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### 1. Introduction

Cancer is the most common type of malignancy without obvious non-specific symptoms in the early stage of malignant tumors.<sup>1,2</sup> We are far from blocking the pace of cancer despite numerous progress achieved in cancer research over the years. However, early diagnosis of cancer can significantly improve the cure and survival rate.<sup>3,4</sup> Common cancer screening methods include genetic testing, imaging examination, endoscopy, pathological examination, and tumor marker detection.<sup>5</sup> Tumor marker detection is the most effective and potential means of detecting cancer at an early stage, which is mainly carried out *via* enzymatic examination. For example, liver cancer and lung cancer can be significantly screened by detecting alkaline phosphatase and glycoproteins, respectively. The occurrence of liver cancer and malignant teratoma can result in an increase in alpha-fetoprotein (AFP).<sup>6</sup> Lung, colorectal and breast cancer can

# A new Bi<sub>2</sub>MoO<sub>6</sub> nano-tremella-based electrochemical immunosensor for the sensitive detection of a carcinoembryonic antigen<sup>†</sup>

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By doping molybdenum (Mo) into bismuth oxide ( $Bi_2O_3$ ), we synthesized novel  $Bi_2MoO_6$  nanohybrids with a unique tremella-like crystal structure via a one-pot hydrothermal method. Such a porous tremella structure of  $Bi_2MoO_6$  possesses a significantly larger surface area than the spherical structure of  $Bi_2O_{3,0}$ which is favorable for the special functionalization and effective immobilization of molecules such as antibodies on the surface of the tremella flaps. As expected, Au nanoparticles grew easily and uniformly outside the surface of the flaps of the as-prepared Bi<sub>2</sub>MoO<sub>6</sub> NTs (Au@Bi<sub>2</sub>MoO<sub>6</sub> NTs), showing preferable conductivity and biocompatibility, and the anti-carcinoembryonic antigen (anti-CEA) was effectively immobilized outside the obtained  $Au@Bi_2MoO_6$  NTs. Acting as a novel label-free immunosensing platform, the anti-CEA-immobilized Au@Bi<sub>2</sub>MoO<sub>6</sub> NTs were used to fabricate an electrochemical immunosensor for the quantitative detection of CEA. The as-prepared Au@Bi<sub>2</sub>MoO<sub>6</sub>-based immunosensor linearly responded to CEA in a wide concentration range from 1 pg mL<sup>-1</sup> to 1  $\mu$ g mL<sup>-1</sup> with a detection limit calculated to be 0.3 pg mL<sup>-1</sup> (S/N = 3), significantly comparable to numerous existing immunosensors. Moreover, the minimum detection concentration of the designed immunosensor was about ten times smaller than that of many Bi and Mo-based sensors toward CEA detection, and the detection limit was lower, revealing higher sensitivity. The satisfactory selectivity and stability made the immunosensor potentially applicable for CEA detection in real samples.

> be diagnosed and evaluated early by detecting the concentration of carcinoembryonic antigen (CEA).<sup>7–10</sup> Therefore, the quick and sensitive detection of tumor markers is significantly important for the early diagnosis and treatment of cancer.

> In recent years, electrochemical immunosensors have received considerable attention due to their numerous advantages such as simplicity, sensitivity, and low cost.11 Voltammetric immunosensors usually use an electrolyte solution containing reversible redox species such as ferricyanide  $([Fe(CN)_6]^{3-/4-})$  for good reversible oxidation-reduction.<sup>12</sup> On the other hand, unlabeled voltammetric immunosensors are fabricated by dropping the redox substance on the electrode surface to bind the antibody through chemical bonds, thereby eliminating the direct contact of the electrode with the antibody.12 The key of this approach is the selection of the material modifying the electrode so as to accelerate electron transfer and amplify the signal. Therefore, numerous materials were chosen to improve the sensitivity of the immunosensor. For example, graphene oxide is widely used because of its low cost, large specific surface area, excellent mechanical properties, good electronic properties and excellent thermal properties.7,13-15 Apart from this, mesoporous silica (SiO<sub>2</sub>),<sup>16</sup> photoactive conducting poly(5-formylindole) nanocomposites,<sup>17</sup> magnetic nanomaterials (Fe<sub>2</sub>O<sub>3</sub>, Fe<sub>3</sub>O<sub>4</sub>, etc.),<sup>18,19</sup> ceria (CeO<sub>2</sub>),<sup>20</sup> cuprous

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oxide  $(Cu_2O)^{21}$  and platinum  $(Pt)^{22}$  are commonly used for electrode modification.

Usually, the materials with poor biocompatibility can inevitably cause toxicity, irritation, teratogenicity, and local inflammation of cells and the whole body, after undergoing a shortterm contact, while the long-term contact may exert mutagenic, teratogenic and even carcinogenic effects. Also, the transportation of such materials through blood may cause abnormal coagulation function and hemolysis. Therefore, biocompatibility is a significantly important indicator to be evaluated for materials used in biological applications, including biosensors.23,24 Until now, the application of bismuth (Bi)-based nanomaterials in biosensors has attracted increasing attention due to their good stability in nature and extremely low toxicity to the body. For instance, Han used the cerium-doped CdS-sensitized BiYWO<sub>6</sub> to detect tetracycline, reducing the detection limit to 0.01 ng mL<sup>-1</sup> with good stability.<sup>25</sup> Wu et al. developed a label-free photoelectrochemical (PEC) immunosensor based on CdS nanowires sensitized with a WO<sub>3</sub>@BiOI heterostructure for CEA detection with good stability and high sensitivity.26 An Ag ion-modified bismuth vanadate nanopolyhedron (BiVO<sub>4</sub>( $aAg^+$ ) was utilized as a label to immobilize anti-AFB1 through affinity specific binding.27 Among those Bibased materials, Bi2O3 is an important semiconductor material because of its narrow band-gap (about 2.8 eV), relatively high power and capacity, and electrochemical stability.<sup>28</sup> The Bi<sub>2</sub>O<sub>3</sub> nanoparticles (NPs) synthesized via a hot solvent method have good photocatalytic performance.<sup>29</sup> Also, polycrystalline Bi2O3 was used to construct a new nano-bio-based amperometric glucose biosensor,30 and Bi2O3 nanorods were produced to modify an indium-tin-oxide electrode for the quantitative detection of mycotoxin,31 revealing the good biocompatibility of  $Bi_2O_3$ . However, the conductivity of  $Bi_2O_3$  is not good enough and somehow limits its application in an electrochemical analysis. Moreover, molybdenum (Mo) containing nanomaterials have received considerable attention in recent years due to their good biocompatibility and high metallic-like electrical conductivity. The palladium NP-functionalized threedimensional wrinkly amorphous MoS<sub>x</sub> composites were used as an electrochemical immunosensing platform to determine insulin.32 The hierarchically 1D MoO2 particles exhibited remarkable electrocatalytic activity with good long-term cycle stability for the hydrogen evolution reaction (HER) in acidic media.33 An amino-functionalized coral-like MoS2@Cu2O hybrid with increased surface area and conductivity was used to amplify the signal.<sup>34</sup> Gao successfully developed Au@Pd/MoS<sub>2</sub>modified multi-walled carbon nanotubes (MWCNTs) to improve high specific surface area and good biocompatibility.35

Usually,  $Bi_2O_3$  shows a spherical or nanowire structure<sup>28,36</sup> with a relatively small specific surface area and low electron transfer rate, which is not favorable for the amplification of electrical signals, the effective immobilization of biomolecules and even the deposition of other NPs. In this study, Mo was doped into  $Bi_2O_3$  to prepare a Bi-based hybrid material  $(Bi_2MOO_6)$  *via* a one-pot hydrothermal method. As expected, the spherical structure of  $Bi_2O_3$  was changed to a porous tremella-like structure ( $Bi_2MOO_6$  NTs) with a large surface area by

incorporating Mo into  $Bi_2O_3$ , which is beneficial for the metal NPs to grow and the antibody to bind on the flap surface of the  $Bi_2MoO_6$  NTs specifically. By comparison, both the electron transfer and biocompatibility of  $Bi_2MoO_6$  NTs were significantly improved, which was favorable for the fabrication of an electrochemical immunosensor. As expected, Au NPs easily grew on the flaps of  $Bi_2MoO_6$  NTs (Au@Bi\_2MoO\_6 NTs), further enhancing the electron transfer performance and biocompatibility of the hybrid  $Bi_2MoO_6$  NTs. To the best of our knowledge, it is the first time to synthesize tremella-like  $Bi_2MoO_6$  nanohybrid and use it as an electrochemical immunosensing platform to detect CEA, where the excellent analytical performance was achieved toward CEA detection. Scheme 1 illustrates the preparation of the  $Bi_2MoO_6$  NT-based electrochemical immunosensor toward CEA detection.

### 2. Experimental

#### 2.1. Reagents

The antibody of CEA (anti-CEA), CEA, prostate-specific antigen (PSA), immunoglobulin G (IgG), albumin from bovine serum (BSA) and AFP were purchased from Shanghai Linc-Bio Science Co. Ltd (Shanghai, China). Barium nitrate pentahydrate  $(Bi(NO_3)_3 \cdot 5H_2O)$ , concentrated HNO<sub>3</sub> (65–68%), polyvinylpyrrolidone (PVP), NaOH (99.99%), ethylene glycol (EG, >99%). glutaraldehyde (GA), CTAB, potassium hexacyanoferrate( $\pi$ ) trihydrate (K<sub>4</sub>Fe(CN)<sub>6</sub>), potassium hexacyanoferrate(III) (K<sub>3</sub>Fe(CN)<sub>6</sub>), sodium borohydride (NaBH<sub>4</sub>), sodium citrate, chloroauric acid (HAuCl<sub>4</sub>), trisodium citrate dihvdrate  $(Na_{3}C_{6}H_{5}O_{7}\cdot 2H_{2}O),$ potassium chloroaurate (KAuCl<sub>4</sub>), ascorbic acid (AA), 3-aminopropyl)triethoxysilane (APTES), disodium phosphate (Na<sub>2</sub>HPO<sub>4</sub>) and sodium dihydrogen phosphate(NaH<sub>2</sub>PO<sub>4</sub>) were obtained from Aladdin Industrial Corporation (Shanghai, China). Molybdenum acetylacetonate ((MoO<sub>2</sub>(acac)<sub>2</sub>) was provided by Tansoole (Shanghai, China). All other chemicals were of analytical reagent grade and used without any further treatment. Deionized water and absolute ethanol were used throughout the experiment.

#### 2.2. Apparatus

Scanning electron microscopy (SEM) measurements were performed on an FEI QUANTA FEG250 coupled to an INCA Energy X-MAX-50. X-ray photoelectron spectroscopy (XPS) measurements were carried out using a single-color AlK $\alpha$  source with ESCALAB 250 XI. UV-Vis absorption spectra were recorded on a UV-Vis 1901 spectrophotometer (Phoenix). All electrochemical measurements were accomplished on a CHI660D workstation (Chenhua Instrument Shanghai Co., Ltd, China). X-ray diffraction (XRD) were obtained on a Rigaku Ultimate IV (Rigaku, Japan).

#### 2.3. Preparation of the Bi<sub>2</sub>O<sub>3</sub> nanocrystals

0.182 g of  $Bi(NO_3)_3 \cdot 5H_2O$  was dissolved in 5 mL 1.0 mol L<sup>-1</sup> HNO<sub>3</sub> solution, immediately followed by the addition of 0.064 g NaOH, 0.6 g PVP and 25 mL EG. The obtained solution was then transferred to a 50 mL Teflon reactor, which was sealed in



a stainless steel autoclave and heated at 150  $^\circ C$  for 3 h. The cooled solution was centrifuged at 10 000 rpm for 10 min to collect Bi\_2O\_3 NPs, which were then thoroughly washed and freeze-dried for use.<sup>36</sup>

#### 2.4. Preparation of the MoO<sub>2</sub> nanocrystals

Typically, 0.08 g MoO<sub>2</sub>(acac)<sub>2</sub> was gradually dissolved in 20 mL of a mixed solution containing absolute ethanol and 5 mL deionized water in a molar ratio of 3 : 1 under stirring. After stirring for 2 h, the solution was heated to 180 °C and kept for 10 h. Next, the solution was cooled to room temperature and then centrifuged to obtain the precipitate of MoO<sub>2</sub> nanocrystals, which was washed with ethanol several times and freeze-dried for subsequent use.<sup>37</sup>

#### 2.5. Preparation of the Bi<sub>2</sub>MoO<sub>6</sub> NTs

The Bi<sub>2</sub>MoO<sub>6</sub> NTs were prepared *via* a one-pot synthesis method. First, 0.05 g Bi  $(NO_3)_3 \cdot 5H_2O$  was dissolved in 20 mL absolute ethanol and stirred for 1 h. Then, 0.08 g MoO<sub>2</sub>(acac)<sub>2</sub> was added into the solution, followed by 1 h stirring. Next, 0.5 g CTAB was successively dissolved in the mixture. After stirring for 1 h, the solution was transferred into a Teflon-lined stainless-steel autoclave for 12 h at 160 °C. Bi<sub>2</sub>MoO<sub>6</sub> NTs were finally obtained by centrifuging the solution at 10 000 rpm for 10 min, which were then washed with ethanol and ultrapure water three times and dried in a drying oven at 60 °C for 8 h.

# 2.6. Amino functionalization of Bi<sub>2</sub>MoO<sub>6</sub> NTs and preparation of gold seeds

0.012 g Bi<sub>2</sub>MoO<sub>6</sub> NTs were dispersed into 30 mL absolute ethanol, followed by the addition of 1.0 mL of ATPES under stirring. After 3 h of stirring, the solution was refluxed at 70 °C for 1.5 h under stirring for the amino functionalization. Finally, the solution was centrifuged at 10 000 rpm for 5 min to collect the NH<sub>2</sub> group-functionalized Bi<sub>2</sub>MoO<sub>6</sub> NTs (Bi<sub>2</sub>MoO<sub>6</sub>–NH<sub>2</sub>), which were dispersed in 15 mL absolute ethanol for subsequent use.

A solution of gold seeds was prepared based on a previously reported method.<sup>38</sup> Briefly, 200  $\mu$ L of a 10 mM HAuCl<sub>4</sub> solution was added into 10 mL of deionized water, and 200  $\mu$ L of 10 mM trisodium citrate was then rapidly added in under stirring. 10 min later, 200  $\mu$ L of a 100 mM NaBH<sub>4</sub> solution was pipetted into the mixture, which was stirred for 30 min till the solution color changed to red.

#### 2.7. Modification of Bi<sub>2</sub>MoO<sub>6</sub> NTs with Au NPs

First, 1.0 mL of the above prepared  $Bi_2MOO_6-NH_2$  NTs was ultrasonically dispersed in 10 mL of absolute ethanol. Then, a 60 µL gold nanoseed-containing solution was subsequently added under stirring, immediately followed by the addition of a 300 µL 10 mM HAuCl<sub>4</sub> solution. Second, 300 µL of 10 mM sodium citrate was added into the mixed solution. After the solution was stirred for 5 min, 100 µL 0.1 M AA was pipetted into the mixed solution to allow the growth of Au NPs for 30 min.

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Finally, the resultant product was centrifuged repeatedly at 10 000 rpm for 10 min with ethanol. After being dried in an oven at 60 °C for 8 h, the final Au NP-modified  $Bi_2MoO_6$  NTs (Au@Bi\_2MoO\_6 NTs) were stored at room temperature for subsequent use. The schematic of the synthetic material is fully illustrated in Scheme 2.

#### 2.8. Immunoassay of CEA based on Au@Bi2MoO6 NTs

After the bare GCE was polished with 0.3 µm and 0.05 µm alumina slurry, respectively, and dried at room temperature, a certain amount of Au@Bi2MoO6 NTs was dropped onto the electrode surface. 0.2 mM GA (2.5%) was dropped on the Au@Bi<sub>2</sub>MoO<sub>6</sub> NT-modified GCE at 30 °C for 1 h as a cross-linker to connect anti-CEA. Afterward, 6  $\mu$ l of 75 ng mL<sup>-1</sup> anti-CEA was dropped on the surface of the functionalized electrode and incubated at 30 °C for 1 h, followed by washing with PBS and air-drying at 30 °C. Then, 6 µL BSA (1%) was pipetted on the surface of the anti-CEA immobilized electrode surface and incubated for 60 min to cover the inactive sites. After being washed with PBS and air-dried sequentially, the Au@Bi<sub>2</sub>MoO<sub>6</sub> NT-based electrochemical immunosensor was finally obtained and stored at 4 °C for CEA detection. Scheme 1 shows the fabrication of the Au@Bi2MoO6 NT-based immunosensor toward CEA detection.

#### 2.9. Electrochemical measurements

All the electrochemical measurements were carried out in the solution of PBS (pH = 6.5) containing 5 mM  $[Fe(CN)_6]^{3-/4-}$  and 0.1 M KCl through a three-electrode system using a differently modified glassy carbon electrode (GCE, d = 3 mm), a platinum wire and a silver/silver chloride (Ag/AgCl) as the working, auxiliary and reference electrodes, respectively. The cyclic voltammetries (CV) were obtained in the scanning potential range from -0.2 to 0.8 V at a sweep speed of 0.1 V s<sup>-1</sup>. The square wave voltammetry plots were performed in the scan range from 0.0 to 0.6 V. The electrochemical impedance spectroscopy (EIS) was

scanned from 0.01 to 100000 Hz (amplitude: 0.005 V, quiet time: 2 s). Before the detection, the as-prepared Au@Bi<sub>2</sub>MoO<sub>6</sub> NTbased immunosensor was incubated with CEA at different concentrations at 30 °C for 60 min. Right after the immune combination between anti-CEA and CEA, the electrodes were washed with PBS to remove the unbound CEA.

### 3. Results and discussion

# 3.1. Characterizations of $\mathrm{Bi}_2\mathrm{MoO}_6$ NTs and Au@Bi\_2MoO\_6 NTs

3.1.1 SEM and XRD analysis. By comparison, both Bi<sub>2</sub>O<sub>3</sub> and MoO<sub>2</sub> were synthesized, showing a spherical shape with a particle size of about 300 nm (Fig. 1A and B). After Mo and Bi were mixed to prepare the hybrid, the morphology of the hybrid changed greatly, from the original sphere to a tremella-like nanostructure (Fig. 1C and D, the inset is a photo of real tremella). Although the particle size (950-1000 nm) increased, the surface area of the obtained porous Bi2MoO6 NTs was greatly enlarged due to the formation of a tremella structure. The change in morphology indicated that the two elements were not simply mixed, but formed a nanohybrid. More importantly, such a porous tremella nanostructure is good for the further surface modification of Bi2MoO6. Fig. S2<sup>†</sup> shows the XRD patterns of the as-prepared Bi<sub>2</sub>MoO<sub>6</sub> and pure Bi<sub>2</sub>O<sub>3</sub>. The peaks from left to right correspond to (131), (002), (210), (212), (260), (331), (133) and (391) of Bi<sub>2</sub>MoO<sub>6</sub> (JCPDS no. 84-0787), a single orthorhombic crystal, confirming the successful preparation of the Bi<sub>2</sub>MoO<sub>6</sub> hybrid crystal. In addition, Au NPs with an average diameter of 50 nm were easily and uniformly decorated on the flap surface of Au@Bi<sub>2</sub>MoO<sub>6</sub> NTs as expected (Fig. 1E and F).

Moreover, the mapping analysis of  $Au@Bi_2MoO_6$  NTs indicated that the metals of Bi, Mo and Au were uniformly distributed throughout  $Au@Bi_2MoO_6$  NTs (Fig. 2), verifying the successful synthesis of the  $Bi_2MoO_6$  nanohybrid and the uniform distribution of Au NPs on the flap surface of  $Bi_2MoO_6$  NTs.



Scheme 2 The schematic for the synthesis of Au@Bi2MoO6 NTs.



Fig. 1 SEM images of (A) Bi<sub>2</sub>O<sub>3</sub>, (B) MoO<sub>2</sub>, (C and D) Bi<sub>2</sub>MoO<sub>6</sub>, and (E and F) Au@Bi<sub>2</sub>MoO<sub>6</sub> in different magnification scales.

3.1.2 XPS and UV characterizations. XPS was also performed to determine the elemental composition of the asprepared Au@Bi2MoO6 NTs, as shown in Fig. 3. The binding peaks of Mo, Bi, O and Au elements are observed in the survey spectrum (Fig. 3A), confirming their coexistence inside the Au@Bi<sub>2</sub>MoO<sub>6</sub> NTs. In the fitted spectrum of Mo3d (Fig. 3B), the two peaks at 235.05 eV and 235.1 eV correspond to the binding between Mo and O. The Bi-O bond is reflected by the presence of a binding peak at 164.15 eV and 158.85 eV, as shown in Fig. 3C, the fitted spectrum of Bi4f.<sup>39</sup> Also, the binding of O with both Bi and Mo was proved by the presence of a peak at 531.95 eV in the O1s fitted spectrum (Fig. 3E). All the results were indicative of the successful formation of Bi<sub>2</sub>MoO<sub>6</sub> NTs. In addition, in Fig. 3D, the Au4f spectrum represented the XPS signature of the Au4f doublet (4f<sup>5/2</sup> and  $4f^{7/2}$ ) at 87.00 eV and 83.35 eV, suggesting the presence of Au NPs in Bi<sub>2</sub>MoO<sub>6</sub> NTs. Fig. 3F shows the UV-vis absorption spectra of Bi<sub>2</sub>MoO<sub>6</sub> NTs before and after the modification of Au NPs. By comparison, a strong absorption peak at 570 nm is observed for Bi<sub>2</sub>MoO<sub>6</sub> NTs after Au NPs grew outside, further confirming the formation of Au NPs on Bi<sub>2</sub>MoO<sub>6</sub> NTs.

**3.1.3 Properties of electron transfer and biocompatibility.** Fig. 4A and B show the CV and EIS plots of bare GCE and GCEs modified with Bi<sub>2</sub>O<sub>3</sub>, MoO<sub>2</sub>, Bi<sub>2</sub>MoO<sub>6</sub> and Au@Bi<sub>2</sub>MoO<sub>6</sub> NTs, respectively. After the modification of  $Bi_2O_3$ , the current slightly decreased and the semi-circle clearly increased compared with the bare GCE, revealing the poor conductivity of  $Bi_2O_3$ . As expected, the incorporation of Mo into  $Bi_2O_3$  enhanced the electron transfer rate of  $Bi_2MOO_6$  NTs, indicating the good conductivity of  $Bi_2MOO_6$  NTs, which was likely caused by the lattice occupancy of Mo inside the  $Bi_2O_3$  crystal structure, and the decoration of Au NPs further improved the conductivity of  $Bi_2MOO_6$  NTs, preferred for the fabrication of the electrochemical immunosensor.

Both contact angle and toxicity toward 4T1 cells were tested to explore the hydrophilicity and biocompatibility of Au@Bi<sub>2</sub>-MoO<sub>6</sub> NTs (Fig. 4C and D). As shown in Fig. 4C, the initial contact angle of Au@Bi<sub>2</sub>MoO<sub>6</sub> NTs was 33.7–34.8°, showing favorable hydrophilicity. The modification of GA further reduced the contact angle to  $20.4-21.6^{\circ}$ , revealing better hydrophilicity, which is helpful for the immobilization of biomolecules, and the contact angle continued to decrease to  $14.3-15.1^{\circ}$  after the Au@Bi<sub>2</sub>MoO<sub>6</sub> NT-modified GCE was incubated with anti-CEA, revealing the successful immobilization of anti-CEA on Au@Bi<sub>2</sub>MoO<sub>6</sub> NTs.

Fig. 4D shows the cellular activity of the 4T1 cells treated with Au@Bi<sub>2</sub>MoO<sub>6</sub> NTs at different concentrations. Clearly, Au@Bi<sub>2</sub>MoO<sub>6</sub> NTs did not affect the viability of the 4T1 cells



ig. 2 The mapping analysis of (A) Au@Bi<sub>2</sub>MoO<sub>6</sub>; and elements of (B) Mo, (C) Bi and (D) Au.

even when the concentration of Au@Bi<sub>2</sub>MoO<sub>6</sub> NTs reached 200 ppm. These results indicate the high biocompatibility and low cytotoxicity of Au@Bi<sub>2</sub>MoO<sub>6</sub> NTs.

#### 3.2. Electrochemical behaviors of the Bi<sub>2</sub>MoO<sub>6</sub>@Au NTbased immunosensor

The CVs of the as-prepared Bi<sub>2</sub>MoO<sub>6</sub>@Au NT immunosensor were carried out in 5.0 mM  $[Fe(CN)_6]^{3^{-/4-}}$  containing 0.1 M KCl (pH = 6.5) at different scan rates to study the electrochemical process. As demonstrated in Fig. 5A, the peak current (*I*) was dependent on the scan rate: both the anodic and cathodic peak currents increased with the increase in the scan rate from 10 to 400 mV s<sup>-1</sup> and were directly proportional to the square root of the scan rate ( $\nu^{1/2}$ ), as shown in Fig. 5B, revealing that the electrochemical process of the as-prepared Bi<sub>2</sub>MoO<sub>6</sub>@Au NT-based immunosensor was controlled by diffusion.

DPV plots of differently modified GCEs were obtained to verify the successful layer-by-layer preparation (Fig. 5C). As can be seen, the Au@Bi<sub>2</sub>MoO<sub>6</sub> TN-modified GCE (curve a) shows the highest current peak, which decreased after Ab was immobilized (curve b). BSA was used to cover the non-specific site on the electrode surface, which led to a further current decrease (curve c). The incubation of Au@Bi<sub>2</sub>MoO<sub>6</sub>-Ab-BSA with CEA continuously reduced the current, confirming the successful immobilization of CEA (curve d). The decreased in current can be attributed to the deposited proteins, which may prevent the interfacial electron transfer and reduce the active sites accessible to ferricyanide,<sup>40</sup> verifying the successful layer-by-layer modification of biomolecules on the Au@Bi<sub>2</sub>MoO<sub>6</sub> NT-modified electrode. Fig. 5D compares the response signal of the Au@Bi<sub>2</sub>MoO<sub>6</sub> NT-based immunosensor before and after the immobilization of CEA. A sensitive response to CEA was observed using the as-prepared immunosensor.

#### 3.3. Analytical performance, reproducibility and selectivity

As discussed above, a label-free immunosensor was designed based on Au@Bi2MoO6 NTs that directly converted the competitive immune response into measurable electrochemical signals. In order to achieve the best analytical performance of the Au@Bi2MoO6 NT-based immunosensor toward CEA detection, the experimental conditions were well optimized, which included the concentration of Au@Bi2MoO6 NTs, the pH of PBS, the concentration of anti-CEA and the antibody-antigen reaction (see the ESI S2 and Fig. S2<sup>†</sup>). Under the optimal conditions, the analytical performance with SWV of the Au@Bi<sub>2</sub>MoO<sub>6</sub> NTbased immunosensor was examined toward CEA at different concentrations. As shown in Fig. 6A and B, the peak current was proportionally weakened as the concentration of CEA increased owing to the binding of more CEA molecules to anti-CEA on the electrode surface (Fig. 6A). A linear relationship between the peak current (*I*) and the logarithm of the CEA concentration (*c*) was achieved from 1 pg mL<sup>-1</sup> to 1000 ng mL<sup>-1</sup>, where an equation of  $I = 96.791 - 6.0913 \lg c$ , was obtained with the correlation coefficient and limit of detection (S/N = 3)





Fig. 3 XPS spectra of the  $Bi_2MoO_6$  NTs. (A) Survey spectrum of  $Bi_2MoO_6$  NTs and the fitted spectra of (B) Mo3d, (C) Bi4f, (D) Au4f, (E) O1s. (F) UV spectra of  $Bi_2MoO_6$  NTs and  $Au@Bi_2MoO_6$  NTs.

calculated to be 0.9976 and 0.3 pg mL<sup>-1</sup>, respectively (Fig. 6B). The concentration of CEA in healthy adults is usually below 2.5 ng mL<sup>-1</sup> and higher than 20 ng mL<sup>-1</sup> in bodies at risk of cancer. However, the concentration of CEA varies between cancers. For example, the low level of CEA in colon tissue was reported to be 2.5–5.0  $\mu$ g L<sup>-1</sup>, but could greatly increase in patients with liver cancer.<sup>7</sup> Even so, the detection range of the designed immunosensor was sufficient to support the CEA detection in samples of various cancers with good sensitivity.

In addition, Table 1 compares the analytical behaviors of the current  $Au@Bi_2MoO_6$  NT-based immunosensor with some other existing immunosensors toward CEA with respect to detection range and limit. The minimum detection concentration of the designed immunosensor was about ten times smaller than that of numerous existing immunosensors toward CEA detection, including Mo and Bi-based sensors, and the detection limit was lower, revealing higher sensitivity. Upon the comparison, a conclusion could be made that the  $Au@Bi_2MoO_6$  NT-based immunosensor showed more comparable advantages

in both detection range and detection limit, providing a promising alternative for CEA detection.

Five different electrodes were separately modified with  $Au@Bi_2MoO_6$  NTs to fabricate the immunosensor so as to evaluate the reproducibility. Fig. 6C shows the response of the five individually prepared immunosensors to 1.0 ng mL<sup>-1</sup> of CEA under the same conditions. It was found that no obvious difference in the peak current was observed among the five immunosensors with a relative standard deviation of 2.16%, revealing the satisfactory reproducibility of the designed Au@Bi\_2MoO\_6 NT-based immunosensor for CEA detection.

Moreover, IgG, PSA, AFP and BSA were selected to examine the specificity of the Au $(Bi_2MOO_6 NT)$ -based immunosensor for CEA detection (Fig. 6D). In the presence of each interferent at 100 ng mL<sup>-1</sup>, the fabricated immunosensor did not show a significantly different response to 1 ng mL<sup>-1</sup> CEA, and the detection behavior with the interfering substance present (100 fold higher) was not much different from that only with CEA, proving the satisfactory specificity of the present immunosensor, which is indicative of the preferable selectivity.



Fig. 4 (A) CV and (B) EIS plots of bare GCE and GCEs modified with  $Bi_2O_3$ ,  $Bi_2MoO_6$  and  $Au@Bi_2MoO_6$  NTs, respectively; (C) contact angles of  $Au@Bi_2MoO_6$  NTs,  $Au@Bi_2MoO_6$ -GA and  $Au@Bi_2MoO_6$ -GA-Ab; (D) cellular activity of 4T1 treated with  $Au@Bi_2MoO_6$  NTs at different concentrations.



**Fig. 5** (A) CVs of the proposed immunosensor at different scan rates (from outer to inner: 400, 300, 200, 100, 50, 20 and 10 mV s<sup>-1</sup>); (B) the linear relationship between the square root of the scan rate and peak current; (C) voltammetric plots of GCEs modified with (a)  $Au@Bi_2MOO_6 NTs$ , (b)  $Au@Bi_2MOO_6-Ab$ , (c)  $Au@Bi_2MOO_6-Ab-BSA$  and (d)  $Au@Bi_2MOO_6-Ab-BSA-CEA$ ; (D) DPV plots of  $Au@Bi_2MOO_6 NTs$  before and after the incubation of CEA.





Fig. 6 (A) Voltammetric responses and (B) the calibration curve of the  $Au@Bi_2MoO_6$  NT-based immunosensor to 0.001, 0.01, 0.05, 1, 10, 400 and 1000 ng mL<sup>-1</sup> CEA in the solution containing 5 mM  $[Fe(CN)_6]^{3-/4-}$  and 0.1 M KCl. (C) The reproducibility and (D) the specificity of the immunosensor.

**Table 1** Analytical performances of different electrochemical immunosensors toward CEA detection

Immunosensor	Linear range (ng mL <sup>-1</sup> )	Detection limit (pg mL <sup>-1</sup> )	Ref.
Cu-Au ND/CNT-CSs	0.025-25	0.5	41
3D-G/nDA/Con A	0.025 25	90	42
Co <sub>2</sub> (OH) <sub>2</sub> CO <sub>2</sub> -CeO <sub>2</sub>	0.002-75	0.51	43
Au-g-C <sub>3</sub> N <sub>4</sub> ·NHs	0.02-80	6.8	44
AuNP/TiO <sub>2</sub> -Gr/Thi/GCE	0.1-10.0	10	45
Au-PB-Fe <sub>3</sub> O <sub>4</sub>	0.01-80	4	46
AuNP/NBeERGO/GCE	0.001-40	0.45	7
AuNP/MWCNT/CS/GCE	0.3-2.5	10	47
MoS <sub>2</sub> nanosheets	0.1-100	34	48
Mo-Mn <sub>3</sub> O <sub>4</sub> /MWCNT/CS	0.1 - 125	4.9	8
I-BiOCl/CdS-10	0.01 - 40	2	49
Au@Bi <sub>2</sub> MoO <sub>6</sub> NTs	0.001 - 1000	0.3	This work

<sup>*a*</sup> CNTs: carbon nano-tube arrays; CSs: carbon spheres; 3D-G: 3D graphene; pDA: polydopamine; Con A: concanavalin A; NHs: nanohybrids; PB: Prussian blue; NB-ERGO: Nile blue A hybridized electrochemically reduced graphene oxide; MWCNTs: multiple-wall carbon nanotubes; CS: chitosan; CdS: cadmium sulfide.

## 4. Conclusions

In this study, we synthesized a novel  $Bi_2MoO_6$  nanohybrid with a tremella-like structure by doping Mo into  $Bi_2O_3$ . The combination of Bi with Mo led to the change of the morphology from sphere to tremella with a larger surface area and obvious enhancement in the conductivity due to the synergistic effects of Bi and Mo. After being decorated with Au NPs, both the conductivity and biocompatibility of the synthesized  $Au@Bi_2-MoO_6$  NTs were further improved, and thus used as an electrochemical immunosensing platform to detect CEA. The proposed immunosensor exhibited promising analytical performance toward CEA in a wide concentration range. The detection limit was comparable to that of other immunosensors for CEA detection. Moreover, both the specificity and the reproducibility of the immunosensor were qualified and superior to other materials in terms of biocompatibility, showing a great prospect in clinical CEA detection.

## Conflicts of interest

There is no conflict of interest in this work.

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