\(^{2+}\), Mn\(^{2+}\), Fe\(^{3+}\) and Cr\(^{3+}\).

Results and Discussion

The solution of the synthesized gold colloid has a characteristic burgundy color owing to containing non-agglomerated gold nanoparticles having diameters of less than 40 nm.\(^{33-35}\) This estimation is supported both by the UV-vis spectra and TEM image of the synthesized gold nanoparticles. From the UV-vis spectra (Fig. 2A), the non-agglomerated gold sol has a plasmon absorption peak, \(\lambda_{\text{max}}\), of 529 nm. Figure 2B shows a TEM image of the gold nanoparticles with an average diameter of 30.5 nm.

Electrochemical characterization of the gold nanoparticles modified screen-printed carbon electrode was described in our previous report.\(^ {31}\) The electrochemical surface area of the modified electrode was evaluated by the charge that passed in a reduction of the gold oxide peak using a conversion factor of \(\mu \text{C cm}^{-2}\).\(^ {36-41}\) The electrochemical area of the gold nanoparticles modified screen-printed carbon electrode used in this work was determined to be 0.004 cm\(^2\).

Figure 3 shows a cyclic voltammogram of a mercaptosuccinic acid gold nanoparticles modified Screen-printed carbon electrode prior to aluminium ion accumulation measured in a 40 mM sodium acetate buffer with 0.5 M KCl. Upon the accumulation of the modified electrode in 4.14 \(\mu\text{M}\) of aluminium for 10 min, the anodic (+300 mV) and cathodic (170 mV) process of potassium ferricyanide were notably enhanced. This signal enhancement was attributed to the binding of aluminium through oxygen on the carboxylate group with a ratio of 2:1 of
mercaptosuccinic acid to Al\textsuperscript{3+}. Table 1 illustrates the electrochemical data for the screen-printed carbon electrode, the gold nanoparticles modified screen-printed electrode and the mercaptosuccinic acid gold nanoparticles modified screen-printed electrode before and after complexation with aluminium ion. From the $\Delta E_p$ values, the mercaptosuccinic acid gold nanoparticles modified screen-printed electrode demonstrated a higher electron transfer rate after complexation with aluminium ion compared to the gold nanoparticles modified electrode and an unmodified electrode. The positively charge aluminium ion is classified as a typical hard metal ion, and hence is expected to form stable complexes with carboxylic groups containing negatively-charge oxygen.\textsuperscript{42,43} The linear dependence of the peak current of a mercaptosuccinic acid gold nanoparticles modified screen-printed carbon electrode after a 10 min preconcentration in 41.4 $\mu$M Al\textsuperscript{3+} for 10 min.

**Table 1** Electrochemical data for gold nanoparticles modified electrode (SPE\textsubscript{AuNP}), mercaptosuccinic acid gold nanoparticles prior (SPE\textsubscript{AuNP\_MSA}) and after (SPE\textsubscript{AuNP\_MSA\_Al}) complexation with aluminium ion

| Electrode               | $E_p$/V | $E_p$/V | $\Delta E_p$/V | $i_{pa}$/$i_{pc}$ |
|------------------------|---------|---------|----------------|------------------|
| SPE\textsubscript{AuNP} | 0.31    | 0.15    | 0.16           | 0.91             |
| SPE\textsubscript{AuNP\_MSA} | 0.34    | 0.13    | 0.21           | 0.90             |
| SPE\textsubscript{AuNP\_MSA\_Al} | 0.29    | 0.18    | 0.11           | 0.84             |

Fig. 4 Peak currents versus the scan rate for the mercaptosuccinic acid gold nanoparticles modified screen-printed carbon electrode after the preconcentration of 4.14 $\mu$M Al\textsuperscript{3+} for 10 min.

Fig. 5 Effect of the pH on the anodic current response of the modified screen-printed carbon electrode after the preconcentration of 4.14 $\mu$M Al\textsuperscript{3+} for 10 min.

Fig. 6 Effect of the preconcentration time on the anodic current response of the modified screen-printed carbon electrode after the accumulation of 4.14 $\mu$M Al\textsuperscript{3+}.

Fig. 7 Differential pulse voltammograms of complexed Al\textsuperscript{3+} at a mercaptosuccinic acid gold nanoparticles modified screen-printed carbon electrode after a preconcentration time of 10 min in a 40 mM sodium acetate buffer (pH 3.6) containing various concentrations of Al\textsuperscript{3+} (1), (2), 1.0 $\times$ 10$^{-3}$, (3), 1.0 $\times$ 10$^{-2}$, (4), 0.1 (5), 0.3 (6), 1.0 (7), 3.0 (8), 5.0 and (9) 10.0 ppm. Measurement was carried out in 0.04 M acetate buffer pH 3.6 with scan rate of 0.1 V s$^{-1}$. Inset: The DPV current response of a mercaptosuccinic acid gold nanoparticles modified screen-printed electrode to different aluminium concentrations.

The degree of binding of Al\textsuperscript{3+} to the mercaptosuccinic acid monolayer has a pH dependence. The response of the mercaptosuccinic acid gold nanoparticles modified screen-printed carbon electrode towards aluminium detection was investigated by varying the pH of the accumulation solution between pH 1.6 and 7.6. Deprotonation of the acidic carboxylate group occurred at higher pH values, which favoured the formation of a mercaptosuccinic acid–Al\textsuperscript{3+} complex. As illustrated in Fig. 5, the current response of the mercaptosuccinic acid gold nanoparticles modified electrode after complexing with Al\textsuperscript{3+} increases with the solution pH, reaching a maximum value at pH 3.6. At pH values greater than 5, the formation of sparingly soluble aluminium hydroxides occurred, which eventually led to a decrease in the amount of free aluminium ions available for binding with mercaptosuccinic acid.\textsuperscript{42} For a pH of 7.6, there appeared to be an increase in the current measured, but due to the poor reproducibility of the electrode...
response, such an increase is unlikely to be significant.

The effect of the preconcentration time on the current response of the mercaptosuccinic acid gold nanoparticles modified screen-printed carbon electrode in 4.14 μM of Al³⁺ in a 40 mM sodium acetate buffer (pH 3.6) containing 0.5 M KCl is illustrated in Fig. 6. The anodic current response increases with an increase of the preconcentration time, and reaches a plateau region at a time of 10 min. Thus, a preconcentration time of 10 min was chosen for further analysis.

Differential pulse voltammetry (DPV) was employed with a mercaptosuccinic acid gold nanoparticles modified screen-printed carbon electrode for the detection of lower levels of aluminium. The DPV peak currents of a modified electrode in 40 mM sodium acetate buffer (pH 3.6) containing 0.5 M KCl after the accumulation of various concentrations of aluminium(III) ion for 10 min is show in Fig. 7. The sensor displayed a wide linear dynamic range, with concentrations ranging from 0.041 to 12.4 μM (8.90 ppb). To the best of our knowledge, this is the first reagentless electrochemical aluminium sensor that has exhibited such a significantly low detection limit for Al³⁺. The low detection limit demonstrated by the sensor is ascribed to the three-dimensional monolayer of mercaptosuccinic acid formed on the gold nanoparticles modified electrode. On gold nanoparticles arrays, a greater disorder structure of the three-dimensional monolayer of mercaptosuccinic acid is formed relative to the compact monolayer adsorbed on a planar gold electrode. The three-dimensional monolayer could capture more aluminium(III) ion since the amount of the self-assembled mercaptosuccinic acid is greatly increased on gold nanoparticles relative to that of a planar gold substrate. Table 2 exhibits the performance of the aluminium(III) ion sensor that was developed in this work and the reported sensors. The chosen interference ions were based on their complexation affinities with mercaptosuccinic acid and their occurrence in water. A study of three different ratios of Al³⁺ to the interference ion was carried out; Table 3 gives the results of the study. There is no significant interference from all of the ions in the 1:0.1 and 1:1 ratio. However, at a ratio of 1:10, Cu²⁺ and Fe³⁺ demonstrated more than 30% of interference. The interferences of Cu²⁺ and Fe³⁺ is not surprising since both Cu²⁺ and Fe³⁺ are hard metal ions that have high complexation affinities towards the electron-rich carboxylate group. Besides, the atomic radius of Al³⁺ and Fe³⁺ are almost similar: 54 pm for Al³⁺ and 64 pm for Fe³⁺. Thus, these two ions will bind with the same ligand. The analytical application of the mercaptosuccinic acid gold nanoparticles modified screen-printed carbon electrode was demonstrated in a determination of the Al³⁺ content in local tap water and different kinds of tea leaves. According to the results illustrated in Table 4, the Al³⁺ concentration measured with the

| Interfering ion | % Interference | Interference ratio (Al³⁺: interfering ion) |
|----------------|----------------|------------------------------------------|
| Na⁺           | 3.96 ± 0.01    | 1:0.1                                    |
| K⁺            | 1.50 ± 0.07    | 1:1                                      |
| Mg²⁺          | 5.79 ± 0.06    | 1:10                                     |
| Ca²⁺          | 1.65 ± 0.07    |                                          |
| Mn²⁺          | 3.72 ± 0.01    |                                          |
| Fe²⁺          | 3.26 ± 0.24    |                                          |
| Cr³⁺          | 2.74 ± 0.15    |                                          |

Table 4 Determination of aluminium(III) ion concentration in real samples using standard method ICP-MS and mercaptosuccinic acid gold nanoparticles modified screen-printed carbon electrodes

In order to employ the sensor for real samples analysis, it is crucial to evaluate the selectivity of the mercaptosuccinic acid gold nanoparticles modified screen-printed carbon electrode. The chosen interference ions were based on their complexation affinities with mercaptosuccinic acid and their occurrence in water. A study of three different ratios of Al³⁺ to the interference ion was carried out; Table 3 gives the results of the study. There is no significant interference from all of the ions in the 1:0.1 and 1:1 ratio. However, at a ratio of 1:10, Cu²⁺ and Fe³⁺ demonstrated more than 30% of interference. The interferences of Cu²⁺ and Fe³⁺ is not surprising since both Cu²⁺ and Fe³⁺ are hard metal ions that have high complexation affinities towards the electron-rich carboxylate group. Besides, the atomic radius of Al³⁺ and Fe³⁺ are almost similar: 54 pm for Al³⁺ and 64 pm for Fe³⁺. Thus, these two ions will bind with the same ligand. The analytical application of the mercaptosuccinic acid gold nanoparticles modified screen-printed carbon electrode was demonstrated in a determination of the Al³⁺ content in local tap water and different kinds of tea leaves. According to the results illustrated in Table 4, the Al³⁺ concentration measured with the
developed aluminium(III) ion sensor exhibited a good correlation with the standard method ICP-MS with a confidence level of 95%. This demonstrated that the developed sensor produces compatible analysis that overcomes as the standard method.

Fig. 8 Effect of the storage time on the anodic current of the aluminium(III) ion sensor after the perconcentration of 4.14 μM Al³⁺ in a 0.04 M acetate buffer solution at pH 3.6 with a 10 min accumulation time.

Conclusions

The approach employed here for the preconcentration of aluminium(III) ion via a self-assembled layer and the mediation of the potassium ferricyanide redox behavior during aluminium(III) ion binding in this work has enhanced the amount of aluminium being captured, and thus improved the sensitivity of the sensor with a detection limit of down to the ppb level. The developed aluminium(III) ion sensor was successfully employed for the detection of Al³⁺ in real samples. A miniature aluminium(III) ion sensor for rapid, accurate, sensitive and selective aluminium determination has been developed.

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References

1. C. N. Martyn, Lancet, 1990, 336, 430.

2. J. Savory, J. Clin. Chem., 1994, 40, 1477.
3. D. R. Williams, J. Inorg. Biochem., 2000, 79, 275.
4. P. Zatta, E. Lain, and C. Cagnolini, Eur. J. Biochem., 2000, 267, 3049.
5. V. Rondeau and D. Commenges, “The epidemiology of aluminium and Alzheimer’s disease”, Chap. 3, in “Aluminium and Alzheimer’s Disease”, ed. C. Exley, 2001, Elsevier B. V., Amsterdam, 59.
6. T. P. Platen, Brain Res. Bull., 2001, 55, 187.
7. P. D. Darbre, D. Pugazhendhi, and F. Mannaio, J. Inorg. Biochem., 2011, 105, 1484.
8. R. W. Gensemer and R. C. Playle, Crit. Rev. Environ. Sci. Technol., 1999, 29, 315.
9. O. Momot and B. Synzynys, Int. J. Environ. Res. Public Health, 2005, 2, 214.
10. K. Jana, M. Peter, B. Marek, and M. Jan, Anal. Chim. Acta, 2005, 547, 119.
11. A. J. Downard, H. K. J. Powell, and S. Xu, Anal. Chim. Acta, 1991, 251, 157.
12. J. J. Hernandez-Brito, M. D. Gelado-Caballero, J. Perez-Pena, and J. A. Herrera-Melian, Analyst [London], 1994, 119, 1593.
13. J. Di, S. Bi, T. Yang, and M. Zhang, Sens. Actuators, B, 2004, 99, 468.
14. F. Zhang, S. Bi, J. Zhang, N. Bian, F. Liu, and Y. Yang, Analyst [London], 2000, 125, 1299.
15. J. Opdyke, Talanta, 1997, 44, 1081.
16. S. Bi, X. Yang, F. Zhang, X. Wang, and G. Zou, Fresenius’ J. Anal. Chem., 2001, 370, 984.
17. A. J. Downward, B. O’Sullivan, and K. J. Powell, Pergamon, 1996, 15, 3469.
18. G. Chen, S. Bi, L. Dai, M. Cao, Y. Chen, and X. Wang, Anal. Lett., 1999, 32, 865.
19. Y. Tang, S. Chong, X. Yang, and R. F. Shen, Int. J. Electrochem. Sci., 2013, 8, 4194.
20. W. Yang, J. J. Gooding, and D. B. Hibbert, J. Electroanal. Chem., 2001, 516, 10.
21. R. S. Freire and L. T. Kubota, Electrochim. Acta, 2004, 49, 3795.
22. W. Yang, J. J. Gooding, and D. B. Hibbert, Analyst [London], 2001, 126, 1573.
23. E. Chow, D. B. Hibbert, and J. J. Gooding, Electrochem. Commun., 2005, 7, 101.
24. E. Chow, D. B. Hibbert, and J. J. Gooding, Anal. Chim. Acta, 2005, 543, 167.
25. M. Chikae, K. Idegami, K. Kerman, K. Nagatani, M. Ishikawa, Y. Takamura, and E. Tamiya, Electrochem. Commun., 2006, 8, 1375.
26. I. Syancara, K. Vytas, K. Kalcher, K. Walczarius, and J. Wang, Electroanalysis, 2008, 21, 7.
27. S. Liu, X. Li, Y. Li, Y. Li, J. Li, and L. Jiang, Electrochim. Acta, 2005, 51, 427.
28. N. Sandhyarani and T. Pradeep, Int. Rev. Phys. Chem., 2003, 22, 221.
29. J. Zhang and M. Oyama, Electrochem. Commun., 2007, 9, 459.
30. Y. Cui, C. Yang, W. Zeng, M. Oyama, W. Pu, Y. Zheng, and J. Zhang, Anal. Lett., 2007, 40, 2151.
31. P. S. Wong, S. Nathan, and Y. H. Lee, AIP Conf. Proc., 2013, 1571, 725.
32. K. Stolarczyk, B. Palys, and R. Bilewicz, J. Electroanal. Chem., 2004, 564, 93.
33. K. Stolarczyk and R. Bilewicz, Electroanalysis, 2004, 16, 1609.
34. M. M. Maye, Y. Lou, and C. J. Zhong, Langmuir, 2000, 16,
35. K. C. Grabar, R. G. Freeman, M. B. Hommer, and M. Natan, *Anal. Chem.*, 1995, 67, 735.
36. J. Turkevich, *Gold Bull.*, 1985, 18, 86.
37. J. Turkevich, *Gold Bull.*, 1985, 18, 125.
38. A. Bonanni, M. Pumera, and Y. Miyahara, *Phys. Chem. Chem. Phys.*, 2011, 13, 4980.
39. T. I. Abdulin, O. K. Bondar, I. I. Niktina, E. R. Bulatov, M. V. Morozov, A. Hilmudinov, A. Salakhov, and M. Culha, *Bioelectrochemistry*, 2009, 22, 37.
40. J. C. M. Hoogvliet, B. Dijksma, B. Kamp, and W. P. Bennke van *Anal. Chem.*, 2000, 9, 2016.
41. W. H. Mulder, J. J. Calvente, and R. Andreu, *Langmuir*, 2001, 17, 3273.
42. K. Arihara, T. Ariga, N. Takashima, K. Arihara, T. Okajima, F. Kitamura, K. Tokuda, and T. Ohsaka, *Phys. Chem. Chem. Phys.*, 2003, 5, 3758.
43. P. Rubini, A. Lakatos, D. Champmartin, and T. Kiss, *Coord. Chem. Rev.*, 2002, 228, 137.
44. M. H. Mashhadizadeh and R. P. Talemi, *Anal. Chim. Acta*, 2011, 692, 109.
45. E. Laviron, *J. Electroanal. Chem.*, 1979, 52, 355.
46. M. O. Finot and M. T. McDermott, *J. Electroanal. Chem.*, 2000, 488, 125.
47. R. K. Shervedani, Z. Rezvaninia, H. Sabzyan, and H. Z. Boeini, *Anal. Chim. Acta*, 2014, 825, 34.
48. P. Liu, Y. N. Yao, S. D. Wu, H. J. Dong, G. C. Feng, and X. Y. Yuan, *Microchim. Acta*, 2005, 174, 329.
49. J. R. Scott, L. S. Baker, W. R. Everett, C. I. Wilkins, and I. Fritsch, *Anal. Chem.*, 1997, 69, 2636.
50. G. A. M. Mersal and H. A. Arida, *Int. J. Electrochem. Sci.*, 2011, 6, 1116.