

**Application of metal oxide-carbon  
nanocomposites and metal-organic  
frameworks (MOFs) for highly sensitive  
electrochemical sensors**

**Weiwei Qiu**

**September, 2020**

**Shimane University, Japan**

Electrochemical sensor plays an important role in the research of analytical chemistry because of its sensitivity, rapidity, low cost, portable detection device, low energy consumption and easy miniaturization and integration. It has been applied in many fields, such as biomedicine, environmental protection, electrochemical catalysis, and so on. Recently, the functionalization of metal-oxide and MOFs had been attracted wide attention based on their excellent performance, and take part in the construction of electrochemical sensor is one of their most promising applications, their intervention provides a broad space for the development of electrochemical sensors in the direction of practicality, miniaturization, intelligence and multi-function, they can effectively realize the immobilization of biomolecules and chemical molecules, signal amplification, and high-throughput on-line real-time monitoring of the electrochemical sensor. Therefore, the application of the functional metal-oxide and MOFs provides a new strategy for the study of biomolecules and chemical molecules in the electrochemical sensing field.

**Chapter 1:** The brief introduce of electrochemistry; the functionalization of metal-oxide and MOFs were described. Moreover, some questions of the previous studies were pointed out and the significance and purpose of this study were stressed.

**Chapter 2:** The functionalization of metal-oxide and their application in electrochemical sensors.

2-1 Porous nanododecahedron of  $\text{Co}_3\text{O}_4/\text{C}$  nanocomposites was synthesized by calcination of the Co-based MOF (ZIF-67) in air at 400 °C and was used for fabricating a highly sensitive and low oxide potential nitrite ion ( $\text{NO}_2^-$ ) sensor. The structure and morphology characterization show that ZIF-67 behaves as an ideal sacrificial template and converted to  $\text{Co}_3\text{O}_4/\text{C}$  with regular shape. Electrochemical analysis shows that the excellent electrocatalysis performance toward the oxidation of  $\text{NO}_2^-$  based on the synergy of  $\text{Co}_3\text{O}_4$  and carbon in the nanocomposite. At  $\text{NO}_2^-$  concentration from 2 nM to 8 mM, a fast response time within 3 s is revealed and 1.21 nM of ultralow detection limit is achieved as the steady-state current signal linear increase. Using the nanocomposite acts as an electrochemical sensing material for determination of  $\text{NO}_2^-$  in the real samples, the results are satisfactory.

2-2 A thin nanosheet structure of  $\text{ZrO}_2/\text{C}$  was prepared using UiO-67 with a flat cuboid structure as precursor. The peculiar and fluffy structures endowed materials with high surface areas that tremendously improved the adsorption capacity of

electrode materials for heavy metal ions. Thus, ZrO<sub>2</sub>/C as an electrode material was used to simultaneous detection of Pb(II) and Cd(II) in 0.1 M HAc-NaAc buffer by differential pulse anodic stripping voltammetry (DPASV). Under the optimal conditions, the results showed that prepared sensor has the high sensitivity, good stability and low interference of the detection for two metal ions, and the limit detections for Pb(II) and Cd(II) of 0.007 μM and 0.019 μM were estimated, respectively. Furthermore, it was also successfully applied for the detection of trace Pb(II) and Cd(II) in real water samples with a satisfactory result.

2-3 The yolk-shell structured SnO<sub>2</sub>-C nanospheres have been prepared by a hydrothermal reaction of SnCl<sub>2</sub>·2H<sub>2</sub>O and glucose, followed by carbonization under 500 °C in air condition. Then an inorganic/organic hybrid film bearing SnO<sub>2</sub>-C and polytyrosine (pTyr) is fabricated by electro-polymerization of SnO<sub>2</sub>-C modified electrode in tyrosine solution. The modified electrode is utilized as a supporting platform for covalent immobilization of cauliflower mosaic virus 35s (CaMV35s) promoter gene fragments to construct an electrochemical DNA sensor. Chronocoulometric experiments show that the loading density of probe DNA (pDNA) and hybridization efficiency are determined to be as high as 4.54×10<sup>13</sup> strands cm<sup>-2</sup> and 83.2%, respectively. Upon hybridization with target DNA (tDNA), the probe DNA that lied flat on the electrode surface through hydrogen bonding with pTyr is erected, reducing the charge repulsion and steric hindrance for [Fe(CN)<sub>6</sub>]<sup>3-/4-</sup> diffusion. So a “signal-off” response strictly dependent on hybridization reaction is achieved in electrochemical impedance spectroscopy. The response mechanism is predicted by theoretical calculation. Owing to the high probe density and hybridization efficiency of the sensor, a wide kinetic linear ranging from 1.0 aM to 100 pM and an ultralow detection limit of 0.53 aM for target sequence are obtained. The biosensor also presents high recognition ability toward the DNA samples extracted from real transgenic and non-transgenic soybeans, showing great promising of the biosensor for facile monitoring of transgenic product.

**Chapter 3:** The functionalization of metal-organic frameworks (MOFs) and their application in electrochemical sensors

3-1 A flexible metal-organic framework (MOF) of Cu<sub>2</sub>(*trans*-1,4-cyclohexanedicarboxylic acid)<sub>2</sub> (Cu<sub>2</sub>(CHDC)<sub>2</sub>) has been synthesized by a facile hydrothermal method. The physical characterization experiments show that the

$\text{Cu}_2(\text{CHDC})_2$  presents unique flower-like shape, large surface area and high electroactivity. Then gold nanoparticles (AuNPs)/ $\text{Cu}_2(\text{CHDC})_2$  modified electrode was prepared and utilized as an electroactive matrix for thrombin aptamer immobilization. The electrochemical assay shows that the AuNPs can effectively enhance the electrochemical signal of the  $\text{Cu}_2(\text{CHDC})_2$ . Upon the binding of the electrode-confined aptamer with the thrombin, the electrochemical signal of the  $\text{Cu}_2(\text{CHDC})_2$  decreases obviously due to the change of the microenvironment of the sensing interface. Thus a label-free electrochemical sensing strategy for thrombin was realized. The aptasensor displays excellent performance with wide linear range, ultralow detection limit of 0.01 fM (S/N=3), and favorable specificity. Also, the aptasensor was applied for determination of thrombin in the human serum samples, and the satisfactory results are obtained. The results imply that the proposed sensor can be potentially used for the early diagnosis of disease and clinical monitoring.

3-2 Direct, strong and specific coordination between  $\text{Zr}^{4+}$  and phosphate group ( $-\text{PO}_4^{3-}$ ) provides new avenue to construct Zr-MOF-based high-performance electrochemical biosensors. In this work, a rational, sensitive and reusable electrochemical aptasensing strategy for Ochratoxin A (OTA) was proposed using *in-situ* coordination-assembled UiO-66 as signal amplification platform in the design, the OTA aptamer was pre-hybridized with supporting strands that immobilized on the gold electrode surface. Then the classic Zr-MOF of UiO-66 was *in-situ* immobilized on the terminal of OTA aptamer through coordination between  $\text{Zr}^{4+}$  and  $5'-\text{PO}_4^{3-}$  modified on OTA aptamer. Furthermore, the signal probe with electroactive tag of methylene blue was *in-situ* assembled on UiO-66 also by the Zr-O-P bond. Because of large surface area and rich active sites of  $\text{Zr}^{4+}$ , the comparative assay shows that the UiO-66 greatly enhances the analytical performance of the aptasensor. A wide range from 0.1 fM to 2.0  $\mu\text{M}$  and an ultralow detection limit of 0.079 fM (S/N = 3) for target OTA were achieved. In addition, because the aptasensor was designed on the basis of the auxiliary strand-based competitive binding strategy, 11 times reusability of the aptasensor can be realized in accompany with the detection process. The aptasensor can also be applied for detection of OTA in the red wine sample, demonstrating a promising prospect of the biosensor for food safety monitoring.

**Chapter 4:** Conclusions and scope of these studies were described.