ACS APPLIED MATERIALS & INTERFACES

Research Article

www.acsami.org

Three-Dimensional Cu Foam-Supported Single Crystalline Mesoporous Cu_2O Nanothorn Arrays for Ultra-Highly Sensitive and Efficient Nonenzymatic Detection of Glucose

Chaoqun Dong,[†] Hua Zhong,[‡] Tianyi Kou,[†,⊥] Jan Frenzel,[§] Gunther Eggeler,[§] and Zhonghua Zhang[*,†]

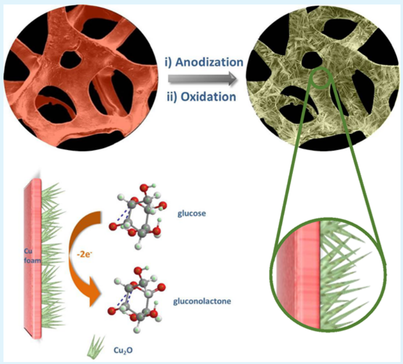
[†]Key Laboratory for Liquid−Solid Structural Evolution and Processing of Materials (Ministry of Education), School of Materials Science and Engineering, Shandong University, Jingshi Road 17923, Jinan 250061, P. R. China

[‡]Dermatological Department, Qilu Hospital of Shandong University, Jinan Culture Road 107, Jinan 250012, P. R. China

[§]Institut für Werkstoffe, Ruhr Universität Bochum, Bochum 44780, Germany

Ⓢ *Supporting Information*

ABSTRACT: Highly sensitive and efficient biosensors play a crucial role in clinical, environmental, industrial, and agricultural applications, and tremendous efforts have been dedicated to advanced electrode materials with superior electrochemical activities and low cost. Here, we report a three-dimensional binder-free Cu foam-supported Cu_2O nanothorn array electrode developed via facile electrochemistry. The nanothorns growing in situ along the specific direction of $<01\bar{1}>$ have single crystalline features and a mesoporous surface. When being used as a potential biosensor for nonenzyme glucose detection, the hybrid electrode exhibits multistage linear detection ranges with ultrahigh sensitivities (maximum of 97.9 mA mM^{-1} cm^{-2}) and an ultralow detection limit of 5 nM. Furthermore, the electrode presents outstanding selectivity and stability toward glucose detection. The distinguished performances endow this novel electrode with powerful reliability for analyzing human serum samples. These unprecedented sensing characteristics could be ascribed to the synergistic action of superior electrochemical catalytic activity of nanothorn arrays with dramatically enhanced surface area and intimate contact between the active material (Cu_2O) and current collector (Cu foam), concurrently supplying good conductivity for electron/ion transport during glucose biosensing. Significantly, our findings could guide the fabrication of new metal oxide nanostructures with well-organized morphologies and unique properties as well as low materials cost.



KEYWORDS: *biosensors, catalysis, nanostructures, nanothorn arrays, hybrid materials*

■ INTRODUCTION

Highly sensitive and efficient detection of glucose concentration plays a critical role in clinical, environmental, industrial, and agricultural applications, and various approaches to glucose sensing have been explored based on electrochemical, fluorescent, optical, transdermal, and acoustic signals.[1,2] Among these techniques, the electrochemical biosensors have aroused more interest in the past few decades, owing to their unbeaten virtues such as high sensitivity, lower detection limit, high selectivity, and easy operation.[3−5] Most previous research on the electrochemical detection of glucose involved the use of glucose oxidase (GOD), which can identify glucose molecules quickly and accurately by catalyzing the oxidation process of glucose to gluconolactone.[6,7] Conversely, because of the intrinsic properties of enzymes, GOD-based biosensors suffer from poor reproducibility, complex enzyme immobilization, and high sensitivity to external conditions (for example, temperature, pH, humidity, and so forth) leading to a decrease in GOD activity in certain cases.[8,9] Furthermore, the high price of enzymes impedes the broader applications of enzymatic glucose. Because of these properties, the emergence of nonenzyme biosensors has provided another choice for stable and cost-effective glucose biosensing devices.[10]

The intimate relationship between the microstructures and corresponding biological sensing properties of the active materials, such as dimension, shape, porosity, and surface area, has stimulated tremendous efforts to develop novel enzyme-free electrode materials to realize the optimization of mass and charge transport and then minimize resistances during biosensing.[11−13] Nanostructured metal oxides have been found to possess interesting nanomorphology, multiple oxidation states, and good biological compatibility.[6,14,15] These unique properties of nanosized metal oxides could alleviate the problems of expensive enzymatic glucose sensors. Nevertheless, metal oxides possess inferior electronic conductivity, which greatly restricts their wide applications for biosensors with superior performance.[11] For the electronic conductivity of oxides to be improved, it is normal to construct composite materials by hybridizing with carbon-based materi-

Received: June 29, 2015
Accepted: August 25, 2015
Published: August 25, 2015

DOI: 10.1021/acsami.5b05738
ACS Appl. Mater. Interfaces 2015, 7, 20215−20223

als[16−18] and noble metal nanoparticles.[19,20] Moreover, the intimate interface contact between the current collector and highly electrocatalytic materials is crucial for enhancing the electronic conductivity of electrodes and taking full advantage of electroactive substances.

Among various nonenzymatic metal oxide-based glucose sensors, nanostructured copper oxides (Cu_2O and CuO) arouse considerable attention owing to their outstanding electrochemical activity, low-cost, ease of synthesis, and other advantages.[21−23] For example, Kong et al.[24] developed a copper oxide electrode with a hollow structure and good glucose sensing properties. However, it is currently a formidable task to fabricate glucose biosensors with superior performance that can continuously detect low glucose concentrations in unconventional body fluids (like tears, saliva, etc.).[11,21]

Here, we report a three-dimensional (3D) Cu foam-supported mesoporous Cu_2O nanothorn array electrode, fabricated through a facile and economic electrochemical route, as an enzyme-free electrochemical glucose detector. The nanothorns growing along the specific direction of <$01\bar{1}$> have single crystalline features and a mesoporous surface. Most importantly, such a hybrid electrode can detect ultralow-concentration glucose (ultrahigh sensitivity: 97.9 mA mM^{-1} cm^{-2} and an ultralow detection limit: 5 nM). This remarkable biosensing performance can be attributed to the synergistic effect of the dramatically enhanced surface area of the electrocatalytic material (Cu_2O) and the perfect architecture in which mesoporous Cu_2O nanothorn arrays grow in situ on the Cu substrate surface.

EXPERIMENTAL SECTION

Fabrication of the Cu Foam-Supported Cu_2O Electrode. The Cu foam-supported Cu_2O was prepared by first anodization using a two-electrode system (Cu foam as the anode and a graphite plate as the cathode) at room temperature, followed by cyclic voltammetry (CV) electro-oxidation in a three-electrode configuration (Pt foil as the counter electrode and Ag/AgCl electrode as the reference electrode) controlled by a potentiostat (CHI 660E, Shanghai, Chenhua). The electrolyte for anodization was a 0.4 M $H_2C_2O_4$ aqueous solution with a small amount of HF, and the electro-oxidation was performed in a 1 M KOH aqueous solution. Thus, the hybrid electrode (Cu_2O nanothorn arrays on Cu foam) was obtained. The detailed experimental procedure and the calculating method of the mass of the active material (here, Cu_2O nanothorns) growing on the substrate were demonstrated in our previous work.[25] The mass loading of Cu_2O nanothorn arrays per area was 1.72 mg cm^{-2}.

Characterization. X-ray diffraction (XRD, Rigaku D/max-rB) with Cu Kα radiation was used to analyze the phase constitution of the as-synthesized samples. X-ray photoelectron spectroscopy (XPS, ESCALAB 250) was performed to obtain surface elemental information on the hybrid electrode. All reported binding energy values were calibrated to the C 1s peak at 284.8 eV. Scanning electron microscope (SEM, LEO 1530 VP) and transmission electron microscope (TEM, FEI Tecnai G2) with selected-area electron diffraction (SAED) were used to characterize the surface morphology and structure of the Cu foam-supported Cu_2O electrode. A V-Sorb 2800P surface area and pore size analyzer was used to obtain nitrogen adsorption/desorption isotherms at 77 K.

Electrochemical Measurements. All of the CV and amperometric tests were conducted using a potentiostat (CHI 660E, Shanghai, Chenhua) in a three-electrode cell (Pt foil as the counter electrode and Ag/AgCl electrode as the reference electrode) at room temperature. The Cu foam-supported Cu_2O electrode served directly as the working electrode for the detection of glucose. The CVs were collected in a 0.1 M NaOH aqueous electrolyte with and without various concentrations of glucose. The amperometric responses of the Cu foam-supported Cu_2O electrode to glucose were measured at the applied potential of 0.55 V (vs Ag/AgCl), and the glucose concentrations ranged from 0.1 μM to 1 mM. In addition, for the sake of showing its potential for practical applications, the Cu foam-supported Cu_2O electrode was utilized to detect blood glucose concentrations of human serum samples.

RESULTS AND DISCUSSION

As illustrated in Figure 1, we proposed such a kind of hybrid structure that nanothorn-like Cu_2O in situ grows on the skeleton surface of the Cu foam with 3D continuous skeletons (Figure 2a). First, the unique mesoporous nanothorn-like structure of Cu_2O provides a high specific surface area and high usage of active materials and produces interconnected nanoporous channels that can effectively facilitate charge/ion transfer and mass transport for the electrocatalysis. Second, highly conductive Cu foam serves both as the current collector and the substrate to support the active materials, which can promote the transfer of electrons well. Simultaneously, the 3D continuous large pores could accelerate the glucose transport to the skeleton-supported catalysts. Furthermore, the in situ growth of Cu_2O nanothorns on the Cu foam facilitates the integration of electroactive materials and current collector without any additional contact resistance or additive/binders. Such a unique structure was predicted to promote the biosensing performance toward the glucose oxidation to a great extent.

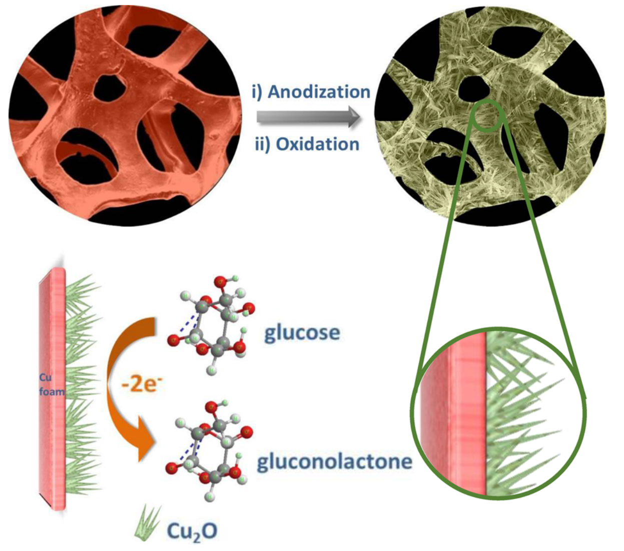


Figure 1. Schematic illustration showing the fabrication of the 3D Cu foam-supported mesoporous Cu_2O nanothorn array electrode and its function in the electrocatalytic oxidation of glucose.

On the basis of the concept described above, the Cu foam-supported Cu_2O nanothorn array electrode was successfully synthesized by the aforementioned method. The XRD pattern of the Cu foam-supported Cu_2O electrode is given in Figure S1, showing Bragg reflections of Cu and Cu_2O phases. The diffraction peaks at 2θ of 36.4°, 42.3°, 61.3°, and 73.5° agree well with the (111), (200), (220), and (311) reflections of Cu_2O (JCPDS no. 05-0667), respectively. Moreover, three diffraction peaks located at 2θ of 43.3°, 50.4°, and 74.1° were indexed to the face centered cubic (fcc) Cu (JCPDS no. 04-0836). The elemental information that the nanostructured

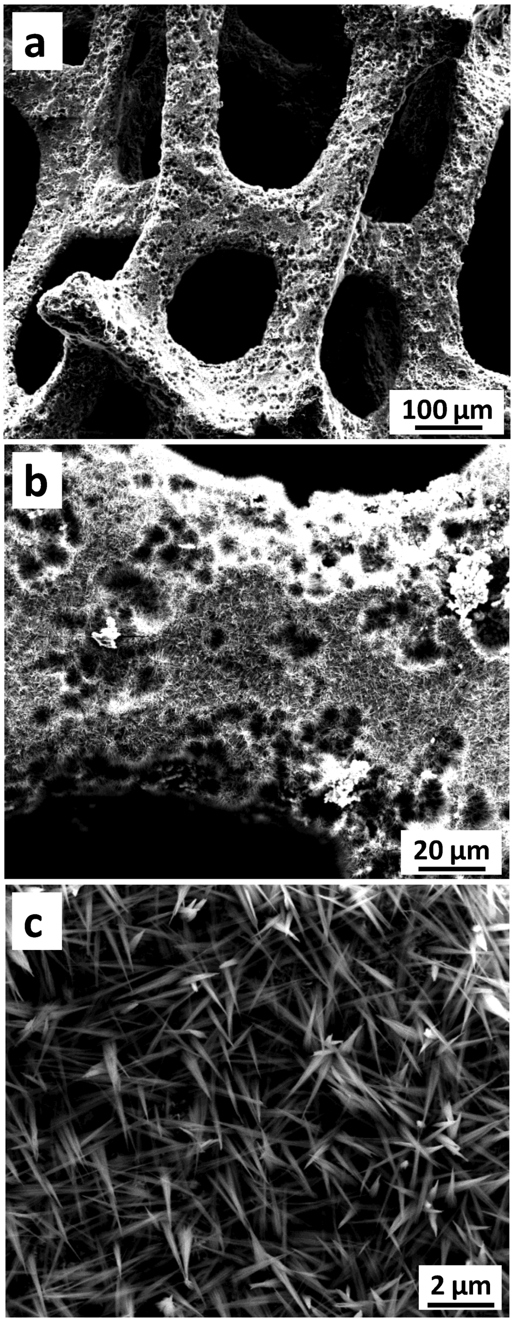


Figure 2. Typical low- (a,b) and high-magnification (c) SEM images of the Cu foam-supported Cu_2O nanothorn array electrode.

Cu_2O grows on the Cu foam was also supported by the XPS results after surface etching by Ar^+ sputtering (Figure 3 and Figure S2). The Cu $2p_{3/2}$ spectrum (Figure 3a) reveals the presence of a peak located at 932.3 eV. However, this peak cannot be directly ascribed to Cu^+ because the Cu $2p_{3/2}$ binding energy peaks of metallic copper and Cu_2O are so similar that the two substances cannot be definitely discerned only by the peak position of Cu $2p_{3/2}$. Nevertheless, weak satellite peaks between 941.0 and 948.0 eV can be clearly observed, which is a typical characteristic of Cu_2O.[26,27] Furthermore, the Auger electron spectrum (Cu $L_3M_{4,5}M_{4,5}$) of the as-prepared electrode was also obtained under X-ray radiation (Figure 3b). The binding energy peak position of Cu $L_3M_{4,5}M_{4,5}$ is 569.8 eV, which matches well with the electron state of Cu_2O, and the binding energy peak of CuO is invisible.[26] Therefore, the aforementioned XPS results can again confirm the information of Cu_2O growing on the skeleton surface of Cu foam.

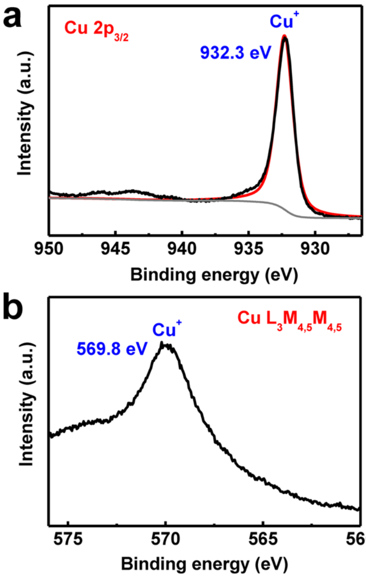


Figure 3. (a) XPS spectrum (Cu $2p_{3/2}$ core peak) and (b) Auger spectrum (Cu $L_3M_{4,5}M_{4,5}$ peak) of the Cu foam-supported Cu_2O nanothorn array electrode.

Figure 2 presents low and high magnification SEM images of the as-obtained hybrid electrode. Obviously, Cu_2O with a particular nanothorn-like morphology in situ grows on the surface of skeletons of the Cu substrate, and its surface roughness is remarkably enhanced. With careful observation (Figure 2c), we can find that nanothorns with several micrometers in length interconnect with each other, giving rise to micron-sized channels among the nanothorns, which are expected to facilitate the fast diffusion of electrolytes onto the surface of the nanothorns.

TEM was used to determine further details of the nanothorn-like structure (Figure 4 and Figure S3). The nanothorns are confirmed to have widths of ~20−40 nm and lengths of several micrometers. They are self-assembled at an angle to the skeleton surface of the Cu foam, forming nanothorn arrays interconnected with multiple junctions (Figure 4a and Figure S3a). Some nanothorns tend to form clusters with similar growth directions. The SAED pattern (inset in Figure 4b) shows that the nanothorns have single crystalline features. This spot-type pattern can be attributed to the [011]-zone-axis diffraction of the fcc Cu_2O. Moreover, the diffraction spots are indexed according to the (*h k l*) reflections of Cu_2O (JCPDS no. 05-0667), which are consistent with the XRD results (Figure S1). Unexpectedly, the higher magnification TEM image (Figure 4c) indicates an obviously porous characteristic of the nanothorns surface. The pores are ~2−6 nm in diameter, being expected to dramatically enhance the surface area of the nanothorns. Eventually, the N_2 adsorption/desorption results (Figure S4) verify the mesoporous structure of the as-obtained electrode, and the specific surface area determined by Brunauer−Emmett−Teller (BET) is 173.34 m^2 g^{-1} (calculated according to the Cu_2O mass). Moreover, even if the whole mass of the Cu foam-supported Cu_2O nanothorn arrays electrode is taken into account, the BET value is still as large as 5.36 m^2 g^{-1}. The HRTEM images of the Cu_2O nanothorns (Figure 4d and Figure S3b) provide further insight into its

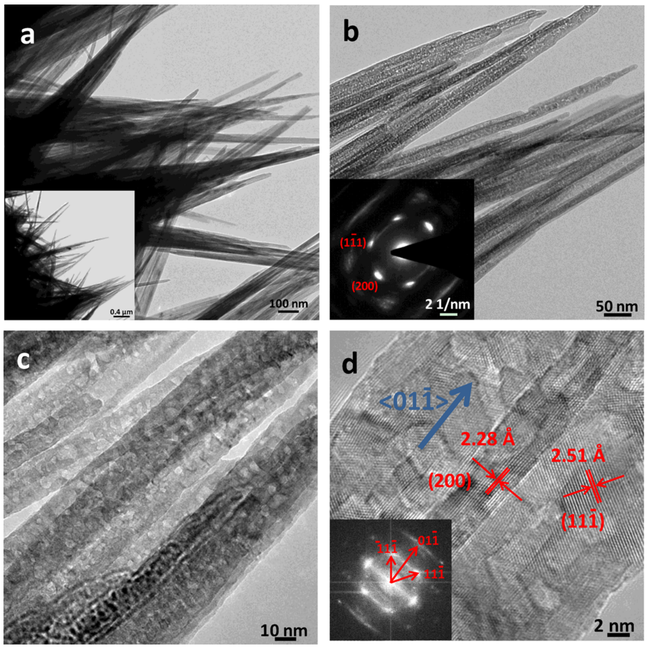


Figure 4. (a−c) TEM images of the Cu_2O nanothorn arrays grown on the skeleton of Cu foam. (a, inset) Corresponding low-magnification TEM image. (b, inset) A [011] zone axis SAED pattern obtained from Cu_2O nanothorns. (d) HRTEM image of a Cu_2O nanothorn. (d, inset) FFT pattern corresponding to the HRTEM image.

crystalline structure. The spacings of some lattice fringes are approximately 2.28 and 2.51 Å, which are close to the *d* spacing of the (200) and $(11\bar{1})$ planes of crystalline Cu_2O. The fast Fourier transformation (FFT) was also performed to further investigate the crystalline nature of the nanothorns (inset in Figure 4d and inset in Figure S3b). The corresponding spot verifies the single crystalline characteristic of the Cu_2O nanothorns. Combining the FFT pattern with the HRTEM image (Figure 4d), we can conclude that the nanothorns grow along the specific direction of $<01\bar{1}>$, as indicated by the blue arrow. On the basis of the aforementioned results, the Cu foam-supported Cu_2O nanothorn arrays were successfully achieved as we had assumed.

In this work, the Cu foam-supported Cu_2O nanothorn array electrode was explored as a nonenzymatic biosensor for glucose detection, and its electrocatalytic activity was assessed by CV measurements. Figure 5a presents the CV results of the Cu foam-supported Cu_2O electrode in a 0.1 M NaOH aqueous solution with diverse glucose concentrations (from 0 to 0.8 mM). Upon the stepwise glucose addition, significant enhancement of anodic currents can be seen, whereas the cathodic peak currents obviously decrease, suggesting excellent catalytic properties of the Cu foam-supported Cu_2O electrode toward glucose oxidation. Although the underlying mechanism is currently unknown, it has been recognized that a Cu(III) species, rather than Cu(I) or Cu(II), serves as the mediator for electron transfer.[28,29] The possible mechanism is proposed as follows for glucose detection. First, Cu(I) is electrochemically oxidized to $Cu(OH)_2$ and then transformed to CuO. Then, the produced CuO is oxidized to CuOOH. According to the following reactions, the CuO/CuOOH redox couple could catalyze the oxidation of glucose to form gluconolactone, giving rise to an enhancement of anodic currents and a decline of the cathodic currents[30,31]

$$Cu_2O + 3H_2O \rightarrow 2Cu(OH)_2 + H_2 \quad (1)$$

$$Cu(OH)_2 \rightarrow CuO + H_2O \quad (2)$$

$$CuO + OH^- \rightarrow CuOOH + e^- \quad (3)$$

$$CuOOH + e^- + glucose \rightarrow CuO + OH^- + gluconolactone \quad (4)$$

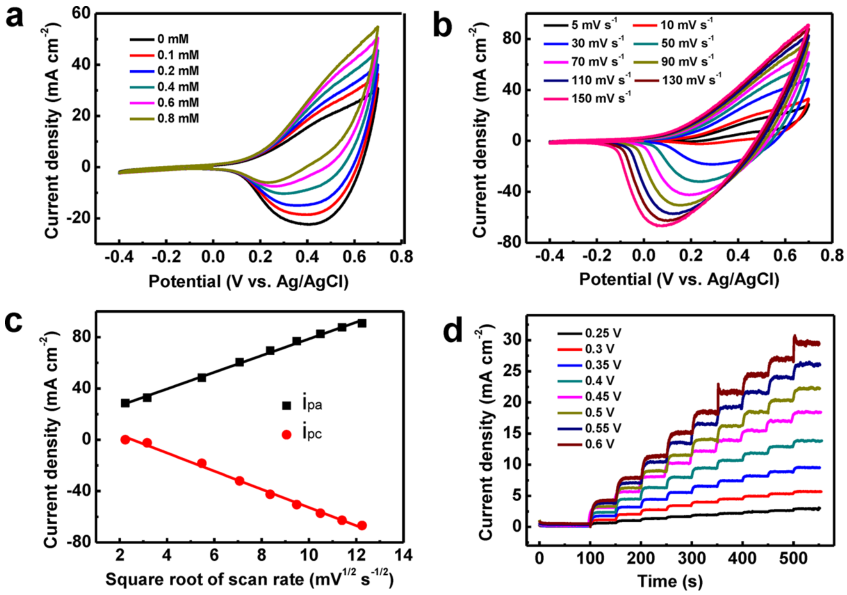


Figure 5. (a) CV curves of the Cu foam-supported Cu_2O nanothorn array electrode in a 0.1 M NaOH solution containing different concentrations of glucose (from 0 to 0.8 mM) at a scan rate of 20 mV s^{-1}. (b) CVs of the Cu foam-supported Cu_2O electrode in the 0.1 M NaOH solution containing 0.5 mM glucose at various scan rates. (c) Plots of peak currents as a function of the square root of the scan rate. (d) Amperometric response of the Cu foam-supported Cu_2O electrode at various potentials (vs Ag/AgCl) in a 0.1 M NaOH solution with the successive addition of 0.1 mM glucose.

DOI: 10.1021/acsami.5b05738
ACS Appl. Mater. Interfaces 2015, 7, 20215−20223

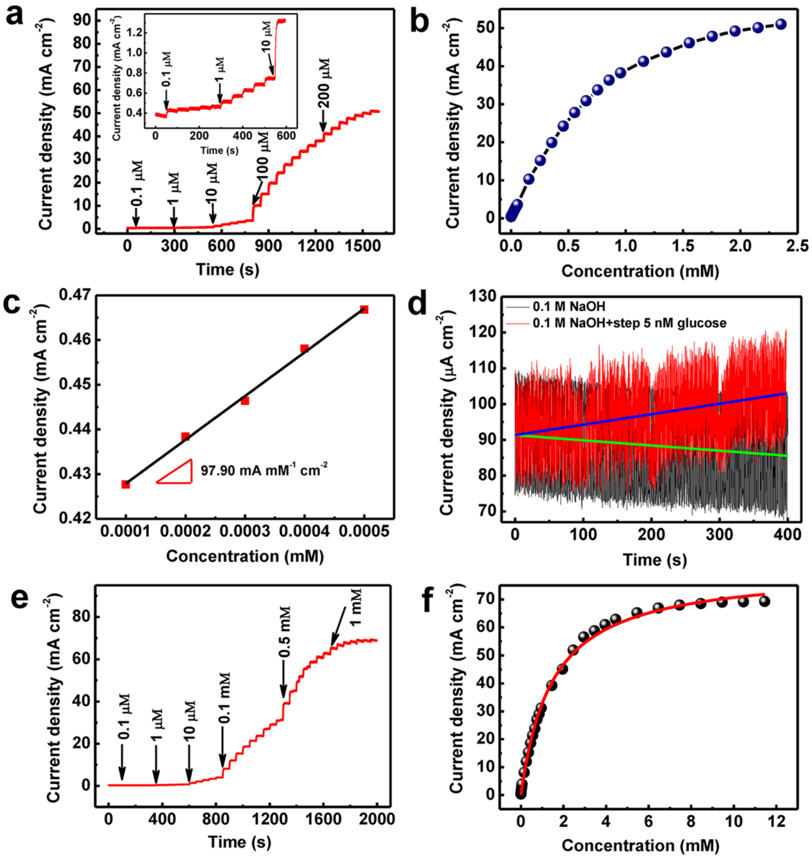


Figure 6. (a) Typical amperometric response and (b) the corresponding calibration curve of the Cu foam-supported Cu_2O nanothorn array electrode at 0.55 V vs Ag/AgCl with the successive addition of glucose from 0.1 μM to 200 μM in the 0.1 M NaOH solution. (a, inset): amperometric response toward 0.1 ~ 10 μM glucose. (c) Glucose sensitivity of the Cu foam-supported Cu_2O electrode for successive addition of 0.1 μM glucose. (d) Amperometric response to the 0.1 M NaOH solution with and without the extremely low limit concentration of 5 nM glucose. (e) Amperometric response and (f) the corresponding calibration curve of the Cu foam-supported Cu_2O electrode at 0.55 V vs Ag/AgCl with the successive addition of glucose from 0.1 μM to 1 mM in the 0.1 M NaOH solution.

Furthermore, the CVs of the Cu foam-supported Cu_2O electrode in the 0.1 M NaOH solution containing 0.5 mM glucose at various scan rates were recorded, as depicted in Figure 5b. It is noted that both the anodic and cathodic peak current densities are enhanced with increasing scan rate, whereas the cathodic peak potentials shift negatively, suggesting a quasi-reversible electron transfer reaction for the above electrochemical reaction.[32] Moreover, the peak current densities for both the oxidation and reduction are directly proportional to the square root of the scan rate, as depicted in Figure 5c. This demonstrates that the redox reaction on the Cu foam-supported Cu_2O electrode is a typical diffusion-controlled electrochemical process.[31] The diffusion coefficient (D) for the transfer of glucose during the electrocatalysis was calculated on the basis of the Randles−Sevcik equation[33,34]

$$I_p = 2.69 \times 10^5 n^{3/2} A D^{1/2} C v^{1/2} \tag{5}$$

where I_p is the peak current density, n is the electron transfer number, A is the electrode surface geometrical area, C is the bulk concentration, and v is the scan rate. From the slope of I_p vs $v^{1/2}$, the diffusion coefficient of glucose was calculated to be 0.29 cm^2 s^{-1}.

For the optimal amperometric parameter for the detection of glucose to be acquired, the potential dependence of the current response was studied with the continuous addition of 0.1 mM glucose under stirred conditions (Figure 5d and Figure S5). A notably enhanced current response can be seen due to each addition of glucose when a potential between 0.25 and 0.6 V vs Ag/AgCl was applied. Furthermore, the sensitivity of the Cu foam-supported Cu_2O electrode increases with the incremental applied potential. However, the background current and noise also increase accordingly with the increasing potential. After comparison, the optimal potential was determined to be 0.55 V relative to Ag/AgCl, which was used in the following amperometic measurements. In addition, the current densities show good linear correlations with the glucose concentration at various applied potentials (0.25−0.6 V vs Ag/AgCl), suggesting wide applications of the present hybrid electrode for glucose biosensing (Figure S5).

Figure S6a displays the chronoamperometry response of the Cu foam-supported Cu_2O nanothorn array electrode in the 0.1 M NaOH solution with and without various concentrations of glucose. It can be seen that an increasing concentration of glucose leads to a remarkable increase in the current. The relationship between current density and the minus square root of time at the stable stage of electrocatalysis is shown in Figure S6b, and it shows a good linear relationship over a certain time range. The D value of glucose can also be calculated according to the Cottrell equation[34]

$$j = nFD^{1/2} C \pi^{-1/2} t^{-1/2} \tag{6}$$

Table 1. Comparison of the Performance of the Cu Foam-Supported Cu_2O Electrode with Previously Reported Non-Enzymatic Glucose Sensors with Excellent Properties

electrode material	potential (V vs Ag/AgCl)	sensitivity (mA mM^{-1} cm^{-2})	detection limit (μM)	ref
hollow CuO polyhedron	0.55	1.112	0.33	24
CuO/SG	0.5	1.298	0.08	3
Cu foam	0.5	3.397	12.96	35
CuO nanoellipsoids	0.55	2.555	0.072	14
S/NPG/Co_3O_4	0.26	12.5	0.005	11
CuO NT arrays	0.32	1.89	0.1	36
3D porous nickel	0.5	2.9	0.07	37
$Ni(OH)_2$/3D graphene	0.55	2.65	0.34	1
Cu foam-supported Cu_2O nanothorn arrays	**0.55**	**97.9**	**0.005**	**present work**

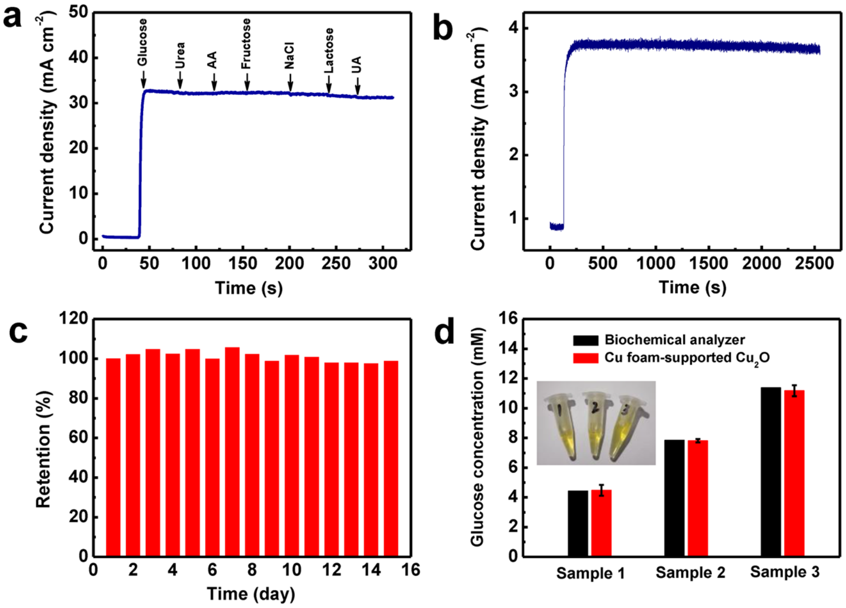


Figure 7. (a) Amperometric response of the Cu foam-supported Cu_2O nanothorn array electrode toward the addition of 1 mM glucose and various 0.02 mM interfering species in the 0.1 M NaOH solution at 0.55 V vs Ag/AgCl. (b) Amperometric response of the Cu foam-supported Cu_2O electrode to 0.1 mM glucose in a 0.1 M NaOH solution at 0.55 V vs Ag/AgCl for a long running time (2500 s). (c) Long-term stability of the Cu foam-supported Cu_2O electrode over 15 days. (d) The detection of glucose concentration in human serum samples by a biochemical analyzer and the Cu foam-supported Cu_2O electrode. (d, inset) Photograph of the serum samples. Here, the blood glucose data of the serum samples by the biochemical analyzer were provided by the biochemical lab of Shandong University Qilu Hospital, Jinan, P. R. China.

where j is the current density, F is the Faraday constant, and t is the time. The D value was estimated to be 0.066 cm^2 s^{-1} using the slope of the line in Figure S6b, which is much larger than that found in previously published results.[16] Furthermore, the value of the catalytic rate constant (K_{cat}) could also be determined from the following equation[34]

$$\frac{j_{cat}}{j_d} = \pi^{1/2}(K_{cat}Ct)^{1/2} \tag{7}$$

where j_{cat} is the catalytic current of glucose oxidation, j_d is the limiting current without glucose, C and t are the concentration of glucose and time elapsed, respectively. For a certain time range (16−64 s), the value of j_{cat}/j_d exhibits a linear dependence on $t^{1/2}$ (Figure S6c). On the basis of the slope of j_{cat}/j_d vs $t^{1/2}$ plot, K_{cat} was obtained as 2.1×10^7 cm^3 mol^{-1} s^{-1}, indicating a fast catalytic rate of the present hybrid electrode.

The Cu foam-supported Cu_2O nanothorn array electrode responds well to the continuous addition of glucose with concentrations of 0.1−200 μM at 0.55 V relative to Ag/AgCl, and the corresponding amperometric curve is presented in Figure 6a. Toward lower glucose concentrations, the sensitive current response curve is shown in the inset of Figure 6a. Owing to the integration of the highly enhanced surface area of the nanoporous Cu_2O nanothorn arrays and the excellent conductivity of the binder-free electroactive material/substrate (current collector) nanostructure, the hybrid electrode gives the steep and stable amperometric response with significantly improved current density after each addition of glucose, even when the glucose concentration was diluted to 0.1 μM. The Cu foam-supported Cu_2O electrode can sensitively and rapidly respond to glucose detection, and the involved current can be enhanced well due to the concentration increase of glucose, which is further verified by the corresponding calibration curve (Figure 6b). As displayed in Figure 6c and Figure S7, the Cu foam-supported Cu_2O electrode displays multilinear detection ranges, strongly depending on the concentration of glucose added. As the glucose is diluted to 0.1 μM, it is astonishing that the Cu foam-supported Cu_2O nanothorn array electrode provides a superb sensitivity of 97.9 mA mM^{-1} cm^{-2} toward the glucose detection. Figure 6d shows the amperometric response in the 0.1 M NaOH solution with and without 5 nM glucose. Despite the relatively large noise, the linear fitting results clearly reveal that the two curves show different variation tendencies, which can further demonstrate that the as-prepared electrodes are able to detect the remarkably low concentration of 5 nM glucose. Such ultra-high sensitivity and ultra-low detection limit are superior to those of all other electrochemical glucose biosensors, which are summarized in Table 1.[1,3,11,14,24,35−37] Figure S8 presents the current−time curve of the Cu foam-supported Cu_2O electrode toward 10 nM glucose, displaying an obvious steplike increase of current due to the glucose addition. Figure 6e displays the typical amperometric detection of the Cu foam-supported Cu_2O electrode at 0.55 V relative to Ag/AgCl owing to the stepwise addition of glucose from 0.1 μM to 1 mM. It is believed that the electrochemical oxidation of glucose is a surface catalytic reaction that normally obeys Langmuir isothermal kinetics.[9,31,38] Thus, the calibration curve of the Cu foam-supported Cu_2O electrode could be fitted by the Langmuir fitting equation. As illustrated in Figure 6f, the calibration curve can be fitted well by the Langmuir equation ($R^2 = 0.998$). The Langmuir fitting equation for the Cu foam-supported Cu_2O electrode is presented as I (mA cm^{-2}) = 81.02 × C_{glucose} (mM)/(1.46 + C_{glucose} (mM)), which can meet the glucose detection for human serum over a wide concentration range (1 μM to 11.4 mM).

Selectivity is also a vital parameter to evaluate the biosensing performance of the electrode for glucose apart from sensitivity.[39] Herein, we also investigate the effects of some species that can interfere with the glucose detection of human beings, such as urea, ascorbic acid (AA), fructose, NaCl, lactose, uric acid (UA), acetamidophenol, and dopamine on the glucose current response. Given that the glucose concentration in human blood is much higher than that of some coexisting interfering species, the anti-interference performance of the Cu foam-supported Cu_2O electrode was tested by the continuous addition of 1 mM glucose, followed by 0.02 mM of the other interferents in the 0.1 M NaOH solution. As presented in Figure 7a and Figure S9, remarkable current enhancement can be seen due to the glucose addition, whereas negligible current responses were seen for the interferents. The results indicate the excellent selectivity of the Cu foam-supported Cu_2O electrode for nonenzymatic detection of glucose. All of the above results suggest that the Cu foam-supported Cu_2O hybrid electrode possesses excellent electrocatalytic performance for glucose oxidation and that it is therefore promising for constructing a highly sensitive/selective glucose biosensor.

Stability is another important issue for biosensing. The stability of the Cu foam-supported Cu_2O nanothorn arrays electrode was also investigated using the current−time measurement toward 0.1 mM glucose at 0.55 V relative to Ag/AgCl for a long period of time. We can see that the current density remains at 98% of its original value over a running time of 2500 s (Figure 7b). Moreover, the long-term stability of the Cu foam-supported Cu_2O electrode was explored by recording the current−time response toward 1 mM glucose over 15 days. Our hybrid electrode was subjected to the exposure of air and tested every day. As displayed in Figure 7c, the amperometric response is approximately 98.7% of the original value after 15 days, suggesting excellent stability of our hybrid electrode.

These predominant properties endow this in situ grown hybrid electrode to exhibit high reliability for analyzing human blood serums. To confirm this conclusion, we further used our hybrid electrode to detect the glucose level in human serum samples (inset of Figure 7d) that were obtained from Shandong University Qilu Hospital. One hundred microliters of human serum was injected into 20 mL of 0.1 M NaOH solution, and the measurement was conducted at 0.55 V relative to Ag/AgCl with stirring. The obtained data are comparable to those measured using a biochemical analyzer in the hospital, which have been summarized in Figure 7d and Table S1. It is clear that the values tested by the hybrid electrode are satisfactory and consistent with the data from the biochemical analyzer, indicating its reliability for glucose determination. Therefore, the Cu foam-supported Cu_2O nanothorn array electrode is an outstanding candidate for the new generation of electrochemical glucose sensing, especially for extremely low concentrations of glucose samples, which is promising for the glucose analysis of unconventional body fluids or diluted blood samples. Moreover, Cu foam is cheap and commercially available, and the two-step electrochemical strategy reported here is very facile. The hybrid electrode can even be produced on a large scale (Figure S10), which signifies its potential for commercialization.

■ CONCLUSIONS

In summary, a unique binder-free electrode with the nanoarchitecture of 3D Cu foam/mesoporous Cu_2O nanothorn arrays was synthesized through a facile two-step anodization/electro-oxidation procedure. Serving as an enzyme-free electrochemical electrode, it exhibits ultra-high sensitivity, an ultra-low detection limit, and excellent selectivity and stability. The overall results illustrate that the Cu foam-supported Cu_2O nanothorn array electrode presents brilliant prospects for glucose detection, especially for the analysis of extremely low concentrations of glucose. The impressive glucose sensing behavior of the Cu foam-supported Cu_2O nanothorns can be attributed to the mesoporous array nanostructure as well as the excellent contact between the electrocatalytic active materials (Cu_2O) and the current collector/substrate (Cu foam), which simultaneously enhances the electrocatalytic activity of the electrode and minimizes the resistances in biosensing.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acsami.5b05738.

> XRD pattern, XPS survey scan spectrum, TEM image, HRTEM image, N_2 adsorption−desorption isotherm and BJH adsorption pore size distribution, amperometric response, and photographs of the Cu foam-supported Cu_2O nanothorn array electrode (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: zh_zhang@sdu.edu.cn. Tel/Fax: +86-531-88396978.

Present Address

⊥Department of Chemistry and Biochemistry, University of California Santa Cruz, 1156 High Street, Santa Cruz, California 95064, United States

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We acknowledge the financial support from the National Natural Science Foundation of China (51371106), National Basic Program of China (973, 2012CB932800), Specialized Research Fund for the Doctoral Program of Higher Education of China (20120131110017), and Young Tip-top Talent Support Project (the Organization Department of the Central Committee of the CPC). Z.Z. also acknowledges financial support from the Alexander von Humboldt Foundation (Germany).

■ REFERENCES

(1) Zhan, B.; Liu, C.; Chen, H.; Shi, H.; Wang, L.; Chen, P.; Huang, W.; Dong, X. Free-Standing Electrochemical Electrode Based on $Ni(OH)_2$/3D Graphene Foam for Nonenzymatic Glucose Detection. *Nanoscale* **2014**, *6*, 7424−7429.

(2) Jiang, D.; Liu, Q.; Wang, K.; Qian, J.; Dong, X.; Yang, Z.; Du, X.; Qiu, B. Enhanced Non-Enzymatic Glucose Sensing Based on Copper Nanoparticles Decorated Nitrogen-Doped Graphene. *Biosens. Bioelectron.* **2014**, *54*, 273−278.

(3) Tian, Y.; Liu, Y.; Wang, W.-p.; Zhang, X.; Peng, W. CuO Nanoparticles on Sulfur-Doped Graphene for Nonenzymatic Glucose Sensing. *Electrochim. Acta* **2015**, *156*, 244−251.

(4) Wang, J. Electrochemical Glucose Biosensors. *Chem. Rev.* **2008**, *108*, 814−825.

(5) Yuan, J.; Wang, K.; Xia, X. Highly Ordered Platinum-Nanotubule Arrays for Amperometric Glucose Sensing. *Adv. Funct. Mater.* **2005**, *15*, 803−809.

(6) Solanki, P. R.; Kaushik, A.; Agrawal, V. V.; Malhotra, B. D. Nanostructured Metal Oxide-Based Biosensors. *NPG Asia Mater.* **2011**, *3*, 17−24.

(7) Ronkainen, N. J.; Halsall, H. B.; Heineman, W. R. Electrochemical Biosensors. *Chem. Soc. Rev.* **2010**, *39*, 1747−1763.

(8) Wang, G.; Lu, X.; Zhai, T.; Ling, Y.; Wang, H.; Tong, Y.; Li, Y. Free-Standing Nickel Oxide Nanoflake Arrays: Synthesis and Application for Highly Sensitive Non-Enzymatic Glucose Sensors. *Nanoscale* **2012**, *4*, 3123−3127.

(9) Zhang, Y.; Liu, Y.; Su, L.; Zhang, Z.; Huo, D.; Hou, C.; Lei, Y. CuO Nanowires Based Sensitive and Selective Non-Enzymatic Glucose Detection. *Sens. Actuators, B* **2014**, *191*, 86−93.

(10) Guo, C.; Huo, H.; Han, X.; Xu, C.; Li, H. Ni/CdS Bifunctional Ti@TiO_2 Core-Shell Nanowire Electrode for High-Performance Nonenzymatic Glucose Sensing. *Anal. Chem.* **2014**, *86*, 876−883.

(11) Lang, X.-Y.; Fu, H.-Y.; Hou, C.; Han, G.-F.; Yang, P.; Liu, Y.-B.; Jiang, Q. Nanoporous Gold Supported Cobalt Oxide Microelectrodes as High-Performance Electrochemical Biosensors. *Nat. Commun.* **2013**, *4*, 2169−2176.

(12) Yang, W.; Ratinac, K. R.; Ringer, S. P.; Thordarson, P.; Gooding, J. J.; Braet, F. Carbon Nanomaterials in Biosensors: Should You Use Nanotubes or Graphene? *Angew. Chem., Int. Ed.* **2010**, *49*, 2114−2138.

(13) Si, P.; Ding, S.; Yuan, J.; Lou, X. W.; Kim, D.-H. Hierarchically Structured One-Dimensional TiO_2 for Protein Immobilization, Direct Electrochemistry, and Mediator-Free Glucose Sensing. *ACS Nano* **2011**, *5*, 7617−7626.

(14) Zhang, X.; Sun, S.; Lv, J.; Tang, L.; Kong, C.; Song, X.; Yang, Z. Nanoparticle-Aggregated CuO Nanoellipsoids for High-Performance Non-Enzymatic Glucose Detection. *J. Mater. Chem. A* **2014**, *2*, 10073−10080.

(15) Hsu, C.-W.; Wang, G.-J. Highly Sensitive Glucose Biosensor Based on Au-Ni Coaxial Nanorod Array Having High Aspect Ratio. *Biosens. Bioelectron.* **2014**, *56*, 204−209.

(16) Wang, L.; Zheng, Y.; Lu, X.; Li, Z.; Sun, L.; Song, Y. *Sens.* Dendritic Copper-Cobalt Nanostructures/Reduced Graphene Oxide-Chitosan Modified Glassy Carbon Electrode for Glucose Sensing. *Sens. Actuators, B* **2014**, *195*, 1−7.

(17) Lu, X.; Ye, Y.; Xie, Y.; Song, Y.; Chen, S.; Li, P.; Chen, L.; Wang, L. Copper Coralloid Granule/Polyaniline/Reduced Graphene Oxide Nanocomposites for Nonenzymatic Glucose Detection. *Anal. Methods* **2014**, *6*, 4643−4651.

(18) Dong, X.-C.; Xu, H.; Wang, X.-W.; Huang, Y.-X.; Chan-Park, M. B.; Zhang, H.; Wang, L.-H.; Huang, W.; Chen, P. 3D Graphene-Cobalt Oxide Electrode for High-Performance Supercapacitor and Enzymeless Glucose Detection. *ACS Nano* **2012**, *6*, 3206−3213.

(19) Xiao, X.; Wang, M.; Li, H.; Pan, Y.; Si, P. Non-Enzymatic Glucose Sensors Based on Controllable Nanoporous Gold/Copper Oxide Nanohybrids. *Talanta* **2014**, *125*, 366−371.

(20) Ding, Y.; Liu, Y.; Parisi, J.; Zhang, L.; Lei, Y. A Novel NiO-Au Hybrid Nanobelts Based Sensors for Sensitive and Selective Glucose Detection. *Biosens. Bioelectron.* **2011**, *28*, 393−398.

(21) Li, Y.; Wei, Y.; Shi, G.; Xian, Y.; Jin, L. Facile Synthesis of Leaf-Like CuO Nanoparticles and Their Application on Glucose Biosensor. *Electroanalysis* **2011**, *23*, 497−502.

(22) Dong, J.; Ren, L.; Zhang, Y.; Cui, X.; Hu, P.; Xu, J. Direct Electrodepostion of Cable-Like CuO@Cu Nanowires Array for Non-Enzymatic Sensing. *Talanta* **2015**, *132*, 719−726.

(23) Long, M.; Tan, L.; Liu, H.; He, Z.; Tang, A. Novel Helical TiO_2 Nanotube Arrays Modified by Cu_2O for Enzyme-Free Glucose Oxidation. *Biosens. Bioelectron.* **2014**, *59*, 243−250.

(24) Kong, C.; Tang, L.; Zhang, X.; Sun, S.; Yang, S.; Song, X.; Yang, Z. Templating Synthesis of Hollow CuO Polyhedron and Its Application for Nonenzymatic Glucose Detection. *J. Mater. Chem. A* **2014**, *2*, 7306−7312.

(25) Dong, C.; Bai, Q.; Cheng, G.; Zhao, B.; Wang, H.; Gao, Y.; Zhang, Z. Flexible and ultralong-life cuprous oxide microsphere-nanosheets with superior pseudocapacitive properties. *RSC Adv.* **2015**, *5*, 6207−6214.

(26) Martin, L.; Martinez, H.; Poinot, D.; Pecquenard, B.; Cras, F. L. Comprehensive X-ray photoelectron spectroscopy study of the conversion reaction mechanism of CuO in lithiated thin film electrodes. *J. Phys. Chem. C* **2013**, *117*, 4421−4430.

(27) Svintsitskiy, D. A.; Stadnichenko, A. I.; Demidov, D. V.; Koscheev, S. V.; Boronin, A. I. Investigation of oxygen states and reactivities on a nanostructured cupric oxide surface. *Appl. Surf. Sci.* **2011**, *257*, 8542−8549.

(28) Wu, H.-X.; Cao, W.-M.; Li, Y.; Liu, G.; Wen, Y.; Yang, H.-F.; Yang, S.-P. In situ growth of copper nanoparticles on multiwalled carbon nanotubes and their application as non-enzymatic glucose sensor materials. *Electrochim. Acta* **2010**, *55*, 3734−3740.

(29) Kang, X.; Mai, Z.; Zou, X.; Cai, P.; Mo, J. A sensitive nonenzymatic glucose sensor in alkaline media with a copper nanocluster/multiwall carbon nanotube-modified glassy carbon electrode. *Anal. Biochem.* **2007**, *363*, 143−150.

(30) Khan, R.; Ahmad, R.; Rai, P.; Jang, L.-W.; Yun, J.-H.; Yu, Y.-T.; Hahn, Y.-B.; Lee, I.-H. Glucose-Assisted Synthesis of Cu_2O Shuriken-Like Nanostructures and Their Application as Nonenzymatic Glucose Biosensors. *Sens. Actuators, B* **2014**, *203*, 471−476.

(31) Felix, S.; Kollu, P.; Raghupathy, B.; Jeong, S. K.; Grace, A. N. Electrocatalytic Activity of Cu_2O Nanocubes Based Electrode for Glucose Oxidation. *J. Chem. Sci.* **2014**, *126*, 25−32.

(32) Ci, S.; Huang, T.; Wen, Z.; Cui, S.; Mao, S.; Steeber, D. A.; Chen, J. Nickel Oxide Hollow Microsphere for Non-Enzyme Glucose Detection. *Biosens. Bioelectron.* **2014**, *54*, 251−257.

(33) Xiao, X.; Ulstrup, J.; Li, H.; Zhang, J.; Si, P. Nanoporous Gold Assembly of Glucose Oxidase for Electrochemial Biosensing. *Electrochim. Acta* **2014**, *130*, 559−567.

(34) Bard, A. J.; Faulkner, L. R. *Electrochemical Methods: Fundamentals and Applications*; John Wiley and Sons: New York, 2001; Chapter 6.

(35) Jin, J.; Zheng, G.; Ge, Y.; Deng, S.; Liu, W.; Hui, G. A Non-Enzyme Electrochemical Qualitative and Quantitative Analyzing Method for Glucose, D-Fructose, and Sucrose Utilizing Cu Foam Material. *Electrochim. Acta* **2015**, *153*, 594−601.

(36) Xu, L.; Yang, Q.; Liu, X.; Liu, J.; Sun, X. One-Dimensional Copper Oxide Nanotube Arrays: Biosensors for Glucose Detection. *RSC Adv.* **2014**, *4*, 1449−1455.

(37) Niu, X.; Lan, M.; Zhao, H.; Chen, C. Highly Sensitive and Selective Nonenzymatic Detection of Glucose Using Three-Dimensional Porous Nickel Nanostructures. *Anal. Chem.* **2013**, *85*, 3561−3569.

(38) Ding, Y.; Wang, Y.; Su, L.; Bellagamba, M.; Zhang, H.; Lei, Y. Electrospun Co_3O_4 Nanofibers for Sensitive and Selective Glucose Detection. *Biosens. Bioelectron.* **2010**, *26*, 542−548.

(39) Chen, L. Y.; Fujita, T.; Ding, Y.; Chen, M. W. A Three-Dimensional Gold-Decorated Nanoporous Copper Core-Shell Composite for Electrocatalysis and Nonenzymatic Biosensing. *Adv. Funct. Mater.* **2010**, *20*, 2279−2285.