



# Highly selective electroanalysis for chloride ions by conductance Signal outputs of solid-state AgCl electrochemistry using silver-melamine nanowires



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## ABSTRACT

Silver (Ag)-melamine (MA) nanowires were fabricated by the controlled supramolecular self-assembly with conductive hollow Q-graphene (QG) scaffolds to be modified onto the electrodes for sensing chloride ions. Once adding  $\text{Cl}^-$  ions, the QG@MA-Ag modified electrodes, which might otherwise display an Ag oxidation peak at about 0.29 V, could exhibit stable and sharp peaks of solid-state Ag/AgCl electrochemistry at lowering potentials approaching to zero. Moreover, both of the  $\text{Cl}^-$  responses of currents (I) and voltages (V) could vary rationally depending on  $\text{Cl}^-$  concentrations. The responses in conductance (I/V) were thereby conversed alternatively as the signal outputs to ensure the highly selective detection of  $\text{Cl}^-$  ions, with no significant interference from other kinds of halogen ions. The as-developed electroanalysis strategy can facilitate the evaluation of  $\text{Cl}^-$  ions over a broad linear concentration range of 0.25  $\mu\text{M}$ –250 mM, with the detection limit down to 0.16  $\mu\text{M}$ . The feasibility of the chloride sensor was subsequently demonstrated in probing  $\text{Cl}^-$  ions separately in sweat and hela cells. Such a detection method with the signal outputs of conductance may feature a new electroanalysis format tailored for highly selective and ultrasensitive analysis of trace-level  $\text{Cl}^-$  ions for the early diagnosis of chloride-indicative diseases.

## 1. Introduction

Chloride ( $\text{Cl}^-$ ) ions in the animal extra- and intra-cells can take part in various physiological processes such as the control of membrane potential and the regulation of cell volume [1–4]. Especially, the diagnosis of some serious diseases like Cystic fibrosis entails the detection of chloride as a meaningful marker in human body fluids like sweat [5,6]. For example, Cystic fibrosis can be indicative with the  $\text{Cl}^-$  concentrations over 60 mM [7–9]. Moreover, intracellular chloride plays a vital role in the antiviral and apoptosis of human cells [10,11], thus making the evaluation of intracellular  $\text{Cl}^-$  ions a hot topic of clinical importance. Up to date, many classic analysis methods have been developed for the determination of  $\text{Cl}^-$  ions mainly including the Mohr method [12], ion chromatographic colorimetry [13,14], inductively coupled plasma optical emission spectrometry (ICP-OES) [15], and fluorimetric assay [11,16]. For example, Graefe and co-workers fabricated a fluorescent sensor for probing chloride in cells [14]. Naozuka et al. reported an ICP-OES route for the determination of  $\text{Cl}^-$  ions in milk [15]. Unfortunately, most of these detection technologies with

bulky measurement instruments may be challenged by some inherent limitations like complicated operation, time consumption, cost ineffectiveness, and especially field-deployable inability. In particular, they may still be trapped practically by the low analysis selectivity and sensitivity in the evaluation of  $\text{Cl}^-$  ions in some biomedical samples (*i.e.*, cells and sweat) with limited volumes. Alternatively, increasing efforts have been devoted to the chloride analysis by electrochemical detection technologies with high analysis sensitivity and portable devices for the on-site applications [17–20]. For example, Javier et al. developed a disposable screen-printed sensor to measure  $\text{Cl}^-$  ions in sweat [21]. Cinti and colleagues have constructed a filter papers-based electrochemical platform for the  $\text{Cl}^-$  determination in serum and sweat [20]. Nevertheless, the current electroanalysis methods have usually been performed at high electrochemical potentials, which may risk the interference from some electroactive substances possibly co-existing in the complicated backgrounds, showing the substantially restrained detection selectivity. Therefore, exploring a rapid, selective, sensitive, and portable electroanalysis strategy for probing chloride has become an attractive but challenging target to pursue.

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Recent years have witnessed the design of various electrochemical sensors with silver (Ag) nanomaterials due to their high electron transferring and electrochemical redox activities [22–24]. However, Ag nanomaterials can be challenged by the notorious instability, which may prevent their large-scale analysis applications in the reality. Moreover, some researchers have devoted to the applications of melamine (MA) with three free amino groups and three aromatic nitrogen atoms [25,26], which can be readily polymerized to strongly bind with various heavy metal ions like  $\text{Ag}^+$  and  $\text{Cr}^{2+}$  ions [27–29]. For example, Cao and colleagues utilized the MA-formaldehyde polymer to remove  $\text{Cr}^{2+}$  ions [27]. Our group also synthesized the MA-silver nanomaterials for sensing sulfides in blood [28]. Yet, the prepared MA-silver nanomaterials might in a way suffer from the low conductivity and aqueous instability for the practical electroanalysis applications. In addition, a new conductive nanocarbon material of Q-graphene (QG), which consists of hollow carbon nanospheres of multilayer graphene and different types of carbon allotropes, has recently emerged for designing drug-delivery carries and optical or electrochemical sensing devices [30–32]. For example, a drug delivery system was fabricated using QG as nanocarrier for killing lung cancer cells, showing the dual functions of targeted drug delivery and fluorescence imaging [31].

Inspired by these pioneering works above, in the present work, hollow QG was utilized alternatively as the conductive scaffold to mediate the synthesis of MA-Ag nanocomposites by the supramolecular self-assembly route. It was discovered that the resulted QG@MA-Ag nanowires could display the nanowire structure with large surface-to-volume ratio and high aqueous stability. Moreover, the electrodes modified with QG@MA-Ag nanowires could exhibit a Ag oxidation peak at 0.29 V, in contrast to the ones without QG of 0.45 V [28]. More importantly, once  $\text{Cl}^-$  ions were introduced, a considerably stable and sharp peaks of solid-state Ag/AgCl electrochemistry could be attained at the lowering potentials approaching to zero (*i.e.*, about 0.10 V). However, the currents (I) and voltages (V) of the electrochemical responses to  $\text{Cl}^-$  ions could rationally depend on the concentrations of  $\text{Cl}^-$  ions. The conductance (I/V) responses were thereby conversed as the signal outputs for the electroanalysis of  $\text{Cl}^-$  ions with the high detection selectivity and sensitivity, which might help to circumvent any interference from some electroactive substances possibly co-existing in the complicated media. As expected, other kinds of small molecules and ions, especially halogen ions of fluoride, bromide, and iodine ions, would not conduct any significant interference on the electroanalysis of chloride ions. Subsequently, the application feasibility of the developed electroanalysis strategy was demonstrated in the evaluation of  $\text{Cl}^-$  ions separately in samples of sweat and hela cells lysate. To the best of our knowledge, this is the first report on the electroanalysis of chloride ions alternatively through the signal outputs of conductance, featuring a new format of detection candidate for highly selective and ultrasensitive analysis of trace-level  $\text{Cl}^-$  ions.

## 2. Experimental section

### 2.1. Reagents

Melamine (MA), silver nitrate, and sodium chloride were purchased from Sinopharm Chemical Reagent Co. (China). Nafion solution (5.0%) was provided by Sigma-Aldrich (Beijing, China). Q-graphene (QG) was obtained from Graphene Supermarket (Calverton, United States). Hela cells were purchased from Shanghai SunBio Biomedical technology Co., Ltd. All other reagents were of analytical grade. Deionized water (> 18 Mohm) was obtained from an Ultrapure water system (Pall, USA). All glass containers were cleaned in turn by aqua regia and ultrapure water.

### 2.2. Apparatus

Scanning electron microscopy (SEM, Hitachi E-1010, Japan) and

UV-3600 spectrophotometer (Shimadzu, Japan) were utilized for the characterization of the prepared materials. Electrochemical measurements were conducted with an electrochemical workstation CHI 760D (CH Instrument, Shanghai, China) connected to a personal computer. A three-electrode system was applied consisting of a glassy carbon working electrode, which was first polished with alumina powder and then ultrasonically cleaned with water and alcohol, a Pt wire counter electrode, and an Ag/AgCl reference electrode.

### 2.3. Synthesis of QG@MA-Ag nanowires

The QG@MA-Ag nanowires were synthesized using QG as scaffold at the MA-to-Ag ratio of 4/2. Briefly, MA (40 mM) was prepared using 50.4 mg of MA dissolved in 10 mL of water at 60 °C and then cooled to room temperature. An aliquot of 20 mg QG was dispersed by ultrasound into 10 mL MA (40 mM) to yield QG@MA. Under vigorous stirring, 10 mL of silver nitrate (20 mM) was dropped into 10 mL QG@MA mixture to be aged for 1.0 h, followed by the centrifugation about 15 min at 4000 rpm. After that, the obtained black QG@MA-Ag nanowires were washed separately with water and alcohol, each for three times. Subsequently, the products were dried under vacuum to be stored in dark.

### 2.4. Preparation of the QG@MA-Ag modified electrodes

An aliquot of QG@MA-Ag nanowires was first dispersed into 1.0 mL water to be sonicated for 2.0 min. Furthermore, 20  $\mu\text{L}$  Nafion (5.0%) was added into the QG@MA-Ag suspension to be mixed for one min. An aliquot of 2.5  $\mu\text{L}$  of above suspension (4.0 mg/mL) was dropped onto the surface of glassy carbon electrodes to be air-dried for future usage.

### 2.5. Electroanalysis tests of chloride ions

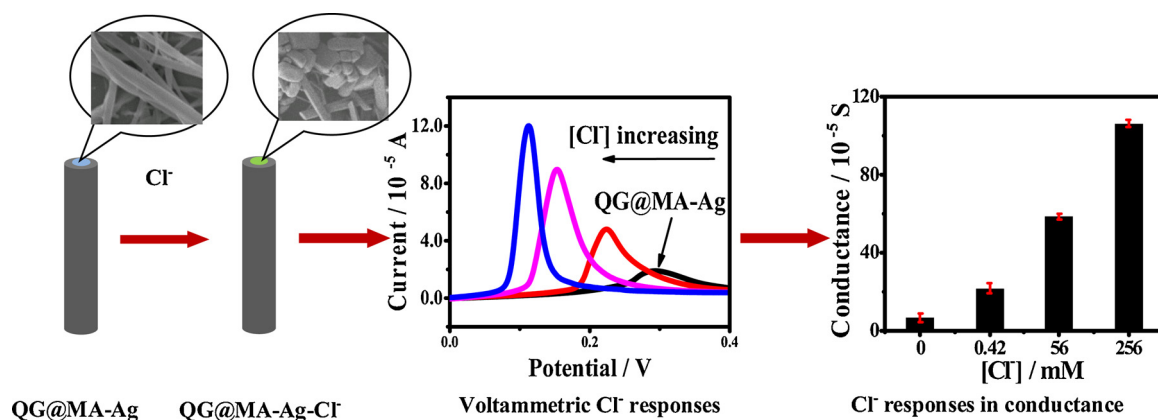
Electrochemical measurements with the electrodes modified with QG@MA-Ag nanowires were performed in buffer (pH 6.0, containing 0.10 M potassium nitrate) by the solid-state Ag/AgCl electrochemistry. An aliquot of chloride ions of different concentrations was separately introduced for the electrochemical measurements. Then, the linear sweep voltammeteries (LSVs) were performed in the potentials ranging from  $-0.20$  to  $0.60$  V at a scanning speed of 100 mV/s. Moreover, the control tests were conducted accordingly with the QG@MA-Ag modified electrodes using other kinds of common ions (0.10 mM) and small molecules (0.50 mM), including  $\text{F}^-$ ,  $\text{Br}^-$ ,  $\text{I}^-$ ,  $\text{CO}_3^{2-}$ ,  $\text{PO}_4^{3-}$ ,  $\text{SO}_4^{2-}$ ,  $\text{Ac}^-$ ,  $\text{Zn}^{2+}$ ,  $\text{Fe}^{3+}$ ,  $\text{Pb}^{2+}$ ,  $\text{Cr}^{2+}$ ,  $\text{Ba}^{2+}$ ,  $\text{Cu}^{2+}$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{NH}_4^+$ , lactic acid, and urea. Subsequently, under the optimized detection conditions, the QG@MA-Ag modified electrodes were applied for sensing  $\text{Cl}^-$  ions with different concentrations in buffer (0.50  $\mu\text{M}$  - 250 mM). Besides, according to the same procedure, the developed electroanalysis method was applied for the evaluation of  $\text{Cl}^-$  ions separately spiked in the samples of sweat and hela cells lysates, of which the lysis of hela cells was performed according to the procedure detailed elsewhere [33].

Of note, all of the error bars in the present work represent the relative standard deviations (RSDs) of five quantitative results.

## 3. Results and discussion

### 3.1. Main fabrication procedure and sensing principle of QG@MA-Ag nanowires

It is well established that MA with aromatic nitrogen atoms and amino groups can be readily self-assembled with  $\text{Ag}^+$  ions [30]. Herein, QG@MA-Ag nanowires were synthesized simply by the controlled supramolecular self-assembly route using hollow QG as the scaffold. Herein, on the one hand, the hexatomic ring-containing QG should perform the strong  $\pi$ - $\pi$  stacking interaction with the benzene ring-containing MA of nanocomposites. On the other hand, the carboxyl



**Scheme 1.** Schematic illustration of the step-by-step setup of the QG@MA-Ag nanowires-modified electrodes showing the Cl<sup>-</sup> concentrations-dependent voltammetric responses of voltages and currents, which are converted into the responses in conductance to Cl<sup>-</sup> ions for the rational signal outputs (top: SEM images of the resulting products).

groups and hydroxyl groups derivatized on the surface of QG might separately conduct the strong electrostatic adsorption and hydrogen bonds with the amino groups-derivatized MA of nanocomposites. The so obtained QG@MA-Ag nanowires were employed for the electroanalysis of Cl<sup>-</sup> ions based on the solid-state AgCl electrochemistry. The main sensing principle and procedure are schematically illustrated in Scheme 1. Of note, the Ag nanoparticles in the QG@MA-Ag modified on the electrodes could first be electrochemically oxidized to Ag<sup>+</sup> state, which would form AgCl in the presence of Cl<sup>-</sup> ions to feature the behavior of solid-state Ag/AgCl electrochemistry. One can note that QG@MA-Ag nanowires modified on the electrodes could display the varying morphological structures before and after adding Cl<sup>-</sup> ions, as revealed by the SEM images (top). More importantly, the electrochemical responses to different Cl<sup>-</sup> concentrations could exhibit varying characteristic signals of solid-state Ag/AgCl electrochemistry, in which the changing currents (I) and voltages (V) could rationally depend on the Cl<sup>-</sup> concentrations. Accordingly, the responses in conductance (I/V) could be converted as the signal outputs for the electroanalysis of Cl<sup>-</sup> ions, which would aid to achieve the high detection selectivity by circumventing any interference from other electroactive substances possibly co-existing in the complicated media.

### 3.2. Characterization of QG@MA-Ag nanowires

Scanning electron microscopy (SEM) was employed to characterize QG@MA-Ag nanowires before and after the additions of Cl<sup>-</sup> ions (Fig. 1). As manifested in Fig. 1A, QG@MA-Ag nanowires could be formed with uniform nanowire-like morphologies with a width of about 250 nm, as clearly revealed in the amplified view (insert), which could be stably suspended in water, in contrast to native MA (data not

shown). Upon the introduction of Cl<sup>-</sup> ions, to our surprise, the nanowires could be broken to yield the blocky aggregates (Fig. 1B), which should be resulted from the interaction between Cl<sup>-</sup> and Ag<sup>+</sup> ions in QG@MA-Ag nanowires producing the AgCl precipitations.

### 3.3. Electrochemical sensing properties of QG@MA-Ag modified electrodes

Electrochemical investigations were conducted on the Cl<sup>-</sup>-sensing properties of the QG@MA-Ag

modified electrodes through the solid-state Ag/AgCl electrochemistry (Fig. 2). Fig. 2A shows the electrochemical characteristics of the developed electrodes before and after adding Cl<sup>-</sup> ions, taking the bare and MA-Ag modified ones as the controls. One can note that the QG@MA-Ag modified electrode could display a silver oxidation peak at about 0.29 V, in contrast to the MA-Ag modified electrode at about 0.48 V. Accordingly, the introduction of QG scaffold should dramatically improve the conductivity of the QG@MA-Ag modified electrodes. More importantly, in the presence of Cl<sup>-</sup> ions, they could produce sharp and larger oxidation peaks at the lowering potentials approaching to zero, depending on the Cl<sup>-</sup> concentrations used. Herein, the electrochemical redox process for Cl<sup>-</sup> responses might take place on the QG@MA-Ag modified electrodes as follows:

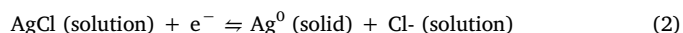
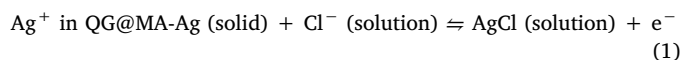
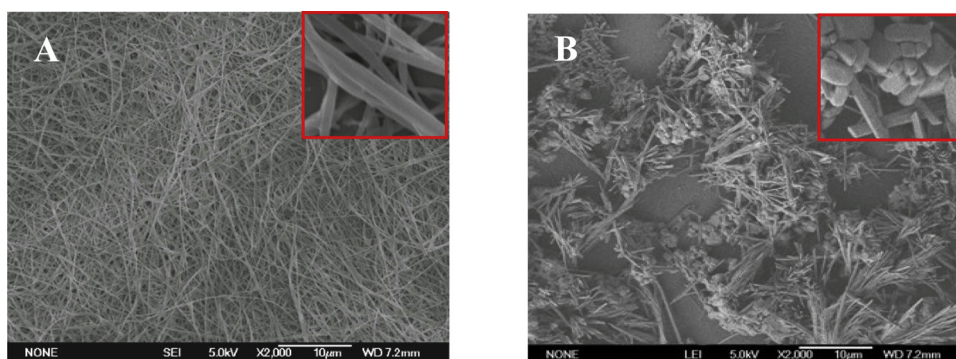


Fig. 2B illustrates a comparison of conductivity between the electrodes modified separately with QG@MA-Ag nanowires and MA-Ag. Unexpectedly, the QG@MA-Ag modified electrode could exhibit the



**Fig. 1.** SEM images of QG@MA-Ag nanowires with wirelike morphologies (A) before and (B) after the addition of Cl<sup>-</sup> ions, which were synthesized at the Ag-to-MA ratios of 2/4 (insert: the magnitude-amplified views).

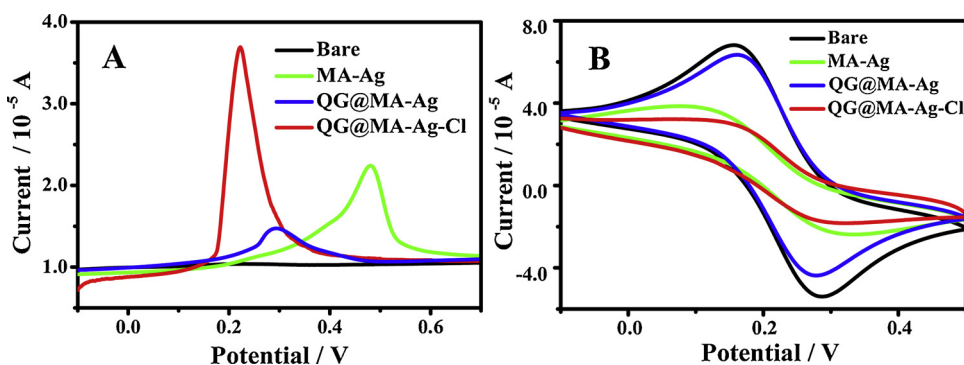


Fig. 2. (A) Characteristic electrochemical LSV responses and (B) conductivity investigation using  $K_3[Fe(CN)_6]$  for the QG@MA-Ag modified electrodes before and after the addition of  $Cl^-$  ions, taking the bare and MA-Ag modified electrodes as the controls. The electrochemical measurements were conducted at a sweep rate of 100 mV/s.

cyclic voltammetry (CV) signal substantially similar to that of the bare electrode, of which the current was much larger than that of the MA-Ag modified electrode. The data indicate that greatly improved conductivity could be expected for the QG@MA-Ag materials presumably due to the inclusion of conductive QG scaffold. Importantly, the addition of  $Cl^-$  ions could cause a large decrease in the conductivity of the QG@MA-Ag modified electrode to expect the  $Cl^-$  electroanalysis.

### 3.4. Optimization of main electroanalysis conditions

The effects of the analysis conditions on the electroanalysis performances of the QG@MA-Ag modified electrodes for sensing  $Cl^-$  ions were investigated by the conductance outputs, mainly including QG@MA-Ag dosages, pH values, ionic strengths, and response time (Fig. 3). It was found that the  $Cl^-$ -induced responses in conductance could increase with increasing QG@MA-Ag dosages till 5.0 mg/mL, over which the signals would gradually decrease (Fig. 3A), presumably due to that the QG@MA-Ag modifiers might be stacked onto the electrodes with too high density, resulting in the decrease in the conductance. Accordingly, 5.0 mg/mL of QG@MA-Ag nanowires was chosen as the optimal one for the modification of electrodes. Fig. 3B shows that the

pH-dependent conductance responses of the electrodes, showing the biggest conductance at pH 6.0 to be selected in the experiments. Meanwhile, Fig. 3C shows that the ion strengths in  $KNO_3$  concentrations could exert an influence on the conductance responses peaking at the optimal 100 mM, which should be the optimal one to be selected. Furthermore, electrochemical investigations were carried out for the  $Cl^-$ -response time of the QG@MA-Ag modified electrodes (Fig. 3D). One can note that the electrochemical reaction can be completed within 40 s, which is thus considered as the suitable time for the electroanalysis of  $Cl^-$  ions thereafter.

Moreover, the electroanalysis reproducibility of the QG@MA-Ag modified electrodes was explored by ten repeated experiments of  $Cl^-$  ions detections, showing basically the similar responses to  $Cl^-$  ions (Fig. 4A). Besides, the sensing stability of the developed electrodes was studied (Fig. 4B). To our surprise, the conductance responses to  $Cl^-$  ions were found to display no significant change, even if the QG@MA-Ag modified electrodes were stored for 12 months. These results indicate that the developed electroanalysis method can exhibit the high reproducibility and storage stability of modified electrodes to ensure the robust detections of  $Cl^-$  ions.

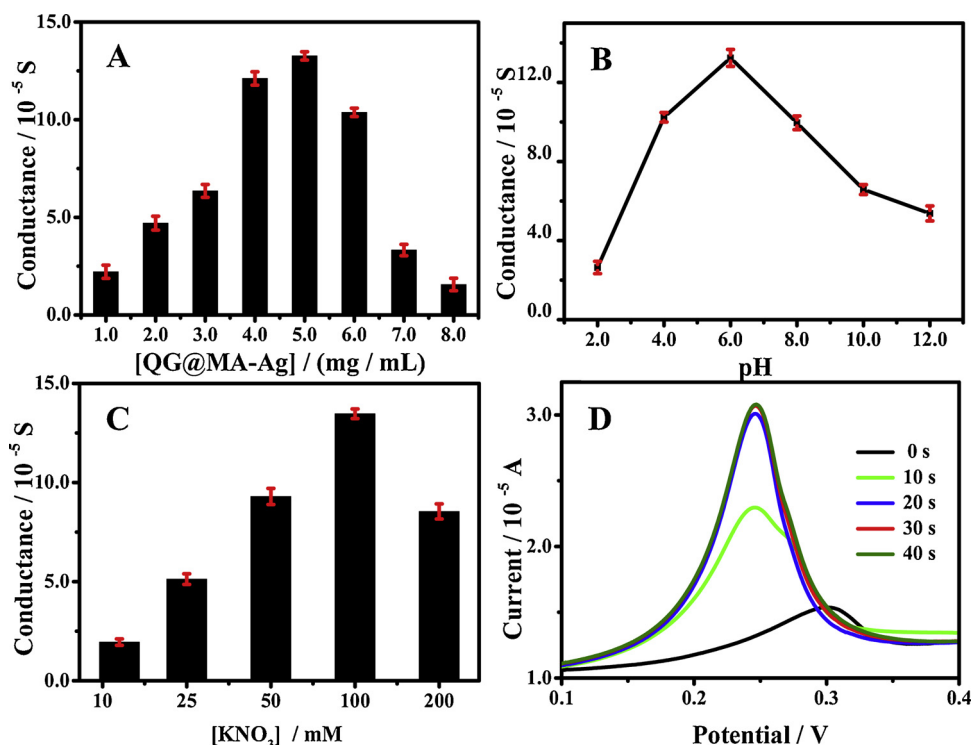


Fig. 3. The electrochemical conductance responses of the QG@MA-Ag modified electrodes to  $Cl^-$  ions depending on (A) QG@MA-Ag dosages, (B) pH values, (C) ion strengths in  $KNO_3$  concentrations, and (D) reaction time for the signal outputs of solid-state AgCl electrochemistry.

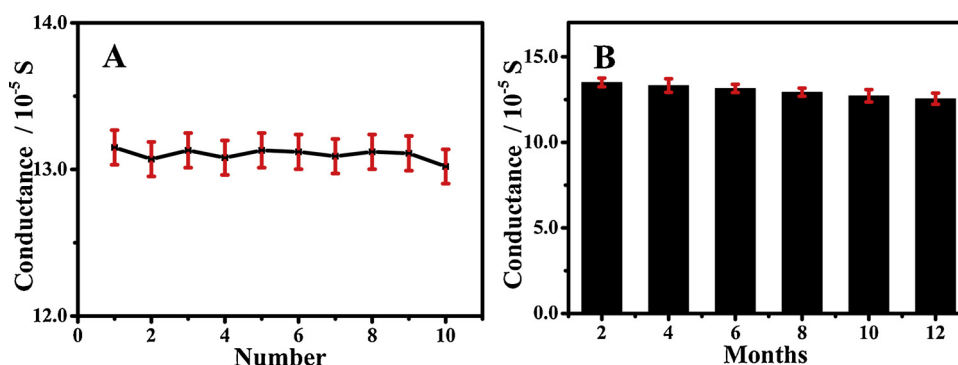


Fig. 4. (A) The sensing reproducibility of the electroanalysis for  $\text{Cl}^-$  ions using different QG@MA-Ag modified electrodes. (B) The storage stability of QG@MA-Ag modified electrodes stored in dark over different time intervals to be repeatedly applied for the electroanalysis of  $\text{Cl}^-$  ions.

### 3.5. Electroanalysis selectivity of the chloride sensor

The electroanalysis selectivity of the developed chloride sensor was investigated using the QG@MA-Ag modified electrodes. Considering the similar properties of halogen ions that might conduct the possibly serious interference, the electroanalysis for different kinds of halogen ions ( $\text{F}^-$ ,  $\text{Cl}^-$ ,  $\text{Br}^-$ , and  $\text{I}^-$ ) were comparably conducted (Fig. 5). It can be found from Fig. 5A that the other halogen ions of  $\text{F}^-$ ,  $\text{I}^-$ , and  $\text{Br}^-$  ions could also exhibit the large electrochemical LSV responses but at the different potentials fixed as about 0.29 V, 0.080 V and -0.18 V, respectively. In contrast, the electrochemical responses to  $\text{Cl}^-$  ions could be ranging from 0.12 to 0.25 V. Accordingly, the data indicate that other kinds of halogen anions might exert no significant interference on the electroanalysis of  $\text{Cl}^-$  ions by the solid-state Ag/AgCl electrochemistry especially in the controlled potentials range (i.e., 0.10–0.26 V), even though they might have much lower levels or hardly co-exist with chloride ions in biological samples like sweat. Such a fact was further confirmed in the electrochemical responses to  $\text{Cl}^-$  ions separately mixed with  $\text{F}^-$ ,  $\text{Br}^-$ , and  $\text{I}^-$  ions (Fig. 5B). Moreover, the selective  $\text{Cl}^-$  electroanalysis was carried out by comparing with other common ions and small molecules possibly co-existing in sweat and cells (Fig. 6). One can find that the tested other analytes alone could present negligibly low responses (Fig. 6A). Also, each of these tested substances was separately mixed with  $\text{Cl}^-$  ions to be electrochemically determined, manifesting the approximated responses to  $\text{Cl}^-$  ions alone (Fig. 6B). Accordingly, the possibly-co-existing small molecules and other ions especially the congeneric halogen ions could present no significant interference on the  $\text{Cl}^-$  electroanalysis.

### 3.6. Electroanalysis of chloride in samples

Under the optimized conditions, the developed electroanalysis method was applied for sensing  $\text{Cl}^-$  ions with different concentrations

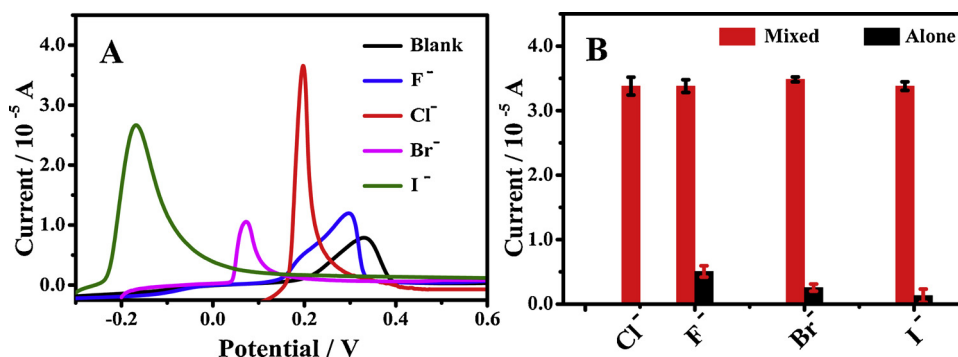


Fig. 5. Electrochemical LSV responses of the QG@MA-Ag modified electrodes to (A)  $\text{Cl}^-$  ions (1.0 mM) and other kinds of halogen anions of  $\text{F}^-$ ,  $\text{Br}^-$ , and  $\text{I}^-$  ions (2.0 mM) alone, and (B)  $\text{Cl}^-$  ions mixed separately with these ions over the potentials ranging from 0.15 V to 0.25 V.

in buffer (Fig. 7). One can find from Fig. 7A that the current responses of the QG@MA-Ag modified electrodes could increase as increasing  $\text{Cl}^-$  concentrations, whereas the potential responses could gradually decrease approaching to zero. A broad linear relationship was thereby obtained for the responses in conductance versus  $\text{Cl}^-$  concentrations ranging from 0.25  $\mu\text{M}$  to 250.0 mM (Fig. 7B), with the limit of detection (LOD) of about 0.16  $\mu\text{M}$ , estimated by  $3\sigma$  rule.

Subsequently, the developed electroanalysis method was practically applied to probe  $\text{Cl}^-$  ions separately spiked in samples of sweat and hela cells lysates (Fig. 8), in which the conductance responses to different  $\text{Cl}^-$  concentrations were calculated. Fig. 8A describes the calibration curve for the electroanalysis of  $\text{Cl}^-$  ions in sweat. A relationship was obtained for the conductance responses over  $\text{Cl}^-$  concentrations linearly ranging from 0.30 mM to 10 mM, with LOD of about 0.10 mM. It is well established that the normal reference of chloride in human sweat should be below 40 mM [5,6], and the sweat chloride is recommended to be commonly detected over the range of 10–160 mM [34]. Therefore, the developed sensor should fully meet with the need for the evaluation of chloride levels in human sweat. Moreover, the application feasibility of the electroanalysis strategy was explored for the detection of  $\text{Cl}^-$  ions with different concentrations spiked in hela cells lysates (Fig. 8B). It can be seen that the intracellular  $\text{Cl}^-$  ions could be analyzed with the concentrations linearly ranging from 0.50  $\mu\text{M}$  to 1.0 mM, with the LOD of 0.20  $\mu\text{M}$ . As is well known, the chloride levels in cells may variously range from 2.0 mM to 90 mM [35]. Obviously, the developed method can allow for the evaluation of  $\text{Cl}^-$  ions in cells, even though the practical intracellular chloride to be detected may be obtained substantially with trace levels because of limited volumes of chloride-containing fluids from the cells.

Besides, the analysis performances of the developed electroanalysis strategy were compared with those of other kinds of detection methods for  $\text{Cl}^-$  ions reported previously, with the results summarized in Table 1. One can see that most of the documented detection methods

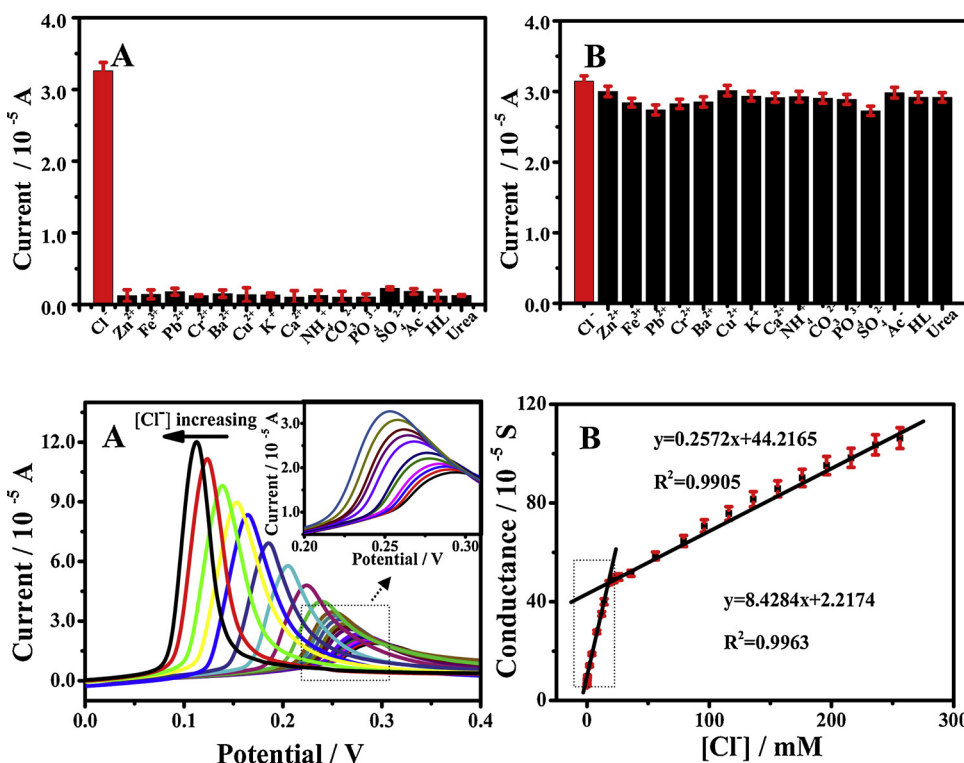


Fig. 6. Electrochemical LSV responses of the QG@MA-Ag modified electrodes to (A) different anions (Zn<sup>2+</sup>, Fe<sup>3+</sup>, Pb<sup>2+</sup>, Cr<sup>2+</sup>, Ba<sup>2+</sup>, Cu<sup>2+</sup>, K<sup>+</sup>, Ca<sup>2+</sup>, NH<sub>4</sub><sup>+</sup>, CO<sub>3</sub><sup>2-</sup>, PO<sub>4</sub><sup>3-</sup>, SO<sub>4</sub><sup>2-</sup>, Ac<sup>-</sup>, lactic acid, urea, and ions, each at 2.0 mM) alone, and (B) Cl<sup>-</sup> ions (1.0 mM) mixed separately with these ions over the potentials ranging from 0.15 V to 0.25 V.

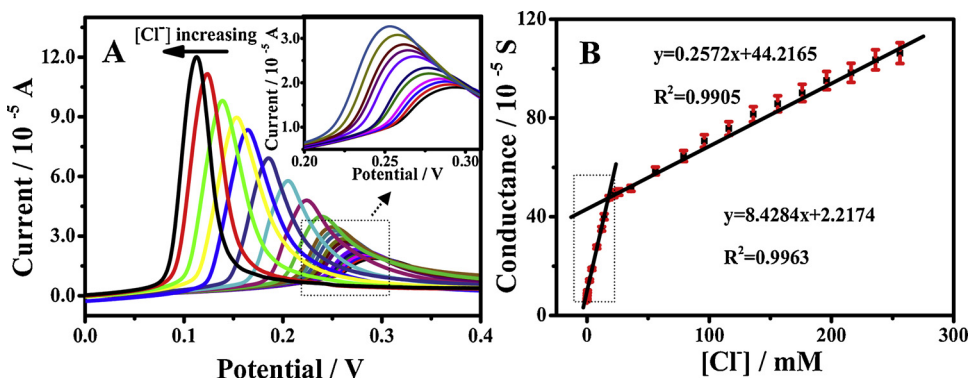


Fig. 7. (A) Electrochemical LSV responses of the QG@MA-Ag modified electrodes to Cl<sup>-</sup> ions of different concentrations (insert: amplified view for the responses to Cl<sup>-</sup> ions at low concentrations). (B) The calibration curve for the relationships between the conductance responses and different concentrations of Cl<sup>-</sup> ions in phosphate buffer (pH 6.0).

may facilitate the detection of chloride ions with the concentrations ranging from 10  $\mu$ M to 200 mM [36–38]. In contrast, the developed electroanalysis method can present the better detection performances in terms of detection ranges and LODs. Therefore, the developed chloride sensor may promise the practical applications for monitoring Cl<sup>-</sup> ions in various biological samples like sweat and hela cells.

#### 4. Conclusions

In a summary, highly conductive QG@MA-Ag nanowires were successfully synthesized by the supramolecular self-assembly route using hollow QG as the scaffold. It was discovered that the electrodes modified with QG@MA-Ag nanowires could exhibit highly stable and especially sharp response peaks of solid-state Ag/AgCl electrochemistry at the lowering potentials approaching to zero, in the presence of Cl<sup>-</sup> ions. Moreover, both of the electrochemical responses of currents and potentials to Cl<sup>-</sup> ions could change rationally depending on the Cl<sup>-</sup> concentrations. An electroanalysis method was thereby developed for probing Cl<sup>-</sup> ions alternatively by the signal outputs of conductance (I/V) so conversed. The developed chloride electroanalysis strategy can

Table 1

Comparison of analytical results among different analysis methods for probing Cl<sup>-</sup> ions.

Electroanalysis methods	Linear ranges	LODs	References
Silver-polypropylene based sensor	100 $\mu$ M–20 mM	18.83 $\mu$ M	[36]
Calyx [4] arene-based sensor	10 $\mu$ M–100 mM	25.1 $\mu$ M	[37]
Reagent-free paper-based sensor	10–200 mM	1.0 mM	[38]
QG@MA-Ag-based sensor	0.25 $\mu$ M–250 mM	0.16 $\mu$ M	This work

possess some outstanding advantages over the electroanalysis ones using other kinds of electroactive probes or labels. First, the prepared QG@MA-Ag nanowires could present high surface-to-volume ratios to expect the large-scale absorption of targets (*i.e.*, Cl<sup>-</sup> ions). Second, the sensing responses by way of the electrochemical process of solid-state Ag/AgCl could achieve the large currents at considerably low peaking potentials. Third, the electroanalysis of chloride in the media with high-level salts like sweat could be realized with high analysis selectivity and reproducibility. Fourth, the responses in conductance (I/V) could be conversed alternatively as the signal outputs for probing Cl<sup>-</sup> ions,

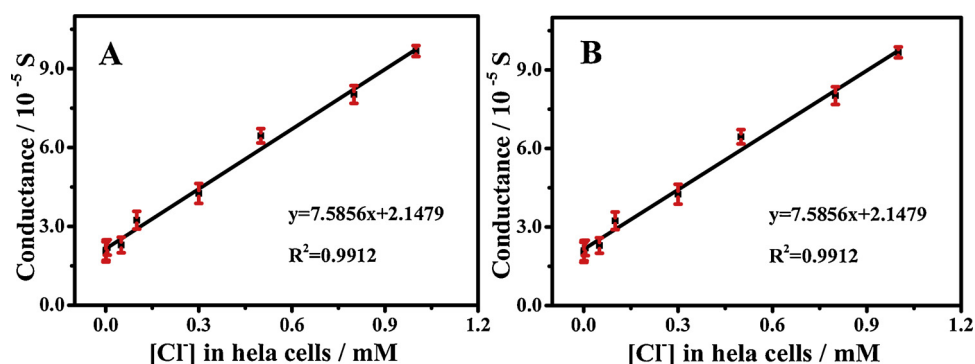


Fig. 8. The calibration curves for describing the relationships between the conductance responses and different concentrations of Cl<sup>-</sup> ions spiked in the samples of (A) sweat and (B) hela cells lysates.

which may ensure the highly selective analysis of chloride especially in the media containing other kinds of halogen ions. Finally, the developed electroanalysis method could facilitate the evaluation of Cl<sup>-</sup> ions with the levels down to 0.16 μM, which detection performances are comparably better than those of the current electroanalysis methods. Such a chloride sensor with the signal outputs of conductance may feature a new format of electroanalysis for the highly selective and ultrasensitive monitoring of Cl<sup>-</sup> ions in the fields of clinical diagnosis, environmental monitoring, food safety.

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