Nitrogen-doped graphene-silver nanodendrites for the non-enzymatic detection of hydrogen peroxide

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Abstract
An organic-metal hybrid film based on nitrogen-doped graphene-silver nanodendrites (Ag-NG) was fabricated on an indium tin oxide (ITO) electrode using a simple electrophoretic and electrochemical sequential deposition approach. The microwave-assisted method was utilized for the synthesis of nitrogen-doped graphene. This method involves a three-step process consisting of graphite oxidation, exfoliation, and finally chemical reduction with the use of hydrazine as the reducing agent, which leads to the simultaneous reduction of graphene oxide and production of nitrogen-doped graphene. The morphology and structure of the as-fabricated electrode were determined by X-ray diffraction, field emission electron microscopy and transmission electron microscopy. The as-prepared Ag-NG-modified ITO electrode exhibited superior electrocatalytic activity toward hydrogen peroxide (H₂O₂) reduction, with a wide linear detection range of 100 µM to 80 mM (r² = 0.9989) and a detection limit of 0.26 µM with a signal-to-noise ratio of 3. Furthermore, the fabricated non-enzymatic H₂O₂ electrochemical sensor exhibited excellent stability and reproducibility.

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1. Introduction

In recent years, there has been considerable interest in hydrogen peroxide (H₂O₂) detection due to its wide range of applications, such as in food production (as a disinfecting agent), the textile industry (as a bleaching agent), fuel cell devices (as an energy storage site), chemical synthesis (as an active reagent) and even in many oxidative biological reactions (as an essential mediator) [1]. The methods for H₂O₂ detection include chemiluminescence, fluorescence, titration, chromatography, and electrochemistry, among others. Of these detection methods, the use of electrochemical sensors has proven to be a simple and effective approach, and these sensors have been widely used due to their high sensitivity, good selectivity and easy operation [2]. Furthermore, in comparison to enzymatic detection, electrochemical sensors based on the non-enzymatic technique possess the advantages of low cost, high stability and good reproducibility.

Therefore, to improve the sensitivity of non-enzymatic sensors, simple metal nanoparticles, such as Pt [3], Au [4] and Pd [5], with extraordinary electrocatalytic activities have been utilized to modified electrodes for the detection of H₂O₂.

It is well known that silver (Ag) nanostructures have good catalytic activity toward H₂O₂ reduction, and they have been widely developed for enzymeless-based H₂O₂ sensors. Considerable effort has recently been focused on designing Ag nanostructures with various morphologies, such as nanowires [6], nanobars [7], nanobelts [8] and multiple twinned structures [9]. Of these different morphologies, nanodendritic structures composed of trunks and multiple hierarchical symmetrical branches have attracted substantial research interest due to their unique optical, electronic and catalytic properties [10]. It can be observed that silver nanodendrites (Ag NDs) can form porous structures on the surfaces of electrodes due to the high surface area compare of Ag nanoparticles (Ag NPs), which can form a dense film on the electrode surface [11]. Therefore, Ag NDs exhibit better catalytic performance than do Ag NPs. A number of different methods have been employed to prepare Ag nanostructures, such as electrochemical deposition [12], thermal evaporation [13], chemical
vapor deposition [14] and the template approach [15], but electrochemical deposition is a relatively simple and versatile technique for this purpose.

In contrast, graphene is a single sheet of two-dimensional sp²-hybridized carbon nanosheets arranged in a honeycomb lattice. Graphene has recently attracted considerable attention due to its extraordinary physical and chemical properties, such as its high surface area, high thermal conductivity, high chemical stability and rapid charge carrier mobility [16,17]. Many theoretical and experimental studies have demonstrated that the chemical doping of graphene with foreign atoms such as nitrogen, boron, chlorine, phosphorus, fluorine, hydrogen, and sulfur is a promising approach to further modulate and tailor its electronic properties, to manipulate its surface chemistry and to introduce a considerable number of defects into the graphene lattice [18,19]. Among these elements, nitrogen is considered an excellent dopant for graphene due to its comparable atomic size and valence electrons. Furthermore, strong valence bonds can be formed between the nitrogen lone pair electrons and the graphene π-electron system. Therefore, nitrogen doping can induce the creation of a band gap in the graphene energy levels, which is accompanied by the transformation of graphene to an n-type semiconductor. This process leads to a significant increase in the electron conductivity, spin density and charge distribution of the carbon atoms, which lead to the formation of an activation region on the graphene surface [20] that increases its ability to bind guest molecules. Compared to other active inorganic compounds such as Prussian blue [21] and conductive polymers–metal nanocomposites such as Polyaniline–Palladium nanocomposites [22], N-graphene not only has excellent electrocatalytic activity and biocompatibility, but also has the advantage of large surface area, which is useful for adsorption of more Ag NDs on the surface of N-graphene by π–π stacking. This is very important for improving the sensitivity of H₂O₂ detection. Various methods, such as chemical vapor deposition, laser ablation, and ammonia plasma treatment [23], have been used to synthesize nitrogen-doped graphene (N-graphene); however, these methods involve high energy consumption.

In this work, N-graphene was electrophoretically deposited (EPD) on an indium tin oxide (ITO) electrode. Ag NDs were deposited as a second layer via electrochemical deposition. The N-graphene was synthesized using a microwave-assisted method that consists of a three-step process of graphite oxidation, exfoliation, and finally chemical reduction with the use of hydrazine as a reducing agent at low temperature. This approach could simultaneously realize the reduction of graphite oxide (GO) and its doping with nitrogen atoms. Furthermore, microwave irradiation is a rapid and highly efficient method for transferring energy into the reaction system. The as-fabricated Ag NDs-N-graphene-modified ITO electrode (Ag-NG) was utilized as a non-enzymatic H₂O₂ sensor and exhibited high stability, excellent reproducibility and good electrocatalytic activity for the rapid detection of H₂O₂ over a wide linear range from 100 μM to 80 mM.

2. Experimental methods

2.1. Chemical reagents

All chemicals (NaH₂PO₄, Na₃HPO₄, H₂O₂ (30 wt%) and AgNO₃) were purchased from Merck Co. and were of analytical grade and used without further purification. Double-distilled water (resistance = 18.3 MΩ) was used in all experimental procedures. Phosphate-buffered saline (PBS) solution was prepared by mixing stock solutions of NaH₂PO₄ and Na₃HPO₄. Each experimental detection of H₂O₂ was performed using a freshly prepared solution. All experiments were conducted at ambient temperature.

2.2. Synthesis of N-graphene and graphene via the microwave-assisted method

N-graphene was synthesized using a simple method that employed GO as a starting material. The Hummers method was used to synthesize the GO [17]. The exfoliation process consisted of sonicating the graphite oxide dispersion (0.2 mg mL⁻¹) in an ultrasonic bath for 30 min to obtain a yellow-brown dispersion. The chemical reduction reaction was initiated by adding 0.8 mL of hydrazine to the 30 mL GO dispersion. Subsequently, the product was irradiated under the high power mode in a microwave oven for 5 min to obtain a stable black dispersion of N-graphene sheets. The lower density N-graphene suspension was collected from the solution by centrifuging and was dried at 50 °C. Graphene was prepared using the same procedure but with the absence of the hydrazine solution.

2.3. EPD of N-graphene-modified and graphene-modified ITO electrodes

The experimental set-up for the EPD of N-graphene-modified ITO and graphene-modified ITO electrodes is reported elsewhere [17]. Two milligrams of the as-synthesized N-graphene was dispersed in 40 mL of isopropyl alcohol under sonication for 5 min to obtain a homogenous suspension (0.05 mg L⁻¹). The suspension was adjusted to pH 3 with a dilute HCl solution before EPD. ITO glass substrates with an area of 10 mm × 20 mm were immersed in a 5% HF solution for a few minutes to remove the native oxide layer, followed by washing in acetone and distilled water before being vertically immersed into the suspension. The linear distance between the two electrodes was maintained at 10 mm. The DC potential and deposition time were set at 20 V and 5 min, respectively, during the EPD to form an N-graphene-modified ITO electrode film. The freshly coated film was dried at 50 °C in an oven to remove the excess solvent from the EPD process.

2.4. Electrochemical deposition of Ag NDs

The electrochemical deposition of Ag NDs was performed in a three-electrode electrochemical cell by chronoamperometry at -0.6 V with respect to an Ag/AgCl reference electrode. The N-graphene-modified ITO electrode (with an active area of 1 cm²) was used as the working electrode, and a platinum foil with an area of 2 cm² was used as the counter electrode. The solution contained 40 mM Ag(NH₂)₂OH, which was prepared by adding ammonia (1 wt%) to a 50 mM silver nitrate solution until complete dissolution of the precipitates. Distilled water at a volume ratio of 1:12 (Ag(NH₂)₂OH: water) was subsequently added for the chronoamperometric deposition of the Ag NDs-N-graphene-modified ITO electrode for 10 min. The final product (Ag-NG) was washed with distilled water and dried at 50 °C in a conventional oven. The same procedure was used for the electrochemical deposition of the Ag NDs-graphene-modified ITO electrode (Ag-G).

2.5. Characterization

The crystal structures of the products were characterized using an automated X-ray powder diffractometer (XRD, PANalytical's Empyrean) with monochromated CuKα radiation (λ=1.54056 Å). The particle sizes and structural characteristics of the as-synthesized products were determined using a transmission electron microscope (TEM-FEIG-4020, 500 kV) and a high-resolution field emission scanning electron microscope (FESEM-Hitachi SU8000). The samples were ultrasonicated in distilled water before
the TEM and FE-SEM characterizations. X-ray photoelectron spectroscopy (XPS) analysis was carried out using an ESCALAB MK II X-ray photoelectron spectrometer with Mg as the excitation source. Raman spectroscopy was performed using a Renishaw Invia Raman Microscope instrument with laser excitation (λ = 514 nm). Electrochemical measurements were performed with a potentiostat/galvanostat (Autolab PGSTAT30) from Ecochemie (Netherlands).

3. Results and discussion

3.1. Crystal structures

Fig. 1(a) presents the X-ray diffractograms of GO and of the graphene-modified and N-graphene-modified ITO electrodes after EPD. An intense and sharp diffraction peak for GO appears at 2θ = 9.8°, which is attributed to the (001) lattice plane, corresponding to an interlayer d-spacing of 0.90 nm between the stacked GO nanosheets [16]. As a comparison, after the microwave irradiation of GO, the diffractogram shows the disappearance of this strong peak and the appearance of a (002) peak at 2θ = 32.62° and 31.58°, corresponding to d-spacings of 0.27 and 0.28 nm for graphene and N-graphene, respectively [24,25]. This result suggests that the GO was reduced to graphene sheets during the microwave-assisted process, with the removal of the functional groups. Moreover, the downshift of the (002) peak from graphene to N-graphene indicates that the interlayer spacing in N-graphene was enhanced as a result of the nitrogen doping. The crystal structures of the Ag-G-modified and Ag-NG-modified ITO electrodes at -0.6 V after 30 min of electrochemical deposition are

Fig. 2. (a) FESEM image of N-graphene on an ITO substrate after EPD; (b) and (c) low- and high-magnification FESEM images of the Ag NDs coated on the N-graphene-modified ITO electrode after electrochemical deposition.
The remaining peaks at 2θ values of 38.115°, 44.229°, 64.443° and 77.397° can be indexed to the (111), (200), (220) and (311) lattice planes, respectively, of the cubic structure of electrodeposited Ag (JCPDS card no. 01-087-0597), with the lattice constant $a = b = c = 4.086$ Å. Moreover, the appearance of the high intensity peak of the (111) plane indicates dendritic growth along the (111) plane of cubic silver. The ratios of the peak intensities of (111)/(200) and (111)/(220) of Ag-NG are 3.16 and 6.25, respectively, and are higher than the conventional values viz. 2.5 and 4.0. This result is due to the formation of a non-spherical morphology of Ag [26].

3.2. Morphology and chemical composition

Fig. 2(a) shows an FESEM image of the N-graphene-modified ITO electrode before the deposition of Ag NDs. As shown, the surface of the N-graphene thin film is highly smooth, while the typical wrinkles and ripple-like features are slightly visible. A representative FESEM image of AG NDs are shown in Fig. 2(b), which demonstrates a well-ordered dendritic nanostructure. Figs. 2(c) and (d) present the FESEM images of the electrochemically deposited Ag NDs on the N-graphene-modified-ITO electrode. Fig. 2(c) clearly shows that the as-deposited Ag NDs are uniformly embedded in the N-graphene surface; however, a number of Ag NDs protrude from the edges of the N-graphene sheets. Furthermore, the higher magnification FESEM image in Fig. 2(d) clearly reveals the presence of small gaps between the individual Ag NDs and N-graphene nanosheets. This porous structure could facilitate gas diffusion and ionic transport for enhancing the electrochemical reduction of $H_2O_2$. Further investigation of the composite morphology was performed using TEM.
Figs. 3(a) and (b) present TEM images of the Ag-NG composite after its removal from the ITO electrode by ultrasonication. As can be seen, the N-graphene sheets show crumpled silk veil waves due to the local stress induced by the loss of oxygen and the introduction of nitrogen in the N-graphene structure. Moreover, Fig. 3(b) clearly shows that the as-fabricated Ag-NG composite electrode consists of a large amount of dendritic structures. Furthermore, the Fig. 3(c) and (d) present a representative TEM image of Ag NDs. As shown, the individual Ag ND has an elegant two-dimensional dendritic structure with long trunk and uniformly arranged parallel branches. The side branches are symmetric and form an angle of approximately 70° with the trunk. Moreover, the diameters of the trunk and the side branches are approximately 1 μm and 400 nm, respectively.

Raman spectroscopy is a powerful technique for investigating the structural and electronic properties of carbon compounds. Fig. 4 shows the Raman spectra of pristine GO and of the Ag-G-modified and Ag-NG-modified ITO electrodes, where the D, G and 2D bands are centered at approximately 1359, 1587 and 2681 cm⁻¹, respectively. In addition to these three peaks, the Ag-NG-modified ITO electrode presents a weak D' band located at 1628 cm⁻¹ [27]. The G band arises from the in-plane bond stretching of the C-C sp² bond, whereas the D and D' bands (activated by inter-valley and intra-valley double-resonant Raman process, respectively) are associated with the various types of defects, such as vacancy-like defects and sp³ defects, that can be produced by oxidation and hydrogenation, grain boundary edges, domain boundaries and electron doping [27]. Notably, although both the D and D' bands are activated by defects, the nature of these defects differs. Nitrogen doping in the graphene lattice leads to the presence of a D' band in the Raman spectrum of Ag-NG. The presence of a D band in the Raman spectra of both Ag-G and Ag-NG indicates that the densities of defects in these samples are similar due to the introduction of vacancies during the microwave-assisted process.

In contrast, the intensity of the 2D band (activated by a two-phonon double-resonant Raman process) is reciprocal to the electron-hole scattering rate [28]. Moreover, the intensity ratios of the D to G band (I_D/I_G) in GO and in the Ag-G-modified and Ag-NG-modified ITO electrodes are 0.61, 0.74 and 0.79, respectively, indicating an increase in the density of defects in graphene and N-graphene after the microwave-assisted reaction and nitrogen doping. However, the intensity of the 2D band in pristine GO is higher than that in the Ag-G-modified and Ag-NG-modified ITO electrodes; thus, the intensity ratio of the 2D to G band (I_D/I_G) decreases from 0.28 for GO to 0.19 and 0.17 for Ag-G and Ag-NG, respectively, which is further support for the increase in the defect density and successful reduction of GO. Note that the intensity of the 2D band is reciprocal to the electron-hole scattering rate. Thus, nitrogen doping creates defects in the graphene lattice, which leads to an increase in electron-hole scattering and a decrease in the 2D band intensity.

To further investigate the chemical composition and nitrogen content in N-graphene, X-ray photoelectron spectra (XPS) are presented in Fig. 5. The wide-scan spectra of GO reveals the presence of carbon and oxygen, and the presence of nitrogen in N-graphene clearly indicates that nitrogen was successfully doped into the graphene lattice during the reduction of GO. The spectrum of GO exhibits the C1s peak at 283.2 eV and the O1s peak at 531.6 eV [20]. The calculated C/O atomic ratio is approximately 0.69. However, after the microwave-assisted reduction with hydrazine, the intensity of the O1s peak significantly decreased and the C/O atomic ratio reached 3.31, indicating a successful reduction of GO. Moreover, the N1s peak at 400 eV is clearly observed in the N-graphene spectrum with a N/C atomic ratio of 0.17. The oxygen functionalities on the surface of GO and N-graphene are identified by deconvoluting the C1s peak into three different regions. As shown in Fig. 5b, the high-resolution C1s spectra of GO can be deconvoluted into two different strong peaks at 284.6 and 286.9 eV, which are assigned to C-C epoxide and C-O hydroxyl groups, respectively [20], and the weak peak at 288.8 eV is attributed to the O-C=O 9552; O bond of GO [20]. In addition, the C1s spectrum of N-graphene exhibits the same oxygen groups as for GO, but with a considerable decrease in the intensity of the oxygenated carbons (C-O and C=O 9552; O) in the higher energy region (286–290 eV) after the microwave-assisted process in the presence of hydrazine, confirming the effective recovery of the π-electron system of graphene, as shown in Fig. 5c [20].

Deconvolution of the N1s peak of N-graphene can provide detailed

![Fig. 5](image_url)
information on the nitrogen functional groups. As shown in Fig. 5d, the N1s peak can be deconvoluted into three different regions at 398.4, 400.2 and 402.6 eV, which are assigned to three different types of N-containing groups: pyridinic N, pyrrolic N and oxidized nitrogen, respectively [20]. Pyridinic N are the N atoms at the edges of the graphene planes, each of which is bonded to two carbon atoms and donates one p-electron to the aromatic π-electron system. Pyrrolic N are the N atoms that are bonded to two carbon atoms and contribute two p-electrons to the π-electron system, whereas oxidized nitrogens are the oxidized pyridinic nitrogen atoms, which are bonded to two carbon atoms and one oxygen atom.

Nitrogen adsorption-desorption analysis reveals typical Brunauer–Emmett–Teller specific surface areas (S_{BET}) of 462 m² g⁻¹ for the Ag–NG electrode, with an average pore size of ~32 nm, which is higher compared to that of the pure N-graphene (316 m² g⁻¹ and ~25 nm) (Fig. 6). This result could be due to the roughened N-graphene surface with the presence of Ag NDs.

3.3. Enhanced electrocatalytic activity for H₂O₂ reduction

The electrochemical detection of H₂O₂ was performed on the Ag–NG-modified ITO electrode, and Fig. 7(a) presents the cyclic voltammograms (CVs) of bare ITO, graphene-modified ITO, N-graphene-modified ITO, Ag NDs-modified ITO and Ag–NG-modified ITO in N₂-saturated 0.1 M PBS at pH 7.2 in the presence of 1.0 mM H₂O₂. It can be clearly observed that the bare ITO electrode has the weakest response for the detection of H₂O₂. In contrast, the N-graphene-modified ITO electrode exhibits a remarkable catalytic peak current density of approximately 5.6 mA cm⁻² at ~0.7 V in the presence of H₂O₂, which is considerably higher than that of the bare ITO, graphene-modified ITO and Ag NDs-modified ITO electrodes. However, the Ag–NG-modified ITO electrode has the strongest response among the five electrodes, with the lowest onset reduction potential of ~0.40 V and highest current density peak of approximately 7.61 mA cm⁻² for H₂O₂ reduction. This result demonstrates that both nitrogen doping in the graphene lattice and the presence of Ag NDs can improve the electrocatalytic activity of graphene toward H₂O₂ reduction. Additionally, no obvious reduction current is observed for the Ag–NG-modified ITO electrode in the absence of H₂O₂.

The reason for the enhancement of electrochemical detection of H₂O₂ by N-graphene compared to graphene may be attributed to the increase in structural defects and oxygen-containing groups due to the incorporation of nitrogen into the graphene lattice during the microwave-assisted process. As shown in Fig. 2c and Fig. 4, the microwave-assisted process creates more structural defects on graphene, which leads to an enhancement in the amount of unsaturated carbon atoms at the graphene edge sites. These unsaturated carbon atoms are very reactive toward oxygen and form oxygen-containing groups when exposed to air during the microwave-assisted process. Therefore, the structural defects and oxygen-containing groups catalyze the reduction of H₂O₂. Furthermore, the background current of N-graphene-modified ITO is higher than that of Ag NDs-modified ITO electrode which may be attributed to the large surface area of the N-graphene-modified ITO electrode. It should be noted that the reduction peak current of H₂O₂ at the bare ITO, graphene-modified ITO and N-graphene-modified ITO is very low compared to the AG NDs-modified ITO electrode. An obvious reduction peak of H₂O₂ at the Ag NDs-modified ITO electrode is observed at ~0.35 V, which illustrates the excellent catalytic activity for the reduction of H₂O₂ by the Ag NDs. However, the reason for the enhanced reduction of H₂O₂ in Ag-NG...
Table 1

<table>
<thead>
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<th>Type of electrode</th>
<th>Limit of detection (µM)</th>
<th>Sensitivity (µmM⁻¹)</th>
<th>Linear range (nM)</th>
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<td>0.005–1.2</td>
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<td>Prussian blue/GCE</td>
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<td>10⁻³–10</td>
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<td>[32]</td>
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<tr>
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<td>--</td>
<td>0.1–100</td>
<td>[36]</td>
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<td>N-graphene-Ag Nds/ITO</td>
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<td>0.1–80</td>
<td>This work</td>
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compared to N-graphene could be due to the increase in the surface area of N-graphene with the presence of Ag NPs. According to the BET results (Fig. 6), the deposition of Ag NPs on N-graphene sheets effectively increases the total surface area of N-graphene accompanied by the formation of large numbers of porous channels in the Ag–NG composite. Therefore, O₂ gas and OH⁻ anions could be readily transported through these channels while Ag NPs facilitates the detection of H₂O₂. Therefore, the Ag–NG electrode shows the best performance as a H₂O₂ sensor.

The catalytic activity toward H₂O₂ reduction was examined by performing cyclic voltammetry at different scan rates to investigate the sensitivity of the Ag–NG-modified ITO electrode. Fig. 7(b) shows the CVs of the Ag–NG-modified ITO electrode in a N₂-saturated 0.1 M PBS solution at pH 7.2 with 1 mM H₂O₂ at different scan rates; the peak currents increase linearly as the scan rate increases from 10 to 100 mV s⁻¹. Moreover, the reduction peak is shifted slightly to negative potentials. This could be assigned to changes in the electrocatalytic activity and kinetic effect of Ag–NG-modified ITO surface on the reduction of H₂O₂. Therefore, the results illustrate that the electrochemical reduction of H₂O₂ on the Ag–NG-modified ITO electrode is a surface-controlled process [29]. Fig. 8 presents the amperometric responses of the Ag–NG-modified ITO electrode in a N₂-saturated 0.1 M PBS solution at pH 7.2 with successive additions of H₂O₂ at an applied potential of -0.40 V vs. Ag/AgCl. Well-defined steady-state current responses at the Ag–NG-modified ITO surface are obtained after each addition of H₂O₂, and the maximum current responses are recorded within 2 s, demonstrating the rapid current response of the electrochemical sensor. The inset of Fig. 8 shows the calibration curve of the current and H₂O₂ concentration. The Ag–NG-modified ITO electrode displays a linear increase as the concentration increases from 100 µM to 80 mM, with a correlation coefficient of 0.9989 and detection limit of 0.26 µM at a signal-to-noise ratio of 3. The linear regression equation can be expressed as I (µA) = 88.47 (µmM⁻¹cm⁻²) × 5.348. Moreover, the amperometric response to 1 mM H₂O₂ in PBS (0.1 M, pH 7.2) was obtained over a continuous 45 min period. The response of the Ag–NG-modified ITO electrode remained stable throughout the entire experiment, with only 4.3%, 8.6% and 11.2% decreases in current at 10, 30 and 48 min, respectively. The reproducibility of the modified electrode was evaluated by measuring the current response to H₂O₂ under the same conditions. The relative standard deviation (RSD) of the current response to 1 mM H₂O₂ was 4.1% for 6 successive determinations. All of these measurements indicate that the Ag–NG-modified ITO electrode exhibits good stability and reproducibility for the electrocatalytic reduction of H₂O₂ and that the electrochemical performance of this sensor is comparable with that of sensors based on other materials, as shown in Table 1.

It is worth mentioning that the most important achievement of this work is the use of ITO as a cheap substrate compared to the GCE and a facile electrophoretic deposition method for the fabrication of the sensor electrodes. Indeed, electrophoretic deposition can be a substitute for other methods for the preparation of the sensor substrate from carbon materials, conductive polymer and other organic materials, in the fabrication of sensor electrodes based on conductive polymer-metal composite or other organic-metal composite electrodes.

4. Conclusion

N-graphene nanosheets with N:C atomic ratios of up to 0.17 were successfully synthesized at low temperature using a simple microwave-assisted process and were grown on ITO using EPD. In the second step, Ag NPs were deposited on the N-graphene-modified ITO electrode via electrochemical deposition for the fabrication of a H₂O₂ sensor. As an advanced sensor electrode, the Ag–NG-modified ITO electrode exhibited improved electrochemical performance compared to pure N-graphene-modified and graphene-modified ITO electrodes. The improved electrochemical response is attributed to the enhanced surface area due to the layered structure of N-graphene and the roughened surface from the presence of Ag NPs on N-graphene. The response of the as-fabricated electrochemical sensor was rapid, stable and reliable with a detection limit of 0.26 µM in the range from 100 µM to 80 mM.

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