A non-enzymatic glucose sensor based on the composite of cubic Cu nanoparticles and arc-synthesized multi-walled carbon nanotubes

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\begin{abstract}
A sort of non-enzymatic glucose sensor is fabricated based on a composite of cubic Cu nanoparticles and arc-synthesized multi-walled carbon nanotubes (MWCNTs) by using a substrate-enhanced electroless deposition (SEED) method. The common glassy carbon (GC) electrode is replaced by the cylindrical deposit that contains abundant MWCNTs as a support electrode. These cylindrical deposits can be synthesized by arc discharge in low pressure air atmosphere. The Cu-MWCNTs electrode shows significantly electrocatalytic activity to the oxidation of glucose in 0.1 M NaOH alkaline solution. The amperometric responses to glucose reveal that the fast response achieves within 1 s, the sensitivity is 922 \( \mu \)A M\(^{-1}\) cm\(^{-2}\) with a wide linear in the 0.5–7.5 mM concentration range, and the detection limit is 2.0 \( \mu \)M. The sensor also exhibits high stability and specificity to glucose. Due to the simplicity of the sensor preparation, Cu-MWCNTs electrodes are a good candidate for reliable glucose determination.
\end{abstract}

1. Introduction

Diabetes mellitus is a major public health problem affecting about 150 million people worldwide and has increased worldwide at an alarming rate mainly because of unhealthy diets, aging, obesity and sedentary lifestyles (Zhu et al., 2012). It and its complications lead significantly to ill health, disability, poor quality of life and several other causes of morbidity and mortality (Wang, 2008). This metabolic disorder caused by insulin deficiency and hyperglycemia is reflected by glucose concentration in blood with higher or lower than the normal range of 4.4–6.6 mM (Prehn et al., 2012).

A rapid, simple and reliable glucose sensing is of significantly importance in diagnosis and treatment of diabetes. Till today, electrochemical glucose biosensors are widely used for the entire biosensor market with about 85% portion (Prehn et al., 2012). These glucose sensors are based on the catalytic oxidation of glucose into gluconic acid by the enzyme glucose oxidase (GOx). The enzymatic biosensors based on GOx have high sensitivity, good selectivity and reliability. However, the catalytic activity of GOx is sensitive to environmental aspects such as temperature, humidity, pH and chemical reagents due to the nature of enzyme, resulting in the damage of enzyme. Therefore, non-enzymatic glucose sensors are highly desirable based on the direct oxidation of glucose on the electrode surface without using the fragile enzyme. Compared with enzymatic biosensors, the non-enzymatic sensors exhibit some attractive advantages, such as simple fabrication, low cost, stability and reproducibility.

Recently, many glucose sensors have been studied in various micro- and nanomaterials, such as platinum (Yang et al., 2006; Xie et al., 2007), gold (Yu et al., 2007; Zhang et al., 2011), copper (Yang et al., 2010; Pop et al., 2012; Lu et al., 2012), nickel (Shamsipur et al., 2010; Nie et al., 2011), palladium (Zeng et al., 2011; Meng et al., 2009) and metal oxides (Siegenthaler et al., 2008; Jiang and Zhang 2010). Among them, Cu-based nanomaterials exhibit remarkable catalyzed capability for glucose detection. For example, Kang et al., (2007) electrochemically deposited Cu nanoclusters on a MWCNT modified GC electrode to fabricate a Cu-CNT composite sensor. However, most fabrication of these similar nanostructures are always tedious because of complicated multi-step processes.

Electroless deposition has proven to be an especially useful and convenient method for allowing the deposition of metal nanoparticles onto the surface of carbon nanotubes (CNTs) because of a redox potential lower than that of CNTs (Byrne et al., 2009). Qu and Dai (2005) reported that metal ions could be readily reduced to metal nanoparticles onto the nanotube support without using reducing agents by supporting CNTs with a metal...
substrate of a redox potential lower than that of CNTs. This process was designated as substrate-enhanced electroless deposition (SEED). The SEED method is facile, effective and inexpensive for electroless deposition of Cu nanoparticles on MWCNTs.

CNTs possess excellent electronic properties, mechanical properties, a good chemical stability and a large surface area (Zhao et al., 2011). Moreover, arc-synthesized MWCNTs are essentially straight and defect free, and they are considered the most perfect in contrast to nanotubes grown by chemical vapor deposition (CVD). For example, the electric and thermal conductivity and mechanical properties of arc-synthesized nanotubes are 1–2 orders of magnitude better than those of CVD-grown CNTs (Okotrub et al., 2007). Generally, arc-synthesized MWCNTs exist in the soft black central region of a cylindrical deposit on the surface of cathode in the arc discharge system (Zhao et al., 2012). The cylindrical deposit with high conductivity is composed of the soft black central region (mostly MWCNTs) and the outer hard shell (sintered graphitic materials).

Herein, we utilize the cylindrical deposit instead of the common GC electrode as a support electrode, which tremendously simplified the preparation process of modified electrode. A promising, continuous, large-scale and low-cost synthetic method for preparing the cylindrical deposits that contain abundant MWCNTs is demonstrated. In our method, the cheapest and most accessible air replaces expensive high purity gas sources. Then a novel composite electrode of cubic Cu nanoparticles and arc-synthesized MWCNTs as a non-enzymatic glucose sensor has been fabricated by the SEED method. The high conductive cylindrical deposit and the efficient electrical network by means of cubic Cu nanoparticles directly anchoring on MWCNTs can not only improve the electron transfer rate but also increase their active area and enhance the sensitivity for glucose determination. After a study of the catalytic oxidation of glucose, the Cu-MWCNTs electrode with high stability and high sensitivity for sensing glucose has been discussed.

2. Experimental

2.1. Reagents

CuSO$_4$·5H$_2$O, sodium hydroxide, glucose, ascorbic acid and uric acid were purchased from Shanghai Chemical Corporation. All chemicals were used as received without any further purification. High-quality deionized water was used for fresh preparation of all solutions.

2.2. Apparatus

Morphologies and structures of the obtained samples were characterized using a field emission scanning electron microscope (FESEM, Ultra 55, Carl Zeiss) and a transmission electron microscope (TEM, JEM-2100, JEOL). Raman spectra were recorded at room temperature on a Renishaw inVia Raman spectrometer with laser excitation wavelength of 532 nm (40 mW). XRD profile was performed with a Bruker D8 Discover X-ray diffractometer.

Electrochemical measurements were performed on a CHI 660B electrochemical analyzer (CH Instrument Company, Shanghai, China). All experiments were carried out by a three-electrode system with the self-made electrode as the working electrode, a Pt wire as the auxiliary electrode, and an Ag/AgCl (3 M KCl) as the reference electrode.

The blood serum sample experiments for detecting glucose concentration were performed by the Cu-MWCNTs nanocomposite electrode. 50 μL of blood serum samples (provided by Shanghai First Municipal Hospital) was added to 10 mL of 0.1 M NaOH solution, and the current responses were obtained at 0.63 V, respectively. For comparison, glucose concentrations in blood serum samples were determined by a biochemical analyzer (OneTouch Ultra, LifeScan Inc., US).

2.3. Preparation of the Cu-MWCNTs nanocomposite electrode

The large scale preparations of MWCNT electrodes were done in a direct current (DC) arc discharge apparatus. Fig. 1(a) shows a schematic of the preparation process. The arc discharge system consists of a horizontal anode and a vertical hexagonal prism cathode assembly installed in a stainless steel cylindrical chamber. The anode fixed to the helical rod holder in the transmission device is a pure graphite rod with 8 mm in diameter and 150 cm in length, and then is sent to the chamber by a stepper motor. The hexagonal prism graphite of 30 mm edge length and 120 mm height as cathode fixed to a graphite disc of 160 mm diameter and 20 mm height is driven intermittently by a motor with rotational speed of 3 rev min$^{-1}$. The gap between the anode and the cathode is controlled by the stepper motor. The opposite side of anode is composed of a steel blade and a handle, which is used to scrape the cylindrical deposits (mostly MWCNTs in the center region) from the surface of cathode. When arc discharge lasts 2 min, the deposit forms on the surface of cathode. After that, arc is switched off and the graphite cathode is rotated by 60°. At the same time, the deposit at the other side is scraped off with manual adjustment of the handle and falls to the surface of graphite disc.

![Image](image-url)

**Fig. 1.** (a) Schematic of the arc discharge apparatus for continuously preparing cylindrical deposits, and inset shows some cylindrical deposit products. (b) Schematic of Cu nanoparticle deposition on CNTs via the SEED process.
Subsequently, it is collected automatically in the container by the remover. After the end of this process, the arc is switched on and a new deposit begins to generate. The use of water cooling for the electrodes and the arc chamber can help maximize the yield of CNTs.

The arc discharge condition in this work is described in detail as follows. The chamber was filled with air as the buffer gas. The pressure of air was introduced at about 8 kPa. A gap of 1–2 mm between two electrodes was maintained during the preparation process. The DC current and voltage applied usually were about 80 A and 20 V, respectively.

Before the preparation of Cu-MWCNTs nanocomposite electrode, cylindrical deposits were heated simply from 30 to 750 °C at 15 °C min\(^{-1}\) rate and then maintained at 750 °C for 30 min in air. Fig. 1(b) shows the SEED configuration used for the preparation of cubic Cu nanoparticles and MWCNTs composite electrode. Zinc foil with 0.5 mm thick was used as the substrate. Zinc foil was polished firstly by sandpaper in order to remove oxidation layer, and then cleaned ultrasonically in acetone. The cylindrical deposits were placed on the zinc foil and immersed in 0.01 M CuSO\(_4\) aqueous solution. And they were separated from the zinc foil in order to terminate the SEED process after 20 min. Then the products were washed with deionized water and dried naturally. Finally, the Cu-MWCNTs nanocomposite electrodes were ready.

The outer hard shell of Cu-MWCNTs composite electrode is a good conductor with a very excellent electrical conductivity. And the average sheet resistance of Cu-MWCNTs electrode is reduced from about 0.485 \(\Omega\)/square to about 0.0623 \(\Omega\)/square before and after deposition of Cu nanoparticles. So the electrical conductivity of the whole Cu-MWCNTs composite electrodes is very good. The Cu-MWCNTs composite electrodes are firstly connected by welding a metal wire on the outer hard shell with conductive silver paste and then connected to the electrochemical analyzer through the welded metal wire.

3. Results and discussion

3.1. Structural characterization

The cylindrical deposit formed on the surface of cathode exhibits a core-shell constitution. The oblique and top view optical images of a typical cylindrical deposit are shown in Fig. 2(a). The cylindrical deposit is about 9 mm in diameter, and about 3 mm in height. It is made up of two different textures and morphologies, the soft black central region and the outer hard shell. A large quantity of MWCNTs exists in the soft black central region and the outer hard region is composed of graphitic materials. It is obvious

![Image](image_url)
that parallel columns with highly ordered structure aligned along the cylinder axis of deposit growth are observed in the soft black central region, as shown in Fig. 2(b). The deposit was heated simply at 750 °C for 30 min in air. The structural schematic of longitudinal section of the cylindrical deposit after heat process is illustrated at right of Fig. 2(a). The columns with about 35 μm in diameter and a fluffy material filling the interstitial spaces between columns are observed from Fig. 2(c). The surface morphology of a column is shown in Fig. 2(d). It can be clear that these filament-like MWCNTs with some small graphitic nanoparticles entangle together. The surface of the outer hard graphitic shell exhibits honeycombed graphitic platelets with passages due to oxidation etching, as shown in Fig. 2(e), which should increase the surface area. The diameter of passages is about 200–300 nm. The high concentration of purified MWCNTs existed in the intercolumnar space is shown in Fig. 2(f). Fine and long MWCNTs with random orientation are observed and they are totally free of carbon nanoparticles and graphite platelet. The interior morphology of a columnar structure is exhibited in Fig. 2(g). A significant amount of graphitic platelets and particles accompanied by some MWCNTs are observed. The longitudinal section image of outer shell shows that it is formed with a layered structure of graphitic platelets (Fig. 2(h)).

In order to deeply characterize the structures of the inner region and outer shell of the cylindrical deposit, TEM and Raman spectra are performed, respectively (Fig. S1). The details are shown in Supplemental information.

A large amount of Cu nanoparticles is electrolessly deposited onto the walls of MWCNTs by the SEED process, as shown in Fig. 3(a). Little Cu nanoparticles form spontaneously on the nanotube sidewalls at first, and then grow gradually into cubic sharp. MWCNT walls are coated simultaneously with these cubic Cu nanoparticles, just like sugarcoated haws on a stick (Fig. 3(b)). TEM image of Fig. 3(c) shows a clear profile and fine structures of some cubic Cu nanoparticles on a straight MWCNT. Inset of Fig. 3(c) shows HRTEM lattice image of cubic Cu nanoparticle. The fringes of (1 1 1) planes with a lattice spacing of about 0.21 nm are clearly observed. Fig. 3(d) shows the XRD pattern of Cu-MWCNTs nanocomposite. The peak of 2θ=25.9 indicates the existence of MWCNTs. Three prominent peaks are observed at 43.3, 50.1 and 74.3, corresponding to (1 1 1), (2 0 0) and (2 2 0) planes of face-centered-cubic (FCC) Cu. It clearly demonstrates that crystalline Cu nanoparticles with a strong (1 1 1) orientation are coated on the walls of nanotubes. This agrees well with the TEM results.

3.2. Electrocatalytic oxidation of glucose

Fig. 4(a) shows cyclic voltammograms of cylindrical deposit and Cu-MWCNTs electrode are recorded separately in 0.1 M NaOH solution with the presence and absence of 0.5 mM glucose at a scan rate of 100 mV s⁻¹. The potential is a range from 0.0 to 0.8 V vs. SCE. In the absence of glucose, no reaction peak current appears from cylindrical deposit (curve a) and Cu-MWCNTs electrode (curve c) responses. Upon the addition of 0.5 mM glucose, cylindrical deposit (curve b) still generates no reaction peak current. However, a pair of well-defined redox peaks at 0.67 V and 0.24 V are observed from curve (d), indicating that cubic Cu nanoparticles demonstrate excellent electrocatalytic activity toward the oxidation of glucose, and MWCNTs and other carbonic species from the cylindrical deposit provide a large surface and high conductivity for fast electron transfer.

Cyclic voltammograms of Cu-MWCNTs electrode in 0.1 M NaOH solution with 0.5 mM glucose at different scan rates, as shown in Fig. 4(b). The peak-to-peak separation becomes more and more wide with increasing scan rates from 10 to 150 mV s⁻¹. Meanwhile,
the peak currents increasingly shift to high current values. Inset of Fig. 4(b) shows the dependences of anodic and cathodic peak currents on scan rates. Both the anodic and the cathodic peak current values increase highly linearly with increased scan rates (correlation coefficients $R^2=0.992$ and 0.991 for anodic and cathodic peaks, respectively). The results indicate the surface adsorption of glucose molecules dominates the electrochemical kinetics.

3.3. Amperometric response of Cu-MWCNTs electrode toward glucose

Fig. 5(a) shows the amperometric response of Cu-MWCNTs electrode for a successive addition of 0.5 mM glucose at 40 s in 0.1 M NaOH solution at optimal potential of 0.63 V. A step-style increase in current responses generates after each addition of glucose. It can be observed that the Cu-MWCNTs electrode responds quickly and reaches a steady-state current within 1 s (top inset of Fig. 5(a)), indicating that cubic Cu-MWCNTs nanocomposite sensor exhibits an extremely rapid and sensitive response characteristics toward glucose. This might be due to the fact that fast diffusion of glucose molecules occurs in the three-dimensional network of Cu-MWCNTs nanocomposite and arc-prepared cylindrical deposit with highly electroconductive performance promotes electron fast transfer. As shown in bottom inset of Fig. 5(a), the current response $i$ ($\mu$A) vs. glucose concentration (mM) in the range of 0.5–7.5 mM exhibits a good linearity with a correlation coefficient $R^2=0.9987$ and a slope of 86.32 $\mu$Am M$^{-1}$. The sensitivity of cubic Cu-MWCNTs nanocomposite sensor is 922922 $\mu$Am M$^{-1}$ cm$^{-2}$ by dividing the slope of the linear regression equation by the electroactive surface area. The detection limit is 2.0 $\mu$M at a signal-to-noise ratio of 3.

3.4. Reproducibility, stability and specificity of the Cu-MWCNTs electrode

The reproducibility of Cu-MWCNTs electrode was examined by measuring the current responses upon 0.1 mM glucose in 0.1 M NaOH solution. After 10 successive measurements, the electrode generated reproducible current was analyzed in terms of the relative standard deviation (RSD) of 4.2%. In a series of 5 electrodes separately prepared in the same way, a RSD of 5.8% was obtained. These results demonstrate that the Cu-MWCNTs electrode displays the acceptable reproducibility for detecting glucose.

In order to evaluate the stability of Cu-MWCNTs electrode, the current responses to 0.1 mM glucose were measured in 0.1 M NaOH solution at 0.63 V with every 2 days intervals, as shown in Fig. 5(b). When the electrode was not measured, it was placed in air. It was observed that the response current could remain about 90% of its first signal after 20 days storage, indicating that the Cu-MWCNTs electrode has good stability.

The interfering electrochemical signals caused by some symbiotic easily oxidizable compounds such as uric acid (UA) and ascorbic acid (AA) are one of the major challenges in non-enzymatic glucose
detection. Although these interfering species of UA (0.1 mM) and AA (0.1 mM) are generally much lower than glucose concentration (3–8 mM) in a normal physiological sample, they can produce oxidation currents comparable to that of glucose due to their higher electron transfer rates (Park et al., 2003). Inset of Fig. 5(b) shows the interfering measurements with continuous addition of 1 mM glucose and 0.1 mM interfering species to 0.1 M NaOH solution. A remarkable glucose signal was obtained, whereas very small responses were detected, which means that the interfering species can be nearly neglected compared to glucose. These results indicate that the Cu-MWCNTs electrode is highly specific to glucose regardless of the presence of interfering species.

3.5. Application to determine glucose in serum samples

To verify the reliability of the sensor, three blood serum samples were analyzed using the independently Cu-MWCNTs composite electrodes (one electrode per sample). The determined results were compared with those measured with a biochemical analyzer in Table 1. The results are basically in an acceptable range of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning, the U-M/SJTU Collaborative Research Program and the Analytical and Testing Center of SJTU.

Acknowledgments

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.bios.2013.02.032.

References


Table 1 Determination of glucose concentrations in blood serum samples (n= 3).

<table>
<thead>
<tr>
<th>Sample</th>
<th>Biochemical analyzer (mM)</th>
<th>Our sensors (mM)</th>
<th>RSD (%)</th>
<th>Added (mM)</th>
<th>Recovery (%)</th>
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<td>1</td>
<td>4.5</td>
<td>4.46</td>
<td>2.01</td>
<td>0.5</td>
<td>98</td>
</tr>
<tr>
<td>2</td>
<td>5.3</td>
<td>5.24</td>
<td>4.24</td>
<td>0.5</td>
<td>97</td>
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<tr>
<td>3</td>
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<td>5.11</td>
<td>3.28</td>
<td>0.5</td>
<td>102</td>
</tr>
</tbody>
</table>

* Each sample was measured for three times.