Facile One-pot Synthesis of Hollow-structured CuS/Cu$_2$S Hybrid for Enhanced Electrochemical Determination of Glucose

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ABSTRACT

A novel non-enzymatic glucose sensor based on hollow-structured copper sulfide/cuprous sulfide (CuS/Cu$_2$S) hybrid was developed by using a facile and one-pot solvothermal method. The crystal structure, morphology and surface property of the prepared CuS/Cu$_2$S hybrid were characterized by X-ray diffraction spectroscopy, scanning electron microscopy, transmission electron microscopy, energy dispersive X-ray spectroscopy and X-ray photoelectron spectroscopy. The electrochemical performances of this hybrid modified glassy carbon electrode for glucose oxidation were monitored by cyclic voltammograms and amperometric technology. Results showed that the novel integrated electrode exhibited excellent electrocatalytic performances to the oxidation of glucose with a wide line range of 3.0–1100.0 µM, high sensitivity of 321.3 µA mM$^{-1}$ cm$^{-2}$, low detection limit of 1.1 µM (36/S), fast response, good anti-interference ability and excellent stability. The proposed sensor was successfully applied for the determination of glucose in human blood serum sample with satisfactory recoveries.

Keywords: Non-enzymatic Glucose Sensor, Hollow-structured Copper Sulfide/Cuprous Sulfide Hybrid, Solvothermal Method, Electro-catalytic

1. Introduction

Glucose is an essential nutrient for metabolism in living organisms. The heat released by its oxidation reaction is an important source of energy for human life activities. Once the glucose content is disordered, it will pose a threat to human life and health, such as diabetes, which killed millions of people every year due to it often associated with severe autoimmune diseases, kidney failure, genetic diseases and heart disease, peripheral nerve damage, and even certain cancers. Therefore, it is important to develop a simple, fast and sensitive detection of glucose in public health, clinical diagnosis and disease control. Since Clark and Lyons first reported glucose detection based on the enzyme electrode in 1962, the enzyme-based glucose biosensors caused widespread concern due to its high sensitivity and selectivity. Unfortunately, the enzyme is expensive and its electrocatalytic activity is easy to be affected by pH, temperature and humidity, which limit the application of glucose oxidase biosensor. Consequently, the development of highly sensitive, selective and stable non-enzymatic glucose sensor has attracted wide attention.

At present, numerous materials have been developed to modify electrodes for non-enzymatic glucose detection, such as noble metals,3,4 alloy,5,6 metal sulfides,7,8 and metal oxides.9,10 Among these materials, Cu$_2$S shows great potential in electrochemical sensors for glucose detection due to its moderate price, good catalytic oxidation performance and environmental friendly.11 Currently, Cu$_2$S with different morphologies has been used for the detection of glucose with excellent performance, such as flower-like,12 sphere,13 nanosheets,14 clews,15 and nanotubes.16 Similarly, CuS with different morphologies has also been applied to the detection of glucose with superior performance, such as nanorods-like,17 and nanoplates.18,19 Furthermore, hybrid materials have been proven to obtain the properties combination of various materials involved, in which the hybrid catalysts exhibit enhanced electrocatalysis resulting from the synergistic components effects.20 For instance, Zhao et al. confirmed that Au-Ag hybrid nanoparticles possess better electrochemical H$_2$S detection performance compared with the corresponding Au and Ag nanoparticles.21 However, limited investigation about the CuS/Cu$_2$S hybrid in electrochemical glucose detection is available.22

In addition, hollow structures have attracted extensive attention because of their interesting structurally induced physical and chemical properties and the great potential for widespread application. Compared with solid counterparts, hollow structures with pervious and porous shells possess high surface area and low density,23,24 which could improve the electrocatalysis. Besides, hollow structures are beneficial for facilitating electrolyte penetration and shorting mass and charge transport pathways of the electrode to promote electrochemical reaction and expedite reaction rate. Moreover, hollow structures can effectively withstand the strain in the chemical reaction process to improve the electrocatalysis stability of materials.25

Here, a facile, low-cost, one-pot strategy for the synthesis of hollow-structured copper sulfide/cuprous sulfide (CuS/Cu$_2$S) hybrid is developed via a solvothermal route with cuprous oxide (Cu$_2$O) as a sacrificial template. After that, a newly non-enzymatic glucose sensor was fabricated based on this hollow-structured CuS/Cu$_2$S hybrid. Scheme 1 shows the process of the CuS/Cu$_2$S hybrid synthesis and its application for glucose detection. Cyclic voltammograms and amperometric technology were carried out to study the electrochemical performances of the sensor. Owing to the hybrid composition and the hollow structures, the non-enzymatic glucose sensor exhibits outstanding properties, including a wide linear range, low detection limit and high sensitivity.
2. Experimental Section

2.1 Chemicals
Polyethylene glycol 6000 (PEG 6000), CuCl$_2$·2H$_2$O, thioacetamide (CH$_3$CSNH$_2$), NaOH, N$_2$H$_4$·H$_2$O, ethanol, glucose were obtained from Sinopharm Chemical Reagent Co., Ltd. All reagents were of AR grade. All solutions were prepared with distilled water.

2.2 Apparatus and instruments
X-ray diffraction (XRD) was carried out on a Bruker X-ray diffractometer (D8 Advance). The morphology of the prepared products was studied by scanning electron microscope (SEM, Zeiss, EVO-18) and transmission electron microscopy (TEM, JEOL, JEM-2100). Elemental analysis was performed on an energy dispersive X-ray spectroscopy (EDX, Oxford) attached to the SEM and X-ray photoelectron spectroscopy (XPS, Thermo, ESCALAB250Xi). Electrochemical experiments were performed on CHI 660D electrochemical workstation (Chenhua) with a conventional three-electrode system, which a bare glassy carbon electrode (GCE, 3 mm) was polished with 0.05 µm alumina powder, it was then ultrasonically cleaned with water, ethanol successively, followed drying by nitrogen for stand-by. 5 mg CuS powder, it was then ultrasonically cleaned with water, ethanol respectively, followed drying under vacuum overnight.

2.3 Synthesis of hollow tubular CuS

The hollow tubular CuS was prepared according to the reference with slight modification.²⁶ 2.0 mmol CuCl$_2$·2H$_2$O and 4 mmol CH$_3$CSNH$_2$ were dissolved in 30 ml distilled water, respectively. After that, the above two solutions were mixed and stirred vigorously for 0.5 h, then transferred into a Teflon-lined stainless steel autoclave and maintained at 150 °C for 10 h. After cool down to room temperature, the product was separated by centrifugation at 8000 rpm, cleaned with distilled water and ethanol for 3 times, respectively. Finally, it was dried under vacuum overnight.

2.4 Synthesis of Cu$_2$O

The Cu$_2$O was synthesized as following.²⁷ Briefly, 0.03 mmol PEG (Mw 6000) and 1.0 mmol CuCl$_2$·2H$_2$O were dissolved in 200 ml distilled water under vigorous magnetic stirring and subsequently 1.5 ml 5 M NaOH was added dropwise into the mixture under constant stirring and maintain for 15 min. After that, 1.5 ml 13.7 M N$_2$H$_4$·H$_2$O solution was added and stirred 20 min. The resulted product was separated by centrifugation at 8000 rpm, cleaned with distilled water and ethanol for 3 times, respectively. Finally, it was dried under vacuum overnight.

2.5 Synthesis of hollow-structured CuS/Cu$_2$O hybrid

The synthesis of hollow-structured CuS/Cu$_2$O hybrid was similar to that of hollow tubular CuS except that the previous solvent water was replaced by the resulted product obtained from the stage of the synthesis of Cu$_2$O. The resulted product was then separated by centrifugation at 8000 rpm, washed with distilled water and ethanol for 3 times, respectively, followed drying under vacuum overnight.

2.6 Electrode modification

The bare GCE (Φ = 3 mm) was polished with 0.05 µm alumina powder, it was then ultrasonically cleaned with water, ethanol successively, followed drying by nitrogen for stand-by. 5 mg CuS/Cu$_2$S hybrid was dispersed into 5 ml ethanol to obtain 1 mg/mL CuS/Cu$_2$S suspension. After that, 5 µL suspension was dropped onto the GCE surface. The finally obtained electrode was denoted as CuS/Cu$_2$S/GCE. For comparison, CuS/GCE and Cu$_2$O/GCE were prepared via a similar route.

3. Results and Discussion

3.1 Structure and morphology

Figure 1 displays the XRD patterns of the as-prepared CuS, Cu$_2$O and CuS/Cu$_2$S hybrid. All observed diffraction peaks in the curve of CuS could be perfectly indexed to the hexagonal phase CuS (JCPDS 78-0876). The XRD pattern of Cu$_2$O displays the cubic phase of Cu$_2$O (JPCDS 65-3288). In addition, the peaks of hybrid material show the crystallinity combination of two phases. Amazingly, four peaks available at 2θ of 30.43, 34.36, 35.50, 46.29 are correspond to d (312), d (315), d (402), d (110) planes of the Cu$_2$S,²⁸ while the diﬀraction peaks of CuS/Cu$_2$S hybrid were almost disappeared, which indicate the CuS/Cu$_2$S hybrid was successfully obtained with cuprous oxide as a sacrificial template through the synthesis strategy. What’s more, the diﬀraction peaks of Cu$_2$O indicate the layers with a predominant monoclinic phase.

The morphologies of the obtained CuS, Cu$_2$O, CuS/Cu$_2$S hybrid were investigated using SEM and TEM (Figs. 2a, 2b, 2c, 2d, 2e and 2f). It is found that CuS sample consist of numerous hollow microtubes with inner diameters was about 0.6 µm and the CuS sample in CuS/Cu$_2$S hybrid is similar to CuS. More, the diﬀraction peaks in the XRD pattern of CuS/Cu$_2$S hybrid were almost disappeared, which indicate the CuS/Cu$_2$S hybrid was successfully obtained with cuprous oxide as a sacrificial template through the synthesis strategy. What’s more, the diﬀraction peaks of CuS/Cu$_2$S hybrid were almost disappeared, which indicate the CuS/Cu$_2$S hybrid was successfully obtained with cuprous oxide as a sacrificial template through the synthesis strategy.
shows the Cu2O particles present an regular octahedral shape with diameters about 1 µm, which consist with the TEM result (Fig. 2d). Moreover, Fig. 2d exhibits the internal structure of Cu2O was solid. The morphology of hybrid material displays numerous tubular and octahedral shapes (Fig. 2e). What’s more, the tube and octahedron show hollow structure from the TEM image (Fig. 2f), which demonstrates again hollow-structured CuS/Cu2S hybrid was synthesized by using Cu2O octahedron as sacrificial template. And the formation mechanism of hollow-structured CuS/Cu2S hybrid can explain as follows: on one hand, S2− released from the decomposition of thioacetamide undergoes an exchange reaction with O2− of Cu2O to generate Cu2S. In addition, the diffusion velocity of O2− was faster than that of S2−, which causes Cu2O crystallites to continuous transfer mass from the inside out during the formation of Cu2S with a sustained supply of S2− for the exchange reaction, thereby forming the hollow structure of Cu2S. On the other hand, thioacetamide combines with the Cu2+ to form complex by the lone pair electrons on nitrogen and sulfur atoms of thioacetamide, after heating, the complex then dissociates and the reaction of Cu2+ with S2− for the exchange reaction, thereby forming the hollow structure of Cu2S. The proposed mechanism of the synthesis of hollow-structured CuS/Cu2S hybrid was described as Eqs. (1)–(6).

\[
\begin{align*}
\text{CuCl}_2 + 2\text{NaOH} & \rightarrow \text{Cu(OH)}_2 + 2\text{NaCl} \\
4\text{Cu(OH)}_2 + \text{N}_2\text{H}_4 & \rightarrow 2\text{Cu}_2\text{O} + 6\text{H}_2\text{O} + \text{N}_2 \\
\text{CH}_3\text{CSNH}_2 + 3\text{OH}^- & \rightarrow \text{CH}_3\text{COO}^- + \text{NH}_3 + \text{S}^{2-} + \text{H}_2\text{O} \\
\text{Cu}_2\text{O} + \text{S}^{2-} + \text{H}_2\text{O} & \rightarrow \text{Cu}_2\text{S} + 2\text{OH}^- \\
\text{CuCl}_2 + 2\text{CH}_3\text{CSNH}_2 & \rightarrow [\text{Cu} \cdot (\text{CH}_3\text{CSNH}_2)_2]\text{Cl}_2 \\
& \rightarrow \text{CuS} + 2\text{HCl} + \text{CH}_3\text{COONH}_4
\end{align*}
\]

The composition of the as-fabricated CuS/Cu2S hybrid was investigated by EDS mapping (Figs. 3a and 3b). The EDS analysis indicates the presence of Cu, S and O elements. What is more, the distribution of Cu and S elements are mainly concentrated on the hybrid except for exist a small amount of residual oxygen. Furthermore, XPS was performed to get elemental state of the CuS/Cu2S hybrid. Figures 3c and 3d show the results of Cu 2p and S 2p, respectively. There are four prominent peaks including Cu 2p3/2 at 953.6 eV, S 2p at 161.6 eV, and C 1s at 284.8 eV.
934.6 eV with the satellite peaks at 943.6 eV and the Cu 2p1/2 at 954.6 eV with the satellite peak at 962.6 eV, suggesting the presence of Cu(II).\textsuperscript{33} In addition, two peaks observed at 931.5 eV and 951.5 eV reveal the presence of Cu(I) (Fig. 3c). Besides, the peaks at 161.6 eV was corresponding to S 2p1/2 for Cu2S and S 2p3/2 for CuS and Cu2S, while 162.8 eV are corresponding to S 2p1/2 for CuS phases (Fig. 3d),\textsuperscript{34,35} respectively, suggesting the CuS/Cu2S hybrid was successfully prepared, in good agreement with the results of the XRD.

3.2 Electrochemical behavior of modified electrodes

EIS was applied to study the interface properties of electrodes (Fig. 4a). The EIS curves consist of a semicircle and a line that represent electron-transfer resistance (R\text{et}) and diffusion limited processed, respectively. The R\text{et} value of bare GCE was about 490 Ω. After GCE modified with CuS, Cu2O or CuS/Cu2S, the R\text{et} value increased dramatically due to the semi-conductive nature of copper-based materials. Moreover, the R\text{et} value of CuS/Cu2S was the largest, indicating the CuS/Cu2S hybrid was successfully modified electrode.

The electrocatalytic activity of the as-prepared CuS, Cu2O and CuS/Cu2S hybrid towards the glucose was studied by cyclic voltammograms (CVs). Figures 4b–4d show the CVs of CuS/GCE (b), Cu2O/GCE (c) and CuS/Cu2S/GCE (d) in 0.1 M NaOH in the absence and presence of 0.4, 0.8, 1.2 mM glucose. Amperometric responses of the CuS/GCE, Cu2O/GCE and CuS/Cu2S/GCE to successive additions of 4 × 10^{-3} M glucose into 0.1 M NaOH at 0.6 V (e).

![Figure 4](image_url)

**Figure 4.** Electrochemical impedance spectroscopy of the modified electrodes in 0.1 M NaOH solution containing 0.1 M KCl and 5 mM K\textsubscript{3}Fe(CN)\textsubscript{6}/K\textsubscript{4}Fe(CN)\textsubscript{6} (a). CVs of CuS/GCE (b), Cu2O/GCE (c) and CuS/Cu2S/GCE (d) in 0.1 M NaOH in the absence and presence of 0.4, 0.8, 1.2 mM glucose. Amperometric responses of the CuS/GCE, Cu2O/GCE and CuS/Cu2S/GCE to successive additions of 4 × 10^{-3} M glucose into 0.1 M NaOH at 0.6 V (e).
For CuS

\[ \text{CuS} + \text{OH}^- \rightarrow \text{CuSOH} + e^- \]  

\[ \text{CuSOH} + e^- + \text{glucose} \rightarrow \text{CuS} + \text{OH}^- + \text{gluconolactone} \]  

For Cu2O or Cu2S

\[ 2\text{Cu}_2\text{O} + 3\text{O}_2 \rightarrow 2\text{Cu}_2\text{O}_2 + 2\text{SO}_2 \]  

\[ \text{Cu}_2\text{O} + 3\text{H}_2\text{O} \rightarrow 2\text{Cu(OH)}_2 + \text{H}_2 \]  

\[ \text{Cu(OH)}_2 \rightarrow \text{CuO} + \text{H}_2\text{O} \]  

\[ \text{CuO} + \text{OH}^- \rightarrow \text{CuOOH} + e^- \]  

\[ \text{CuOOH} + e^- + \text{glucose} \rightarrow \text{CuO} + \text{OH}^- + \text{gluconolactone} \]  

Moreover, the onset potential (about 0.29 V) of the anodic peak at the CuS/Cu2O/GCE was lower than that of CuS/GCE (about 0.35 V) or Cu2O/GCE (about 0.42 V), suggesting that the enhancement of the electrocatalytic activity of electrode in the presence of CuS/Cu2S hybrid. This may be attributed to the porous exteriors, hollow interiors structure provides the smooth mass transport paths, and the backbone benefits the transport of electrons and adsorbed reaction medium, which is more preferable for the electrocatalysis compared with CuS or Cu2O. To obtain a more accurate result of catalytic activity of different modified electrodes, the amperometric technology was carried out to study the current responses of these modified electrodes to successive additions of glucose (Fig. 4e). As expected, the CuS/Cu2S modified electrode possesses the largest current response toward glucose sensing. The current response (about 1.2 µA) is much larger than that of CuS modified GCE (about 0.02 µA) and Cu2O modified GCE (about 0.52 µA), which represents the promising sensing application of hollow-structured CuS/Cu2S hybrid to the detection of glucose.

3.3 The electrochemical kinetics of CuS/Cu2S/GCE towards glucose oxidation

Figure 5a shows the CVs of CuS/Cu2S/GCE at different scan rates in the presence of 0.4 mM glucose. The oxidation peak currents were proportional to the square root of the scan rates (Fig. 5b), indicating the oxidation of glucose may be a typical diffusion-controlled process.

Furthermore, the electrocatalytic kinetics of glucose oxidation at CuS/Cu2S/GCE was evaluated by chronoamperometry technique. Figure 5c shows the chronoamperogram curves for CuS/Cu2S/GCE in various concentrations of glucose. The catalytic rate constant \( K_{cat} \) can be estimated by the following equation:

\[
\frac{I_{cat}}{I_0} = (\pi K_{cat} C_s A)^{1/2}
\]

Where \( I_{cat} \) and \( I_0 \) are the currents in the presence and absence of glucose, respectively. \( C_s \) is the concentration of glucose. This is much higher than that of previously reported copper based electrodes (Table 1), suggesting the high rate capability of CuS/Cu2S for oxidation of glucose. Figure 5d shows the plots of oxidation currents vs. \( t^{-1/2} \) for various glucose concentrations. It can be seen that oxidation current had linear relationship with the minus square root of glucose concentrations. The catalytic rate constant \( K_{cat} \) can be calculated by the following equation:

\[
I_{cat} = nFAD^{1/2}C\tau^{-1/2}t^{-1/2}
\]

Where \( n \) is the number of transferred electrons, \( F \) is the Faraday constant, \( A \) is the surface area of electrode, \( C \) is the glucose concentration, and \( \tau \) is the diffusion layer thickness.
concentrations. The value of $D$ for glucose was calculated to be $6.4 \times 10^{-5}$ cm$^2$ s$^{-1}$, which is compared with that of previous reports (Table 1).

3.4 Optimization of determination condition

To obtain the best response of the CuS/Cu$_2$S/GCE for the determination of glucose, the optimization of applied potential was investigated from 0.45 to 0.65 V. Figure 6a displays the amperometric curves of the CuS/Cu$_2$S/GCE at different applied potentials with successive injection of $4 \times 10^{-5}$ M glucose in 0.1 M NaOH. It can be seen that the current response increases from 0.45 to 0.60 V. When the applied potential was more positive than 0.6 V, the current responses decreased. The slopes of the calibration curve show the highest value with the applied potential of 0.60 V (Fig. 6b). Thus, 0.6 V was selected for the optimized working potential.

3.5 Amperometric determination of glucose

The analytical performance of CuS/Cu$_2$S/GCE to the detection of glucose under optimization conditions was evaluated by amperometric technology. Figure 7a exhibits the current response curves of CuS/GCE, Cu$_2$O/GCE and CuS/Cu$_2$S/GCE upon successive addition of glucose at 0.6 V in 0.1 M NaOH (a). The corresponding calibration curve for CuS/GCE, Cu$_2$O/GCE and CuS/Cu$_2$S/GCE (b).

### Table 1. Comparison of calculated $K_{cat}$ and $D$ on CuS/Cu$_2$S/GCE glucose oxidation with other copper based electrodes.

| Electrode material                  | $K_{cat}$/cm$^3$mol$^{-1}$s$^{-1}$ | $D$/cm$^2$s$^{-1}$ | Reference |
|-------------------------------------|----------------------------------|--------------------|-----------|
| c-MOF@GCE                           | $9.5 \times 10^4$                | /                  | 39        |
| Andanneal-shrunked Cu$_2$O dendrites| 16.9                             | /                  | 40        |
| CuO/OPpy/MWCNTs                     | $8.2 \times 10^5$                | /                  | 41        |
| Cu$_3$/PANI/rGO/GCE                 | $1.27 \times 10^6$               | $7.89 \times 10^{-5}$ | 42        |
| IE Co(OH)$_2$ NSs/Cu$_2$ NCs/GCE    | $1.76 \times 10^5$               | $5.06 \times 10^{-5}$ | 43        |
| CuS/Cu$_2$S/GCE                     | $1.53 \times 10^7$               | $6.4 \times 10^{-5}$ | This work |

Figure 6. Amperometric responses for the CuS/Cu$_2$S/GCE at different potentials with successive addition of $4 \times 10^{-5}$ M glucose in 0.1 M NaOH (a). Calibration curves of glucose versus its concentration at different applied potentials (b).

Figure 7. Amperometric responses of CuS/GCE, Cu$_2$O/GCE and CuS/Cu$_2$S/GCE upon successive addition of glucose at 0.6 V in 0.1 M NaOH (a). The corresponding calibration curve for CuS/GCE, Cu$_2$O/GCE and CuS/Cu$_2$S/GCE (b).
represents the slope of the calibration curve. The Cu$_2$O/GCE presents better linear relationship with a glucose concentration range from 3 to 1100 µM ($I_p$ ($\mu A$) = 0.0107 C ($\mu M$) + 0.2522, $R^2$ = 0.9947) and the LOD was estimated to be 5.4 µM. By contrast, the CuS/Cu$_2$S hybrid shows the detection range of 3–1100 µM ($I_p$ ($\mu A$) = 0.0227 C ($\mu M$) + 0.27, $R^2$ = 0.9967) with the lowest detection limit of 1.1 µM. Moreover, compared with CuS or Cu$_2$O, the CuS/Cu$_2$S generated much higher response current to glucose oxidation, and the sensitivity for glucose sensing over CuS/Cu$_2$S hybrid was calculated to be 321.3 µA mM$^{-1}$ cm$^{-2}$, which is higher than that of CuS (130.2 µA mM$^{-1}$ cm$^{-2}$) or Cu$_2$O (151.4 µA mM$^{-1}$ cm$^{-2}$). The higher electrocatalytic activity of CuS/Cu$_2$S was attributed to the synergy between the CuS and Cu$_2$S. First, lots of active sites and larger surface area were obtained through coupling of CuS and Cu$_2$S. Second, the porous exteriors, hollow interiors structure of Cu$_2$S improved the utilization. Third, the provides hollow structured CuS and Cu$_2$S provided diffusion channels, which facilitated the mass transport and oxidation of glucose, this was confirmed by the value of $D$ and $K_w$. We also compared the electrochemical performance of our proposed glucose sensor with that of previously reported. As shown in Table 2, suggesting that the analytical performance of this sensor is comparable or even better than previous reports.

### 3.6 Selectivity and stability of the proposed sensor

Ascorbic acid (AA), uric acid (UA), dopamine (DA) and NaCl were examined to evaluate the selectivity of the proposed sensor, which may coexist with glucose in many samples. The interference experiment was carried out by successive addition of 0.4 µM glucose and 4.0 µM interfering species to 0.1 M NaOH solution (Fig. 8a). It can be found that obvious current responses were obtained to glucose, whereas negligible responses were recognized for interfering species. Such high selectivity may be attributed to the feasibility of the direct electrocatalytic oxidation of glucose on the electrode and high electronegativity of sulfide ions can electrostatically resist the negatively charged interfering species, such as AA and UA, which negatively charged in 0.1 M NaOH due to the loss of proton. On the other hand, DA was unstable and spontaneously transformed into DA quinone under alkaline condition. This indicates that a high selectivity of the as-prepared CuS/Cu$_2$S/GCE makes this sensor as a promising candidate for glucose sensing application.

Stability is a very vital factor for the sensor. The stability of the CuS/Cu$_2$S/GCE was investigated using amperometric measurement to 4 × 10$^{-5}$ M glucose at 0.6 V for a long time (Fig. 8b). It can be seen that the current density remains 98% of its original current response over an operating time of 2000 s, which demonstrates that the CuS/Cu$_2$S hybrid possesses the excellent durable ability for glucose determination.

### 3.7 Real sample analysis

To verify its practicability, the CuS/Cu$_2$S modified electrode was applied to detect glucose in human blood serum sample by using the calibration curve. 200 µL of the healthy human blood serum sample (obtained from a local hospital) with the glucose concentration of 4.6 mM was dissolved into 20 ml of 0.1 M NaOH medium.

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**Table 2.** Comparison of the analytical performance of the hollow structured CuS/Cu$_2$S hybrid modified electrode with other Cu$_2$S-based non-enzymatic glucose sensors.

| Electrode          | Sensitivity (µA mM$^{-1}$ cm$^{-2}$) | Linear range (µM) | Detection limit (µM) | Reference |
|--------------------|--------------------------------------|--------------------|----------------------|-----------|
| CuS flower         | 1007                                 | 2–5400             | 2.0                  | 12        |
| CuS                | 1085                                 | 20–2500            | 2.0                  | 44        |
| CuS nanotubes      | 7.842                                | 50–5000            | 10                   | 7         |
| Cu$_2$S NPs        | 61.67                                | 10–3100            | 1.3                  | 18        |
| CuS–Cu$_2$S        | 5020                                 | 0.1–500            | 0.33                 | 45        |
| CuSNTs/Cu          | 2205                                 | 2500–6000          | 0.045                | 16        |
| Cu$_2$O/Cu$_2$S    | 2688                                 | 10–1000            | 10                   | 46        |
| Au–Cu$_2$S/3DCF    | 59000                                | 1.98–976.56        | 7.62                 | 9         |
| CuS–Cu$_2$S        | 1923                                 | 1–2000             | 0.33                 | 22        |
| CuS/Cu$_2$S        | 321.3                                | 3–1100             | 1.1                  | This work |

**Figure 8.** Amperometric responses of the CuS/Cu$_2$S/GCE to different chemicals at 0.6 V (a). Amperometric response of the CuS/Cu$_2$S/GCE to 4 × 10$^{-5}$ M glucose in the 0.1 M NaOH solution at 0.6 V for a long period of running time (2000 s) (b).
that, the standard addition method was carried out for the detection of glucose. The recoveries are 96.6 to 101.0 % (Table 3), which indicates the proposed sensor can be applied for the detection of glucose in real samples.

4. Conclusions

This work developed a novel non-enzymatic glucose sensor based on a hollow-structured CuS/Cu2S hybrid, which was successfully synthesized by a one-pot solvothermal route with cuprous oxide as a sacrificial template. Compared with CuS and Cu2O, the as-prepared CuS/Cu2S hybrid shows superior electrocatalytic performances to the oxidation of glucose. The sensors based on CuS/Cu2S hybrid for the detection of glucose exhibit a wide linear response range, fast response, low detection limit and good stability. Thus, the hollow-structured CuS/Cu2S hybrid is a promising electrode material for non-enzymatic glucose detection in practical application.

Acknowledgments

The authors gratefully acknowledge the Foundation of the Guangxi Normal University for Nationalities (2018QN037, 2020YB010) and the Guangxi Higher Institutions Scientific Research Project (2019KY0771, 2021KY0770).

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Table 3. Amperometric determination of glucose in human serum samples (n = 3).

| Samples | Add (µM) | Found (µM) | Recovery (%) | RSD (%) |
|---------|----------|------------|--------------|---------|
| 1       | —        | 42.5       | —            | 1.2     |
| 2       | 100      | 139.1      | 96.6         | 1.9     |
| 3       | 300      | 345.4      | 101.0        | 2.3     |
| 4       | 500      | 540.7      | 99.6         | 1.8     |