

Electrochemiluminescent Immune-Modified Electrodes Based on Ag₂Se@CdSe Nanoneedles Loaded with Polypyrrole Intercalated Graphene for Detection of CA72-4

Xiaohui Lv,[†] Xuehui Pang,[†] Yueyun Li,[‡] Tao Yan,[†] Wei Cao,[†] Bin Du,[†] and Qin Wei^{*†}

[†]Key Laboratory of Chemical Sensing & Analysis in Universities of Shandong, School of Chemistry and Chemical Engineering, University of Jinan, Jinan 250022, People's Republic of China

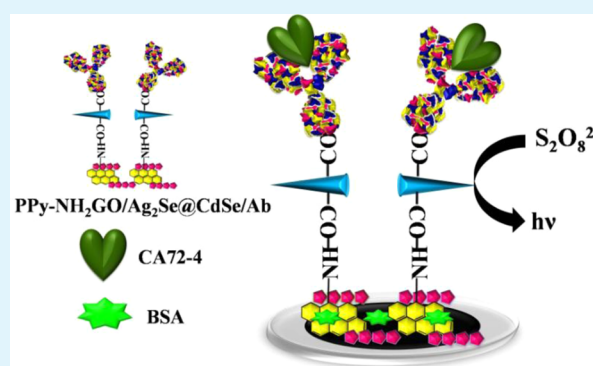
[‡]School of Chemical Engineering, Shandong University of Technology, Zibo 255049, People's Republic of China

S Supporting Information

ABSTRACT: This work described a new electrochemiluminescence (ECL) immunosensor based on polypyrrole intercalated graphene and Ag₂Se@CdSe nanoneedles. The novel nanomaterial Ag₂Se@CdSe, with needle-like morphology, was synthesized for the first time. The prepared Ag₂Se@CdSe nanoneedles exhibited good luminous performance in the presence of K₂S₂O₈. Polypyrrole intercalated amination graphene with high specific binding sites and excellent electrochemical performance was used as the platform for the sensor. The developed ECL immunosensor was used for the detection of CA72-4 with good linear relation in the range from 10⁻⁴ to 20 U/mL and low detection limit of 2.1 × 10⁻⁵ U/mL (S/N = 3). The developed ECL immunosensor with high sensitivity and spectral selectivity can be used for detection of real samples.

Ag₂Se@CdSe nanoneedles could be promising candidate emitter for ECL biosensors in the future.

KEYWORDS: electrochemiluminescence, modified electrodes, Ag₂Se@CdSe nanoneedles, polypyrrole intercalated graphene



INTRODUCTION

In the past 60 years, the incidence and mortality of gastric cancer have seen a sharp worldwide decline. However, just inferior to lung cancer, gastric cancer remains the world's second leading cause of cancer mortality.¹⁻⁴ Under this circumstance, there is an urgent need to develop a sensitive method for detecting gastric cancer. Carcinoembryonic antigen (CEA) and carbohydrate antigen 19-9 (CA19-9), commonly used in the detection of gastric cancer, have a limited clinical utility due to their low sensitivity and specificity. CA72-4 is one of the new tumor markers and seems to exhibit better characteristics compared with the other two markers.⁵ CA72-4 is a reliable tumor marker for evaluating disease stage and activity of gastric cancer^{6,7} and CA72-4 has been widely used to diagnose cancer and monitor immunotherapy. Preoperative levels of CA72-4 may aid in predicting the invasiveness of gastric cancer and in providing prognostic information for patients. Therefore, it is significant to detect early CA72-4 in clinical diagnosis. However, the traditional methods for the determination of CA72-4 typically require skilled operators, extensive sample pretreatment and expensive equipment. In this work, we developed a convenient ECL immunosensor for the sensitive detection of CA72-4.

Electrochemiluminescence (ECL) is a process that involves the generation of species at the electrode surface and then undergoes electron-transfer reactions to form excited states that

emit light.⁸ ECL is superior to fluorescence in terms of sensitivity and signal-to-noise ratio due to the absence of background from unselective photoexcitation.⁹ ECL has now become a powerful analytical technique and been widely used in the areas of immunoassay.¹⁰⁻¹³ The key challenge of ECL immunoassay is the luminescent materials. Three types of luminophores, including luminol,¹⁴ Ru(bpy)₃²⁺¹⁵ and quantum dots (QDs),¹⁶ have been used in ECL immunosensors extensively.¹⁷⁻²⁰ In this work, a novel nanoparticle, named as Ag₂Se@CdSe nanoneedles, was prepared for the first time. In the presence of K₂S₂O₈, Ag₂Se@CdSe nanoneedles have a high luminescent property. This work made use of the cathodic ECL performance of Ag₂Se@CdSe nanoneedles to fabricate convenient, rapid and highly sensitive ECL immune-modified electrodes. The ECL performance of the Ag₂Se@CdSe nanoneedles was also evaluated by detecting CA72-4 concentration in human serum.

Graphene-based materials have attracted extensive attention due to their extraordinary properties, such as unusual electrical properties generated from their long-range π -conjugation, chemical stability, large surface area and broad electrochemical window. All these properties render them as an attractive

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electrode material for sensors.^{21,22} Graphene oxide (GO) is an important carbonous material chemically derived graphene. However, the electrochemical performance of GO is poor because of its poor electrical conductivity and low Faradaic reaction rate. Amino groups that donate electron density to aromatic rings of graphene can improve the conductivity of graphene.²² In addition, amination GO (NH₂GO) could be well dispersed in aqueous solution due to the hydrophilicity of primary amines, hydroxyl and carboxyl. However, in order to obtain an ultrasensitive signal, the electrode materials must exhibit extraordinary properties. Conducting polymers are well-known for their easy processability and outstanding electrical properties. Polypyrrole (PPy) has been considered as one of the most promising electrode materials because of its low cost, easy synthesis and relatively high conductivity.^{23,24} In this work, PPy intercalated NH₂GO (PPy-NH₂GO) was used as the platform of luminous source Ag₂Se@CdSe. The synthetic condition and luminescence property of Ag₂Se@CdSe were investigated. The ECL immunosensor has high sensitivity for CA72-4 with a linear range from 10⁻⁴ to 20 U/mL and the detection limit of 2.1 × 10⁻⁵ U/mL. Herein we provide a promising method for the detection of CA72-4 or other tumor markers in clinical diagnosis.

EXPERIMENTAL SECTION

Reagents. Glassy carbon electrodes (GCE, 4 mm of diameter) were purchased from Huahai Kechuang Trade co., LTD (Beijing, China). CA72-4 and anti-CA72-4 antibodies (anti-CA72-4) were purchased from Shanghai Linc-Bio Science Co., Ltd. (Shanghai, China). Bovine serum albumin (BSA, 96–99%) was obtained from Sigma-Aldrich (Beijing, China). *N,N*-Dimethylformamide (DMF), polyvinylpyrrolidone (PVPK-30) and mercaptoacetic acid were purchased from Sinopharm Chemical Reagent Co., Ltd. 1-Ethyl-3-(3-dimethyl aminopropyl)carbodiimide (EDC) and *N*-hydroxy succinimide (NHS) were obtained from Beijing Dingguo Changsheng Biotechnology Co., Ltd. All other chemicals were of analytical grade and used without further purification. The ultrapure water (≥18.25 MΩ) was used throughout the experiments.

Apparatus. The ECL measurements were carried out on a model MPI-F flow injection chemiluminescence detector (Remax, China), and electrochemical measurements were carried out on CHI 760D electrochemical workstation (Chenhua, China). Fourier transform infrared (FT-IR) spectra were recorded using a VERTEX70 spectrometer (Bruker Co., Germany). Scanning electron microscopy (SEM) images and energy dispersive spectrometry (EDS) were obtained using a field emission SEM (Zeiss, Germany). Electrochemical impedance spectroscopy (EIS) measurements were performed with IM6e electrochemical interface (Zahner, Germany).

Preparation of NH₂GO and PPy-NH₂GO. GO was synthesized from graphite by a previously published method.²⁵ Based on a previously reported method,²² NH₂-GO was prepared by the following process, 0.1 g of GO was dispersed in 40 mL of ethylene glycol under ultrasonication. After further addition of 1 mL of ammonia water, the dark brown solution was transferred to Teflon-lined autoclaves for solvothermal reaction at 180 °C for 10 h. The products were collected by filtration and washed several times with ultrapure water. After that the products were dried at 60 °C for 24 h.

PPy-NH₂GO composites were prepared by in situ polymerization that reported by Saswata Bose and co-workers.²⁴ First, 1.83 g of GO was dispersed in 50 mL of water and 2 g of pyrrole was dissolved in 30 mL of a 1:1 water and ethanol mixture by ultrasonication for 30 min. After that, the two solutions were mixed followed by ultrasonication for another 30 min. Then 20 mL of ferric chloride (0.1 M) was added dropwise to the mixture of pyrrole and GO. The reaction was allowed to continue for 24 h under vigorous stirring. The composites were collected by filtration and washed several times with water and ethanol

mixture. Finally, the composites were dried under vacuum at 60 °C for 24 h.

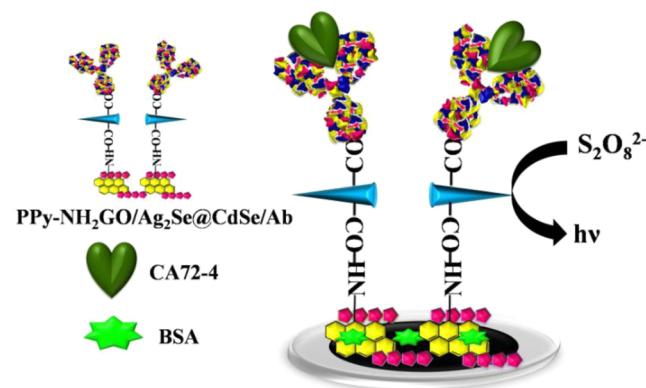
Synthesis of Ag₂Se@CdSe and PPy-NH₂GO-Ag₂Se@CdSe. Briefly, Ag₂Se@CdSe was synthesized as follows: 0.0573 g of CdCl₂·2.5H₂O, 0.011 g of SeO₂ and 0.2 g of polyvinylpyrrolidone k-30 (PVPk-30) were dissolved in 10 mL of DMF adequately. Then 5 mL of mercaptoacetic acid and 0.2 mL of AgNO₃ (4 mM, dissolved in ethanol) were added in the above solution under stirring. Finally, the mixture was transferred into Teflon-lined autoclaves and reacted for 4, 6, 8 and 10.5 h, respectively, at 140 °C. The Ag₂Se@CdSe was washed with isopropyl alcohol three times with centrifugation at 8000 rpm and redispersed in 2 mL of PBS (pH 7.4). Then the mercaptoacetic acid stabilized Ag₂Se@CdSe was obtained.

PPy-NH₂GO-Ag₂Se@CdSe was prepared by the binding between PPy-NH₂GO and Ag₂Se@CdSe. Briefly, the above prepared Ag₂Se@CdSe solution was activated with EDC/NHS, followed by adding 1 mL of PPy-NH₂GO (2 mg/mL) into Ag₂Se@CdSe solution and shocking for 12 h. PPy-NH₂GO can combine with Ag₂Se@CdSe via covalent bond of amino group and carboxyl group²⁶ and physical absorption. After that, PPy-NH₂GO-Ag₂Se@CdSe was obtained by centrifugation and redispersed in 1 mL of PBS (pH 7.4).

Prepared of PPy-NH₂GO-Ag₂Se@CdSe-Ab. 0.1 mL of anti-CA72-4 (1 μg/mL) was added in 1 mL of PPy-NH₂GO-Ag₂Se@CdSe aqueous solution (2 mg/mL) and incubated for 12 h at 4 °C. The extra antibody was removed by centrifugation. The obtained PPy-NH₂GO-Ag₂Se@CdSe-Ab was dispersed in 1 mL of PBS (pH 7.4) and stored at 4 °C when not use.

Fabrication of the ECL Immune-Modified Electrodes. As described in Scheme 1, a glassy carbon electrode (GCE, 4 mm of

Scheme 1. Schematic Diagram for the Fabrication of the ECL Immunosensor



diameter) was used as the substrate. The GCE was polished with 1.0, 0.3 and 0.05 μm alumina slurry and rinsed with water. Then, 6 μL of PPy-NH₂GO-Ag₂Se@CdSe-Ab was dropped on the surface of the GCE and dried at 4 °C. 3 μL of BSA (1%) was used for blocking the nonspecific binding sites. After the GCE/PPy-NH₂GO-Ag₂Se@CdSe-Ab/BSA was washed with PBS (pH 7.4) and dried at 4 °C; 6 μL of CA72-4 with different concentration was incubated on the film. Finally, the prepared modified electrodes were washed with PBS (pH 7.4) and stored at 4 °C until use.

ECL detection of CA72-4. 10 mL of PBS (1/15 M, pH 7.4) containing 55 mM K₂S₂O₈ was added in an ECL detector cell. A three-electrode system consisted of an Ag/AgCl (saturated KCl) electrode as the reference electrode, a platinum wire electrode as the auxiliary electrode and the modified electrodes incubated with different CA72-4 concentrations as the working electrodes was applied. The voltage of the photomultiplier tube (PMT) was set at 800 V. The scanning potential was -1.7 V ~ 0 V. Scan rate was 0.1 V/s. Finally, the modified electrodes were placed in the ECL cell and the ECL signals were measured. The ECL signals decreased with the increase of CA72-4 concentrations. Therefore, the proposed immunosensor could realize the measurement of different concentrations of CA72-4.

RESULTS AND DISCUSSION

Characterization of NH_2GO , $\text{PPy-NH}_2\text{GO}$, $\text{Ag}_2\text{Se@CdSe}$, $\text{PPy-NH}_2\text{GO-Ag}_2\text{Se@CdSe}$. Figure 1A is the SEM

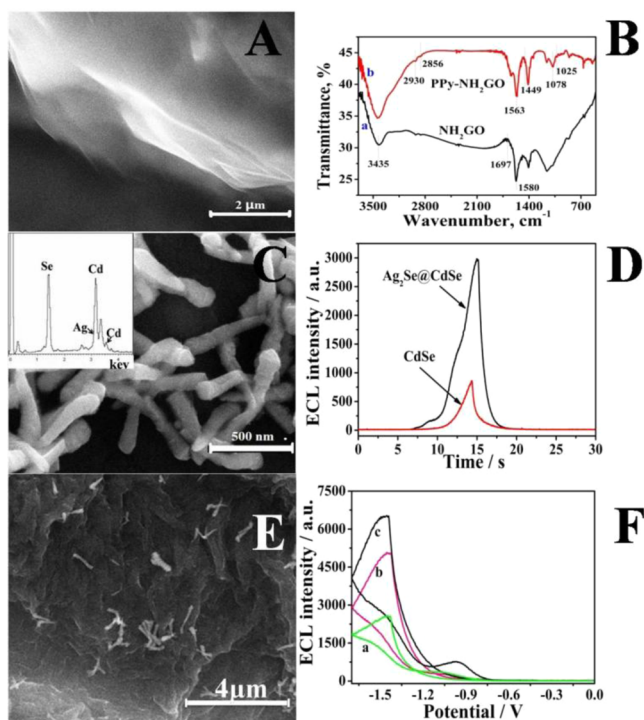


Figure 1. (A) SEM of NH_2GO , (B) FT-IR characterization of NH_2GO (curve a) and $\text{PPy-NH}_2\text{GO}$ (curve b), (C) SEM of $\text{Ag}_2\text{Se@CdSe}$ (inset is the EDS of $\text{Ag}_2\text{Se@CdSe}$), (D) comparison of ECL intensity of $\text{Ag}_2\text{Se@CdSe}$ nanoneedles and CdSe quantum dots (E) SEM of $\text{PPy-NH}_2\text{GO-Ag}_2\text{Se@CdSe}$ and (F) ECL intensity of $\text{Ag}_2\text{Se@CdSe}$ (a), $\text{NH}_2\text{GO-Ag}_2\text{Se@CdSe}$ (b) and $\text{PPy-NH}_2\text{GO-Ag}_2\text{Se@CdSe}$ (c).

image of NH_2GO , which shows a wrinkled paper-like surface. As shown in Figure 1B (curve a), the absorption peaks of $3300\text{--}3500\text{ cm}^{-1}$ in the FT-IR characterization of NH_2GO are the N–H stretching vibration and the peaks at 1580 and 1676 cm^{-1} are the N–H in-plane stretching,²² indicating the successful amination of GO. These absorption peaks also appeared in the FT-IR characterization of $\text{PPy-NH}_2\text{GO}$ (curve b). The presence of PPy in the $\text{PPy-NH}_2\text{GO}$ is confirmed by the appearance of characteristic peaks of PPy at 1563 and 1449 cm^{-1} .²⁴ The peaks at 1025 and 1078 cm^{-1} are due to the C–H in-plane vibration of polypyrrole ring and epoxy group, respectively.²⁴

SEM was applied for characterizing the presence of $\text{Ag}_2\text{Se@CdSe}$ (Figure 1C). It can be observed visually that all products are a needle-like morphology and the size is homogeneous. The inset is the EDS analysis of $\text{Ag}_2\text{Se@CdSe}$; the EDS detector was capable of detecting elements with atomic number equal to or greater than six. The relative amounts of elements can be inferred from relative peak heights of EDS image.²⁷ It is clear that there are Ag, Cd and Se elements simultaneously in the EDS image of $\text{Ag}_2\text{Se@CdSe}$, which demonstrated that the $\text{Ag}_2\text{Se@CdSe}$ nanoneedles were prepared successfully and the ratio of Ag:Cd is about 1:29.2. ECL measurement of $\text{Ag}_2\text{Se@CdSe}$ nanoneedles and CdSe quantum dots are shown in Figure 1D. Obviously, the ECL intensity of $\text{Ag}_2\text{Se@CdSe}$ was higher than CdSe quantum dots, indicating that $\text{Ag}_2\text{Se@CdSe}$

nanoneedles are the promising luminescent materials in the future that can be applied in the ECL analysis.

After modification by PPy, the obtained $\text{PPy-NH}_2\text{GO}$ turned to a plicated structure (Figure 1E), which increased the specific surface area markedly. The increase of specific surface area results in the increase of binding sites and could improve the sensitivity of the sensor. In addition, it can be observed that $\text{Ag}_2\text{Se@CdSe}$ nanoneedles distributed on the $\text{PPy-NH}_2\text{GO}$ surface uniformly. The photographs of the nanocomposites solution of $\text{PPy-NH}_2\text{GO}$ and $\text{PPy-NH}_2\text{GO-Ag}_2\text{Se@CdSe}$, which indicated their good dispersity, are also given in the Supporting Information (Figure S1). The electrochemical performance of $\text{PPy-NH}_2\text{GO}$ was also studied (Figure 1F). The ECL intensity of $\text{PPy-NH}_2\text{GO-Ag}_2\text{Se@CdSe}$ is higher than both $\text{Ag}_2\text{Se@CdSe}$ and $\text{NH}_2\text{GO-Ag}_2\text{Se@CdSe}$, which is attributed to its good electrochemical property such as the excellent conductivity and catalysis of $\text{PPy-NH}_2\text{GO}$. In addition, the increased specific surface area of NH_2GO , after functionalized by PPy, resulted in the large loading of $\text{Ag}_2\text{Se@CdSe}$. All of the above-discussed reasons support the enhancement of ECL intensity and the improvement the sensitivity of the ECL immunosensor.

Characterization of the Immunosensor. The CV behaviors of the bare GCE and $\text{PPy-NH}_2\text{GO-Ag}_2\text{Se@CdSe}$ -modified electrode were investigated (Figure 2A); there is an

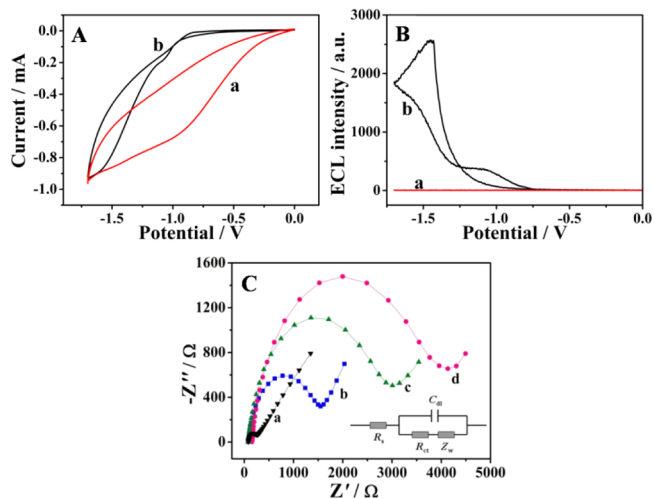


Figure 2. (A) CV behaviors of the bare GCE (a) and $\text{PPy-NH}_2\text{GO-Ag}_2\text{Se@CdSe/GCE}$ (b) measured in $10\text{ mL PBS (pH 7.4)}$ containing $55\text{ mM K}_2\text{S}_2\text{O}_8$, (B) corresponding ECL intensity of panel A, (C) EIS of the electrode at different stages: (a) bare GCE, (b) $\text{PPy-NH}_2\text{GO-Ag}_2\text{Se@CdSe-Ab/GCE}$, (c) $\text{BSA/PPy-NH}_2\text{GO-Ag}_2\text{Se@CdSe-Ab/GCE}$, (d) $\text{Ag/BSA/PPy-NH}_2\text{GO-Ag}_2\text{Se@CdSe-Ab/GCE}$. The inset is the equivalent circuit; the amplitude of the sinusoidal wave was 5 mV and the frequency range examined was $100\text{ kHz to }0.1\text{ Hz}$.

obvious change after the electrode was modified with $\text{PPy-NH}_2\text{GO-Ag}_2\text{Se@CdSe}$. Figure 2B is the corresponding ECL response, and there is not luminescent signal for bare GCE and an obvious luminescent signal for $\text{PPy-NH}_2\text{GO-Ag}_2\text{Se@CdSe}$ -modified electrode was observed, indicating that the ECL signal was produced by $\text{Ag}_2\text{Se@CdSe}$.

To study the assembly of the sensor, EIS was applied to probe the feature of the surface-modified electrode. In the EIS Nyquist plots, the semicircle portion at higher frequencies corresponds to the electron-transfer resistance (R_{ct}), and R_{ct} increases with the increase of semicircle diameter. In Figure 2C,

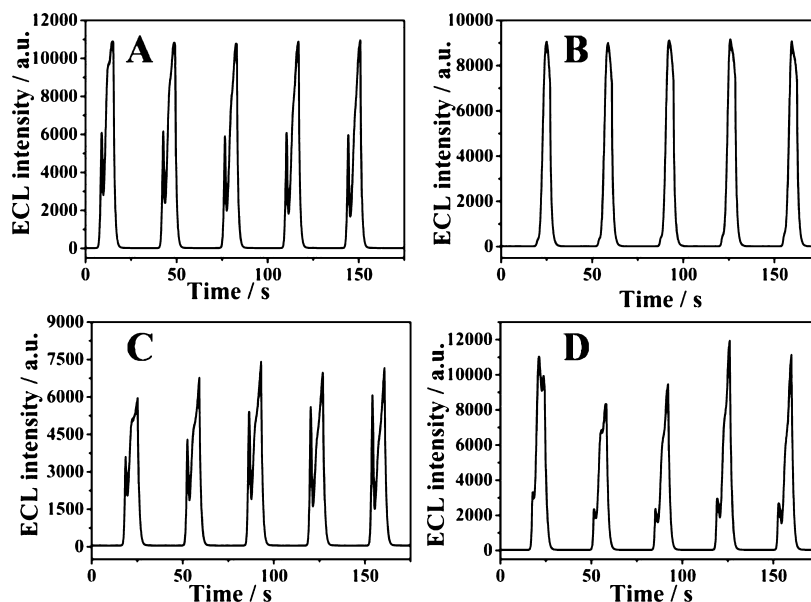


Figure 3. Effect of synthesis time of $\text{Ag}_2\text{Se}@Cd\text{Se}$ nanoneedles to luminescence property, (A) 4 h, (B) 6 h, (C) 8 h and (D) 10.5 h.

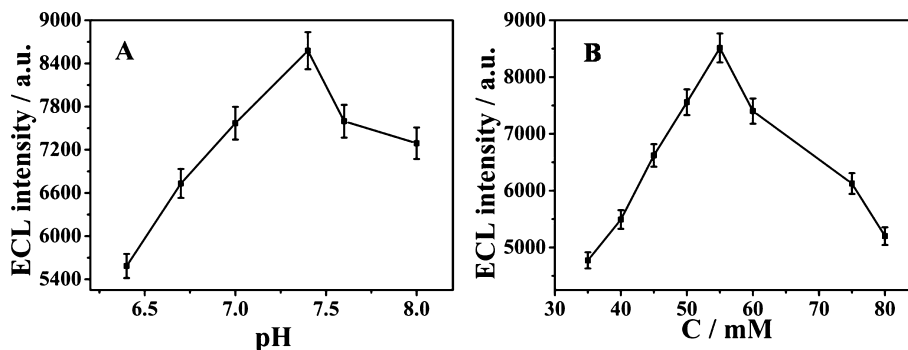


Figure 4. Effect of pH (A) and concentrations of $\text{K}_2\text{S}_2\text{O}_8$ (B) (the concentration of CA72-4 was 0.1 U/mL).

the electrode showed a higher R_{et} (curve b) than the bare GCE (curve a) when coated with $\text{PPy-NH}_2\text{GO-Ag}_2\text{Se}@Cd\text{Se-Ab}$, indicating that $\text{PPy-NH}_2\text{GO-Ag}_2\text{Se}@Cd\text{Se-Ab}$ obstructed electron transfer for the electrochemical probe. When the modified electrode was incubated with BSA and Ag respectively, a larger increase in resistance was observed (curve c and curve d), which is due to the electron transfer kinetics resistance of BSA at the electrode interface and the formation of antigen–antibody complex. All these results indicated that the sensor was fabricated successfully.

■ OPTIMIZATION OF THE EXPERIMENTAL CONDITIONS

Effect of Synthesis Time of $\text{Ag}_2\text{Se}@Cd\text{Se}$. The synthesis time of $\text{Ag}_2\text{Se}@Cd\text{Se}$ nanoneedles was investigated (Figure 3). Obviously, the $\text{Ag}_2\text{Se}@Cd\text{Se}$ nanoneedles displayed the strongest ECL intensity and the most stable signal at 4 and 6 h, respectively. But the signal was not single for 4 h, compared to that for 6 h. The intensity, stability and unicity of the ECL signal are the most important factors that affect the performance of ECL immunoassay. The ECL intensity and stability for 8 and 10.5 h were worse. Therefore, in consideration of the above, 6 h was selected as the optimum time for synthesis of the $\text{Ag}_2\text{Se}@Cd\text{Se}$ nanoneedles.

Effect of pH and Concentration of $\text{K}_2\text{S}_2\text{O}_8$. To obtain the optimal ECL response, the effects of pH values and concentrations of $\text{K}_2\text{S}_2\text{O}_8$ on ECL signal were investigated. The pH values of PBS buffer in the range from 6.4 to 8.0 were evaluated, and the results are shown in Figure 4A. The ECL intensity increased with the increase of pH from 6.4 to 7.4 and then decreased in the range of 7.4 to 8.0. The reason was that at low pH, the proton could be reduced easily at negative potential and the luminescence was inhibited. In addition, the strong oxidant $\text{SO}_4^{\bullet-}$ was consumed at high pH via the scavenging effect of OH^- .^{28,29} So, pH 7.4 was selected as the optimum pH value.

Figure 4B depicts the effect of $\text{K}_2\text{S}_2\text{O}_8$ concentration on ECL intensity. With the increasing of $\text{K}_2\text{S}_2\text{O}_8$ concentration from 20 to 55 mM, the ECL intensity increased significantly because more excited state of $\text{Ag}_2\text{Se}@Cd\text{Se}$ is produced. Further increase of $\text{K}_2\text{S}_2\text{O}_8$ concentration caused the decrease of ECL intensity, which is ascribed to that the excess $\text{S}_2\text{O}_8^{2-}$ would inhibit the producing of excited state of $\text{Ag}_2\text{Se}@Cd\text{Se}$.³⁰ Therefore, 55 mM was selected as the optimal $\text{K}_2\text{S}_2\text{O}_8$ concentration in this work.

ECL Response to CA72-4. Under the optimized conditions, the relationship between the ECL intensity and the CA72-4 concentrations was investigated. The results are shown in Figure 5. It is evident that the ECL intensity was very sensitive to CA72-4 in the range 10^{-4} –20 U/mL. The linear

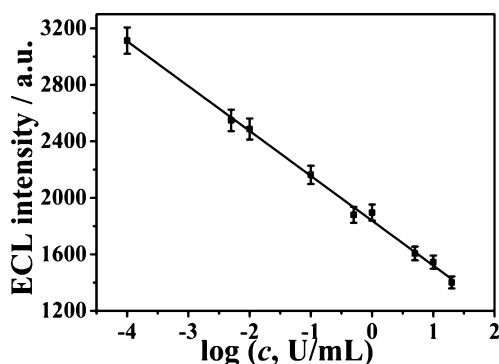


Figure 5. Calibration curve of the immunosensor for different concentrations of CA72-4. Error bar = RSD ($n = 3$).

regression equation was $I = 1838.10 - 317.65 \log c$ with a correlation coefficient of $r = 0.9963$. The detection limit was found to be 2.1×10^{-5} U/mL, which was calculated according to the IUPAC rules ($3S_B/K$, S_B is standard deviations of the blank ($n_B = 10$). K is the slope of the calibration curve line).³¹ Compared with the detection limit for time-resolved immunofluorometric assays (TR-IFMA) (0.55 U/mL),³² immunoradiometric assay (0.8 U/mL)³³ and electrochemical immunosensors (0.1 U/mL),³⁴ the proposed ECL immunosensor has a lower detection limit. The lower detection limit may be the result of two factors: (1) the excellent conductivity and catalytic activity of PPy-NH₂GO could greatly improve the ECL signal; (2) the large specific surface area of NH₂GO after functionalized by PPy could fix a large amount of Ag₂Se@CdSe.

Selectivity, Stability and Reproducibility of the ECL Immunosensor. The selectivity of the sensor for CA72-4 was tested via comparing the ECL response to 0.1 U/mL CA72-4 and 10 ng/mL IgG, IgA, IgM, glucose, BSA and ascorbic acid (VC), respectively. The results are shown in Figure 6A. It was obvious that the developed ECL immunosensor exhibited an excellent specificity to CA72-4.

As shown in Figure 6B, the stability of the immunosensor was examined under the continuous scanning for 19 cycles for the detection of CA72-4 (0.1 U/mL). The relative standard deviation (RSD) was 2.8%, indicating good stability. The reproducibility was also investigated by measuring five successive assays for detection of CA72-4 (0.1 U/mL). The RSD was 2.4%, indicating that the reproducibility of the ECL immunosensor was excellent.

Application. The immunosensor was used to detect the CA72-4 in human serum. The prepared spiked samples were detected by replacing CA72-4 standard samples as mentioned

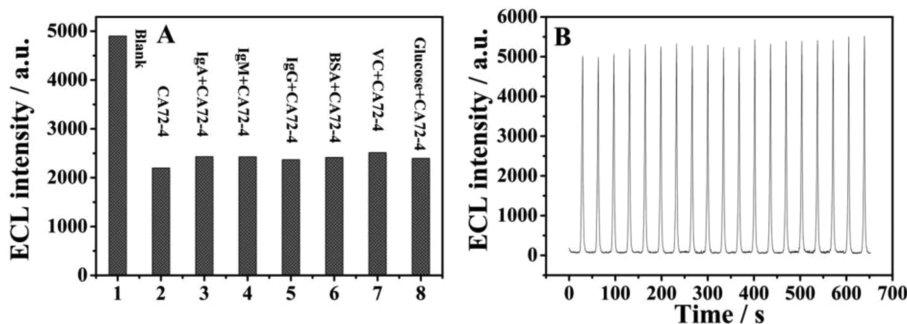


Figure 6. Selectivity (A) and stability (B) of the immunosensor measured in 10 mL PBS (pH 7.4) containing 55 mM K₂S₂O₈.

above. As shown in Table 1, the recovery of the proposed sensor range from 95.6% to 103.72%, indicating that the

Table 1. Recovery of CA72-4 in the Real Samples Using the Proposed ECL Immunosensor Measured in 10 mL of PBS (pH 7.4) Containing 55 mM K₂S₂O₈

spiked samples (U/mL)	measured amounts (U/mL)	RSD (%)	recovery (%)
1	0.956	3.88	95.6
3	2.932	1.99	97.73
5	5.186	1.19	103.72
10	10.305	0.91	103.05

developed ECL immunosensor modified by Ag₂Se@CdSe nanoneedles have the application potential in practical sample testing.

CONCLUSION

Ag₂Se@CdSe nanoneedles were first prepared by a one-pot method and could be used for fabricating ECL immunosensors. The sensors exhibited a strong and stable cathodic ECL signal in the presence of K₂S₂O₈. The ECL immunosensor modified with Ag₂Se@CdSe nanoneedles is easy to fabricate and exhibited acceptable accuracy, precision and good operational stability for the detection of CA72-4. Ag₂Se@CdSe could become a promising candidate material of ECL biosensors in the future.

ASSOCIATED CONTENT

Supporting Information

Photographs of nanocomposites solutions. This material is available free of charge via the Internet at <http://pubs.acs.org>.

AUTHOR INFORMATION

Corresponding Author

*Q. Wei. Tel.: +86 0531 82765730. Fax: +86 531 82765969. E-mail: sdjndxwq@163.com.

Notes

The authors declare no competing financial interest.

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