

Highly Sensitive and Selective Detection of Glucose by Electrochemical Sensor Based on Mesoporous Silica Coated Graphene Oxide Nanosheet

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This study focused on preparation and electrochemical study of mesoporous silica coated graphene oxide nanosheet electrode for determination of glucose. Graphene oxide nanosheets (GO) were prepared using modified Hummer's method on glassy carbon electrode (GCE) and then were chemically coated with mesoporous silica nanoparticles (SiO₂). The morphology and structure of synthesized electrodes were studied by SEM and XRD analyses. The differential pulse voltammetry (DPV) and amperometry techniques were applied for electrochemical studies of glucose sensors. Results of structural characterization showed that the GO was prepared in a crumpled, stacked, expanded nanosheet structure. After coating with SiO₂, SiO₂ nanoparticles were deposited on the GO nanosheets. DPV investigations revealed that the sensor was stable and sensitive for determination of glucose. The amperometry results exhibited that the linear range, limit of detection and sensitivity of sensor were estimated 0 to 900 μM, 0.03 μM and 0.97086 μA/μM cm², respectively, which indicate the limit of detection and sensitivity were more competitive and superior than previous reports of graphene and SiO₂ based glucose sensors in literatures. The selectivity and ability of the prepared sensor were examined for detection of glucose in the real human serum sample which indicates the SiO₂/GO/ GCE was greatly reliable in practical glucose detection.

Keywords: Glucose detection; Electrochemical sensor; SiO₂ nanoparticles; Graphene oxide nanosheets; Real human serum sample

1. INTRODUCTION

Glucose with the molecular formula C₆H₁₂O₆ as the most abundant monosaccharide and simple sugar is an important energy source for human cells. It is mainly fabricated in plants through photosynthesis process using water, carbon dioxide and under sunlight irradiation. Therefore, it is

naturally found in fruits, honey, agave, wheat, rice, potatoes and vegetables. Accordingly, it is circulates in the blood of humans as blood sugar and plays an important role in maintaining blood sugar levels. There is about 4 g glucose in adult humans blood which is regulated by the hormones insulin, incretin and glucagon [1, 2].

With increasing blood glucose levels higher than normal, the hyperglycemia or diabetes as metabolic disorder with humans has occurred. Thus, blood glucose monitoring is a vital analysis in medical blood tests, which has been performed by various techniques such as chromatography, colorimetry, surface enhanced Raman spectroscopy, conductometry, mass spectroscopy, fluorescent spectroscopy and electrochemical methods [3-5]. Between them, researchers have been paying attention to the electrochemical methods as low cost, fast and simple approaches for chemical and biochemical analytic detections [6-8]. Moreover, the electrode surface of electrochemical sensors can be changed and modified to achieve the higher sensitivity and suitable selectivity.

For several decades, application of nanomaterials for modification of electrode surface in all sensors has been shown that the sensing properties not only can be promoted but also the stability and repeatability of sensors can be enhanced [9-12]. Furthermore, hybrid systems and composites showed synergistic effect to enhance the mechanical, chemical and electrical properties of electrochemical sensors. For examples, Su et al. [13] showed that modification of Au@Cu₂O nanocomposite on the surface of glassy carbon displayed remarkable analytical properties for detection of glucose which related to the synergistic effect of Au core and Cu₂O shell. Zou et al. [14] synthesized the ultrathin Ni/Co bimetallic metal–organic-framework nanosheets as glucose electrochemical sensor and showed that the synergistic effect between Ni/Co exhibited not only the excellent electrochemical properties but also enhanced the sensitivity at a low applied potential.

Therefore, this study was focused on preparation of the mesoporous silica coated graphene oxide nanosheets and modification of GCE as electrochemical sensor of glucose. The DPV and amperometry were applied to characterize the electrochemical response of the prepared electrode toward the glucose.

2. EXPERIMENTAL

The Hummers method was applied for preparation of graphene oxide nanosheets from pure graphite powder [15]. Accordingly, 1 g of pure graphite powder (99.95%, 80-100nm, Luoyang Tongrun Info Technology Co., Ltd., China) was ultrasonically added to mixture of 20 ml of sulfuric acid (98%, Langfang Jinhai Chemicals Industry Co., Ltd., China) and 5 ml nitric acid (68%, Shijiazhuang Xinlongwei Chemical Co., Ltd., China). 1 g potassium permanganate (99.99%, Zhengzhou Zhulin Activated Carbon Development Co., Ltd., China) was added to the prepared graphite suspension and then was stirred for 5 hours to achieve dark green suspension. After then, the hydrogen peroxide was slowly dropped in the resulting suspension to eliminate the excess permanganate and manganese dioxide. After 20 minutes stirring, the suspension was diluted with 150 ml deionized water and filtered (Polypropylene, 5-100 μ m, Guangzhou Jielv Environment Technology Co., Ltd., China) and washed with 0.3 M hydrochloric acid (68%, Shijiazhuang Xinlongwei Chemical Co., Ltd., China). The mixture was centrifuged for 10 minutes and then prepared graphene oxide nanosheets was washed with ethanol

(>95%, Hebei Xue Run Biological Technology Co., Ltd., China) and deionized water for several times, respectively. For preparation graphene oxide nanosheet modified GCE, the clean GCE was immersed in prepared solution of sulfuric acid and nitric acid (1:4 v:v) for 20 minutes and then rinsed with deionized water. Next, the GCE was immersed in prepared graphene oxide nanosheets suspension for 24 hours.

For preparation of mesoporous silica coated graphene oxide nanosheet modified GCE, the mixture of 50 mL ethanol, 1 g cetyltrimethylammonium bromide (99%, Wuhan Kemi-Works Chemical Co., Ltd., China), 1ml ammonia (28%, Shijiazhuang Xinlongwei Chemical Co., Ltd., China) were ultrasonically prepared. The modified graphene oxide nanosheet/GCE was immersed into the washed graphene oxide solution for 2 hours. Then, the immersed electrode and solution was transferred on a magnetic stirrer and 2 g tetraethyl orthosilicate (>99%, Anhui Zinca Silicone Technologies Co., Ltd., China) was simultaneously added to the solution with stirring at 40°C for 30 minutes. After that, the electrode was immersed in solution for 12 hours at room temperature without stirring and then it was rinsed. The modified electrode was transferred to the oven and dried at 80 °C for 4 hours.

The morphology of prepared GO and SiO₂/GO modified GCE was characterized by scanning electron microscopy (SEM, JEOL Model JSM 6390F, operating at 10 kV, Inc., Peabody, MA, USA). The structural and crystallinity properties of prepared GO and SiO₂/GO were studied with X-ray diffractometer (XRD, D/max-Ra X-ray diffractometer, Ouyatu, Japan) with Cu K α radiation ($\lambda = 1.5418 \text{ \AA}$).

Electrochemical measurements were conducted in the three-electrode electrochemical cell which containing saturated calomel electrode (SCE) as reference electrode, a Pt wire as the counter electrode and GCE, GO/GCE and SiO₂/GO/GCE as the working electrodes. DPV and amperometry studies were carried out in potentiostat (Autolab PGSTAT 302N, Metrohm, Autolab B.V., Utrecht, Netherlands) on the working electrodes in 0.1 M phosphate buffer solutions (PBS). The 0.1 M PBS was prepared of H₃PO₄ ($\geq 85\%$, Shijiazhuang Xinlongwei Chemical Co., Ltd., China) and NaH₂PO₄ (98%, Langfang Huinuo Fine Chemical Co., Ltd., China). The pH of PBS was adjusted with HCl and NaOH (99%, Shijiazhuang Xinlongwei Chemical Co., Ltd., China) solutions.

3. RESULTS AND DISCUSSION

SEM images of GO and SiO₂/GO modified GCE are shown in Figure 1. As seen in Fig. 1a, graphene oxide is prepared in a crumpled, stacked and expanded structure which indicates randomly aggregated and wrinkled sheets of GO that form a disordered GO structure. After coating of silica, many silica nanoparticles were deposited on the graphene oxide sheets (Fig. 1b).

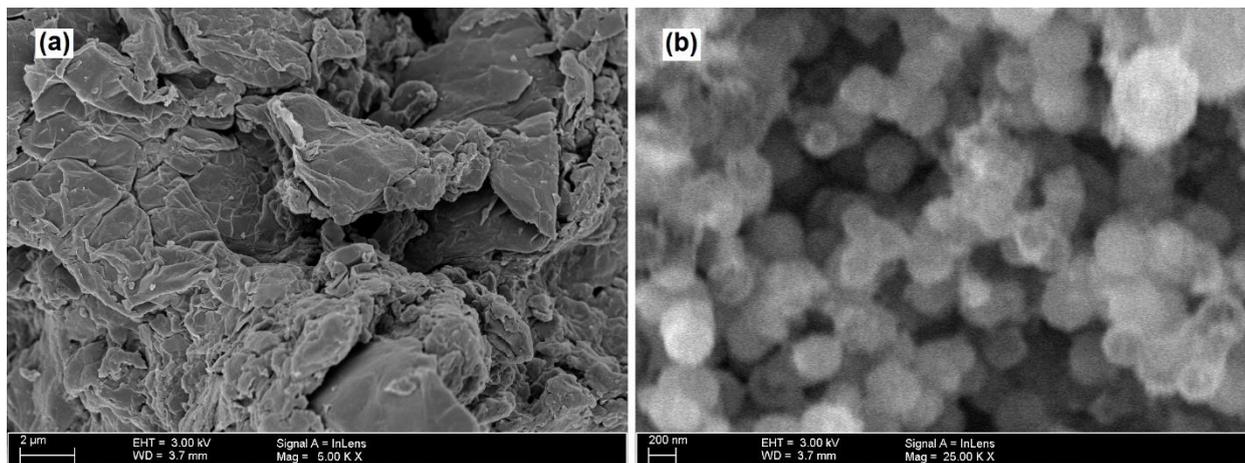


Figure 1. SEM images of (a) GO and (b) SiO₂/GO films.

Figures 2 show recorded XRD patterns of GO and SiO₂/GO powders, respectively. The intense and broad diffraction peak is observed at 26.55° for GO which is associated with the (002) plane of graphite according JCPDS card No. 46-0870. The peak (002) is observed at 26.45° in lower density in XRD patterns of SiO₂/GO which indicates the shift of diffraction peak because of anchoring amorphous SiO₂ on GO nanosheets [16]. Moreover, there is a diffraction peak at 20.95° corresponding to formation of the (100) plane of SiO₂ phase in SiO₂/GO (JCPDS card No.46-1045) [17, 18].

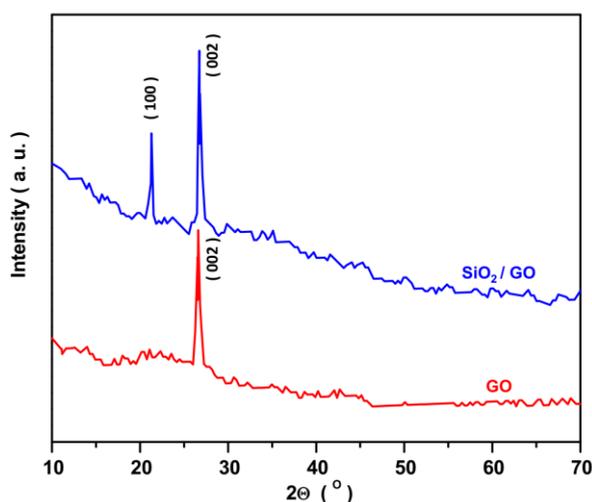


Figure 2. XRD patterns of GO and SiO₂/GO powders.

Figure 3a shows the initial recorded DPV responses of GCE, GO/GCE and SiO₂/GO/ GCE to 3 μM glucose in 0.1 M PBS pH 7.4 at scan rate of 10 mV/s and potential range from 0.0 to 0.7 V. As observed, all the recorded DPVs show peaks at 0.40 V and the higher current was recorded for SiO₂/GO/GCE. Further DPV study was done for investigation of stability of responses of electrodes

toward glucose through the record of successive DPVs of electrodes after injection of the 3 μM glucose. Figure 3b exhibits the second and 100th recorded DPV responses of GCE, GO/GCE and SiO₂/GO/GCE to the presence of 3 μM glucose in electrochemical cells. As seen, there are 28% , 31% and 6% changes for DPV peak current at 0.40 V which indicates the more stability response of SiO₂/GO/ GCE to determination of glucose [19, 20]. Therefore, the higher sensitive and more stable response is observed for SiO₂/GO/GCE in presence of glucose. Accordingly, further electrochemical studies for determination of glucose was performed by SiO₂/GO/GCE.

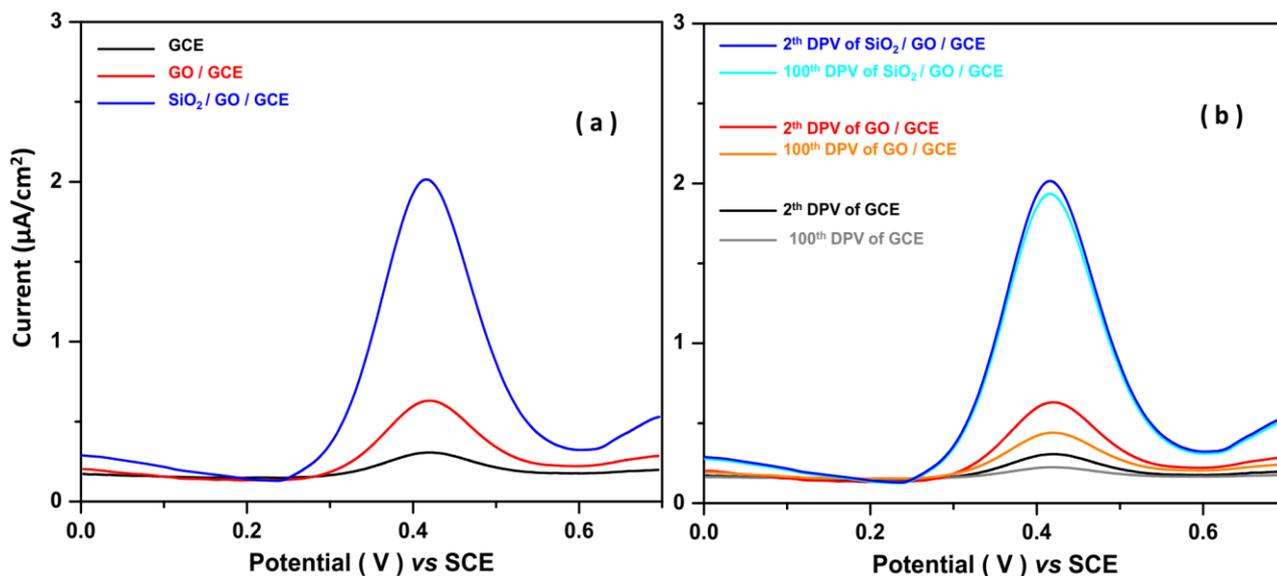


Figure 3. (a) The initial recorded DPV responses, (b) the second and 100th recorded DPV responses of GCE, GO/GCE and SiO₂/GO/GCE in 0.1 M PBS pH 7.4 at scan rate of 10 mVs^{-1} and potential range of 0.0 V to 0.7 V after addition of 3 μM glucose.

The concentration effect of glucose was evaluated for SiO₂/GO/GCE with successive addition of 1 μM glucose in 0.1 M PBS pH 7.4 at scan rate of 10 mV/s and potential range from 0.0 to 0.7 V. Figure 4a shows the increasing the current with increasing the glucose concentration. The calibration graph in Figure 4b displays the linear relationship for increasing the glucose concentration in electrochemical cell as equation of $y = 0.91873 x + 0.03048$ and $R^2 = 0.99796$, which implying the sensitivity of SiO₂/GO/GCE for determination of glucose is 0.91873 $\mu\text{A}/\mu\text{M cm}^2$.

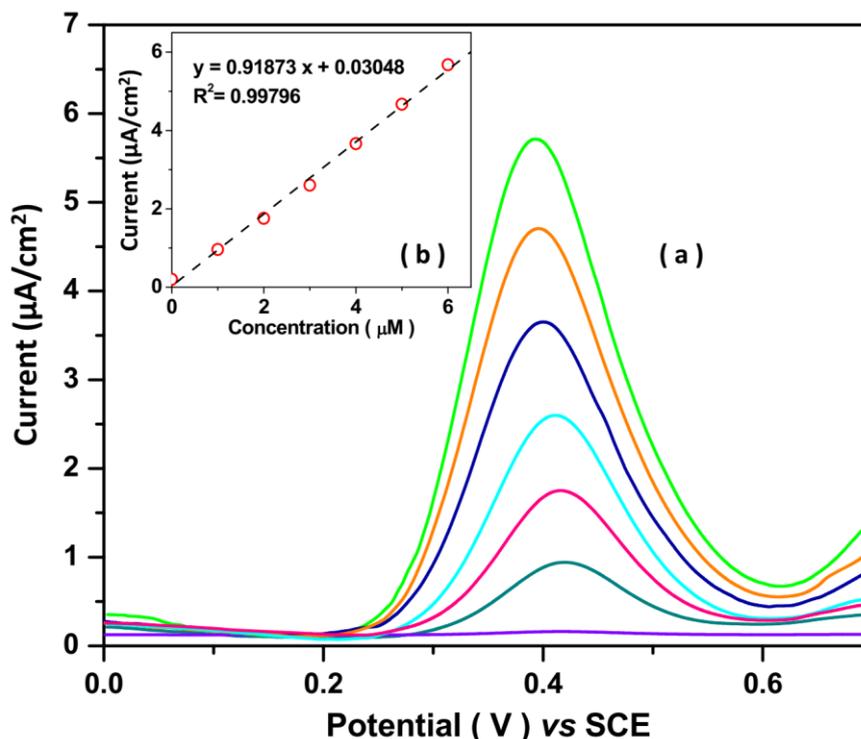


Figure 4. (a) The recorded DPVs of $\text{SiO}_2/\text{GO}/\text{GCE}$ in 0.1 M PBS pH 7.4 at scan rate of 10 mVs^{-1} and potential range of 0.0 V to 0.7 V with successive addition of $1 \mu\text{M}$ glucose; (b) Calibration graph.

The amperometry technique was employed to obtain the more precise sensing properties of $\text{SiO}_2/\text{GO}/\text{GCE}$ for determination of glucose, which contain the linear range, limit of detection and sensitivity of glucose sensor. Figure 5 shows the recorded amperometry and calibration graph of $\text{SiO}_2/\text{GO}/\text{GCE}$ in 0.1 M PBS pH 7.4 at 0.40 V and rotating speed of 1000 rpm with successive addition of $100 \mu\text{M}$ glucose. As shown, there are fast responses to successive addition of $100 \mu\text{M}$ glucose solution and current were increased step by step with addition of each $100 \mu\text{M}$ glucose solution. Thus, the calibration graph shows the linear responses for determination of glucose from 0 to $900 \mu\text{M}$. Moreover, the limit of detection and sensitivity of $\text{SiO}_2/\text{GO}/\text{GCE}$ were obtained $0.03 \mu\text{M}$ and $0.97086 \mu\text{A}/\mu\text{M cm}^2$, respectively.

Table 1 shows the comparison between the sensing properties of $\text{SiO}_2/\text{GO}/\text{GCE}$ with reported graphene and SiO_2 based glucose sensors in literature. It is found from Table 1 that the sensitivity and detection limit of $\text{SiO}_2/\text{GO}/\text{GCE}$ is better than other glucose sensors which indicating the more stability and more active electrochemical sites on nanostructured $\text{SiO}_2/\text{GO}/\text{GCE}$ surface due to synergetic effect of SiO_2 on GO nanosheets structure. Covalent bonding between SiO_2 nanoparticles and GO nanosheets was formed through covalent interaction between $\text{Si}-\text{OH}$ and functional groups of GO which provides portable growth points for SiO_2/GO and enhance effective surface area, the chemical and mechanical stability of prepared electrode [21, 22].

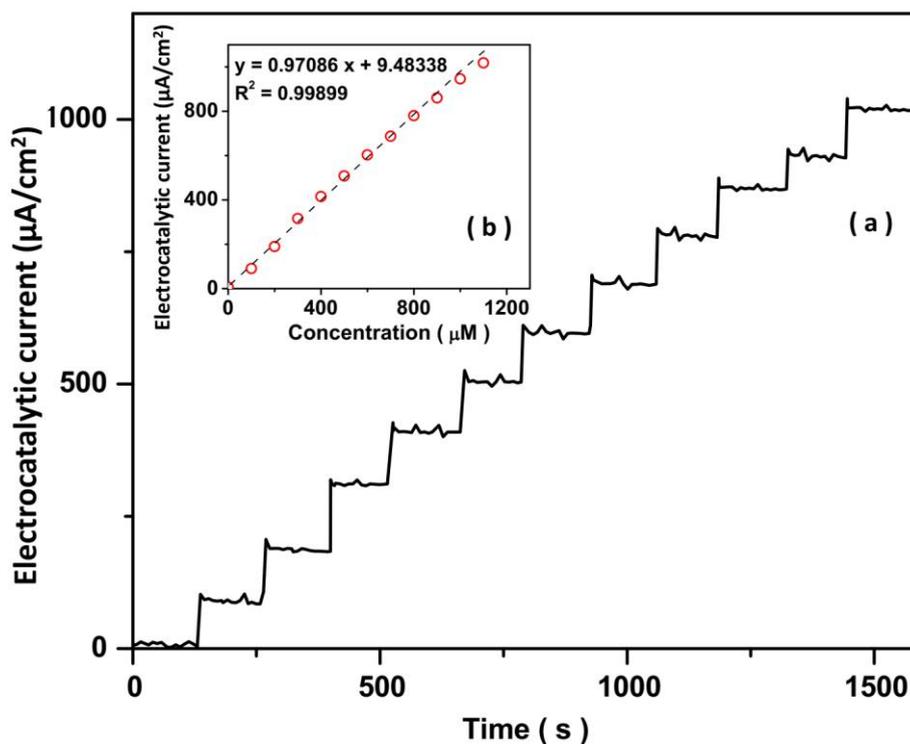


Figure 5. (a) The recorded amperometry and (b) calibration graph of SiO₂/GO/GCE in 0.1 M PBS pH 7.4 at 0.40 V and rotating speed of 1000 rpm with successive addition of 100 μM glucose.

Table 1. Comparison between the sensing properties of SiO₂/GO/GCE with reported graphene and SiO₂ based glucose sensors in literatures.

Electrode	Technique	Linear Range (μM)	limit of detection (μM)	Sensitivity (μA/μM cm ²)	Ref.
Nano-SiO ₂ film	Amperometry	5–2500	0.3	0.0711	[23]
Glucose oxidase/graphene/chitosan nanocomposite	CV	80–12000	20	0.03793	[24]
Chitosan-glucose oxidase composites /AuPt nanoparticles /rGO	Amperometry	0–2400	5	0.048	[25]
Pt nanoflowers/GO	Amperometry	2–20300	2	0.00126	[26]
NiO/Pt/rGO	Amperometry	50–5660	0.2	0.6682	[27]
Glucose oxidase/rGO–MWCNT hybrid film	Amperometry	10–6500	4.7	0.00795	[28]
SiO ₂ /GO/GCE	Amperometry	0-900	0.03	0.97086	This work
	DPV	-	0.03	0.91873	

Further amperometric study was performed for evaluation of interference response of SiO₂/GO/GCE for determination of glucose through addition of various substances. Figure 6 displays

the recorded amperometric response of SiO₂/GO/GCE in 0.1 M PBS pH 7.4 at 0.40 V in two successive additions of 0.2 M glucose solution and 0.02 M of uric acid, maltose, saccharose, fructose, acetaminophen, dopamine, ascorbic acid and a subsequent 0.2 M glucose. These concentrations of substances were selected based on their relative concentrations in human blood [29-31]. Figure 6 illustrates only significant electrocatalytic responses of SiO₂/GO/GCE to additions of glucose solution. Moreover, it has not recorded any remarkable response to addition of other species. Thus, uric acid, maltose, saccharose, fructose, acetaminophen, dopamine and ascorbic acid do not exhibit interference with determination of glucose on SiO₂/GO/GCE surface which indicates highly selective glucose determination by modified electrode. Furthermore, the recorded response of modified electrodes to final additions of glucose solutions indicates to its stable response.

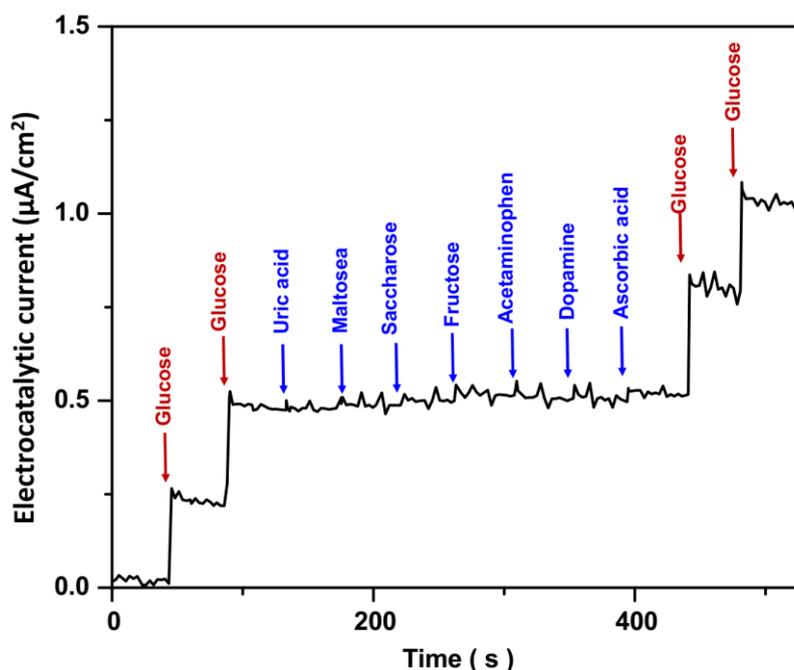


Figure 6. The recorded amperometry response of SiO₂/GO/GCE in 0.1 M PBS pH 7.4 at 0.40 V in successive additions of 0.2 M glucose solution and 0.02 M of uric acid, maltose, saccharose, fructose, acetaminophen, dopamine and ascorbic acid solution.

Table 2. Detection of glucose in real human serum samples using SiO₂/GO/GCE and Accu chek active glucosemeter.

Samples	Detected value by SiO ₂ /GO/GCE	Detected value by Accu chek active glucosemeter
Before meals	4.13 ± 0.51	4.7
After breakfast	5.23 ± 0.73	5.5
After lunch	8.18 ± 0.33	8.3
After dinner	8.34 ± 0.72	8.9

The capability of the SiO₂/GO/GCE was analyzed to glucose concentration detection in real human serum samples. Four serum samples were taken at different times, which contained before meals, after breakfast, after lunch and after dinner. First, the samples were analyzed by Accu chek active blood glucosemeter (Borzonk (Shenzhen) Technology Co., Ltd., China). Then, amperometry technique was applied by adding 10 μ L of serum samples which diluting into 1 mL of 0.01 M PBS pH 7.4 at 0.40. Table 2 shows that the detected values are consistent with the results obtained by Accu chek active glucosemeter. The similar results were reported by Ridhuan et al. [32] for analysis of real human blood samples. Therefore, the SiO₂/GO/GCE is greatly reliable in practical glucose detection.

4. CONCOUSION

This study released fabrication and electrochemical characterization of mesoporous SiO₂ coated GO nanosheets for determination of glucose. GO nanosheets were synthesized via Hummers method and SiO₂ nanoparticles were chemically coated on GO modified electrodes. The morphology and structure of prepared nanostructures were characterized by SEM and XRD analyses that showed GO was produced in a crumpled, stacked, expanded and wrinkled nanosheets. The SiO₂ nanoparticles were deposited on the GO nanosheets. Electrochemical measurements were conducted by DPV and amperometry techniques. The DPV studies revealed the higher sensitive and more stable response for SiO₂/GO/GCE in presence of glucose than the GO/GCE and GCE electrodes. The amperometry results exhibited that the fast linear response, limit of detection and sensitivity of SiO₂/GO/GCE were obtained from 0 to 900 μ M, 0.03 μ M and 0.97086 μ A/ μ M cm², respectively. Comparison between the sensing properties of SiO₂/GO/GCE with reported graphene and SiO₂ based glucose sensors in literatures showed that the sensitivity and detection limit of SiO₂/GO/GCE is better than other glucose sensors which indicating the more stability and more active electrochemical sites on prepared electrode in this study. Study of selectivity and capability of the SiO₂/GO/GCE for determination of glucose in real human serum samples showed the SiO₂/GO/GCE was greatly reliable in practical glucose detection.

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