Two-dimensional nanomaterials for sensing applications

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TWO-DIMENSIONAL NANOMATERIALS FOR SENSING APPLICATIONS

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SCHOOL OF MATERIALS SCIENCE AND ENGINEERING

2018

TWO-DIMENSIONAL NANOMATERIALS FOR SENSING APPLICATIONS

HUANG YING

SCHOOL OF MATERIALS SCIENCE AND ENGINEERING

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Doctor of Philosophy

2018

Statement of Originality

I hereby certify that the work embodied in this thesis is the result of original research and has not been submitted for a higher degree to any other University or Institution.

12-JAN-2018

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Date

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Abstract

Two-dimensional (2D) nanomaterials have recently received increasing research interest because of their intriguing structures and properties. Particularly, 2D metal-organic framework (MOF) and covalent-organic framework (COF) nanosheets are emerging members in the 2D family. The ability to prepare 2D MOF and COF nanosheets is paramount to study their unique properties and potential applications. However, it is still in its infancy. Therefore, my thesis aims to prepare novel ultrathin 2D MOF and COF nanosheet as well as 2D MOF-based composite nanosheets and explore their properties and potential applications in sensors. To this end, the following work has been done.

First, a series of 2D metalloporphyrinic MOF (Cu-TCPP(M), TCPP=tetrakis(4-carboxyphenyl)porphyrin, M=Fe, Co, and Mn) nanosheets with thickness of sub-10 nm were prepared by surfactant-assisted synthetic method, where metalloporphyrins (TCPP(Fe), TCPP(Co), and TCPP(Mn)) were used as ligands and Cu paddle-wheel units were employed as nodes. The obtained 2D MOF nanosheets could act as artificial enzyme, exhibiting excellent peroxidase-like activity. In light of this, Cu-TCPP(Fe) nanosheets were developed as the sensing platform to fabricate colorimetric sensor for the sensitive detection of glucose in serum samples.

Second, 2D MOF-based composite nanosheets (Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co)) were prepared by using 2D Cu-TCPP(Fe) and Cu-TCPP(Co) nanosheets as templates, where Au NPs with small size were grown. Since the obtained Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets had the peroxidase-like activity and glucose oxidase-like activity, they were utilized for mimicking nature multi-enzyme system, achieving the artificial enzyme cascade reaction. Furthermore, Au NP/Cu-TCPP(Fe) composite nanosheets were used as the sensing platform to construct colorimetric sensor for biomolecular detection.

Last, novel 2D imine-linked COF (TPA-COF) nanosheets were prepared by selecting two flexible building units with C_{3v} molecular symmetry. The obtained bulk TPA-COF with a

hexagonal layered structure and sheet-like morphology was easily exfoliated into ultrathin 2D TPA-COF nanosheets, as the bulk TPA-COF has the weak interlayer π - π stacking interaction. The pore channels and individual building units of TPA-COF nanosheet were visualized by using low-dose TEM technique. Moreover, the exfoliated TPA-COF nanosheets were applied as the efficient fluorescence sensing platform for sensitive and selective detection of DNA.

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Abbreviations

0D	Zero-Dimensional
1D	One-Dimensional
2D	Two-Dimensional
3D	Three-Dimensional
ABTS	2,2'-Azino-bis(3-ethylbenzothiazoline-6-sulphonic acid)
AFM	Atomic Force Microscopy
BET	Brunauer-Emmett-Teller
BHT	Benzenhexathiol
BIM	Benzimidazole
BN	Boron Nitride
BPs	Black Phosphorus
BTB	Benzene-1,3,5-tribenzoate
BTPB	1,3,5-Tri(4-phenylboronic acid)benzene
COFs	Covalent-Organic Frameworks
CTAB	Hexadecyltrimethylammonium bromide
CV	Cyclic Voltammetry
DMF	N,N-Dimethylformamide
DMS	2,2-Dimethylsuccinate
DRS	Diffuse Reflectance Spectroscopy
DPV	Differential Pulse Voltammetry
FET	Field-Effect Transistor
EIS	Electrochemical Impedance Spectroscopy
FT-IR	Fourier Transform Infrared
g-C ₃ N ₄	Graphite Carbon Nitride
GOx	Glucose Oxidase
HCR	Hybridization Chain Reaction
HHTP	2,3,6,7,10,11-Hexahydroxtripheylene
HRP	Horseradish Peroxidase

HRTEM	High Resolution Transmission Electron Microscopy
IN	Isonicotinato
MOFs	Metal-Organic Frameworks
NCs	Nanoclusters
NPs	Nanoparticles
o-DCB	1,2-Dichlorobenzene
OPD	o-Phenylenediamine
PVP	Polyvinylpyrrolidone
PY	Pyridine
SAED	Selected Area Electron Diffraction
SEM	Scanning Electron Microscopy
SERS	Surface-Enhanced Raman Scattering
SPR	Surface Plasmon Resonance
SWV	Square Wave Voltammetry
TA	Terephthalic Acid
TAPA	Tris(4-aminophenyl)amine
TCPP	Tetrakis(4-carboxyphenyl)porphyrin
TEM	Transmission Electron Microscopy
TFPA	Tris(4-formylphenyl)amine
TGA	Thermogravimetric Analysis
THB	Pyrogallol
THT	1,2,5,6,9,10-Triphenylenehexathiol
TMB	3,3',5,5'-Tetramethylbenzidine
TMDs	Transition Metal Dichalcogenides
TNP	2,4,6-Trinitrophenol
XRD	X-Ray Diffraction
XPS	X-Ray Photoelectron Spectroscopy

Chapter 1

Introduction

In this chapter, the general introduction and the outline of this whole thesis are described. Based on the previous efforts to prepare ultrathin 2D nanomaterials, it is anticipated that new ultrathin 2D nanomaterials could be prepared and used to study new property as well as develop the sensing platform for detection of various analytes. Such hypotheses guide the content of this thesis. Based on the hypotheses, three objectives of this thesis are presented. First, a series of 2D metalloporphyrinic MOF nanosheets with peroxidase-like activities are to be prepared by surfactant-assisted method and used as the sensing platform to fabricate colorimetric sensor. Second, 2D metalloporphyrinic MOF-based composite nanosheets with peroxidase-like activities and glucose oxidase-like activities are to be prepared and used for fabrication of colorimetric sensor. Third, novel 2D imine-linked COF nanosheets with good stability are to be prepared and used for development of fluorescent sensor. In addition, the findings and outcomes of this thesis are depicted.

1.1 Hypothesis/Problem Statement

Two-dimensional (2D) nanomaterials, including boron nitride (BN), graphene, and transition metal dichalcogenides (TMDs), and so on, have aroused extensive attention in recent years because of their unique structures and properties as well as great applications. As an emerging member of the family of 2D nanomaterials, 2D metal-organic frameworks (MOFs) have now become one of the hottest research topics owing to their fascinating properties, such as ultrathin thickness, large surface area and numerous accessible active sites. Moreover, like their bulk counterparts, 2D MOFs with novel functions can be designed by introducing selected ligands and metal centers. Moreover, the research of 2D MOFs is still in its infancy. As known, metalloporphyrins with a great deal of biological functions have a wide variety of applications. However, they always suffer from catalytic deactivation due to the suicidal self-oxidation. The hypothesis here is that metalloporphyrins may be arranged to form 2D layered MOFs with large specific surface area, tremendous active sites and good water stability, which may protect the metalloporphyrins and produce highly efficient biomimetic catalysis as well as have potential in biosensor application.

2D MOF nanosheets with large surface area and structural tunability have drawn increasing research interest, driven by their broad spectrum of potential applications in gas separation, energy conversion, energy storage, catalysis, sensing, and drug delivery. The feature of 2D MOF nanosheets render them very promising as the material platform to fabricate composites. It should be noted that 2D MOF-based composite nanosheets have enhanced properties and new functionalities superior to those of individual components. In particular, 2D metalloporphyrinic MOF nanosheets have intriguing biomimetic catalysis, which can mimic natural enzyme. However, 2D metalloporphyrinic MOF nanosheets only mimic one kind of enzymes. As known, in nature, many enzymes work together, in which the product of one enzyme is the substrate of the other. The hypothesis here is that integration 2D metalloporphyrinic MOF nanosheets with other nanomaterials may mimic multiple functions of natural multi-enzyme systems, which may have potential in biosensor application.

Since the discovery of graphene, many efforts have been devoted to the development of other new 2D nanomaterials. Very recently, 2D covalent-organic frameworks (COFs) with large surface area, diverse functionality and chemical stability have been regarded as an emerging member in the family of 2D nanomaterials. Their unique properties make them ideal candidates for chemical sensing, antimicrobial coatings and cathode materials. Currently, 2D COF nanosheets are obtained directly from their bulk counterparts, such as solvent-assisted sonication exfoliation, self-exfoliation and mechanical exfoliation. However, the yield of the obtained 2D COF nanosheets is quite low, which is due to the strong interlayer interactions. The hypothesis here is that integration flexible building units into COF skeletons may decrease the interlayer interaction, leading to easy exfoliation of bulk COF into ultrathin 2D COF nanosheets, which may be expected to apply in biosensors.

1.2 Objectives and Scope

According to the aforementioned hypotheses, the following are my objectives and scope.

First, a series of free-standing ultrathin 2D MOF nanosheets (Cu-TCPP(M), TCPP=tetrakis(4-carboxyphenyl)porphyrin, M=Fe, Co, and Mn) will be prepared by surfactant-assisted synthetic method, where metalloporphyrins (TCPP(Fe), TCPP(Co), and TCPP(Mn)) and Cu paddle-wheel units will be employed as ligands and nodes, respectively. The obtained 2D MOF nanosheets will be measured by XRD, SEM, TEM, AFM, and XPS. The biomimetic catalytic activity of the as-prepared 2D MOF nanosheets will be investigated and the potential application of 2D MOF nanosheets as sensing platform for colorimetric detection of glucose in serum samples will be explored.

Second, 2D MOF-based composite nanosheets will be prepared by wet-chemical method, where Cu-TCPP(Fe) and Cu-TCPP(Co) will be selected as templates for growth of Au NPs. The obtained composites will be measured by TEM and XPS. The artificial enzyme cascade reaction will be investigated using 2D MOF-based composite nanosheets as

mimic enzymes. Moreover, the as-prepared composite nanosheets will be used to develop colorimetric sensor for biomolecular detection.

Last, a novel 2D imine-linked COF (TPA-COF) will be prepared by selecting two flexible organic ligands with C_{3v} molecular symmetry (TAPA: Tris(4-aminophenyl)amine and TFPA: Tris(4-formylphenyl)amine). The obtained bulk TPA-COF will be used to produce ultrathin 2D TPA-COF nanosheets by solvent-assisted exfoliation method. XRD, FT-IR, SEM, TEM and AFM will be used to characterize the exfoliated TPA-COF nanosheets. In addition, the potential application of the obtained TPA-COF nanosheets as fluorescent sensing platform for detection DNA would be explored.

1.3 Dissertation Overview

The thesis addresses how to prepare ultrathin MOF and COF nanosheets as well as 2D MOF-based composite nanosheets and how to characterize the obtained nanosheets by using useful techniques. In addition, the thesis also addresses how to design 2D MOF and COF according to their potential application. Finally, the thesis addresses how to explore their properties and potential applications in biosensors.

Chapter 1 provides a rationale for the research and outlines the goals and scope.

Chapter 2 reviews the literature concerning the recent advances on the design of 2D MOF and COF, synthesis of 2D MOF and COF nanosheets as well as 2D MOF-based composite nanosheets, and sensing application of 2D MOF and COF nanosheets.

Chapter 3 discusses the rational design and selection for methods and materials, the preparation, the characterization techniques applied, and the possible application of 2D MOF and COF nanosheets as well as 2D MOF-based composite nanosheets.

Chapter 4 elaborates the preparation and characterization of ultrathin 2D metalloporphyrinic MOF nanosheets (Cu-TCPP(Fe), Cu-TCPP(Co), and Cu-TCPP(Mn)),

the study of the biomimetic catalytic activity of the obtained 2D MOF nanosheets, and the utilization of Cu-TCPP(Fe) nanosheets as sensing platform for colorimetric detection of glucose.

Chapter 5 elaborates the preparation and characterization of 2D metalloporphyrinic MOF-based composite nanosheets, including Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co), the investigation of the biomimetic cascade reaction of the obtained composite nanosheets, and the utilization of the Au NP/Cu-TCPP(Fe) for biomolecular detection.

Chapter 6 elaborates the preparation and characterization of 2D TPA-COF nanosheets and the utilization of the obtained COF nanosheets as sensing platform to fabricate fluorescent sensor for detection of DNA.

Chapter 7 draws together the threads of this thesis, summarizes the whole thesis, and elaborates some relative future work that can be done.

1.4 Findings and Outcomes/Originality

This research leads to the following novel outcomes:

1. Surfactant-assisted synthetic method is an effective method to prepare ultrathin 2D MOF nanosheets with new properties and functions. By designing and choosing metalloporphyrin as ligand and $\text{Cu}_2(\text{COO})_4$ paddle-wheel as metal node, ultrathin 2D metalloporphyrinic MOF nanosheets have been prepared by surfactant-assisted synthesis. The obtained ultrathin 2D MOF nanosheets have biomimetic catalytic activities, which are better than those of bulk counterparts. In addition, the as-prepared Cu-TCPP(Fe) nanosheets are used as nanoplatform to construct colorimetric sensor for glucose detection in the presence of glucose oxidase (GOx). The colorimetric sensor shows excellent sensitivity and good selectivity. Furthermore, the proposed sensor is used for the detection of glucose in serum samples.

2. The ultrathin 2D metalloporphyrinic MOF nanosheets can be utilized as a new kind of template for growth Au NPs to prepare composites (Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co)), which show novel properties and functions better than those of individual components. The obtained composites combine the peroxidase-like activity of 2D metalloporphyrinic MOF nanosheets and the glucose oxidase (GOx)-like activity of Au NPs, achieving an artificial enzymatic cascade reaction to mimic the natural dual enzyme system. Moreover, the Au NP/Cu-TCPP(Fe) composite nanosheets can be used to detect biomolecule, such as glucose.

3. The preparation of 2D TPA-COF can be achieved by elaborately designing and choosing flexible building units with C_{3v} molecular symmetry. The obtained TPA-COF can be easily exfoliated into 2D TPA-COF nanosheets via simple solvent-assisted exfoliation method due to the weak interlayer interaction. Importantly, the clearly pore channels and individual building units in the 2D TPA-COF nanosheets can be visualized using low-dose imaging technique of TEM. The as-prepared TPA-COF nanosheets show excellent fluorescence quenching ability, thus it can be used to develop fluorescent DNA sensor with excellent sensitivity and good selectivity.

Chapter 2

Literature Review

This chapter aims at providing the recent advances in synthesis and sensing application of 2D MOF and COF nanosheets as well as 2D MOF nanosheet-based composites. First, the general information of 2D MOF and COF nanosheets is introduced. Second, the synthetic methods to prepare 2D MOF and COF nanosheets are summarized. Third, 2D MOF nanosheet-based composites are described. Fourth, the sensing applications of 2D MOF nanosheets and 2D MOF nanosheet-based composites as well as 2D COF nanosheets are presented. Last, the questions are discussed based on literature summarized and context of this thesis are presented.

2.1 Overview

The discovery of graphene has aroused the increasing interest on exploring other 2D nanomaterials, including Transition metal dichalcogenides (TMDs),^[1] graphitic carbon nitride (g-C₃N₄),^[2] black phosphorus (BPs),^[3] and so on.^[4-6] Compared with zero-dimensional (0D) nanoparticles, one-dimensional (1D) nanowires and three-dimensional (3D) networks, 2D nanosheets have ultrathin thickness and high surface area as well as many highly accessible active sites, making them promising in a broad spectrum of applications including sensing, catalysis, gas separation, electronic devices, energy storage, and biomedicine.^[7] These outstanding applications have also driven the synthesis of different kinds of 2D MOF and COF nanosheets. Up to now, the synthesis and application of 2D MOF and COF nanosheets are still in their infancy. Top-down and bottom-up methods have been used for preparation of 2D MOF and COF nanosheets. 2D MOF and COF nanosheets have been explored for gas adsorption, gas separation, catalysis, sensing, energy storage, and drug delivery because of their unique properties.

2.1.1 The general information of 2D MOFs and COFs

MOFs, as a class of crystalline porous materials, consist of inorganic metal ions or clusters linked by organic ligand molecules to form crystalline frameworks.^[8] The crystal structures and properties as well as functions of MOFs can be finely tailored by changing organic ligands, metal ions or clusters, and the coordination modes. It should be noted that MOFs not only form 3D structures but also form 2D structures. For 2D MOFs, their synthesis depends on the ligand symmetry and coordination mode between ligands and metal ions or clusters.^[9] As shown in Figure 2.1a, a hexagonal, square or triangular ordered 2D network can be assembled by designing organic ligands with three-, four- and six-fold symmetry, and metal ions or clusters with a connecting point. In addition, 2D MOFs can also be designed by choosing linear ligand molecules with two-fold symmetry and metal components with three- or four-fold symmetry (Figure 2.1b). It is worth pointing out that coordination bond formation between ligands and metal ions or clusters plays an important role in forming nanosheets with good quality and most of the reported

2D MOF nanosheets exhibit layered structures.^[9]

Figure 2.1 Schematic illustrations of (a) a metal ion or cluster, organic ligand molecules with three-, four- and six-fold symmetry and (b) metal ions or clusters with three- and four-fold symmetry and a linear ligand. (a and b) Reproduced with permission.^[9] Copyright 2017, Royal Society of Chemistry.

COFs, a class of crystalline porous materials, are constructed from organic building units connected by reversible covalent bonds to form highly ordered 2D or 3D networks.^[10] The structure of COFs relies on the geometry and dimension of the organic units. Therefore, the properties and functions of COFs can be tuned by alternating the organic building units and covalent linkage topology schemes. For 2D COFs, the organic building units are covalently integrated into 2D atomic layers, which further stack via van der Waals interaction to crystallize bulk layered structures with periodically aligned channels parallel to stacking direction.^[11] As illustrated in Figure 2.2, the self-condensation of C_2 -symmetric units can lead to 2D hexagonal COFs. In addition, 2D hexagonal COFs can also be obtained by choosing two C_3 -symmetric organic building units or combining C_3 -symmetric organic building units and C_2 -symmetric organic building units. Furthermore, the combination of C_4 -symmetric organic building units and C_2 -symmetric organic building units can generate 2D tetragonal COFs, which can be used to design a large

variety of π -conjugated COFs different from hexagonal COFs.^[11] Therefore, this molecular designability makes 2D COFs ideal as novel material platform with tunable structures and functions.

Figure 2.2 Schematic illustration of geometry of building units classified into different reactive groups. Reproduced with permission.^[11] Copyright 2012, Royal Society of Chemistry.

2.1.2 The synthesis of 2D MOF and COF nanosheets

As known, the synthesis of novel 2D MOF and COF nanosheets with desired size, thickness and composition plays a vital role for exploration of various properties and potential applications. Generally, two methods, namely, top-down method and bottom-up method, have been used to prepare 2D MOF and COF nanosheets.^[12] Top-down methods rely on the exfoliation of bulk MOFs and COFs into nanosheets, including mechanical delamination, sonication-assisted liquid exfoliation, shear force-assisted liquid exfoliation, self-exfoliation, intercalation-assisted liquid exfoliation, and sequential post-synthetic modification. As layered bulk MOFs and COFs have strong in-plane coordination bonds or covalent bonds and weak interlayer interactions (e.g., van der Waals forces), top-down methods are the effective ways to break the interactions between layers. Different from top-down methods, bottom-up methods are more versatile. A great deal of 2D MOF and COF nanosheets could be synthesized by choosing various precursors and using bottom-up methods. Compared with top-down methods, bottom-up methods could be used for synthesis of 2D MOF and COF nanosheets with high yield and

large scale. Importantly, it needs to restrict the growth of 2D MOF and COF nanosheets along the vertical direction in the bottom-up methods. Generally, bottom-up methods include liquid/air or liquid/liquid interface method, three-layer method, and surfactant-assisted method.

Top-down method. Layered bulk 2D MOF crystals can be exfoliated into ultrathin 2D MOF nanosheets using sonication-assisted liquid method, because each layer of the layered bulk 2D MOF crystals is stacked by using weak van der Waals forces and an intensive tensile stress generated from sonication can break the weak interlayer interaction.^[4] Similar to sonication-assisted liquid exfoliation of graphene and other 2D nanomaterials,^[13] it is noteworthy that good matching of surface energy between the layered bulk 2D MOF crystals and solvents is of crucial importance for achieving efficient exfoliation. The first example for exfoliation of bulk 2D MOF crystals into thin layers of sheets was reported by Zamora et al.^[14] In their experiment, bulk crystals of $[\text{Cu}_2\text{Br}(\text{IN})_2]_n$ (IN=isonicotinato) were first prepared by employing isonicotinic acid, CuBr_2 , KBr and KOH as precursors. Figure 2.3a shows the structure of single-layer framework. One copper dimer is connected by a bromine ligand and two carboxylate-bonded isonicotinato ligands as well as two N-coordinated isonicotinato ligands. Each layer is stacked along the a axis to form the bulk crystal (Figure 2.3b). Then, the single atomic layer of $[\text{Cu}_2\text{Br}(\text{IN})_2]_n$ was successfully prepared by sonication of bulk crystal in water, and characterized by atomic force microscopy (AFM). Figure 2.3c depicts that the $[\text{Cu}_2\text{Br}(\text{IN})_2]_n$ nanosheets are deposited on the surface of highly oriented pyrolytic graphitic (HOPG) substrate and the thickness of the as-prepared 2D nanosheets is $5 \pm 0.15 \text{ \AA}$ consistent with the theoretical thickness of monolayer of $[\text{Cu}_2\text{Br}(\text{IN})_2]_n$. Besides water, several other solvents have been utilized for exfoliation of layered bulk 2D MOFs into 2D MOF nanosheets, such as acetone,^[15] methanol,^[16] ethanol,^[17] N,N-dimethylformamide (DMF),^[18] and isopropyl alcohol (IPA).^[19]

Alternatively, a soft-physical exfoliation method combining ball-milling and sonication is another efficient method for exfoliation of layered bulk MOF crystals. As a representational example, Yang et al. demonstrated the synthesis of ultrathin $\text{Zn}_2(\text{bim})_4$

(bim=benzimidazole) nanosheets by ball-milling and sonication of bulk $\text{Zn}_2(\text{bim})_4$ crystals in a mixture of methanol and propanol.^[20] Figure 2.3d displays the structure of $\text{Zn}_2(\text{bim})_4$. Within each layer, each Zn ion connects with four ligands in a distorted tetrahedral configuration and each ligand links two Zn atoms by a bis-monodentate fashion. The bulk $\text{Zn}_2(\text{bim})_4$ crystal was formed by stacking different layer together through van der Waals interactions (Figure 2.3e). Transmission electron microscopy (TEM), AFM, and selected-area electron diffraction (SAED) pattern were utilized to characterize the morphology, thickness, and crystal structure of the obtained $\text{Zn}_2(\text{bim})_4$ nanosheets (Figure 2.3f-i). The results indicated the ultrathin nature of the exfoliated nanosheet with thickness of 1.12 nm. This method can also be used for preparation of $\text{Zn}_2(\text{bim})_3$ nanosheets.^[21]

Figure 2.3 (a,b) Crystal structure of $[\text{Cu}_2\text{Br}(\text{IN}_2)]_n$. (c) AFM image of $[\text{Cu}_2\text{Br}(\text{IN}_2)]_n$ nanosheets. Inset: The height cross-section measured along the green line. (a-c) Reproduced with permission.^[14] Copyright 2010, Royal Society of Chemistry. (d,e) Crystal structure of $\text{Zn}_2(\text{bim})_4$. (f) AFM image and height profile of $\text{Zn}_2(\text{bim})_4$ nanosheets. (g) TEM image and the photograph of Tyndall effect of $\text{Zn}_2(\text{bim})_4$ nanosheets. (h) TEM image of a typical $\text{Zn}_2(\text{bim})_4$ nanosheet. (i) Top: TEM image of $\text{Zn}_2(\text{bim})_4$ nanosheet. Bottom: SAED pattern of $\text{Zn}_2(\text{bim})_4$. (d-i) Reproduced with permission.^[20] Copyright 2014, American Association for the Advancement of Science.

Besides the aforementioned top-down methods, shear force-assisted liquid exfoliation method is also efficient for exfoliation of layered bulk $\text{Ni}_8(5\text{-bbdc})_6(\mu\text{-OH})_4$ crystals into 2D nanosheets.^[22] Bulk $\text{Ni}_8(5\text{-bbdc})_6(\mu\text{-OH})_4$ crystals were dispersed in hexane, frozen in liquid nitrogen bath, and then thawed in hot water bath. The 2D nanosheets were obtained by repeating the freeze-thaw cycles. In this case, the shear force comes from volumetric change of hexane between liquid phase and solid phase. In addition, intercalation-assisted liquid exfoliation method is another promising way for fabrication of ultrathin 2D MOF nanosheets from layered bulk MOF crystals. For instance, 4,4'-dipyridyl disulfide can be intercalated into layered porphyrin MOF crystals by coordination bonding with metal nodes, and then the obtained intercalated compound can be easily exfoliated into free-standing MOF nanosheets by selective cleavage of the disulfide bond using trimethylphosphine.^[23]

Similar to 2D MOF nanosheets, 2D COF nanosheets can be obtained by exfoliation of bulk COF crystals using sonication-assisted exfoliation method. Berlanga et al. proved the sonication-assisted exfoliation of bulk 2D COF crystals.^[24] It is the first example for preparation of COF nanosheets. Bulk COF-8 crystals were synthesized by condensation reaction of 2,3,6,7,10,11-hexahydroxytriphenylene (HHTP) and 1,3,5-tri[4-phenylboronic acid]benzene (BTPB). After that, 2D COF nanosheets with thickness of 4-10 nm were obtained by sonicating COF-8 crystals in CH_2Cl_2 . However, COF nanosheets with boronate-ester linkages displayed poor hydrolytic and oxidative stability, which have driven the exploration of stable 2D COF nanosheets. Bearing this in mind, bulk 2D hydrazone-linked COF-43 with excellent chemical and thermal stability was prepared under solvothermal conditions by condensation reaction of 2,5-diethoxyterephthalohydrazide with 1,3,5-tris(4-formylphenyl)benzene, which was then exfoliated into ultrathin 2D COF nanosheets by sonicating or directly immersing in dioxane or H_2O (Figure 2.4a).^[25] Other solvents, such as IPA^[26], DMF^[27] and toluene^[28], have been utilized for exfoliation of bulk 2D COF crystals.

Apart from sonication-assisted exfoliation method, a simple, safe, and eco-friendly mechanical delamination approach has been successfully used for exfoliation of bulk 2D

COF crystals into ultrathin nanosheets. Mechanical delamination can be divided into two categories: mechanical grinding and ball milling. Banerjee and coworkers demonstrated the successful exfoliation of a series of thermally and chemically stable bulk 2D COF crystals into ultrathin 2D COF nanosheets by mechanical grinding approach (Figure 2.4b).^[29] Bulk 2D COFs with high thermal and chemical stability, including TpPa-1, TpPa-2, TpPa-NO₂, TpPa-F₄, TpBD, and so on, were prepared by using Schiff-base condensation reaction. These COFs were exfoliated into few-layer COF nanosheets using a simple mechanical grinding route, and then the as-prepared COF nanosheets were characterized by TEM, AFM, XRD and FT-IR. The results confirmed that COF nanosheets exhibited sheet-like morphology and structural integrity after delamination as well as good stability in water, acidic and basic solution similar to their bulk counterparts. Very recently, a redox-active anthraquinone based COF nanosheets with thickness of 5 nm were obtained by ball milling of bulk DAAQ-TFP-COF crystals.^[30]

Figure 2.4 (a) Schematic representation of the exfoliation of bulk COF-43 into COF-43 nanosheets by sonication-assisted liquid exfoliation method. Reproduced with permission.^[25] Copyright 2013, American Chemical Society. (b) Schematic representation of the mechanical delamination of bulk COF into COF nanosheets. Reproduced with permission.^[29] Copyright 2013, American Chemical Society.

Although sonication-assisted liquid exfoliation method and mechanical delamination have many advantages, such as easy operation and high efficiency, there are still several disadvantages that would restrict the practical application of 2D COF nanosheets. Therefore, many efforts have been devoted to the development of other top-down method, such as self-exfoliation and post-synthetic modification. The key point of these methods is to weaken π - π stacking between layers. Bearing this in mind, Banerjee et al. rationally designed and synthesized guanidinium halide based ionic COF, in which positive charge of guanidinium was sandwiched by two halide ions layers, disturbing the π - π stacking interactions between adjacent layers in bulk COF crystals.^[31] Self-exfoliation of the synthesized ionic COF crystals into ultrathin COF nanosheets in water was realized due to the weak π - π stacking. In addition, post-synthetic modifications could also weaken the π - π stacking to exfoliation of bulk 2D COF crystals into ultrathin COF nanosheets. For example, N-hexylmaleimide molecules were incorporated into anthracene-based 2D COF (DaTp) crystals through [4+2] cycloaddition reactions, resulting in the exfoliation of bulk DaTp into DaTp nanosheets.^[32] Very recently, TpASH COF with hydroxyl group has been elaborately designed and synthesized by salt-mediated Schiff-base condensation. The hydroxyl group could be utilized for further post-synthetic modification to obtain functionalized TpASH COF nanosheets.^[33]

Bottom-up method. Bottom-up method is used to synthesize 2D MOF nanosheets by directly assembling metal ions and ligands at proper experimental conditions. The key factor of this bottom-up method is to limit the perpendicular growth of MOFs. Bearing this in mind, various synthetic methods are applied to limit the perpendicular growth of MOFs, such as liquid/liquid interfacial synthesis, gas/liquid interfacial synthetic method, three-layer synthetic method, surfactant or molecule-assisted synthetic method, and kinetically controlled synthetic method. For the interfacial synthesis, the liquid/liquid interfacial synthesis is used to produce multi-layered MOF nanosheets (Figure 2.5a), while gas/liquid interfacial synthesis is suitable for creating single- or few-layered MOF nanosheets (Figure 2.5b,c). In a typical process, liquid/liquid interfacial synthesis means that an aqueous solution of metal ion lays on an organic solution including ligands to form liquid/liquid interface. For air/liquid interfacial synthesis, a small amount of organic

solution containing ligands is gently dropped onto the surface of metal ion solution. Air/liquid interfacial synthesis in a Langmuir-Blodgett trough can also be used to prepare densely packed single- or few-layer nanosheets, in which the aqueous solution of metal ions fill in the trough and then a small amount of ligands in organic solvent is spread on the surface of metal ions solution.^[9]

Figure 2.5 Schematic representations of (a) liquid/liquid interfacial method, (b,c) gas/liquid interfacial method for preparation of MOF nanosheets. (a-c) Reproduced with permission.^[9] Copyright 2017, Royal Society of Chemistry.

Up to now, many 2D MOF nanosheets have been synthesized by using the interfacial method, such as a series of NAFS,^[34-37] nickel bis(dithiolene),^[38] THTNi (THT=1,2,5,6,9,10-triphenylenehexathiol),^[39] cobalt bis(dithiolene),^[40] CuBDC,^[41] ZnBDC,^[41] Cu(1,4-NDC) (NDC=naphthalenedicarboxylate),^[41] Fe-(py)₂Ni(CN)₄

(py=pyridine),^[42] bis(terpyridine)zinc(II),^[43] bis(dipyrrinato)zinc(II),^[44] and porphyrin-hybridized bis(dipyrrinato)zinc(II).^[45] Taking nickel bis(dithiolene) as an example, single- or few-layer nickel bis(dithiolene) MOF nanosheets could be synthesized through the air/liquid interfacial method.^[38] An ethyl acetate solution containing benzenehexathiol (BHT) was gently dropped on the nickel(II) acetate and NaBr solution surface by using microsyringe. The nickel bis(dithiolene) nanosheets were obtained after the evaporation of ethyl acetate and then transferred onto HOPG (Figure 2.6a). As displayed in Figure 2.6b,c, the sheet-like structure is clearly observed on the surface of bare HOPG in an AFM phase image and the thickness of as-prepared nickel bis(dithiolene) nanosheets is 0.6 nm as well as the smooth surface is shown in AFM topological image.

Figure 2.6 (a) Schematic representation of the gas/liquid interfacial synthesis of nickel bis(dithiolene) nanosheets. (b) AFM phase image of nickel bis(dithiolene) nanosheets with its cross-sectional analysis for red line. (c) AFM image of a nickel bis(dithiolene) nanosheet. Inset: The height cross-section measured along the white line. (a-c) Reproduced with permission.^[38] Copyright 2013, American Chemical Society.

Although interfacial method was well established for many 2D MOF nanosheets, it is hard to prepare large-scale production of 2D MOF nanosheets due to the limited interface

area. Bearing this in mind, a three-layer synthetic method was developed for high-yield production of 2D CuBDC MOF nanosheets.^[46] Figure 2.7a shows the scheme of three-layer method, in which the volume ratios of DMF and acetonitrile in the top layer, middle layer and bottom layer are 1:2, 1:1, and 2:1, respectively. The top layer contains $\text{Cu}(\text{NO}_3)_2$ and bottom layer contains BDC ligand. When Cu^{2+} and BDC ligand slowly diffuse into the middle layer, CuBDC MOF nanosheets are formed in the highly diluted middle layer and then precipitate under gravity, avoiding the over-growth. Figure 2.7b describes the structure of CuBDC MOF, where Cu^{II} dimer is linked by BDC ligands. The square structure of nanosheets with size of 0.5–4 μm and thicknesses of 5–25 nm was proved by AFM and SEM (Figure 2.7c,d). It should be noted that this method can also be extended to synthesize other 2D MOF nanosheets, including 2D ZnBDC MOF nanosheets, 2D CoBDC MOF nanosheets, 2D Cu(1,4-NDC) MOF nanosheets and 2D Cu(2,6-NDC) MOF nanosheets.

Figure 2.7 (a) Schematic representation of three-layer method for preparation of CuBDC nanosheets. (b) Crystal structure of CuBDC. (c) AFM image of CuBDC nanosheets with height profiles measured along the blue and red lines. (d) SEM image of CuBDC nanosheets. (a-d) Reproduced with permission.^[46] Copyright 2015, Nature Publishing Group.

Recently, our group have demonstrated that the surfactant-assisted synthetic method could be used for preparation of ultrathin 2D MOF nanosheets.^[47] Surfactant is the key

factor for preparation of 2D MOF nanosheets, because it reduces the surface energy and controls the vertical growth of MOFs as well as inhibits the aggregation of the obtained MOF nanosheets. Taking Zn-TCPP MOF as an example, as shown in Figure 2.8, the traditional method is just used to prepare bulk Zn-TCPP MOF without the help of surfactant. Compared with traditional method, the surfactant-assisted synthetic method can be used for preparation of ultrathin Zn-TCPP MOF nanosheets. The surfactant, such as poly(vinylpyrrolidone) (PVP), can attach on the Zn-TCPP MOF surface to restrict their vertical growth and stabilize the obtained Zn-TCPP MOF nanosheets. Besides Zn-TCPP MOF nanosheets, other MOF nanosheets, including Co-TCPP, Cu-TCPP, Cd-TCPP, and Zn-TCPP(Fe), could also be prepared by using the same method.

Figure 2.8 Schematic illustrations of the different methods for preparation of Zn-TCPP MOF. Reproduced with permission.^[47] Copyright 2015, Wiley-VCH.

Apart from surfactant, small molecules, including pyridine, formic acid, trimethylamine, etc., facilitate the growth of 2D MOF nanosheets, such as $[\text{Cu}_2(\text{ndc})_2(\text{dabco})]_n$ nanosheets,^[48] $\text{Hf}_6\text{O}_4(\text{OH})_4-(\text{HCO}_2)_6(\text{BTB})_2$ (BTB=benzene-1,3,5-tribenzoate) nanosheets,^[49] HfBTE (BTE=4,4',4''-(benzene-1,3,5-triyl-tris(ethyne-2,1-diyl))tribenzoic acid)) nanosheets,^[50] Zr-TCBPE (TCBPE=4',4'',4''',4''''-(ethane-1,1,2,2-tetrayl)tetrakis([1,1'-biphenyl]-4-carboxylic acid)) nanosheets,^[51] and NiCo-UMOF nanosheets.^[52] The role of small molecule is similar to surfactant, which is used to weaken surface energy, stabilize the MOF nanosheets and restrict the growth of MOF along the vertical direction. In addition, kinetically controlled synthesis method has also

been utilized for preparation of NUS-8(Zr) and NUS-8(Hf) nanosheets with a thickness in the range from 10 nm to 20 nm and highly exposed Lewis acid sites.^[53] The reason is due to fast nucleation and precipitation of intermediate under the heterogeneous modulated hydrothermal conditions. Furthermore, combining top-down and bottom-up methods can also be employed for synthesis of MOF nanosheets, such as UiO-67 nanosheets,^[54] and MOP nanosheets.^[55]

Different from 2D MOF nanosheets, it is difficult to prepare 2D COF nanosheets by using bottom-up synthetic methods due to the strong π - π stacking between adjacent layers. Up to now, only a few literatures have been reported to prepare single- or few-layer COFs by bottom-up methods, including surface-mediated synthesis, interfacial synthesis and microwave irradiation method. For surface-mediated synthesis, it means that designed organic building units are deposited onto a substrate, followed by heating or placing under high/low vacuum to activate the covalent-bond formation for growth of single- or few-layer COFs. In this method, substrates play a significant role in the growth of single-layer COFs, which not only offer an ideal interface to template the covalent reaction in 2D but also promote the ordering of ligands on surface based on epitaxial effects. As known, metal,^[56] HOPG^[57] and graphene^[58,59] have been used as substrates for growth of single-layer COF, and scanning tunneling microscope (STM) and AFM are used to characterize the molecular structures, defects and domain sizes of the obtained single-layer COFs.^[60] However, the low throughput and strong coupling with substrates are the disadvantages of this method, which inspires the synthesis of COF nanosheets by other bottom-up techniques.

Alternatively, interfacial synthesis is another representative bottom-up approach for preparation of 2D COF nanosheets. As a representational example, Zhang et al. reported the design and preparation of 2D COF nanosheets at the air/water interface.^[61] Figure 2.9a indicates that the imine-link 2D COF nanosheets is prepared from two aromatic building blocks (terephthalaldehyde and 1,3,5-trihexyl-2,4,6-tris(4-aminophenyl)benzene). A dilute solution of the two aromatic building blocks in chloroform was diffused on the surface of water on the Langmuir-Blodgett trough, leading to the formation of

homogeneous COF nanosheets. Optical microscopy, SEM and AFM (Figure 2.9b-e) indicated that the obtained 2D COF nanosheets with sizes in the range of several hundred nanometers to several micrometers were monolayer with thickness of about 0.7 nm. In addition, very recently, microwave irradiation method has been developed to synthesize viologen-based conjugated COF nanosheets with several layers thickness.^[62] It is worth mentioning that microwave irradiation not only prompted the reaction rates but also enhanced the crystallinity of products.

Figure 2.9 (a) Synthesis of polyimine network. (b) Optical microscopy image of polyimine nanosheets. (c) SEM image of polyimine nanosheets. (d) AFM image of polyimine nanosheet. (e) The corresponding height profiles of polyimine nanosheet. (a-e) Reproduced with permission.^[61] Copyright 2016, Wiley-VCH.

2.1.3 2D MOF nanosheet-based composites

The feature of 2D MOF nanosheets has inspired research on the preparation of 2D MOF nanosheet-based composites. 2D MOF nanosheets can be considered as a template for growth of other materials. On the other hand, integration of 2D MOF nanosheets with other nanomaterials can obtain new properties and functions, better than that of single component. To date, noble metal,^[63,64] metal nanocluster,^[65] metal disulfide,^[66] metal hydroxide,^[67] carbon nanomaterial^[16] and MXene^[68] have been integrated into 2D MOF nanosheets, leading to form 2D MOF nanosheet-based composites. The obtained composites combine the advantages of both nanomaterials, which may improve the performance or achieve new application.

Figure 2.10 (a) Schematic representation of preparation of 2D MOF-based composite. (b) TEM image of CuS/Cu-TCPP composite. (c) HRTEM image of CuS nanoparticle. (d) EDS element mapping of CuS/Cu-TCPP composite. (a-d) Reproduced with permission.^[66] Copyright 2016, Wiley-VCH.

Taking CuS/CuTCPP as an example, as shown in Figure 2.10a, CuS/Cu-TCPP composite nanosheets are synthesized through the simple sulfidation reaction, in which metal ions from Cu-TCPP nanosheets react with sulfide ions from thioacetamide to in-situ form CuS on the Cu-TCPP nanosheet surface.^[66] The obtained composite nanosheets were characterized by TEM, SAED pattern and EDS mapping, indicating that some CuS nanoparticles were grown on the Cu-TCPP nanosheet surface and the crystal structure of Cu-TCPP nanosheets was unchanged (Figure 2.10b-d). In addition, CdS/Cd-TCPP and CoS/Co-TCPP composite nanosheets can also be synthesized using the similar method.

2.1.4 The sensing applications of 2D MOF and COF nanosheets

The 2D MOF and COF nanosheets have intriguing and tailorable properties, making them ideal candidates in a broad spectrum of applications, including catalysis, gas separation, gas absorption, energy storage and conversion, sensing and biomedicine.^[69,70] To date, their applications in these fields are still at their early stage, especially for sensors. Many efforts have been devoted to the development of the sensing application of 2D MOF and COF nanosheets due to their physicochemical and structural versatility. They can be used as sensing platform for the development of optical sensors. In addition, they can also be used as electrochemical materials for electrochemical sensors and biosensors.

Optical sensors. Optical sensors, with facile, efficient, and sensitive features, have been paid great attention for a long time in analytical chemistry, which can be utilized for detection of various targets based on the measurement of change of light intensity, lifetime and polarization.^[71] The main techniques used in optical sensors are photoluminescence, reflectance, scattering, diffraction, absorbance and chemiluminescence. Based on these techniques, different fluorescent, colorimetric, chemiluminescence, surface-enhanced Raman scattering (SERS) and surface plasmon resonance (SPR) sensors have been developed. For fluorescence sensors, similar to other 2D nanomaterials, 2D MOF nanosheets, with no or negligible fluorescence emission, large surface area and ultrathin thickness, can be considered as efficient fluorescence

quenchers towards fluorescent dyes. Their fluorescence quenching efficiency is higher than that of their bulk counterparts, which is due to the fact that the high specific surface area from the ultrathin dimension renders 2D MOF nanosheets sufficient interaction with fluorescent dye molecules. Based on this property, 2D MOF nanosheets have been used as sensing platform for the development of fluorescent sensors to detect various analytes, such as DNA,^[47] microRNA,^[72] and adenosine.^[73] Usually, they are “turn-on” fluorescent sensors. Taking DNA as example, the principle is shown in Figure 2.11. When the dye-labeled single-stranded DNA (ssDNA) is mixed with 2D MOF nanosheets, the dye-labeled ssDNA is absorbed onto the 2D MOF nanosheet surface caused by the van der Waals interaction, leading to fluorescence quenching of the dye via photoinduced electron transfer (PET) or fluorescence resonance energy transfer (FRET). However, when the complementary target DNA hybridizes with the dye-labeled ssDNA to generate double-stranded DNA (dsDNA), the obtained dsDNA releases from the 2D MOF nanosheet surface owing to the weak interaction between dsDNA and 2D MOF nanosheets caused by the rigidity of double-chain structures, and then the fluorescence of dye is recovered. According to this principle, it is suitable for quantitative detection of target DNA. This principle can also extend to detect multiple-target DNA by using different dye-labeled ssDNA in the same solution. Up to now, different 2D MOF nanosheets, including Cu-TCPP nanosheets, MnDMS (DMS=2,2-dimethylsuccinate) nanosheets and MOF-Ln nanosheets have been used as sensing platform for detection of biomolecules.^[47,72,73] Among them, MOF-Ln nanosheets exhibit interesting fluorescence quenching ability different from other 2D MOF nanosheets, making them ideal for two-color sensing platform. In this case, MOF-Ln nanosheets show different interaction between positive charged dye (e.g. TAMRA) and negative charged dye (e.g. AFM). When TAMRA-labeled ssDNA and FAM-labeled ssDNA were mixed with MOF-Ln nanosheets, the fluorescence intensity of TAMRA and FAM decreased rapidly. However, when TAMRA-labeled ssDNA was hybridized with target DNA to generate dsDNA, the fluorescence was recovered, and the intensity increased with increment of the concentration of target DNA (Figure 2.12a). When FAM-labeled ssDNA was hybridized with target DNA, the fluorescence of FAM was further quenched, and the fluorescence intensity decreased with increment of the concentration of target DNA (Figure 2.12b).

This phenomenon was different from previous work, due to the charge transfer from the FAM to the Ln^{3+} ions. FAM-labeled dsDNA could substitute the adsorbed HPO_4^{2-} ions on the edge of MOF-Ln nanosheets and re-adsorb on the positively charged edge of MOF-Ln nanosheets, making the charge transfer from FAM to Ln^{3+} ions easier. But for TAMRA-labeled dsDNA, the positively charged TAMRA could not substitute the adsorbed HPO_4^{2-} . As a result, the TAMRA-labeled dsDNA would release from the MOF-Ln nanosheets surface, leading to the recovery of fluorescence.

Figure 2.11 Schematic representation of fluorescent DNA sensor based on 2D MOF nanosheets. Reproduced with permission.^[47] Copyright 2015, Wiley-VCH.

Figure 2.12 (a) Top: Visible fluorescence changes of TAMRA-P1 irradiated under 365 nm light. Bottom: Fluorescence emission spectra of TAMRA-P1 with different concentrations of T in the presence of MOF-La nanosheets. (b) Top: Visible fluorescence changes of FAM-P1 irradiated under 365 nm light. Bottom: Fluorescence emission spectra of FAM-P1 with different concentrations of T in the presence of MOF-La nanosheets. (a and b) Reproduced with permission.^[73] Copyright 2017, Nature Publishing Group.

In addition, similar to the other morphology of MOFs, 2D MOF nanosheets also are composed of metal ions or clusters and organic ligands. Normally, when organic ligands with fluorescent properties connect with d^{10} metal ions (e.g., Zn(II) and Cd(II)), the fabricated 2D MOF nanosheets would retain the fluorescent properties originated from the organic ligands. On the basis of this point, many 2D MOF nanosheets can emit strong fluorescence, which was widely used as fluorescence probe for detection of different molecules, such as metal ions,^[19] nitroaromatic explosives,^[74] and ethylamine.^[75] Taking $\text{Ti}_2(\text{HDOBDC})_2(\text{H}_2\text{DOBDC})$ MOF nanosheets as example, these 2D MOF nanosheets were prepared by sonicated-assisted method, which exhibited excellent luminescence compared with their bulk counterparts. They could be used for detection of Fe^{3+} ions with fast response and low detection limit. The response mechanism was attribute to electron transfer between Fe^{3+} and MOF nanosheets.^[19]

More interesting, like bulk MOFs, 2D MOF nanosheets also have nanoscale porosity, which could be utilized as host to confine guest, making them ideal candidates for various applications. Bearing this in mind, Tan and co-workers reported that the 1D pore channels of OX-1 sheets were used for encapsulation of luminescent ZnQ (zinc(II) bis(8-hydroxyquinoline)) to form new photoactive “guest@host” composite. The obtained composite was used to fabricate optochemical sensing for detection of volatile organic compounds (VOCs).^[76] For example, upon exposure to different solvents including methanol, ethanol, IPA, acetonitrile, acetone, 1,4-dioxane, DMF and N,N-dimethylacetamide (DMA), the fluorescence of the obtained composite was fully quenched by methanol due to the proton-induced charge transfer of ZnQ guests in protic solvents. Besides ZnQ, AlQ (Al-(tris-8-hydroxyquinoline)), naphthalene, and fluorescein could be integrated into the pore of OX-1 nanosheets, leading to tunable composite nanosheets sensitive to coupled optoelectronic and chemical perturbations. It is worth pointing out that there is no report in the literature on other optical sensing application of 2D MOF nanosheets, such as colorimetric sensor and SERS sensor.

Figure 2.13 (a) Schematic illustration of electron transfer from picrate to PI-COF nanosheets. (b) Selectivity of PI-COF nanosheet-based fluorescent sensor. (a and b) Reproduced with permission.^[77] Copyright 2017, American Chemical Society.

2D COF nanosheets are assembled from organic ligands through covalent bonding. Thus, 2D COF nanosheets with fluorescence properties can be prepared by choosing suitable organic ligands. This feature of 2D COF nanosheets makes them ideal for fabrication of fluorescent sensors for detection of different molecules. However, it is still in its infancy. Only nitroaromatic analytes were detected by using 2D COF nanosheets as fluorescence probes. As a typical example, Benerjee et al. demonstrated that high luminescence of TfpBDH COF nanosheets displayed a turn-off detection for 2,4,6-trinitrophenol (TNP) in dispersion state and a turn-on detection for TNP in solid state.^[26] Importantly, compared with bulk TfpBDH COFs, 2D TfpBDH COF nanosheets showed enhanced luminescence and improved performance, because nanosheets could facilitate electron transfer between highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO) energy levels compared with bulk counterparts. Very recently, PI-COF nanosheets with high fluorescent feature were synthesized by covalent condensation of tetra(4-aminophenyl) porphyrin and perylenetetracarboxylic dianhydride, followed by sonicated-assisted liquid exfoliation. The obtained PI-COF nanosheets had electron rich benzene ring, electron-deficient imide structure as well as excellent fluorescent properties, which could be utilized to fabricate a fluorescence sensor for detection of TNP.^[77] The mechanism for detection of TNP is shown in Figure 2.13a, the HOMO energy level of TNP is higher than the LUMO energy level of PI-COF nanosheets, which

could make ground-state electron transfer from TNP to PI-COF nanosheets possible, resulting in the fluorescent quenching of PI-COF nanosheets. In addition, this sensor showed excellent selectivity for detection of TNP over other nitroaromatics (Figure 2.13b).

Electrochemical sensors and biosensors. Electrochemical sensors and biosensors have been widely used for detection of a broad range of targets owing to their easy-to-fabrication, low cost, high sensitivity and selectivity as well as portability. The mechanism of electrochemical sensors is based on the electron transfer between working electrode coated electrochemical active material and target suspended in electrolyte solution.^[78] Similar to electrochemical sensors, electrochemical biosensors are based on the electron transfer between bio-recognition elements immobilized on electrodes and target molecules. Bio-recognition elements, as transducers, are enzymes, antibodies, nucleic acids, hormones and tissues.^[79] Normally, the main electroanalytical techniques employed for electrochemical sensors and biosensors are cyclic voltammetry (CV), amperometry, potentiometry, square wave voltammetry (SWV), differential pulse voltammetry (DPV), and electrochemical impedance spectroscopy (EIS). The performances of electrochemical sensors and biosensors are characterized by various parameters, including sensitivity, selectivity, response time and stability. To improve the performance of electrochemical sensors and biosensors, electrode materials with high conductivity, large surface area, biocompatibility, unique target binding characteristics and high electrochemical activity need to be explored. To this end, nanomaterials have been widely investigated, showing great potential of enhanced performance for electrochemical sensors and biosensors owing to their good electrical conductivity, superior electrochemical properties and high surface to volume ratios.^[80] Encouraged by the successful application of graphene and other 2D nanomaterials in electrochemical sensors and biosensors, researchers have devoted to exploring 2D MOF nanosheets used in this field. As known, 2D MOF nanosheets have diverse structures, which can be designed by selecting suitable metal cations, organic ligands or structure motifs. Therefore, 2D MOF nanosheets, used as sensing materials in electrochemical sensors and biosensors, can be designed according to the corresponding target molecules. Taking Co-

TCPP(Fe) nanosheets as example, TCPP(Fe) ligand has the similar structure to heme. In addition, TCPP(Fe) ligand is the cofactor of diverse heme proteins, such as horseradish peroxidase (HRP), catalase, hemoglobin (Hb), cytochrome c (Cyt), and myoglobin (Mb). Integration of TCPP(Fe) into 2D MOF can retain the catalytic activity and stability of TCPP(Fe).^[81] Therefore, Co-TCPP(Fe) nanosheets were synthesized and then assembled as thin films on the surface of electrodes by a Langmuir-Schäfer method (Figure 2.14a). The fabricated electrodes exhibited catalytic activity towards the reduction of H_2O_2 and were used for quantitative detection of H_2O_2 via amperometric method (Figure 2.14b). The modified electrode showed a high sensitivity of $35.4 \mu\text{A cm}^{-2}$ with a linear range of $0.4\text{--}50 \mu\text{M}$ and the detection limit of $0.15 \mu\text{M}$. In addition, as shown in Figure 2.14c, the developed electrode was utilized for real-time tracking of H_2O_2 secreted by human breast adenocarcinoma cell.

Figure 2.14 (a) Schematic representation of the assembly of 2D MOF film. (b) Amperometric responses of H_2O_2 at bare electrode (black line) and Co-TCPP(Fe) modified electrode (green line). (c) Amperometric responses of Co-TCPP(Fe) modified electrode with adding fMLP and catalase without (black line) and with (red line) of human breast adenocarcinoma cells. Inset: The bright-field microscopy image of human breast adenocarcinoma cells. (a-c) Reproduced with permission.^[81] Copyright 2016, Wiley-VCH.

Besides electrochemical sensors, 2D MOF nanosheets have been also explored in electrochemical biosensors. As known, Zr-MOFs showed high affinity toward phosphate groups of biomolecules. With this in mind, 2D Zr-MOF nanosheets were used as electrode materials for fabrication of electrochemical aptamer biosensors. For example, electrochemical biosensor based on 521-MOF nanosheets was developed for detection of mucin 1, exhibiting high sensitivity with a linear range of 0.001–0.5 ng mL⁻¹ and the detection limit of 0.12 pg mL⁻¹.^[82] It should be noted that the conductivity of 2D MOF nanosheets is lower than that of other nanomaterials, such as noble metals, graphene and conductive polymers. Combining 2D MOF nanosheets with high conductive nanomaterials is one of the efficient approaches to solve this problem, improving the performance of electrochemical biosensors. As a typical example, 2D 521-MOF nanosheets embedded with Au nanoclusters (NCs) (AuNCs@521-MOF) were used as electrode materials to immobilize aptamer strands for detection of cocaine, which exhibited excellent sensitivity and selectivity because of the strong affinity, high surface area and good electrochemical conductivity of AuNCs@521-MOF composite nanosheets.^[65]

2.2 Questions to Answer Based on Literature

According to the above-mentioned literature review, significant advance has been achieved in the preparation and potential sensing application of 2D MOF and COF nanosheets as well as 2D MOF-based composite nanosheets. However, there are still many questions need to be answered.

First, numerous methods have been applied to synthesize 2D MOF nanosheets. Among them, surfactant-assisted method has been demonstrated as a useful synthetic method for preparation of 2D MOF nanosheets in high yield. Moreover, many MOFs reported in literatures are not stable in water, limiting their applications in aqueous solution. In addition, 2D MOF nanosheets are mostly used to investigate their applications in fluorescence sensors. Therefore, is it possible to use the surfactant-assisted method to prepare new 2D MOF nanosheets, especially water-stable 2D MOF nanosheets? Is it

possible to explore other properties and develop other optical sensors based on water-stable 2D MOF nanosheets?

Second, although some 2D MOF-based composite nanosheets have been reported recently, they are still in their infancy. In addition, the properties and applications of 2D MOF-based composite nanosheets are rarely studied. To date, 2D MOF-based composite nanosheets have been only used as organic catalysts and photoelectrochemical active materials. Is it possible to synthesize new composite nanosheets using ultrathin 2D MOF nanosheets as templates? One may wonder whether the 2D MOF-based composite nanosheets have other unique properties and potential application in sensing.

Last, tremendous efforts have been devoted to the exploitation of 2D COF nanosheets because of their unique chemical and thermal stability. However, it is difficult to prepare 2D COF nanosheets owing to the strong π - π stacking between adjacent layers. Although some methods have been reported to prepare 2D COF nanosheets, the yield is still low. Is it possible to design suitable organic building block to weaken interlayer interaction in COFs, which can be easily exfoliated into COF nanosheets in high yield? Do the new 2D COF nanosheets have novel properties and functions as well as new applications?

2.3 PhD in Context of Literature

In this thesis, I address the above-mentioned questions via synthesis of new 2D MOF and COF nanosheets as well as 2D MOF-based composite nanosheets, and exploration of new properties and sensing applications of these nanosheets. My contribution in this research direction is illustrated as follows:

First, a new series of ultrathin water-stable 2D metalloporphyrinic MOF nanosheets in high yield are successfully prepared by using surfactant-assisted synthetic method. The new feature of these 2D MOF nanosheets is studied. The obtained 2D MOF nanosheets exhibit higher biomimetic catalysis than that of bulk counterparts, which is demonstrated for the first time. This feature of 2D MOF nanosheets can be used for development of

colorimetric sensor. This study is instructive in exploring new properties of 2D MOF nanosheets.

Second, integration of Au nanoparticles into ultrathin 2D MOF nanosheets is efficient way to prepare 2D MOF-based composite nanosheets. Moreover, the obtained composite nanosheets have unique properties, which can be used to mimic natural enzyme and catalyze the cascade reaction. It should be noted that only Au nanoparticles or 2D MOF nanosheets cannot achieve this novel feature, confirming the importance of the composites. In addition, the potential sensing application of the obtained composite nanosheets has also been proved.

Last, a novel imine-linked COF is synthesized by selecting two flexible molecules with C_{3v} molecular symmetry as building units, exhibiting a hexagonal layered structure and sheet-like morphology. Due to the weak interlayer stacking from the flexible nonplanar building units in COF, COF can be easily exfoliated into ultrathin 2D COF nanosheets. This design can be extended to fabricate other COF nanosheets with new properties and functions. It has been proved that the obtained COF nanosheets can be used as sensing platform for fabrication of fluorescent DNA sensor.

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Chapter 3

Experimental Methodology

The rationale for selection of methods and basic principles for choosing materials are described in this chapter. The chemicals and experimental processes for synthesis of 2D MOF and COF nanosheets as well as 2D MOF-based composite nanosheets are summarized, and then the techniques and equipment for characterization used in experiments are introduced. Finally, the fabrication and measurement of sensing platforms based on 2D MOF and COF nanosheets as well as 2D MOF-based composite nanosheets are presented.

3.1 Rationale for selection

First, metalloporphyrinic MOFs (Cu-TCPP(Fe), Cu-TCPP(Co), and Cu-TCPP(Mn)) were chosen as nanomaterials and surfactant-assisted method was used for synthesis of the ultrathin metalloporphyrinic MOF nanosheets. In nature, enzymes with high specificity and selectivity are important biomacromolecules for life, because they can efficiently catalyze life-sustaining biological transformation.^[1] However, enzymes exhibit a few of intrinsic disadvantages, such as low physical and chemical stability, high purification cost, susceptibility to protein denaturation and unstable catalytic activity, which hinder their widespread applications.^[2] Numerous efforts have been dedicated to the exploitation of artificial enzymes. Among various artificial enzymes, nanomaterial-based products have drawn great attention due to their outstanding properties.^[3] As known, various kinds of MOFs can be designed and prepared by selecting different metal cations and organic ligands as well as connection modes.^[4] It is expected to design and synthesize MOFs with particular properties and functions as well as desiring applications. Therefore, MOFs can be considered as promising candidates for mimicking natural enzymes due to their structural versatility, high and tunable porosity and specific functionalities. Herein, metalloporphyrins are used as organic building units for fabrication of MOF, because they have been widely utilized to mimic the functionalities of natural biological systems. In addition, incorporation of metalloporphyrins into MOF materials can maintain and enhance the functionalities of metalloporphyrins. Moreover, if metalloporphyrins are arranged to form 2D layered MOF, it may be ideal system to show highly efficient biomimetic catalysis owing to the high density of catalytically active sites and large specific surface area. From material point of view, it is anticipated that a series of ultrathin water-stable 2D metalloporphyrinic MOFs can be prepared. It is of great importance to further explore their biomimetic catalytic activities. From method point of view, there are several approaches to prepare 2D MOF nanosheets. Among them, surfactant-assisted method developed by our group exhibits the great potential for synthesis of 2D MOF nanosheets in high yield. This method has been utilized to synthesize porphyrinic MOF nanosheets. It is believed that this method can be used to prepare metalloporphyrinic MOF nanosheets. From the application point of view, on the

basis of the design, the metalloporphyrinic MOF nanosheets may possess the biomimetic catalytic activity, which might be used as sensing platform for development of colorimetric sensor.

Second, 2D metalloporphyrinic MOF-based composite nanosheets (Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co)) were selected as materials and wet-chemical method was used for preparation of composite nanosheets. As known, there are many multi-enzyme complexes in biological system, which would catalyze two or more reactions. In this way, the product of one enzyme is the substrate of other enzyme.^[5] Like enzymes, multi-enzyme complexes also have the intrinsic disadvantages. It is an efficient way to explore composite nanomaterials to mimic multifunction of multi-enzyme complexes. From material point of view, the feature of MOF inspires the design of MOF-based composite to mimic multi-enzyme system. Integration of MOF with other nanomaterials can combine the beneficial properties of individual components into one system and produce new function. According to the aforementioned results, 2D metalloporphyrinic MOF nanosheets can be used as biomimetic catalysis. If one kind of nanomaterials has another biomimetic catalytic activity different from 2D metalloporphyrinic MOF nanosheets, combining them together might realize cascade reaction, which is important to mimic the multi-enzyme system. In addition, 2D nanosheets have been proved to be the excellent template for growth of different kinds of nanomaterials. For example, 2D metal chalcogenide nanosheets, including MoS₂ and TaS₂, have been used as template to grow noble metals, exhibiting excellent electrocatalytic activity towards the hydrogen evolution.^[6,7] Similar to 2D metal chalcogenide nanosheets, 2D metalloporphyrinic MOF nanosheets also have the ultrathin and layered structure, which might be utilized as template for growth of nanomaterials. According to previously reported work, Au NPs can mimic glucose oxidase, which is different from the function of 2D metalloporphyrinic MOF nanosheets. Therefore, it is expected to synthesize composite nanosheets containing 2D metalloporphyrinic MOF and Au NPs, which may realize new function different from individual component. From method view point of view, there are many methods to synthesize composite nanomaterials. Among them, wet-chemical synthetic method is an efficient method for preparation of composite nanomaterials

owing to the relatively low cost, high yield, ease of implementation, and ability to prepare nanostructures with controllable size and morphology. Thus, it is feasible to extend this method to synthesize 2D metalloporphyrinic MOF-based composite nanosheets. From the application point of view, composite nanosheets with new properties might be used as sensing platform for biomolecular detection.

Last, TPA-COF was selected as material and sonication-assisted method was used to exfoliate bulk TPA-COF into nanosheets. As known, COFs have excellent physical and chemical stability. However, COFs have strong π - π interlayer stacking originating from the organic building units. Compared to MOF nanosheets, it is difficult to prepare COF nanosheets in high yield. From material point of view, the unlimited choices of organic building units give rise to numerous kinds of COFs with diverse structures and functionalities. Therefore, 2D COFs with weak π - π interlayer stacking may be designed and synthesized by deliberate selection of organic building units. Flexible building units with C_{3v} molecular symmetry have the nonplanar structure, which can be integrated into 2D COFs. The obtained 2D COFs may have weak π - π interlayer stacking, resulting in easily exfoliating into nanosheets. In addition, reversible reaction plays a crucial role in preparation of 2D COFs. Normally, boronic acid-based condensation reaction, Schiff-base condensation reaction and cyclotrimerization reaction are the three major reversible reactions to crystallize 2D COFs.^[8] Among them, Schiff-base reaction is extensively used to crystallize 2D COFs, which is based on the dehydration of aldehyde and amine. Importantly, 2D COFs based on Schiff-base reaction have enhanced chemical stability compared with other 2D COFs.^[9] Based on flexible building units and reversible reaction mentioned above, it is reasonable to select TAPA and TFPA as organic building units to prepare 2D TPA-COF. Due to the unique properties of 2D TPA-COF, 2D TPA-COF nanosheets might be easily obtained by exfoliation of bulk TPA-COF. From the method point of view, there are several methods for exfoliation of bulk COFs into 2D COF nanosheets. Among them, sonication-assisted method is a simple and efficient way to exfoliate layered bulk COFs by selecting appropriate solvent. Considering the feature of designed TPA-COF, it is reasonable to obtain TPA-COF nanosheets via sonication-assisted method in high yield. The weak π - π interlayer stacking in TPA-COF might be

easily broke by sonicating TPA-COF in ethanol or other organic solvents. From application point of view, the obtained 2D TAP-COF has high chemical stability due to the Schiff-base reaction and high surface area, which may have potential application in sensor. In addition, it has been proved that ultrathin 2D nanomaterials (e.g., graphene, MoS₂, WS₂, MnO₂, and g-C₃N₄) are considered as good sensing platform for fabrication of fluorescent DNA sensor. Thus, this concept may be extended on 2D TPA-COF nanosheets.

3.2 Synthesis

3.2.1 Chemicals

Copper(II) nitrate trihydrate (Cu(NO₃)₂·3H₂O, 99%), polyvinylpyrrolidone (PVP, average mol wt 40,000), hexadecyltrimethylammonium bromide (CTAB, 99%), gold(III) chloride trihydrate (HAuCl₄·3H₂O, 99.9%), N,N-dimethylformamide (DMF, 99.8%), 3,3',5,5'-tetramethylbenzidine (TMB, 99%), glucose (99.5%), hydrogen peroxide (H₂O₂, 30%), glucose oxidase (GOx, from *Aspergillus Niger*), sodium borohydride (NaBH₄, 90%) and human serum samples were purchased from Sigma-Aldrich. 1,2-dichlorobenzene (o-DCB, 99%), tris(4-aminophenyl)amine (TAPA, 98%), acetic acid (AcOH, 99.5%), tris(4-formylphenyl)amine (TFPA, 96%) were purchased from Tokyo Chemical Industry Co., Ltd. [5,10,15,20-Tetrakis(4-methoxycarbonylphenyl)porphyrinato]-Fe(III) Chloride (TCPP(Fe)), [5,10,15,20-Tetrakis(4-methoxycarbonylphenyl)porphyrinato]-Co(III) Chloride (TCPP(Co)) and [5,10,15,20-Tetrakis(4-methoxycarbonylphenyl)porphyrinato]-Mn(III) Chloride (TCPP(Mn)) were purchased from Frontier Scientific. Ethanol, acetone, dichloromethane, and methanol were purchased from Merck. 1,3,5-tris(4-formylphenyl)benzene (TFPB) was prepared based on the published method,^[10] Trifluoroacetic acid (CF₃COOH, 99%) was purchased from Alfa Aesar. DNA strands were prepared by Integrated DNA Technologies Pte Ltd. All chemicals were used as received. The deionized water was obtained from the Milli-Q System (Millipore).

3.2.2 Preparation of bulk Cu-TCPP(M) (M=Fe, Co, Mn) MOFs

$\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$ (4.8 mg) and TCPP(Fe) (or TCPP(Co) or TCPP(Mn)) (8.8 mg) were weight out in 8 mL capped vial. Then DMF (1.5 mL) and ethanol (0.5 mL) were added into the above capped vial prior to add trifluoroacetic acid (5 μL). After that, the aforementioned capped vial was heated at 80 °C for 24 h. Then the reaction mixture was naturally cooled down to room temperature. The resulting crystals were collected by centrifugation at the speed of 8000 r.p.m for 5 min. Later, the product was washed twice with ethanol. Finally, the obtained bulk MOFs were redispersed in ethanol.

3.2.3 Preparation of Cu-TCPP(Fe) and Cu-TCPP(Co) nanosheets

A 20 mL vial was charged with $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$ (2.4 mg), PVP (10.0 mg), trifluoroacetic acid (40 μL , 1.0 M), DMF (9 mL) and ethanol (3 mL). The above vial was sonicated for 1 min to generate homogeneous mixture. Meanwhile, the TCPP(Fe) (or TCPP(Co)) solution was prepared by dissolving TCPP(Fe) (or TCPP(Co)) (4.4 mg) in a mixture of DMF (3 mL) and ethanol (1 mL). Afterwards, the TCPP(Fe) (or TCPP(Co)) solution was dropwisely added into the aforementioned vial under stirred conditions. After that, the mixed solution was sonicated for 15 min. Then the vial was heated at 80 °C for 4 h. Later, the reaction mixture was naturally cooled down to room temperature. The final product was collected by centrifugation at the speed of 10000 r.p.m for 5 min and then washed twice with ethanol. Finally, the obtained 2D Cu-TCPP(Fe) (or Cu-TCPP(Co)) nanosheets were redispersed in water.

3.2.4 Preparation of Cu-TCPP(Mn) nanosheets

A 20 mL vial was charged with $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$ (2.4 mg), CTAB (10.0 mg), trifluoroacetic acid (100 μL , 1.0 M), DMF (9 mL) and ethanol (3 mL). The above vial was sonicated for 1 min to generate homogeneous mixture. Meanwhile, the TCPP(Mn) solution was obtained by dissolving TCPP(Mn) (4.4 mg) in a mixed solution of DMF (3 mL) and ethanol (1 mL). Then the TCPP(Mn) solution was dropwisely added into the

aforementioned vial under stirred condition. After that, the mixed solution was sonicated for 15 min. Then the vial was heated at 80 °C for 4 h. Later, the reaction mixture was naturally cooled down to room temperature. The final product was collected by centrifugation at the speed of 10000 r.p.m for 5 min and then washed twice with ethanol. Finally, the obtained 2D Cu-TCPP(Mn) nanosheets were redispersed in water.

3.2.5 Preparation of Au NP/Cu-TCPP(M) (M=Fe, Co) composite nanosheets

100 μL of HAuCl_4 (10 mM) was added into 10 mL of Cu-TCPP(Fe) (or Cu-TCPP(Co)) nanosheets solution (0.1 mg mL^{-1}), which was stirred for 1 min. After that, 25 μL of ice-cold, freshly prepared NaBH_4 aqueous solution (0.1 M) was quickly added into aforementioned solution. Afterwards, the resulting product was immediately washed twice with water. Then, the final product was collected by centrifugation. Finally, the obtained Au NP/Cu-TCPP(Fe) (or Au NP/Cu-TCPP(Co)) composite nanosheets were redispersed in water.

3.2.6 Preparation of bulk TPA-COF

Tris(4-aminophenyl)amine (TAPA) (5 mg) and tris(4-formylphenyl)amine (TFPA) (5 mg) were weight out in 10 mL Pyrex tube. Afterwards, 1.5 mL of the mixture of o-DCB and ethanol (V/V=4:1) was added into the above Pyrex tube. The above Pyrex tube was sonicated for 1 min to generate homogeneous mixture. Then 0.06 mL of acetic acid (3.0 M) was added into aforementioned solution. After that, the tube was flash frozen under liquid N_2 (77 K), degassed by freeze-pump-thaw cycles for three times, and sealed under vacuum. The sealed tube was heated at 120 °C for 3 days. Later, the bulk TPA-COF was obtained as a yellow precipitate and the precipitate was collected by centrifugation. Afterwards, the collected precipitate was washed with ethanol, acetone, and dichloromethane respectively and then solvent-exchanged with methanol for two or three times. Finally, a deep yellow powder (6.5 mg, 76% isolated yield) was obtained by drying the aforementioned precipitate at 120 °C under vacuum for 12 h. FTIR (powder, cm^{-1}): 1694(w), 1619(m), 1594(s), 1505(s), 1427(w), 1318(m), 1284(m), 1197(w), 1169(m).

3.2.7 Preparation of bulk TPA-COF-2

Tris(4-aminophenyl)amine (TAPA) (5 mg) and tris(4-formylphenyl)benzene (TFPB) (6.7 mg) were weight out in 10 mL Pyrex tube. Afterwards, 1.5 mL of the mixture solution of mesitylene and ethanol (V/V=4:1) was added into above Pyrex tube. The above Pyrex tube was sonicated for 1 min to generate homogeneous mixture. Then 0.06 mL of acetic acid (3.0 M) was added into aforementioned solution. After that, the tube was flash frozen under liquid N₂ (77 K), degassed by freeze-pump-thaw cycles for three times, and sealed under vacuum. The sealed tube was heated at 120 °C for 3 days. Later, the bulk TPA-COF was obtained as a yellow precipitate and the precipitate was collected by centrifugation. Afterwards, the collected precipitate was washed with ethanol, acetone, and dichloromethane respectively and then solvent-exchanged with methanol for two or three times. Finally, a deep yellow powder (7.8 mg, 72% isolated yield) was obtained by drying the aforementioned precipitate at 120 °C under vacuum for 12 h. FTIR (powder, cm⁻¹): 1690(w), 1619(m), 1603(s), 1496(s), 1444(w), 1316(m), 1269(m), 1197(w), 1177(w), 1109(w).

3.2.8 Preparation of TPA-COF nanosheets

TPA-COF nanosheets were prepared from bulk TPA-COF material by ultrasonic exfoliation in organic solvents. Briefly, 6.5 mg of bulk TPA-COF material dispersed in 150 mL of ethanol was sonicated at room temperature in an ultrasonic bath (Brandson, CPX2800H-E, 110 W, 40 KHz) for 3 h. Then the suspension was kept quietly for 24 h to obtain the upper colloidal suspension. After that, the aforementioned upper colloidal suspension was concentrated by centrifugation at the speed of 7,000 rpm for 5 min. Finally, the product was redispersed in ethanol.

3.3 Characterization

It is important to characterize the as-prepared 2D MOF and COF as well as the 2D MOF-based composite nanosheets by using appropriate techniques to obtain their detail

information including crystallinity, composition, size, thickness, morphology, thermal stability, surface and optical properties, because the accurate characterization of the obtained nanomaterials can facilitate the study of relationship between structural characteristics and properties or functionalities. With the rapid development of nanotechnology, tremendous techniques have been widely used to characterize the 2D nanomaterials, such as XRD, SEM, TEM, AFM, and XPS. Since each technique has its own advantage and disadvantage, it is necessary to combine different techniques together to fully understand the structural features of the obtained 2D nanomaterials. Thus, in this section, the various techniques and equipment used for characterization of the prepared nanomaterials will be introduced.

3.3.1 X-Ray diffraction (XRD)

XRD is a powerful and nondestructive technique used to characterize crystalline nanomaterials. Since MOF and COF are porous crystalline materials and each MOF or COF has its unique diffraction pattern, it is suitable to use XRD to get the information on crystal structure, phase, preferred crystal orientation and other structural parameters. When X-ray falls over MOF or COF nanomaterial, it diffracts in a pattern relative to its structure, which is due to the constructive interference of monochromatic X-rays and MOF or COF samples.

In this thesis, the crystal phases of bulk Cu-TCPP(Fe), bulk Cu-TCPP(Co), bulk Cu-TCPP(Mn), bulk TPA-COF, bulk TPA-COF-2, Cu-TCPP(Fe) nanosheets, Cu-TCPP(Co) nanosheets, Cu-TCPP(Mn) nanosheets and TPA-COF nanosheets were identified by XRD. XRD patterns of bulk Cu-TCPP(Fe), bulk Cu-TCPP(Co), bulk Cu-TCPP(Mn), Cu-TCPP(Fe) nanosheets, Cu-TCPP(Co) nanosheets and Cu-TCPP(Mn) nanosheets were collected on a Shimadzu XRD-6000 powder X-ray diffractometer using Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$). The crystalline phase of bulk TPA-COF and bulk TPA-COF-2 was determined on a Bruker D8 diffractometer (German) using Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$), where the step-scanning range was from 3° to 35° and the scan rate was 0.02 deg s^{-1} . A Shimadzu XRD-6000 thin film X-ray diffractometer using Cu K α radiation ($\lambda = 1.5406$

Å) was used to characterize the crystal phase of TPA-COF nanosheets. The XRD samples for bulk Cu-TCPP(Fe), bulk Cu-TCPP(Co), bulk Cu-TCPP(Mn), Cu-TCPP(Fe) nanosheets, Cu-TCPP(Co) nanosheets, Cu-TCPP(Mn) nanosheets and TPA-COF nanosheets were prepared by directly dropping concentrated solutions on a glass substrate. For bulk TPA-COF and TPA-COF-2, their powder was placed on XRD sample holder for test. The obtained XRD patterns were utilized to determine the crystal structure and phase by compared with the simulated patterns.

3.3.2 Scanning electron microscopy (SEM)

SEM, as the simple and fast technique, is frequently applied to characterize the morphology (size, shape and surface topology) and the surface feature of materials. In addition, SEM with high resolution can measure sample surface from several nanometers to several micrometers because of the small de Broglie wavelength of electrons.^[11] When a focused electron beam scans the sample surface, secondary electrons near the sample surface are produced via the inelastic scattering interaction between electrons and sample surface and then picked up by a detector. Finally, the collected signal is used to produce the image of sample surface.

In this thesis, SEM images of Cu-TCPP(Fe) nanosheets, Cu-TCPP(Co) nanosheets, Cu-TCPP(Mn) nanosheets, bulk TPA-COF and bulk TPA-COF-2 were collected on a JEOL JSM-7600 field-emission scanning electron microscope, where the working distance was 6 cm, the accelerating voltage was 5 kV, and the probe current was 6 μ A. For characterization of bulk TPA-COF and TPA-COF-2, their powder was directly put on conductive adhesive. Due to the low conductivity of bulk TPA-COF and TPA-COF-2, a Pt thin layer was coated on their surface. Normally, the thickness of Pt is less than 5 nm. For characterization of Cu-TCPP(Fe) nanosheets, Cu-TCPP(Co) nanosheets and Cu-TCPP(Mn) nanosheets, their solutions were dropped on the SiO₂/Si substrates and then dried at ambient conditions. An obvious contrast between nanosheets and substrate was clearly observed from the SEM images.

3.3.3 Transmission electron microscopy (TEM)

TEM is considered as a strong analytical method for characterization of size, electronic structure, crystal orientation, chemical identify, and exposed crystal facets,^[12] which is widely used to study the 2D nanomaterials. When electrons pass through the thin samples, an image is generated by collecting the interaction signal between electron and samples, which is recoded by a CCD camera. Due to the high voltage used for generation of electrons, the resolution of TEM is higher than that of SEM. Importantly, low-magnification TEM images, high-resolution TEM (HRTEM) images, SAED patterns and element mappings of as-prepared MOF and COF nanosheets as well as composite nanosheets can be obtained from TEM. Low-magnification TEM image is utilized to investigate the lateral size of nanosheets. Due to the sheet-like morphology, the lateral size of nanosheets is easily obtained from low-magnification TEM image. In addition, low-magnification TEM images are used to roughly examine the thickness of nanosheets. The low-magnification TEM image is obtained under the bright-field TEM mode. Therefore, the contrast of nanosheets is utilized to estimate the thickness of nanosheets roughly. In this case, thicker thickness gives darker contrast. HRTEM image and SAED pattern can be employed to evaluate the crystallinity, phase, crystal orientation and exposed crystal facets of nanosheets and composite nanosheets. Single crystalline nanosheets show continuous lattice fringe and the lattice fringe is in the same orientation. Different from single crystalline nanosheets, polycrystalline nanosheets show incontinuous lattice fringe and the lattice fringe is in a random orientation. In addition, the SAED pattern of single crystalline nanosheets gives a clear bright spot, while the SAED pattern of polycrystalline nanosheets gives ring-like pattern. In addition, the distance of crystal lattice fringe of composite nanosheets is used to examine the exposed crystal facets. For element mapping, it is used to study the elemental distribution in the whole nanosheets.

TEM images of Cu-TCPP(Fe) nanosheets, Cu-TCPP(Co) nanosheets, Cu-TCPP(Mn) nanosheets, Au NP/Cu-TCPP(Fe) composite nanosheets, Au NP/Cu-TCPP(Co) composite nanosheets, bulk TPA-COF and TPA-COF nanosheets are obtained on JEM 2100F field

emission transmission electron microscope with the accelerating voltage of 200 kV. Elemental mapping of Cu-TCPP(Fe) nanosheet was obtained on a JEM 2100F field emission transmission electron microscope coupling with an EDS detector. The TEM samples were prepared by dropped a solution of nanosheets or composite nanosheets on copper grids with a holey carbon film and then dried at ambient condition. It should be noted that the TPA-COF nanosheets are easily destroyed under irradiation of electron beam due to the high accelerating voltage during the TEM measurement. Therefore, low-dose TEM technique was used to obtain the HRTEM image of TPA-COF nanosheets using direct-detection electron-counting camera. Low-dose HRTEM image was collected on a Cs-corrected FEI G2 cubed Titan 60-300 electron microscope with a Gatan K2 Summit direct-detection electron-counting camera (DDECC) under an accelerating voltage of 300 kV, a defocus value of -300 nm, a convergence angle of 0.2 mrad, a Cs value of 10 μm , and a focal spread of 5 nm.

3.3.4 Atomic force microscopy (AFM)

AFM is a powerful method used to identify the thickness and lateral size of nanosheets, which is based on detection of the interaction force between a probe tip and nanosheets surface. Then the 3D topographic image of nanosheets with angstrom scale resolution and high sensitivity is obtained based on the force data. The layer number of nanosheets can be proved by analyzing the height profiles.

AFM images of Cu-TCPP(Fe) nanosheets, Cu-TCPP(Co) nanosheets, Cu-TCPP(Mn) nanosheets were collected on a commercial Dimension ICON AFM instrument with Nanoscope V controller (Bruker, USA) in the tapping mode at a scanning rate of 1 Hz. AFM image of TPA-COF nanosheets was obtained on a Dimension 3100 AFM (Veeco, CA, USA), NSCRIPTOR system in the tapping mode at a scanning rate of 1 Hz. AFM samples were prepared by dropping a solution of nanosheets on Si/SiO₂ substrates and dried at ambient condition.

3.3.5 X-Ray photoelectron spectroscopy (XPS)

XPS, a surface-sensitive spectroscopic tool, is widely used for the measurement of the chemical composition, valence state, and crystal phase of nanomaterials, which is reflected in binding energy. As each element has its own unique binding energy peaks, it is easy to identify the elemental composition by XPS. The high sensitivity of XPS is suitable for analyzing the as-prepared nanosheets. When a beam of X-ray irradiates the nanosheets, the binding energy and number of electrons are simultaneously measured, generating the XPS spectrum. It should be noted that XPS is used for the study of surface of nanosheets within 10 nm.

XPS spectra of Cu-TCPP(Fe) nanosheets, Cu-TCPP(Co) nanosheets, Cu-TCPP(Mn) nanosheets, Au NP/Cu-TCPP(Fe) composite nanosheets, Au NP/Cu-TCPP(Co) composite nanosheets were collected on a VG ESCALAB 220I-XL system with a Al K α 1486.7 eV monochromatic X-ray source, where the base pressure is less than 5×10^{-10} mbar. C1s peak (284.5 eV) was used as reference to calibrate the obtained XPS spectra. XPS samples were prepared by dropping concentrated nanosheet solution on a clean Si substrate surface and dried at ambient condition.

3.3.6 Fourier transform infrared (FT-IR) spectroscopy

FT-IR spectroscopy is an effective analytical tool for identify the function groups and chemical bonding information of samples. When sample is exposed by IR radiation, sample molecules selectively absorb radiation of specific wavelength. The resulting signal is collected by detector to generate a spectrum, representing a fingerprint of the sample. Note that each sample molecule has its own unique spectral fingerprint. Normally, the region for infrared absorbance spectroscopy is from 4000 to 400 cm^{-1} .

FT-IR spectra were collected on a Perkin Elmer FT-IR Spectrum GX in the spectral range from 400 to 4000 cm^{-1} . For preparation of FT-IR sample, the standard method was used. Bulk TPA-COF, bulk TPA-COF-2 and TPA-COF nanosheets were mixed with KBr by

grinding, respectively. After that, the mixture was squeezed to form transparent pellet, which was used for FT-IR characterization.

3.3.7 UV-Vis diffuse reflectance spectroscopy (UV-Vis DRS)

UV-Vis DRS is standard tool used for determination of the band gap of semiconductor materials, evaluating the relative change of reflected light on the sample surface. UV-Vis DRS represents the percentage of reflectance as a function of wavelength. It should be noted that a good signal-to-noise of UV-Vis DRS signal would be collected when the film thickness is in the range of 1–3 mm.

UV-Vis DRS of bulk TPA-COF was obtained by a UV-Vis spectrophotometer (UV-Vis-NIR Cary 5000). The band gap was obtained by converting the data to Kubelka-Munk functions. For preparation of UV-Vis DRS sample, concentrated solution of bulk TPA-COF was dropped on the clean glass surface and then naturally dried in air.

3.3.8 Thermogravimetric analysis (TGA)

TGA is commonly utilized to measure the physical and chemical properties of samples, showing the mass loss owing to the decomposition, oxidation or loss of volatiles. According to the information on the TGA, the thermal stability of nanomaterials can be estimated.

TGA of bulk TPA-COF was conducted on a TA Instrument TGA 2950 in the temperature at a range of 30–800 °C under N₂ (30 mL min⁻¹) with heating rate of 10 °C min⁻¹. TGA samples were prepared by directly putting the powder of bulk TPA-COF on the sample pan supported by a precision balance.

3.3.9 Brunauer-Emmett-Teller (BET)

BET is commonly utilized for characterization of specific surface area and pore size distribution of nanomaterials based on the measurement of physical adsorption of gas on nanomaterials surface. Normally, nitrogen is used as gaseous adsorbate.

BET surface area of bulk TPA-COF was obtained from N₂ sorption isotherms at 77 K on a Micromeritics ASAP 2020 surface area and pore size analyzer. In addition, the pore size distribution data of bulk TPA-COF was collected from the nonlocal density functional theory (NLDFIT) model in the Micromeritics ASAP2020 software package. The powder of TPA-COF was directly used for BET measurement.

3.4 Application

3.4.1 Fabrication and assay of 2D MOF-based biomimetic enzyme and colorimetric sensor

Biomimetic enzyme. The catalytic activities of 2D Cu-TCPP(M) nanosheets for oxidation of TMB in the presence of H₂O₂ were studied as follow: for the experiment of 2D Cu-TCPP(Fe) nanosheets, 20 µg mL⁻¹ 2D Cu-TCPP(Fe) nanosheets were incubated with 1 mL solution containing HAc-NaAc buffer solution (10 mM, pH 4.0), TMB (800 µM, used as substrate) and H₂O₂ (1 mM). After the mixed solution was incubated for 10 min at room temperature, UV-Vis spectrum of the mixture was measured. For the experiment of 2D Cu-TCPP(Co) nanosheets, 20 µg mL⁻¹ 2D Cu-TCPP(Co) nanosheets were incubated with 1 mL solution containing HAc-NaAc buffer solution (10 mM, pH 4.0), TMB (800 µM) and H₂O₂ (5 mM). After the mixed solution was incubated for 10 min at room temperature, UV-Vis spectrum of the mixture was measured. For the experiment of 2D Cu-TCPP(Mn) nanosheets, 20 µg mL⁻¹ 2D Cu-TCPP(Mn) nanosheets were incubated with 1 mL solution containing HAc-NaAc buffer solution (10 mM, pH 4.0), TMB (800 µM) and H₂O₂ (25 mM). After the mixed solution was incubated for 10 min at room temperature, UV-Vis spectrum of the mixture was measured.

To compare the performance of 2D Cu-TCPP(M) nanosheets and bulk Cu-TCPP(M), the following experiments were carried out. For the experiment of bulk Cu-TCPP(Fe), 20 $\mu\text{g mL}^{-1}$ bulk Cu-TCPP(Fe) was incubated with 1 mL solution containing HAc-NaAc buffer solution (10 mM, pH 4.0), TMB (800 μM) and H_2O_2 (1 mM). After the mixed solution was incubated for 10 min at room temperature, UV-Vis spectrum of the mixture was measured. For the experiment of bulk Cu-TCPP(Co), 20 $\mu\text{g mL}^{-1}$ bulk Cu-TCPP(Co) was incubated with 1 mL solution containing HAc-NaAc buffer solution (10 mM, pH 4.0), TMB (800 μM) and H_2O_2 (5 mM). After the mixed solution was incubated for 10 min at room temperature, UV-Vis spectrum of the mixture was measured. For the experiment of bulk Cu-TCPP(Mn), 20 $\mu\text{g mL}^{-1}$ bulk Cu-TCPP(Mn) was incubated with 1 mL solution containing HAc-NaAc buffer solution (10 mM, pH 4.0), TMB (800 μM) and H_2O_2 (25 mM). After the mixed solution was incubated for 10 min at room temperature, UV-Vis spectrum of the mixture was measured.

To analyze the reaction kinetics, steady-state kinetics assays of 2D Cu-TCPP(M) nanosheets was carried out with varied concentrations of TMB at room temperature. Kinetic tests were performed by monitoring the absorbance change at 652 nm. For the experiment of 2D Cu-TCPP(Fe) nanosheets, 20 $\mu\text{g mL}^{-1}$ 2D Cu-TCPP(Fe) nanosheets reacted with 1 mL solution containing HAc-NaAc buffer solution (10 mM, pH 4.0), TMB (10-1200 μM) and H_2O_2 (1 mM). For the experiment of 2D Cu-TCPP(Co) nanosheets, 20 $\mu\text{g mL}^{-1}$ 2D Cu-TCPP(Co) nanosheets reacted with 1 mL solution containing HAc-NaAc buffer solution (10 mM, pH 4.0), TMB (10-1200 μM) and H_2O_2 (5 mM). For the experiment of 2D Cu-TCPP(Mn) nanosheets, 20 $\mu\text{g mL}^{-1}$ 2D Cu-TCPP(Mn) nanosheets reacted with 1 mL solution containing HAc-NaAc buffer solution (10 mM, pH 4.0), TMB (10-1200 μM) and H_2O_2 (25 mM). On the basis of the typical enzymatic reaction kinetic assay, the reaction rates were fitted to the following Michaelis-Menten equation:

$$V = V_{\max} \times \frac{[S]}{(K_m + [S])}$$

Where V was the initial reaction rate, $V_{\max}$ was the maximal reaction rate, $[S]$ was the concentration of the substrate and K_m was the Michaelis-Menten constant. Lineweaver-

Burk plot was applied to illustrate kinetic data and calculate the parameters by taking the reciprocal of the whole Michaelis-Menten equation.

$$\frac{1}{V} = \frac{K_m}{V_{\max}[S]} + \frac{1}{V_{\max}}$$

Colorimetric sensor. H₂O₂ detection was carried out as follow: 50 µL of H₂O₂ with different concentration was added to 950 µL solution including HAc-NaAc buffer solution (10 mM, pH 4.0), 800 µM TMB and 20 µg mL⁻¹ 2D Cu-TCPP(Fe) nanosheets. The mixture was used to perform the measurement and the absorbance of the mixed solution was recorded at 652 nm.

Glucose detection was performed as follow: 5 µL of GOx (40 mg mL⁻¹) was added into 100 µL of glucose with different concentration in pH 7.0 buffer solution (0.5 mM Na₂HPO₄). After incubation at 37 °C for 1 h, 895 µL solution containing 10 mM HAc-NaAc buffer solution (pH 4.0), 800 µM TMB and 20 µg mL⁻¹ 2D Cu-TCPP(Fe) nanosheets were added into the aforementioned solution. Then, the obtained mixture was used for the measurement and the absorbance of the mixed solution was recorded at 652 nm. In the control experiments, maltose with the concentration of 5 mM, lactose with the concentration of 5 mM and fructose with the concentration of 5 mM were used to replace glucose, respectively.

3.4.2 Fabrication and assay of 2D MOF composite-based biomimetic enzyme and colorimetric sensor

Biomimetic enzyme. The experiments of the oxidation of TMB catalyzed by Au NPs/Cu-TCPP(Fe) or Au NPs/Cu-TCPP(Co) composite nanosheets were carried out as follow: first, 50 µL of TMB (16 mM, used as substrate) was added into the mixture solution of 200 µL of H₂O₂ (5 mM) and 750 µL of the Au NPs/Cu-TCPP(Fe) or Au NPs/Cu-TCPP(Co) composite nanosheets (200 µg mL⁻¹). Afterwards, the mixture was incubated for 10 min. To prevent the interference from Au NPs/Cu-TCPP(Fe) or Au NPs/Cu-TCPP(Co) composite nanosheets to colorimetric assay, these composite

nanosheets were centrifuged. The resulting supernatants were analyzed by the UV-Vis spectroscopy.

The experiments of glucose oxidation catalyzed by Au NPs/Cu-TCPP(Fe) or Au NPs/Cu-TCPP(Co) composite nanosheets were carried out as following: first, 200 μL of glucose (1 M) was added into 750 μL of the Au NPs/Cu-TCPP(Fe) or Au NPs/Cu-TCPP(Co) composite nanosheets (200 $\mu\text{g mL}^{-1}$) for 4 h. In order to prevent the interference from Au NPs/Cu-TCPP(Fe) or Au NPs/Cu-TCPP(Co) composite nanosheets to colorimetric assay, these composite nanosheets were centrifuged. The resulting supernatant including gluconic acid and H_2O_2 was used to following experiments.

The reaction product, gluconic acid, was tested by a specific colorimetric assay. After mixing the resulting supernatant solution with 250 μL of solution a (5 mM EDTA and 0.15 mM trimethylamine in water), 25 μL of solution b (3 M hydroxylamine (NH_2OH) in water) was mixed with the aforementioned solution. Afterwards, the obtained mixture solution was incubated for 25 min. After that, 125 μL of solution c (1 M HCl, 0.1 M FeCl_3 and 0.25 M CCl_3COOH in water) was added to the above mixed solution. After incubation for 5 min, the obtained solution was used for spectral measurement.

The other reaction product, H_2O_2 , was tested by horseradish peroxidase (HRP)-based colorimetric assay. In a typical process, the resulting supernatant was mixed with 50 μL of HRP (10 $\mu\text{g mL}^{-1}$) and 50 μL of TMB (16 mM). After incubation for 10 min, the obtained solution was used for spectral measurement.

The experiment of artificial enzymatic cascade reaction was carried out as following: after mixing 750 μL of Au NPs/Cu-TCPP(Fe) or Au NPs/Cu-TCPP(Co) composite nanosheets (200 $\mu\text{g mL}^{-1}$) with 200 μL of glucose (1 M) for 4 h, 50 μL of TMB (16 mM) was added into the aforementioned mixed solution. Then the obtained mixed solution was incubated for different time. In order to prevent the interference from Au NPs/Cu-TCPP(Fe) or Au NPs/Cu-TCPP(Co) composite nanosheets to colorimetric assay, these composite nanosheets were centrifuged. After that, the resulting supernatants were

measured by the UV-Vis spectroscopy.

Colorimetric sensor. 200 μL of glucose (0.05–5 mM) was added into 750 μL of Au NPs/Cu-TCPP(Fe) composite nanosheets (200 $\mu\text{g mL}^{-1}$), which was incubated for 4 h. Afterwards, 50 μL of TMB (16 mM) was added into the above-mentioned solution and then incubated for 30 min. In order to prevent the interference from Au NPs/Cu-TCPP(Fe) composite nanosheets to colorimetric assay, these composite nanosheets were centrifuged before spectral measurement.

3.4.3 Fabrication and assay of 2D COF-based fluorescent sensor

Gel electrophoresis analysis. 1% agarose gel was used to test the hybridization chain reaction (HCR)-generated products. Briefly, the Bio-Rad horizontal electrophoresis system (Wide Mini-Sub Cell GT Cell) was used to analyze the gel, where the buffer solution was 0.5 $\times$ Tris-borate-EDTA (TBE) (45 mM Tris, 45 mM boric acid and 1 mM EDTA, pH 8.3), the voltage was 100 V and the time was 90 min. After that, the gel was stained with GelRed for 30 min. A G:BOX system (Syngene) under UV irradiation was used to generate the gel imaging.

Fluorescent DNA sensor. Briefly, 2.5 μL of hairpin DNA probe 1 (H1, 10 μM), 2.5 μL of hairpin DNA probe 2 (H2, 10 μM) and 5 μL of target DNA (T, 0–0.5 μM) were mixed with 440 μL of sodium phosphate-sodium chloride buffer solution (SPSC buffer: 50 mM Na_2HPO_4 and 0.75 M NaCl, pH 7.4) and then hybridized for 4 h. After that, 50 μL of TPA-COF nanosheets solution (0.12 mg mL^{-1}) was added into the above-mentioned solution. Then the obtained mixed solution was incubated for 15 min before fluorescence measurements. The final concentration of T was in the range from 0 to 5 nM. In addition, the excitation wavelength was 590 nm and the emission wavelength was 609 nm.

To compare the performance of bulk TPA-COF and TPA-COF nanosheets, the following experiment was performed: 2.5 μL of hairpin DNA probe 1 (H1, 10 μM), 2.5 μL of hairpin DNA probe 2 (H2, 10 μM) and 5 μL of T (0.5 μM) were mixed with 440 μL of

SPSC buffer (50 mM Na₂HPO₄ and 0.75 M NaCl, pH 7.4) and then hybridized for 4 h. After that, 50 μ L of bulk TPA-COF (0.12 mg mL⁻¹) or TPA-COF nanosheets (0.12 mg mL⁻¹) were added into the above-mentioned solution. Then the obtained mixed solution was incubated for 15 min before fluorescence measurements. The final concentration of T was 5 nM. In addition, the excitation wavelength was 590 nm and the emission wavelength was 609 nm.

The following experiment condition was used to study the selectivity of TPA-COF nanosheet-based fluorescence sensors: after hybridizing 2.5 μ L of hairpin DNA probe 1 (H1, 10 μ M) and 2.5 μ L of hairpin DNA probe 2 (H2, 10 μ M) with 5 μ L of T (0.5 mM) or 5 μ L of single-base mismatch DNA (SM, 0.5 μ M) or 5 μ L of random DNA (R, 0.5 μ M) in 440 μ L of SPSC buffer (50 mM Na₂HPO₄ and 0.75 M NaCl, pH 7.4) for 4 h, 50 μ L of TPA-COF nanosheets solution (0.12 mg mL⁻¹) was added into the above-mentioned solution. Then the obtained mixed solution was incubated for 15 min before fluorescence measurements. The final concentration of T was 5 nM, the final concentration of SM was 5 nM and the final concentration of R was 5 nM. In addition, the excitation wavelength was 590 nm and the emission wavelength was 609 nm.

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Chapter 4

Water-Stable 2D Metalloporphyrinic MOF Nanosheets

A new series of water-stable 2D metalloporphyrinic MOF nanosheets (Cu-TCPP(M), TCPP=tetrakis(4-carboxyphenyl)porphyrin), M=Fe, Co, Mn) are successfully synthesized by surfactant-assisted synthetic method. Compared with bulk MOFs, these 2D MOF nanosheets provide more accessible surface area with high density of active sites for biomimetic catalysis. Experimental results indicate that these 2D MOF nanosheets with high binding affinities and catalytic activities could serve as effective peroxidase mimic in aqueous solution. Furthermore, a simple, low-cost, rapid, selective and sensitive colorimetric sensor has been designed to detect glucose in serum samples.

4.1 Introduction

Inspired by the biological system, tremendous research efforts have been made to the exploration of synthetic systems for mimicking natural enzymes with high catalytic activity and substrate selectivity.^[1,2] As known, in nature, metalloporphyrins play significant roles in many biological functions, including light harvesting, electron transportation, oxygen transportation and catalysis.^[3] However, it has been found that the aggregation of metalloporphyrins would obstruct their energetic characteristics as well as efficiencies in these applications.^[4] Many strategies have been demonstrated to overcome these drawbacks, and one of the most promising approaches is to encapsulate metalloporphyrins into MOFs directly or to use metalloporphyrins as ligands to construct MOFs.^[5-7] In recent years, MOFs have received increasing research attention because of their fascinating structures and intriguing properties. As known, MOFs are crystalline porous materials fabricated by coordinating metal ions or clusters with various ligands, in which ligands and metal ions could be tuned according to their potential applications.^[8,9] Incorporation of biomimetic metalloporphyrins into MOFs, i.e., metalloporphyrinic MOFs, have been reported to enhance their biomimetic catalytic activities and stabilities by preventing their aggregation and suicidal self-oxidation.^[10] However, the practical application of MOFs for biomimetic catalysis is restricted because of the lack of water-stable MOFs with catalytically active metal centers.^[11] To mimic biological systems accurately, it is highly desirable to design MOFs with good water stability.

Recently, 2D layered nanomaterials have aroused great interest owing to their special features.^[12,13] It can be imaged that if metalloporphyrins are neatly arranged to form 2D layered MOFs with high surface areas, a huge number of active sites and good water stability, they may be ideal system to protect the metalloporphyrins and produce highly efficient biomimetic catalysis. More importantly, 2D MOFs with large exposed surface areas are readily accessible to the substrates due to the small diffusion barriers, which is different from conventional bulk MOFs.^[14] Both top-down delamination and bottom-up synthetic method are widely used for the preparation of 2D MOFs.^[15-18] A paramount advantage of bottom-up synthesis method is that the structure can be tuned finely with

metal ions or clusters and organic building ligands. Recently, our group has demonstrated that 2D MOFs with thickness less than 10 nm could be successfully synthesized based on a surfactant-assisted bottom-up method.^[19] Inspired by this method, we may synthesize novel 2D metalloporphyrinic MOFs nanosheets with good water stability, large surface area and high yield.

In this chapter, a new series of water-stable 2D MOFs (Cu-TCPP(M)) nanosheets with thickness of sub-10 nm are prepared by using surfactant-assisted synthesis method, where metalloporphyrins (TCPP(Fe), TCPP(Co) and TCPP(Mn)) and Cu paddle-wheel units are employed as ligands and nodes, respectively. The as-prepared 2D MOFs nanosheets may display high biomimetic catalytic activity due to the metalloporphyrins centers ordered on the surface. As indicated in the catalytic studies, these 2D MOFs nanosheets, especially 2D Cu-TCPP(Fe) nanosheets, with excellent substrate binding affinity and catalytic activity superior to HRP and other mimics, could serve as effective peroxidase mimic in aqueous media. As a proof of concept, taking the advantage of intrinsic peroxidase-like catalytic activity of 2D Cu-TCPP(Fe) nanosheets, a simple, low-cost, rapid, high sensitive and good selective colorimetric method has been developed for the detection of glucose in serum samples.

4.2 Results and Discussion

4.2.1 Synthesis and characterization of 2D MOF nanosheets

2D MOFs nanosheets are synthesized by the reaction of $\text{Cu}(\text{NO}_3)_2 \cdot 3\text{H}_2\text{O}$ and TCPP(M) (M=Fe, Co, Mn) in the presence of the surfactant in a mixture of DMF and ethanol. The as-prepared three kinds of 2D MOFs nanosheets are heterobimetallic MOFs, in which the porphyrin metal and paddle-wheel metal are different, as shown in Figure 4.1, similar to the structures of NAFS-1.^[20] The 2D MOFs are assembled by connecting the 2D “checkerboard” motif of TCPP(M) units with binuclear $\text{Cu}_2(\text{COO})_4$ paddle-wheels for each layered sheet, followed by stacking each layer in an AB packing pattern. Different from the 2D MOF nanofilms on the surface of substrates, the as-prepared 2D

metalloporphyrinic Cu-TCPP(M) nanosheets are directly synthesized in our experiment, where the surfactant molecule is of great importance to the controllable growth of MOFs crystals, resulting in the anisotropic growth of MOFs and assembly of MOF nanosheets with ultrathin feature, similar to the previous work in our group.^[19] The as-prepared 2D Cu-TCPP(M) nanosheets are determined by SEM, TEM, AFM, XRD and XPS.

Figure 4.1 Structures of (a) $\text{Cu}_2(\text{COO})_4$ paddle-wheel metal node, (b) TCPP(M) ligand (M=Fe, Co, and Mn), and (c,d) the corresponding 2D Cu-TCPP(M) layered sheet (M=Fe, Co, and Mn).

The characterization of as-prepared Cu-TCPP(Fe) nanosheets is displayed in Figure 4.2. The Tyndall effect (inset in Figure 4.2a) confirms the fine dispersion of nanosheets in suspension. SEM image (Figure 4.2a) exhibits their sheet-like structure, which is further confirmed by the low-magnification TEM image (Figure 4.2b). It can be seen that the lateral size of nanosheets ranges from hundreds of nanometer to micrometer. The low

contrast in TEM images demonstrates the ultrathin characteristics of 2D Cu-TCPP(Fe) nanosheets. Figure 4.2c displays the TEM image of a typical 2D Cu-TCPP(Fe) nanosheet. Figure 4.2d shows the SAED pattern of the 2D Cu-TCPP(Fe) nanosheet, which exhibits clear bright spots. These spots could be assigned to (110) plane and (100) plane of 2D Cu-TCPP(Fe) nanosheet, confirming its crystalline nature. AFM image (Figure 4.2e) indicates the thickness of 2D Cu-TCPP(Fe) nanosheets is 4.1 ± 1.3 nm. Furthermore, the elemental components of 2D Cu-TCPP(Fe) nanosheets are proved by the corresponding elemental mapping (Figure 4.2f), revealing the uniform distribution of Cu, C, Fe, N and O elements in the obtained 2D Cu-TCPP(Fe) nanosheets.

Figure 4.2 (a) SEM image of Cu-TCPP(Fe) nanosheets. Inset: Tyndall effect of colloidal nanosheets. (b,c) TEM images of Cu-TCPP(Fe) nanosheets. (d) The corresponding SAED pattern of Cu-TCPP(Fe) nanosheet in (c). (e) AFM image of Cu-TCPP(Fe) nanosheets. (f) EDS elemental mapping of Cu-TCPP(Fe) nanosheets.

Figure 4.3 XRD patterns of bulk Cu-TCPP(Fe) MOFs (black line), as-prepared Cu-TCPP(Fe) nanosheets (blue line) and Cu-TCPP(Fe) nanosheets after water treatment for one week (red line).

Furthermore, XRD patterns (Figure 4.3) are used to further identify the crystalline structure and stability of the 2D Cu-TCPP(Fe) nanosheets. Three diffraction peaks of 2D Cu-TCPP(Fe) nanosheets attributed to (110), (002) and (004) are observed. These peaks are similar to those of bulk Cu-TCPP(Fe). More importantly, no visible change on the XRD patterns of 2D Cu-TCPP(Fe) nanosheets is observed upon immersion in water for one week, indicating that no phase transition or framework collapse appears after this treatment. Moreover, the obtained 2D Cu-TCPP(Fe) nanosheets are characterized by XPS, as depicted in Figure 4.4. For TCPP(Fe) ligand, the high-resolution Fe XPS spectrum indicates that the peak positions for Fe $2p_{3/2}$ and Fe $2p_{1/2}$ are estimated to be at 711.2 eV and 724.8 eV, respectively, which is consistent with the previous report.^[21] It is noteworthy that no significant difference in Fe XPS spectra between the TCPP(Fe) ligand and 2D Cu-TCPP(Fe) nanosheets is observed, indicating that the TCPP(Fe) ligand is intact in the fabrication process. The high-resolution O XPS spectrum for the TCPP(Fe) ligand displays two peaks locating at 531.8 eV and 533.4 eV, indexed to carboxylic (C=O) and hydroxyl (C–OH), respectively. For 2D Cu-TCPP(Fe) nanosheets, an obvious decrease on the peak at 533.4 eV is observed, indicative of the formation of Cu-

TCPP(Fe) nanosheets.

Figure 4.4 High-resolution (a) Fe XPS and (b) O XPS spectra of TCPP(Fe) ligand and 2D Cu-TCPP(Fe) nanosheets.

Besides 2D Cu-TCPP(Fe) nanosheets, the 2D Cu-TCPP(Co) and Cu-TCPP(Mn) nanosheets can also be synthesized using the same method. The characterization of 2D Cu-TCPP(Co) and Cu-TCPP(Mn) nanosheets is shown in Figure 4.5. A typical Tyndall effect could be observed in the solution of these two kinds of 2D MOFs nanosheets, confirming their colloidal structures (inset in Figure 4.5a and 4.5d). The SEM images (Figure 4.5a and 4.5d) show their sheet-like structures with size in the range from hundreds of nanometers to micrometers. The low-magnification TEM images (Figure 4.5b and 4.5e) give the same result with the SEM images. Figure 4.5c and 4.5f show the TEM images of the typical sheets of these two kinds of 2D MOFs. The corresponding SAED patterns give clear bright spots assignable to (110) and (100) planes, confirming their crystalline structure (inset in Figure 4.5c and 4.5f). Furthermore, AFM images (Figure 4.6 and 4.7) reveal the thicknesses of 2D Cu-TCPP(Co) and Cu-TCPP(Mn) nanosheets are 3.5 ± 1.2 nm and 4.8 ± 2.8 nm, respectively. The as-prepared 2D Cu-TCPP(Co) and Cu-TCPP(Mn) nanosheets are also studied by XRD (Figure 4.8 and 4.9). The diffraction patterns of these two kinds of bulk MOFs are similar to that of bulk Cu-TCPP(Fe), indicating that they are almost isostructural, even though the central metal of TCPP is different. Similarly, the XRD patterns of nanosheets are consistent with that of

bulk MOFs. Moreover, these two kinds of MOFs nanosheets are treated by water, and no difference is observed, suggesting that structural collapse and phase transfer do not happen in the exposure environment. XPS results (Figure 4.10 and 4.11) further indicate the successful assembly of 2D Cu-TCPP(Co) and Cu-TCPP(Mn) nanosheets. It can be seen that the XPS analysis of TCPP(Co) ligand shows two sharp peaks in the Co region with binding energies of 781.7 eV and 796.7 eV, assigned to the Co 2p_{3/2} and Co 2p_{1/2} levels, respectively. The high-resolution XPS spectrum of Mn 2p of TCPP(Mn) ligand gives two peaks at 641.3 eV and 653.0 eV assignable to Mn 2p_{3/2} and Mn 2p_{1/2}, respectively. It should be noted that these peaks are the same even formation of 2D Cu-TCPP(Co) and Cu-TCPP(Mn) nanosheets. The peak obtained at 533.4 eV assigned to hydroxyl (C-OH) decreases, further indicating the successful assembly of 2D Cu-TCPP(Co) and Cu-TCPP(Mn) nanosheets.

Figure 4.5 (a) SEM image of Cu-TCPP(Co) nanosheets. Inset: Tyndall effect of colloidal nanosheets. (b,c) TEM images of Cu-TCPP(Co) nanosheets. Inset in (c): The SAED pattern of Cu-TCPP(Co) nanosheets. (d) SEM image of Cu-TCPP(Mn) nanosheets. Inset: Tyndall effect of colloidal nanosheets. (e,f) TEM images of Cu-TCPP(Mn) nanosheets. Inset in (f): The SAED pattern of Cu-TCPP(Mn) nanosheets.

Figure 4.6 (a,b) AFM height images of Cu-TCPP(Co) nanosheets. (c) The plot of thickness distribution of Cu-TCPP(Co) nanosheets measured by AFM.

Figure 4.7 (a,b) AFM height images of Cu-TCPP(Mn) nanosheets. (c) The plot of thickness distribution of Cu-TCPP(Mn) nanosheets measured by AFM.

Figure 4.8 XRD patterns of bulk Cu-TCPP(Co) MOFs (black line), as-prepared Cu-TCPP(Co) nanosheets (blue line) and Cu-TCPP(Co) nanosheets after water treatment for one week (red line).

Figure 4.9 XRD patterns of bulk Cu-TCPP(Mn) MOFs (black line), as-prepared Cu-TCPP(Mn) nanosheets (blue line) and Cu-TCPP(Mn) nanosheets after water treatment for one week (red line).

Figure 4.10 High-resolution (a) Co XPS and (b) O XPS spectra of TCPP(Co) ligand and 2D Cu-TCPP(Co) nanosheets.

Figure 4.11 High-resolution (a) Mn XPS and (b) O XPS spectra of TCPP(Mn) ligand and 2D Cu-TCPP(Mn) nanosheets.

4.2.2 2D MOF nanosheets used as biomimetic enzyme

2D Cu-TCPP(M) nanosheets with the large surface area, good water stability and potential catalytically active centers meet the prerequisites for a biomimetic system. The ordered arrangement of metalloporphyrins oriented on the surface of 2D Cu-TCPP(M) nanosheets prompts us to assess their biomimetic performance. In order to test the catalytic activity, these 2D Cu-TCPP(M) nanosheets are utilized to catalyze the oxidation reaction of peroxidase substrate, 3,3',5,5'-tetramethylbenzidine (TMB), which is widely employed to assess the catalytic performance of enzyme mimic in the previous work.^[22] The schematic of this catalytic oxidation reaction could be described in Figure 4.12a, that is, in the presence of H_2O_2 , 2D Cu-TCPP(M) nanosheets catalyze the oxidation of TMB to generate oxidized TMB (oxTMB) with a blue color. As displayed in Figure 4.13, in the absence and presence of H_2O_2 , the negligible absorption is observed, suggesting that there is no oxidation reaction without 2D Cu-TCPP(M) nanosheets. However, upon adding 2D Cu-TCPP(M) nanosheets into the mixture of TMB and H_2O_2 , the obtained solution shows dramatic characteristic absorbance at 652 nm, which could be ascribed to the charge-transfer complexes originated from one-electron oxidation of TMB,^[23] confirming that the as-prepared 2D Cu-TCPP(M) nanosheets possess intrinsic peroxidase-like activity. In the control experiments, the catalytic activities of bulk Cu-

TCPP(M) MOFs with the same concentration are also measured (Figure 4.14). As expected, the catalytic activities of bulk Cu-TCPP(M) MOFs toward the oxidation of TMB are poorer than those of corresponding 2D Cu-TCPP(M) nanosheets, suggesting that more active sites for catalysis may be exposed in ultrathin layered materials.^[24] Furthermore, as illustrated in Figure 4.12b-d, the oxidation of TMB catalyzed by 2D Cu-TCPP(M) nanosheets produces a blue color in the solution with the maximum absorption peak at 652 nm.

Figure 4.12 (a) Schematic illustration of oxidation of TMB catalyzed by 2D MOF nanosheet-based catalyst. (b-d) The catalytic activities of 2D MOF nanosheets. Time-dependent absorption spectra of TMB oxidation catalyzed by 2D MOF nanosheets in the presence of H_2O_2 . Inset: The corresponding photographs.

Figure 4.13 (a) UV-Vis absorption spectra of TMB oxidation in different reaction systems: TMB (purple line), TMB+H₂O₂ (orange line), TMB+H₂O₂+Cu-TCPP(Fe) (green line). (b) UV-Vis absorption spectra of TMB oxidation in different reaction systems: TMB (purple line), TMB+H₂O₂ (orange line), TMB+H₂O₂+Cu-TCPP(Co) (green line). (c) UV-Vis absorption spectra of TMB oxidation in different reaction systems: TMB (purple line), TMB+H₂O₂ (orange line), TMB+H₂O₂+Cu-TCPP(Mn) (green line).

Figure 4.14 (a) UV-Vis absorption spectra of TMB oxidation in different reaction systems: TMB+H₂O₂+Cu-TCPP(Fe) nanosheets (green line), TMB+H₂O₂+bulk Cu-TCPP(Fe) (orange line) and TMB+H₂O₂ (purple line). (b) UV-Vis absorption spectra of TMB oxidation in different reaction systems: TMB+H₂O₂+Cu-TCPP(Co) nanosheets (green line), TMB+H₂O₂+bulk Cu-TCPP(Co) (orange line) and TMB+H₂O₂ (purple line). (c) UV-Vis absorption spectra of TMB oxidation in different reaction systems: TMB+H₂O₂+Cu-TCPP(Mn) nanosheets (green line), TMB+H₂O₂+bulk Cu-TCPP(Mn) (orange line) and TMB+H₂O₂ (purple line).

To gain better insight into the catalytic activity of 2D Cu-TCPP(M) nanosheets, we analyze steady-state kinetics for the catalytic reaction of TMB (Figure 4.15). It can be seen that the typical Michaelis-Menten curves are obtained. In addition, Lineweaver-Burk equation is used to calculate Michaelis-Menten constant (K_m) and maximum initial

velocity ($V_{\max}$). K_m corresponds to the affinity of catalyst for the substrate, and a low K_m value would represent a good affinity.^[25] The calculated values for 2D Cu-TCPP(M) nanosheets and other catalysts are listed in Table 4.1. K_m values of 2D Cu-TCPP(M) nanosheets are lower than those of natural horseradish peroxidase, hemin and other MOFs or nanomaterials-based peroxidase mimics, suggesting a better affinity of the substrate to 2D Cu-TCPP(M) nanosheets. Due to their high surface area and ultrathin feature, TMB may be absorbed onto 2D Cu-TCPP(M) nanosheets efficiently. Similar to natural enzymes, the ability to make substrates close to their active sites would result in high catalytic efficiency.^[26]

Taking 2D Cu-TCPP(Fe) nanosheets for example, we study the possible mechanism of peroxidase-like activity. It may derive from their catalytic activation of H_2O_2 to generate hydroxyl radical ($\cdot OH$), which may react with TMB to form a different color in the solution. Fluorescence experiments are performed to test $\cdot OH$ generated in this reaction. Terephthalic acid (TA) is employed as a fluorescence probe to track $\cdot OH$. After the reaction of TA with $\cdot OH$, the produced 2-hydroxyl terephthalic acid gives unique fluorescence emission around 435 nm.^[27] As shown in Figure 4.16, obvious fluorescence at 435 nm is observed, and the gradual increment on the fluorescence intensity with the concentration of 2D Cu-TCPP(Fe) nanosheets indicates the generation of $\cdot OH$. Furthermore, to confirm the peroxidase-like activity of 2D Cu-TCPP(Fe) nanosheets, other substrates, including o-phenylenediamine (OPD), pyrogallol (THB) and 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulphonic acid) (ABTS), are also tested. It can be seen that 2D Cu-TCPP(Fe) nanosheets also catalyze the oxidation of these substrates with the appearance of the characteristic color (Figure 4.17), confirming that the 2D Cu-TCPP(Fe) nanosheets have peroxidase-like activity to representative peroxidase substrates. The high-yield and robust stability of Cu-TCPP(Fe) nanosheets make them the excellent substitute for HRP and suitable for applications in various fields.

Figure 4.15 Steady-state kinetic assay of 2D Cu-TCPP(M) nanosheets. (a) The plot of reaction velocity (V) versus the concentration of TMB in the presence of 2D Cu-TCPP(Fe) nanosheets. (b) The corresponding double reciprocal plot. (c) The plot of reaction velocity (V) versus the concentration of TMB in the presence of 2D Cu-TCPP(Co) nanosheets. (d) The corresponding double reciprocal plot. (e) The plot of reaction velocity (V) versus the concentration of TMB in the presence of 2D Cu-TCPP(Mn) nanosheets. (f) The corresponding double reciprocal plot.

Table 4.1 Comparison of the kinetic parameters in different catalysts.

Catalyst	K_m (mM)	V_{max} (10^{-8} M s $^{-1}$)	Ref.
HRP	0.434	10.00	[28]
Hemin	4.84	4.69	[29]
PCN-222(Fe)	1.63	N/A	[25]
Fe-MIL-88NH ₂	0.284	10.47	[30]
MIL-53(Fe)	1.08	8.78	[31]
Fe-MIL-101	0.158	5.12	[32]
Fe ₃ O ₄ MNPs	0.098	3.44	[28]
Cu-TCPP(Fe)	0.096	11.46	This work
Cu-TCPP(Co)	0.11	8.85	This work
Cu-TCPP(Mn)	0.27	4.11	This work

K_m : Michaelis constant. V_{max} : maximal reaction velocity. N/A: data not available.

Figure 4.16 The fluorescence spectra of 2-hydroxy terephthalic acid produced by the reaction of hydroxyl radical with terephthalic acid (TA) in different reaction systems: (a) 2D Cu-TCPP(Fe) nanosheets+TA, (b) H₂O₂+TA, (c-e) 10 μ g mL $^{-1}$, 20 μ g mL $^{-1}$, 30 μ g mL $^{-1}$ 2D Cu-TCPP(Fe) nanosheets+H₂O₂+TA at room temperature. The concentration of H₂O₂ is 1 mM and the concentration of TA is 0.5 mM.

Figure 4.17 Reaction images and schemes of oxidation of TMB, OPD, THB and ABTS by H_2O_2 catalyzed by 2D Cu-TCPP(Fe) nanosheets.

4.2.3 2D MOF nanosheet-based colorimetric sensor

As known, natural enzymes have remarkable specificity for their intended substrates and high efficiency for catalyzing a variety of reactions under mild conditions. However, natural enzymes also have some disadvantages, such as low stability due to denaturation and digestion, high cost in preparation, purification and storage, as well as hard to recovery and recycling, limiting their practical applications.^[1,2] Compared with natural enzymes, the as-prepared Cu-TCPP(M) nanosheets have several advantages, such as low cost, ease of preparation and storage, more stable to biodegradation, tunability in catalytic activities, large surface area for further modification and less vulnerable to denaturation. However, like most of artificial enzymes, 2D Cu-TCPP(M) nanosheets are designed to mimic a common natural enzyme. The functional diversity of the artificial enzymes should be expanded in the future work. Overall, 2D Cu-TCPP(Fe) nanosheets, as peroxidase mimic, possess several advantages over natural enzymes, making them promising potential candidates in clinical diagnosis. According to the above-mentioned intrinsic peroxidase-like property of 2D Cu-TCPP(Fe) nanosheets, a facile colorimetric method for detection of H_2O_2 and glucose based on 2D Cu-TCPP(Fe) nanosheets is developed. Because the catalytic activity of 2D Cu-TCPP(Fe) nanosheets is H_2O_2

concentration-dependent, the absorbance change could be used for H_2O_2 detection. Figure 4.18a exhibits the absorbance at 652 nm against H_2O_2 concentration. The linear range is from 0 to 300 μM and the detection limit is estimated to be 0.1 μM . It should be noted that 2D Cu-TCPP(Fe) nanosheets have more advantages over other Fe-based peroxidase mimetics. Since the active sites of 2D Cu-TCPP(Fe) nanosheets are fully exposed on the surface, they can be easily accessed and effectively utilized, leading to exhibit excellent catalytic properties. On the other hand, the diffusion of substrate to active sites of 2D Cu-TCPP(Fe) nanosheets is fast due to the ultrathin feature and large surface area of 2D Cu-TCPP(Fe) nanosheets. Therefore, the as-prepared 2D Cu-TCPP(Fe) nanosheets display enhanced performance toward the detection of H_2O_2 . Furthermore, since H_2O_2 is the main product of GOx-catalyzed reaction, the colorimetric glucose sensor can be developed based on 2D Cu-TCPP(Fe) nanosheet-catalyzed reaction. Considering the different catalytic environments for GOx and 2D Cu-TCPP(Fe) nanosheets, the glucose detection could be carried out in two steps, as shown in Figure 4.18d. Firstly, GOx can catalyze the oxidation of glucose to generate gluconic acid in a buffer solution at pH of 7.0, and at the same time, the substrate oxygen is converted to H_2O_2 . Secondly, TMB substrate would be oxidized with H_2O_2 to generate a blue color in the solution at a pH of 4.0, where 2D Cu-TCPP(Fe) nanosheets serve as the effective catalyst. Figure 4.18b exhibits the absorbance at 652 nm versus glucose concentration. The linear range is from 0 to 200 μM and the detection limit is estimated to be 0.5 μM , which is comparable with previous reports.^[33-36] Importantly, this proposed method is simple without the use of expensive equipment, and the detection could be performed with naked eyes or a cheap spectrometer. Furthermore, the proposed colorimetric sensor displays good selectivity for glucose detection, as illustrated in Figure 4.18c, where negligible responses are observed for glucose analogues (e.g., fructose, lactose and maltose), even their concentrations (5 mM) are higher than the concentration of glucose (0.5 mM). It may be due to the fact that glucose oxidase has high affinity to the oxidation of glucose. In order to assess its reliability in the practical application, the glucose in serum samples is detected using the proposed colorimetric sensor, as summarized in Table 4.2. The range of blood glucose concentration in healthy person is about 3-8 mM. Additionally, the range of blood glucose concentration in diabetic person is about 9-40 mM.^[35] Thus, the proposed colorimetric sensor could be

utilized to detect glucose in the clinical diagnosis.

Figure 4.18 (a) Calibration plot for H_2O_2 detection using 2D Cu-TCPP(Fe) nanosheets. (b) Calibration plot for glucose detection in the presence of 2D Cu-TCPP(Fe) nanosheets and GOx. (c) Selectivity of glucose detection. The concentrations of maltose, fructose, lactose and glucose are 5 mM, 5 mM, 5 mM and 0.5 mM, respectively. (d) Schematic representation of colorimetric glucose detection using 2D Cu-TCPP(Fe) nanosheets and GOx as catalysts.

Table 4.2 Results of glucose detection in serum samples.

Serum ^[a]	Colorimetric method (mM) ^[b]	Recovery Test ^[c]			
		Added (mM)	Found (mM)	Recovery (%)	RSD (%)
No.1	3.63±0.02	0.5	0.51	102.0	3.18
		1.0	0.93	93.0	1.27
No.2	3.82±0.06	0.5	0.53	106.0	2.57
		1.0	1.07	107.0	1.41

^[a]All the samples were diluted 25-fold using buffer solution. ^[b]All samples were analyzed using standard addition method (n=3). ^[c]Recovery test was carried out by addition of glucose standard solution into the serum samples with the same test procedure in the sample analysis.

4.3 Conclusion

In conclusion, a novel series of 2D Cu-TCPP(M) nanosheets with highly water-stable, ultrathin and large-scale properties have been successfully synthesized. Compared with bulk MOFs, these 2D MOFs nanosheets provide a 2D support with accessible surface area, favorable for the diffusion of substrate to the catalytic centers. As expected, the high density of metalloporphyrins catalytic centers ordered on the surface of nanosheets could result in high catalytic efficiency in biomimetic catalytic reaction, showing several advantages over natural enzymes. On the basis of this finding, a low-cost, simple, rapid and sensitive colorimetric sensor is designed for detection of glucose in serum samples. The successful demonstration of this work may open an avenue to develop water-stable and high-yield metalloporphyrinic framework nanosheets for biomimetic catalytic applications by using enzyme-like active centers as building blocks.

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Chapter 5

2D Metalloporphyrinic MOF-Based Composite Nanosheets

In this chapter, the 2D metalloporphyrinic MOF nanosheets are used as templates to prepare composite nanosheets (Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co)), which are obtained by deposition of Au NPs on the surface of Cu-TCPP(Fe) or Cu-TCPP(Co) nanosheets. The as-prepared composite nanosheets are determined by TEM and XPS. Since Au NPs show the GOx-like activity, and metalloporphyrinic MOF nanosheets show the peroxidase-like activity, the obtained composite nanosheets are used to mimic natural enzyme, achieving the cascade reaction without the use of natural enzyme. On the basis of this property, Au NP/Cu-TCPP(Fe) composite nanosheets are employed to fabricate colorimetric sensor for detection of biomolecule, such as glucose.

5.1 Introduction

Enzymes, as macromolecular biological catalysts, are of great importance in life due to their high affinities towards substrates and excellent catalytic efficiency as well as outstanding selectivity.^[1] However, enzymes have some drawbacks, including low stability to environmental condition, high cost of their preparation and low tolerances to many solvents, which stimulate the development of high-efficiency artificial enzymes.^[2] With the rapid growth of nanoscience and nanotechnology, numerous artificial enzymes have been explored to mimic natural enzymes, including carbon nanomaterials,^[3-5] metal oxide nanomaterials,^[6-9] noble metal nanomaterials,^[10-12] and so on.^[13,14] These artificial enzymes have promising potential in applications in the fields of biosensor and biomedicine, but they may only mimic one kind of enzymes. Therefore, it is still a challenge to mimic complex natural multi-enzyme system, especially for cascade reaction, using these synthetic nanomaterials.

Recently, 2D MOF nanosheets have attracted increasing attention due to the unique physical, chemical, optical, electronic, and magnetic properties, which show promising potential in a broad spectrum of applications, such as catalysis, energy conversion and storage, biosensor, gas separation, MALDI-TOF matrices, and white-light communication.^[15-24] Therefore, incorporation of 2D MOF nanosheet with other nanomaterials is an useful approach to fabricate composite nanosheets with new properties and functions.^[25] Composite nanosheets can combine the merits of individual component to improve the performance and give rise to novel applications. It should be noted that 2D MOF-based composite nanosheets are still in their infancy. As chapter 4 mentioned, 2D metalloporphyrinic MOF nanosheets are used as biomimetic enzymes, which can mimic peroxidase, catalyzing the oxidation of substrate in the presence of H_2O_2 . Moreover, because of the sheet-like structure, 2D metalloporphyrinic MOF nanosheets are good candidates as templates for growth of nanomaterials. As known, Au NPs have been explored to mimic GOx, which can catalyze the oxidation of glucose to generate H_2O_2 .^[26] Therefore, combining Au NPs with 2D metalloporphyrinic MOF nanosheets into one system may achieve new function, such as mimic natural multi-

enzyme system.

In this chapter, we use Cu-TCPP(Fe) and Cu-TCPP(Co) nanosheets as templates for growth of Au NPs to prepare composite nanosheets, referred to as Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co). The as-prepared composite nanosheets are used as biomimetic enzyme for mimicking natural multi-enzyme system, realizing the enzymatic cascade reaction. In this cascade reaction, Au NPs serve as GOx mimics to catalyze the oxidation of glucose and 2D metalloporphyrinic MOF nanosheets act as peroxidase mimics to catalyze the oxidation of TMB substrate. Furthermore, the Au NP/Cu-TCPP(Fe) composite nanosheets are used as sensing platform for detection of glucose.

5.2 Results and Discussion

5.2.1 Synthesis and characterization of composite nanosheets

2D Cu-TCPP(Fe) and Cu-TCPP(Co) nanosheets are used as templates for growth of Au NPs, as shown in Figure 5.1a. First, 2D Cu-TCPP(Fe) nanosheets were prepared by the surfactant-assisted method. TEM and SAED pattern confirmed the sheet-like structure and crystalline nature (Figure 5.1b-d). Then Au NPs were grown on the surface of 2D Cu-TCPP(Fe) nanosheets by directly reducing HAuCl_4 with NaBH_4 . The obtained Au NP/Cu-TCPP(Fe) composite nanosheets were characterized by TEM and XPS. As displayed in Figure 5.1e,f and Figure 5.2, we can clearly see that Au NPs with small size are well dispersed on the surface of 2D Cu-TCPP(Fe) nanosheets. Importantly, the 2D Cu-TCPP(Fe) nanosheets retained the crystal structure after growth of Au NPs, which was confirmed by SAED pattern (inset in Figure 5.1e). In addition, Figure 5.1g exhibits the HRTEM image of Au NPs. The lattice distance is 0.23 nm, assignable to (111) planes of Au. In addition, the crystalline nature of Au NPs was further proved by SAED pattern (Figure 5.1h). Furthermore, it can be seen that the high-resolution XPS Au 4f spectrum depicts two peaks located at 83.6 and 87.3 eV, respectively, indicating the metallic state of Au NPs on the surface of 2D Cu-TCPP(Fe) nanosheets (Figure 5.3).^[27] These results suggest that Au NPs are successfully grown on the surface of 2D Cu-TCPP(Fe)

nanosheets and the crystal structure of 2D Cu-TCPP(Fe) remains unchanged.

Figure 5.1 (a) Schematic representation of preparation of Au NP/Cu-TCPP(M) composite nanosheet (M=Fe, Co). (b,c) TEM images of Cu-TCPP(Fe) nanosheets. (d) SAED pattern of Cu-TCPP(Fe) nanosheet. (e,f) TEM images of Au NP/Cu-TCPP(Fe) composite nanosheets. Inset in (e): The corresponding SAED pattern of Cu-TCPP(Fe) nanosheet. (g) HRTEM image of Au NPs. (h) SAED pattern of Au NPs.

Figure 5.2 (a,b) TEM images of Au NP/Cu-TCPP(Fe) composite nanosheet. (c) Size distribution histogram of Au NPs on Cu-TCPP(Fe) nanosheet.

Figure 5.3 High-resolution XPS Au 4f spectrum of Au NP/Cu-TCPP(Fe).

Figure 5.4 (a,b) TEM images of Cu-TCPP(Co) nanosheets. Inset in (b): SAED pattern of Cu-TCPP(Co) nanosheet. (c,d) TEM images of Au NP/Cu-TCPP(Co) composite nanosheets. Inset in (c): The corresponding SAED pattern of Cu-TCPP(Co) nanosheet. Inset in (d): SAED pattern of Au NPs.

Figure 5.5 (a,b) TEM images of Au NP/Cu-TCPP(Co) composite nanosheet. (c) Size distribution histogram of Au NPs on Cu-TCPP(Co) nanosheet.

Figure 5.6 High-resolution XPS Au 4f spectrum of Au NP/Cu-TCPP(Co).

Similar to Au NP/Cu-TCPP(Fe) nanosheets, Au NP/Cu-TCPP(Co) composite nanosheets were synthesized by the same wet-chemical method. First, 2D Cu-TCPP(Co) nanosheets were prepared by surfactant-assisted method, which were characterized by TEM. The TEM images in Figure 5.4a,b indicate that 2D sheet-like structure of Cu-TCPP(Co) with the size in the range from hundreds of nanometers to several micrometers. The SAED pattern of Cu-TCPP(Co) is displayed in inset in Figure 5.4b, confirming the crystal

structure of Cu-TCPP(Co). Then, 2D Cu-TCPP(Co) nanosheets could be used as templates for growth of Au NPs. As shown in Figure 5.4c,d and Figure 5.5, Au NPs with small size were grown on the surface of Cu-TCPP(Co) nanosheets. After growth of Au NPs, the crystal structure of Cu-TCPP(Co) remains unchanged, which is shown in SAED pattern (inset in Figure 5.4c). In addition, crystalline nature of Au NPs was confirmed by the SAED pattern (inset in Figure 5.4d). Besides TEM images, XPS was used to confirm the structure of Au NPs. As shown in Figure 5.6, two peaks at 83.5 and 87.2 eV are assignable to the Au 4f_{7/2} and Au 4f_{5/2} of Au⁰, indicating that Au species were presented in the metallic state. All the aforementioned results proved that Au NPs were successfully deposited on the surface of Cu-TCPP(Co) nanosheets and the reduction process had no influence on the crystal structure of Cu-TCPP(Co).

5.2.2 Composite nanosheets used as biomimetic enzyme and sensing platform

In chapter 4, we have demonstrated that 2D Cu-TCPP(Fe) and Cu-TCPP(Co) nanosheets have peroxidase-like activity. In this chapter, 2D Cu-TCPP(Fe) and Cu-TCPP(Co) nanosheets were used as templates for the growth of Au NPs to obtain Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets. First, we proved the peroxidase-like activities of as-prepared Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets. Figure 5.7a shows the scheme of the catalytic oxidation of TMB in the presence of Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets, where TMB is used as substrate to measure the peroxidase-like activities of Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets.^[28] From Figure 5.7b,c, we can obviously see that Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets catalyze the oxidation of TMB to generate oxidized TMB (oxTMB) with major characteristic absorbance at 652 nm in the presence of H₂O₂, confirming the peroxidase-like activities of Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets. Control experiments indicated that neither TMB alone nor the mixture solution of TMB and H₂O₂ could efficiently catalyze the oxidation of TMB. The above experimental results demonstrated that Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets still maintain the peroxidase-like activities.

Figure 5.7 (a) Schematic illustration of TMB oxidation catalyzed by Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets. (b) UV-Vis absorption spectra of TMB oxidation in different reaction systems: TMB (black line), TMB+H₂O₂ (red line), and TMB+H₂O₂+Au NP/Cu-TCPP(Fe) (blue line). (c) UV-Vis absorption spectra of TMB oxidation in different reaction systems: TMB (black line), TMB+H₂O₂ (red line), and TMB+H₂O₂+Au NP/Cu-TCPP(Co) (blue line).

Then the GOx-like activities of Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets were systematically studied. Since the unsupported Au NPs have been proved to have the GOx-like activity, it is reasonable that the Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets also have the efficient GOx-like activities. Figure 5.8a shows the schematic representation of the glucose oxidation catalyzed by Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets, where Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets catalyze the oxidation of glucose to produce gluconic acid and H₂O₂ in the presence of O₂. Gluconic acid was analyzed by typical gluconic acid-specific colorimetric assay.^[29] An obvious characteristic absorbance band appeared at 500–700 nm in the presence of hydroxamine and Fe³⁺, which indicated that gluconic acid was produced in this catalytic reaction (Figure 5.8b,c). H₂O₂, the other product, was evaluated by HRP-base colorimetric assay.^[30] Upon the addition of HRP and TMB, a characteristic absorbance appeared at

652 nm (Figure 5.8c,d), confirming that H_2O_2 was one of the products in this catalytic reaction.

Figure 5.8 (a) Schematic representation of glucose oxidation catalyzed by Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets. (b,c) UV-Vis absorption spectra of different reaction systems obtained by gluconic acid-specific colorimetric assay: blank (black line), glucose (red line), glucose+Au NP/Cu-TCPP(M) composite nanosheets. (d,e) UV-Vis absorption spectra of different reaction systems obtained by HRP-specific colorimetric assay: blank (black line), glucose (red line), glucose+Au NP/Cu-TCPP(M) composite nanosheets.

Figure 5.9 (a) Schematic illustration of the enzyme-mimetic cascade reaction catalyzed by Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets. (b,c) Time-dependent absorbance of TMB oxidation in Au NP/Cu-TCPP(M) composite nanosheets reaction system. Inset: The corresponding photographs of solutions.

According to the peroxidase-like activity and GOx-like activity of Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets, it is reasonable that an enzyme-mimetic cascade reaction could be realized using Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets as artificial enzymes. In order to confirm it, the catalytic activities of Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets were studied. Figure 5.9a exhibits the principle for the enzyme-mimetic cascade reaction. In the presence of O_2 , Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets catalyze the oxidation of glucose to generate gluconic acid and H_2O_2 , and then the produced H_2O_2 is used for oxidation of TMB catalyzed by Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets. It can be seen that a blue color is produced with a characteristic absorbance at 652 nm owing to the TMB oxidation, as displayed in Figure 5.9b,c. The aforementioned results confirm that the artificial cascade reaction is achieved. In addition, the control experiments were also performed, as shown in Figure 5.10. We could see that neither glucose nor Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets could realize the cascade reaction, confirming that Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets have the GOx-like

and peroxidase-like activities. In our experiment, since Au NPs are directly grown on the surface of Cu-TCPP(M) nanosheets, Au NPs and Cu-TCPP(M) nanosheets are brought into close proximity with each other. This kind of interaction between Au NPs and Cu-TCPP(M) nanosheets may be beneficial to improve the catalytic activity. The reason is that the H_2O_2 produced in the Au NP-catalyzed oxidation reaction of glucose is enriched around the Cu-TCPP(M) nanosheets surface and is very close to the active sites of Cu-TCPP(M) nanosheets, reducing the diffusion of H_2O_2 and making the cascade reaction more effective. This positive effect of the interaction between Au NPs and Cu-TCPP(M) nanosheets is also in good agreement with previous reports.^[31-34] According to the fascinating properties of Au NP/Cu-TCPP(Fe) composite nanosheets, Au NP/Cu-TCPP(Fe) composite nanosheets were used as sensing platform for development of a colorimetric method to detect glucose based on the enzyme-mimicking cascade reaction. Figure 5.11a exhibits absorbance at 652 nm versus glucose concentration. It can be seen that the absorbance at 652 nm increases with the increment of concentration of glucose. In addition, inset in Figure 5.11a indicates that color change could be observed by the naked eyes. The absorption intensity shows good linear dependence on glucose concentration in the range of 10–300 μM , exhibiting a detection limit of 8.5 μM (Figure 5.11b).

Figure 5.10 (a) UV-Vis absorption spectra of TMB oxidation in different reaction conditions: glucose (black line), Au NP/Cu-TCPP(Fe) composite nanosheets (red line), glucose+Au NP/Cu-TCPP(Fe) composite nanosheets (blue line). (b) UV-Vis absorption spectra of TMB oxidation in different reaction conditions: glucose (black line), Au NP/Cu-TCPP(Co) composite nanosheets (red line), glucose+Au NP/Cu-TCPP(Co) composite nanosheets (blue line).

Figure 5.11 (a) Calibration plot for glucose detection using Au NP/Cu-TCPP(Fe) composite nanosheets as catalysts. Inset: The corresponding photography of color changes. (b) Linear relationship plot of absorbance at 652 nm against glucose concentration.

5.3 Conclusion

In summary, Cu-TCPP(Fe) and Cu-TCPP(Co) nanosheets with peroxidase-like activities are employed as templates for growth of Au NPs with GOx-like activities to obtain Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets. Due to the dual enzyme-like activities of Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) composite nanosheets, they can be utilized for mimicking complex natural multi-enzyme system, realizing the enzyme-mimetic cascade reaction. By taking advantage of the unique feature, the as-prepared Au NP/Cu-TCPP(Fe) composite nanosheets are used as sensing platform for detection of glucose. It is expected to explore new enzyme mimics with diverse functions for a wide range of applications.

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Chapter 6

Ultrathin 2D COF Nanosheets

In this chapter, the preparation, characterization and sensing application of 2D TPA-COF nanosheets with ultrathin feature are presented. The bulk TPA-COF with hexagonal layered structure and sheet-like morphology is prepared by selecting two flexible molecules with C_{3v} molecular symmetry as organic ligands. The as-prepared bulk TPA-COF is easily exfoliated into TPA-COF nanosheets owing to the weak interlayer interaction, which are characterized by TEM, AFM, FT-IR and XRD. The obtained 2D TPA-COF nanosheets are utilized as sensing platform for DNA detection with good selectivity and sensitivity.

6.1 Introduction

2D nanomaterials have received intensive attention because of their ultrathin 2D structures and diverse functionalities, 2D nanomaterials have been proved to possess unique physical, chemical and electronic properties, making them great promising in a wide spectrum of applications in catalysis, optoelectronics, batteries, supercapacitors, electronics, sensors and biomedicines.^[1-6] The successful synthesis and application of these 2D nanomaterials have triggered great research interest in design and synthesis of other novel 2D nanomaterials. 2D COF nanosheets, as an emerging member of 2D family, have been prepared recently. Because of the diversity of organic building block and covalent linkage modes, 2D COF nanosheets have been considered as promising material platforms for new functionalities and special applications. In the light of this, it is anticipated that the new 2D COF nanosheets may bring new properties, functions and applications.

The ability to develop various types of effective synthetic methods for fabrication of 2D COF nanosheets is of significance for the further study of their interesting properties, fascinating functions and promising applications. Thus, many effective approaches have been applied for preparation of 2D COF nanosheets. To data, the layered structure of bulk COF are exfoliated into 2D COF nanosheets by different exfoliation techniques, including sonication-assisted exfoliation,^[7-9] self-exfoliation,^[10] mechanical delamination,^[11] ball-milling exfoliation,^[12] sequential post-synthetic modification,^[13] and so on.^[14] However, it is still a challenge to obtain 2D COF nanosheets in high yield because of the strong π - π interaction between layers. Therefore, it is an efficient way to prepare 2D COF nanosheets by exfoliation of bulk COF crystal with weak interlayer interaction.

In this chapter, a new [3+3] imine-linked COF, referenced to as TPA-COF, is synthesized by choosing two flexible molecules as organic building blocks. The obtained bulk TPA-COF crystal with hexagonal layered structure and sheet-like feature has weak interlayer stacking due to the flexible nonplanar building blocks, resulting in easy exfoliation of

bulk TPA-COF into 2D TPA-COF nanosheets. Importantly, the porous structure of the 2D TPA-COF nanosheets is clearly imaged by low-dose TEM technique. In addition, the 2D TPA-COF nanosheets exhibit excellent fluorescence quenching ability, based on which a highly sensitive and selective fluorescence sensor is developed for the DNA detection.

6.2 Results and Discussion

6.2.1 Synthesis and characterization of 2D COF nanosheets

TAPA and TFPA were selected as organic building units for constructing TPA-COF by [3+3] imine condensation reaction. The experimental process is shown in Figure 6.1. The bulk TPA-COF with a deep yellow powder in ~76% yield was prepared by condensing TAPA and TFPA in the mixture solution of o-dichlorobenzene (o-DCB)/ethanol/acetic acid (V/V/V=20/5/1) at 120 °C for 72 h, which was not soluble in common organic solvents. The synthesized bulk TPA-COF crystal was characterized by FT-IR, UV-Vis DRS, TGA, XRD, SEM, and BET. As shown in Figure 6.2, the intensive absorption at 1619 cm^{-1} in the FT-IR spectrum of TPA-COF is assignable to C=N stretching band and the aldehyde band of TFPA (1694 cm^{-1}) is dramatically decreased, confirming the successful formation of imine linkages in bulk TPA-COF. Figure 6.3 is the UV-Vis DRS of bulk TPA-COF material. The UV-Vis DRS spectrum exhibits a reflection edge at around 530 nm, corresponding to a band gap of 2.32 eV. Moreover, the thermal stability of bulk TPA-COF was evaluated by TGA. As shown in Figure 6.4, the bulk TPA-COF remains stable up to 500 °C.

To characterize the crystalline structure and unit cell parameters of bulk TPA-COF, XRD analysis, the structural simulation and Pawley refinement were carried out (Figure 6.5, Table 6.1 and Table 6.2). As shown in Figure 6.5a, the peaks at 5.01°, 8.72°, 10.13° and 13.47° correspond to the diffractions of (100), (110), (200), and (210) planes, respectively. Importantly, the peak at 21.40° was π - π stacked (001) planes of bulk TPA-COF crystal. Based on geometry and connection mode of TAPA and TFPA, bulk TPA-

COF crystal were modeled in possible eclipsed and staggered 2D structures by the Materials Studio software package.^[15] As displayed in Figure 6.5a, the eclipsed 2D stacking model both in the peak position and intensity matches well with the experimental XRD pattern of bulk TPA-COF. In contrast, staggered 2D stacking model is not consistent with the experimental XRD pattern of bulk TPA-COF. It can be seen that TPA-COF with eclipsed packing was generated from the reaction of TAPA and TFPA. The structure was constructed with unit cell parameters of $a=b=21.1036$ Å, $c=3.92$ Å, $\alpha=\beta=90^\circ$ and $\gamma=120^\circ$. In addition, the Pawley refinement was carried out by the Materials Studio Forcite module.^[15] The Pawley-refined XRD pattern well reproduced the experimental XRD pattern, yielding unit cell parameters of $a=b=20.9239$ Å, $c=3.92$ Å, $\alpha=\beta=90^\circ$ and $\gamma=120^\circ$. The TPA-COF is consisted of one dimensional open channels of ~ 18 Å and is configured in π -stacking mode by a distance of 3.92 Å (Figure 6.5b). The interlayer distance obtained from simulated model is consistent with the value calculated from the (001) diffraction in experimental XRD profile (4.1 Å). Furthermore, the morphology of bulk TPA-COF was determined by SEM. As exhibited in Figure 6.5c, the bulk TPA-COF shows sheet-like structure. The bulk TPA-COF showed reversible type-I isotherms with a pore volume of $0.89 \text{ cm}^3 \text{ g}^{-1}$ and pore size of ~ 15 Å (Figure 6.5d). The BET and Langmuir surface areas were estimated to $1136.5 \text{ m}^2 \text{ g}^{-1}$ and $1489.4 \text{ m}^2 \text{ g}^{-1}$, respectively.

Figure 6.1 Schematic representation of the preparation and structure of bulk TPA-COF.

Figure 6.2 FT-IR spectra of TFPA, TAPA and TPA-COF.

Figure 6.3 UV-Vis DRS spectrum of bulk TPA-COF. Inset: Kubelka-Munk function plot.

Figure 6.4 TGA plot of bulk TPA-COF.

Figure 6.5 (a) XRD patterns of bulk TPA-COF. (b) Crystal structure model of bulk TPA-COF. (c) SEM image of bulk TPA-COF. (d) N₂ adsorption and desorption isotherms of bulk TPA-COF. Inset: The pore size distribution of bulk TPA-COF.

Table 6.1 Crystallographic information of the modelled bulk TPA-COF.

Sample	TPA-COF
Empirical formula	$C_{39}H_{27}N_5$
F_w	565.67
Stacking model	slipped-AA
a [Å]	20.9239
b [Å]	20.9239
c [Å]	3.9196
α [deg]	90
β [deg]	90
γ [deg]	120
Interlayer distance (Å)	3.9196

Table 6.2 Atomistic coordinates for the modelled bulk TPA-COF.

Atom site label	Atom site fraction x	Atom site fraction y	Atom site fraction z
C1	0.37183	0.62668	-0.14702
C2	0.4403	0.65566	0.02069
C3	0.47739	0.61641	0.04039
C4	0.44703	0.54521	-0.10145
C5	0.37933	0.51706	-0.27493
C6	0.34261	0.5567	-0.29826
N7	0.47799	0.4995	-0.08907
C8	0.63324	0.37813	0.11562
C9	0.56491	0.35436	-0.04723
C10	0.53258	0.39806	-0.05113
C11	0.56711	0.46782	0.10666
C12	0.6349	0.4913	0.27129
C13	0.66744	0.44752	0.2756
C14	0.53452	0.51509	0.09967
H15	0.46453	0.70984	0.13806
H16	0.52958	0.64108	0.17815
H17	0.35684	0.46312	-0.39568
H18	0.29058	0.53325	-0.4351
H19	0.53735	0.30091	-0.17221
H20	0.48058	0.38012	-0.18395
H21	0.6619	0.54424	0.40395
H22	0.7198	0.46693	0.40556
H23	0.56151	0.5643	0.26512
N24	0.66667	0.33333	0.11601
N25	0.33333	0.66667	-0.1601

On the one hand, the as-prepared bulk TPA-COF had the layered and sheet-like structure. On the other hand, it had weak interlayer interaction due to the flexible nonplanar organic building units. Thus, ultrathin 2D TPA-COF nanosheets could be easily exfoliated from the as-prepared bulk TPA-COF by using simple sonication-assisted liquid exfoliation method. The morphology, thickness and structure of the exfoliated TPA-COF nanosheets were determined by TEM, AFM, XRD, and FT-IR. From the low-magnification TEM image in Figure 6.6a, the 2D nanosheet-like structure can be clearly observed. The low contrast in TME image confirms the ultrathin feature of TPA-COF nanosheets. The typical Tyndall phenomenon observed in TPA-COF nanosheets solution proved its colloidal structure (inset in Figure 6.6a). The thickness of TPA-COF nanosheets was characterized by AFM. It can be seen that the thickness of TPA-COF nanosheets is 3.5 ± 0.3 nm (Figure 6.6b). Note that, the structure of the ultrathin TPA-COF nanosheets was easily destroyed by using conventional HRTEM due to the strong electron beam. In order to visualize the honeycomb-like porous structure of the as-prepared ultrathin 2D TPA-COF nanosheets, a low-dose TEM technique^[16] by combining the regular TEM with a direct-detection electron-counting camera was used to obtain the HRTEM image of TPA-COF nanosheets with a total electron dose as low as $\sim 20 \text{ e}^- \text{ \AA}^{-2}$. Figure 6.6c is a HRTEM image of TPA-COF nanosheet taking along the [001] direction. In addition, we achieved the information transferred up to $4 \text{ \AA}$, evidenced by the fast Fourier transform (FFT, inset in Figure 6.6c). These results confirm the structure integrity under low-dose condition. From the enlarged and denoised HRTEM image of TPA-COF nanosheet in Figure 6.6d, we can clearly see the hexagonally arranged white contrasts surrounded by six black dots, which shows a perfect match with the simulated HRTEM (inset in Figure 6.6d). Based on the simulated HRTEM, it can be obviously seen that the white contrasts correspond to 1D pore channels and the six black dots are attributed to the organic building units. Importantly, the contrast transfer function (CTF) of the objective lens was used to process the image to get structural model of TPA-COF nanosheets. Figure 6.6e is the CTF-corrected image, where “three-claw” contrast is obtained by elongating the black dot in raw image along three directions. In addition, lattice averaging and symmetry imposing were used to make it more identifiable for visualizing the structure of TPA-COF nanosheet (Figure 6.6f, left). We also achieve the projected potential map simulated

from the proposed structure (Figure 6.6f, right). It is noteworthy that there is a good match between the processed image and the simulated map, which confirms that the “three-claw” is assignable to the three benzene rings of tridentate TAPA or TFPA molecules.

In addition, the exfoliated TPA-COF nanosheets were further determined by XRD. As displayed in Figure 6.7, the TPA-COF nanosheets give the same XRD pattern as the bulk TPA-COF, indicating the crystal structure of TPA-COF nanosheets. It should be noted that the intensity of the first peak is lower than that of bulk TPA-COF. The result is in good agreement with previous reports on the exfoliation of other layered COFs.^[11,13] Moreover, the FT-IR spectra of TPA-COF nanosheets and bulk TPA-COF were almost identical, indicating their same structures (Figure 6.8). All the aforementioned results confirm that the exfoliated TPA-COF nanosheets have the same structure as bulk TPA-COF.

Figure 6.6 (a) TEM image of exfoliated TPA-COF nanosheets. Inset: Tyndall effect of the TPA-COF nanosheets suspension. (b) AFM image of exfoliated TPA-COF nanosheets. (c) Low-dose HRTEM image of a typical TPA-COF nanosheet. Inset: The corresponding FFT. (d) Enlarged and denoised (using a Wiener filter) HRTEM image. Inset: Simulated HRTEM image. (e) CTF corrected and denoised HRTEM image. (f) Left: Symmetry-imposed and lattice-averaged as well as CTF-corrected image. Right: Simulated projected potential map.

Figure 6.7 XRD patterns of TPA-COF nanosheets and bulk TPA-COF.

Figure 6.8 FT-IR spectra of TPA-COF nanosheets and bulk TPA-COF.

As control experiment, another 2D layered COF, referred as to TPA-COF-2, was prepared by using TFPB and TAPA as organic ligands. The experiment process is shown in Figure 6.9. XRD analysis, the structural simulation and Pawley refinement were used to characterize the crystalline structure and unit cell parameters of bulk TPA-COF-2 (Figure

6.10a,b, Table 6.3 and Table 6.4). The bulk TPA-COF-2 showed peaks at 4.29° , 7.43° , 8.71° and 11.47° , corresponding to the diffractions of (100), (110), (200), and (210) planes, respectively. The peak at 21.67° could be indexed to (001) plane because of the π - π stacking between COF layers. Similar to bulk TPA-COF, the experimental XRD pattern of bulk TPA-COF-2 was consistent with the simulated pattern obtained by the eclipsed 2D stacking model (Figure 6.10a). The unit cell parameters of bulk TPA-COF-2 were calculated to be $a = b = 23.4586 \text{ \AA}$, $c = 3.90 \text{ \AA}$. The crystal structure has one dimensional open channels of $\sim 24 \text{ \AA}$ extending along the c axis, with the interlayer separation of $3.90 \text{ \AA}$ (Figure 6.10b). FT-IR spectra revealed a typical stretching band arising from C=N at 1619 cm^{-1} and the decreased aldehyde band of TFPB (1686 cm^{-1}), indicating the successful formation of imine linkages in bulk TPA-COF-2 (Figure 6.10c). In addition, as shown in Figure 6.10d, the bulk TPA-COF-2 also has the sheet-like morphology. These results revealed that bulk TPA-COF and bulk TPA-COF-2 had the similar crystal structures and morphology. In order to exfoliate the bulk crystals into nanosheets, both bulk TPA-COF and bulk TPA-COF-2 with the same concentration were dispersed in ethanol and then treated with sonication for 3 h. After sedimentation for 24h, the Tyndall effects of the two colloidal suspensions were observed. It can be seen that a typical Tyndall phenomenon was observed for the TPA-COF nanosheet suspension. However, TPA-COF-2 colloidal suspension was almost colorless with very weak Tyndall effect, suggesting the very low concentration of TPA-COF-2 nanosheets (Figure 6.11). Compared to bulk TPA-COF, bulk TPA-COF-2 was difficult to exfoliate. The reason may be due to the increasing interlayer π - π stacking interactions in TPA-COF-2 originating from the nearly planar conformation and strong π systems of TFPB.

Figure 6.9 Schematic representation of the preparation and structure of bulk TPA-COF-2.

Figure 6.10 (a) Experimental and simulated XRD patterns of bulk TPA-COF-2. The asterisks (*) revealed peak may come from spatially confined solvent molecules embedded in bulk TPA-COF-2. (c) Crystal structures of bulk TPA-COF-2 along the [001] (left) direction and [100] (right) direction. (d) SEM image of bulk TPA-COF-2.

Table 6.3 Crystallographic information of the modelled bulk TPA-COF-2.

Sample	TPA-COF-2
Empirical formula	$C_{45}H_{30}N_4$
F_w	626.75
Stacking model	slipped-AA
a [Å]	23.4586
b [Å]	23.4586
c [Å]	3.8991
α [deg]	90
β [deg]	90
γ [deg]	120
Interlayer distance (Å)	3.8991

Table 6.4 Atomistic coordinates for the modelled bulk TPA-COF-2.

Atom site label	Atom site fraction x	Atom site fraction y	Atom site fraction z
C1	0.07127	0.03766	0.11696
C2	0.10543	0.10075	0.26378
C3	0.17398	0.13773	0.24887
C4	0.20962	0.11202	0.09055
C5	0.17607	0.04885	-0.0541
C6	0.10757	0.01227	-0.04219
N7	0.27967	0.15141	0.07409
C8	0.31668	0.1295	-0.04417
C9	0.38807	0.17192	-0.06239
C10	0.42683	0.14459	-0.15433
C11	0.49518	0.18421	-0.17027
C12	0.52543	0.25173	-0.09676
C13	0.4861	0.27888	-0.00707
C14	0.41787	0.23924	0.01075
C44	1.59771	1.29349	-0.10695
C47	1.73497	1.37279	-0.10665
N43	0.07127	0.03766	0.11696

Figure 6.11 Photograph of Tyndall effect of TPA-COF nanosheet suspension and TPA-COF-2 nanosheet suspension.

6.2.2 2D COF nanosheet-based fluorescent sensor

Rapid, cost-effective, sensitive, and selective assay of nucleic acid is of great importance in clinical diagnostic, gene profiling, drug discovery, food safety and environmental monitoring.^[17] Until now, many methods have been developed to detect nucleic acid.^[18,19] Among them, fluorescent sensors with simple, rapid, sensitive and selective features have been constructed for detection of nucleic acid. Taking advantage of their different affinities toward different DNA chains (ssDNA and dsDNA), 2D nanomaterials, including graphene,^[20,24] C_3N_4 ,^[25] MoS_2 ,^[26,27] WS_2 ,^[28] TiS_2 ,^[29] $Cu-TCPP$,^[30] and so on,^[31,33] have been used as sensing platform to fabricate fluorescent DNA sensors. Considering the similar structural feature, the obtained TPA-COF nanosheets are utilized as a new sensing platform for fabrication of fluorescent DNA sensor. The design principle of the proposed fluorescent DNA sensor is displayed in Figure 6.12a. The Texas red-labeled hairpin DNA is used as one probe (H1) and unlabeled hairpin DNA is used as another probe (H2). All DNA sequences employed in here are listed in Table 6.5. Firstly, the fluorescence quenching ability of TPA-COF nanosheets is investigated. As displayed in Figure 6.12b, the solution composed of H1 and H2 shows an intense fluorescence emission. After adding TPA-COF nanosheets, the fluorescence of the solution quenched within 15 min, confirming the excellent fluorescence quenching ability of TPA-COF nanosheets. The reason might be ascribed to the π - π stacking interactions between TPA-COF nanosheets and H1 as well as H2. Note that the fluorescence was greatly recovered

when target DNA (T) was added. The reason is due to the fact that T triggered the hybridization chain reaction (HCR) between H1 and H2 to generate long dsDNA and the formed long dsDNA can easily leave from TPA-COF nanosheets, leading to the recovery of fluorescence intensity.^[34] The results confirm that the interaction between TPA-COF nanosheets and HCR-generated long dsDNA is weaker than the interaction between TPA-COF nanosheets and hairpin DNA (H1 and H2). However, when T was just added into H1 solution, the fluorescence intensity was slightly recovery owing to the one-step hybridization reaction between H1 and T. The results indicated that HCR amplified the fluorescence signal, which might improve the performance of the proposed fluorescent DNA sensor. In addition, Gel electrophoresis is used to prove the HCR-generated long dsDNA, as shown in Figure 6.13. The result is consistent with previous report.^[34] Furthermore, compared to the bulk TPA-COF, TPA-COF nanosheets exhibited an enhanced fluorescence quenching ability, which may be due to the large specific area of TPA-COF nanosheets (Figure 6.12c and Figure 6.14).

According to the aforementioned results, the proposed TPA-COF nanosheet-based fluorescence sensor can be used for quantitative detection of DNA. Figure 6.12d exhibits the fluorescence spectra of H1+H2 in the presence of TPA-COF nanosheets with addition of different concentration of T. The fluorescence intensity increases with the increment of the concentration of T. Importantly, the fluorescence intensity exhibits good linear dependence on the concentration of T in the range from 0 to 1 nM (Figure 6.15a). In addition, the detection limit of the proposed fluorescence sensor is 20 pM. The result is comparable with those fluorescence sensors based on other 2D nanomaterials (Table 6.6). It can be seen that our developed fluorescent DNA sensor based on TPA-COF nanosheets has good sensitivity. The as-prepared ultrathin TPA-COF nanosheets have the aromatic π -electron system originating from organic ligands, allowing for the adsorption of ssDNA and leading to the efficient fluorescence quenching of dye. As a result, the background signal can be suppressed and then the detection sensitivity is improved. On the other hand, the target DNA triggers HCR between two hairpin probes, amplifying the response signal. In addition, the selectivity of the proposed fluorescence sensor was evaluated. As displayed in Figure 6.15b, compared with the single-based mismatch DNA (SM) and

random DNA (R), T gives rise to the great recovery of fluorescence intensity, suggesting that the TPA-COF nanosheet-based fluorescence sensor has excellent selectivity.

Figure 6.12 (a) Schematic representation of fluorescent DNA sensor based on TPA-COF nanosheet. (b) Fluorescence spectra of H1+H2 (I), H1+H2+T+TPA-COF nanosheets (II), H1+T+TPA-COF nanosheets (III), and H1+H2+TPA-COF nanosheets (IV). Inset: Kinetic curves of H1+H2 and H1+H2+T in the presence of TPA-COF nanosheets. (c) The quenching efficiency of TPA-COF nanosheets and bulk TPA-COF. (d) Fluorescence emission spectra of H1+H2 with different concentrations of T in the presence of TPA-COF nanosheets.

Table 6.5 DNA sequences used in this chapter.

Name	Sequence (5'–3')
Hairpin probe 1 (H1)	Texas Red- TTAACCCACGCCGAATCCTAGACTCAAAGTAGTCTAGGATTCGG CGTG
Hairpin probe 2 (H2)	AGTCTAGGATTCGGCGTGGGTAAACACGCCGAATCCTAGACTAC TTTG
Target DNA (T)	AGTCTAGGATTCGGCGTGGGTAA
Single-base mismatch DNA (SM)	AGTCTAGGATTCAGCGTGGGTAA
Random DNA (R)	TATCGCAAGGCGCATACCGGGTCG

Figure 6.13 Gel electrophoresis analysis of HCR products. Lanes 1 and 6: DNA markers; Lane 2: 2 μM H1; Lane 3: 1 μM H1+1 μM H2; Lane 4: 1 μM H1+1 μM H2+50 nM T; Lane 5: 1 μM H1+1 μM H2+300 nM T.

Figure 6.14 (a) Fluorescence spectra of H1+H2, H1+H2+T+bulk TPA-COF, H1+H2+bulk TPA-COF. (b) Fluorescence quenching curves of H1+H2+T+bulk TPA-COF, H1+H2+bulk TPA-COF.

Figure 6.15 (a) Calibration plot for DNA detection in the presence of TPA-COF nanosheets. Inset: The corresponding linear calibration plot for DNA detection. (b) Selectivity of the DNA sensor in the presence of TPA-COF nanosheets with T, SM, and R.

Table 6.6 Comparison of 2D nanomaterial-based fluorescent DNA sensors.

2D nanomaterials	Fluorescent reporter	Sensitivity	Comments	Ref.
Graphene oxide (GO)	FAM	2 nM	-	[20]
GO	FAM, ROX, Cy5	100 pM	Multiplexed analysis	[21]
GO	FAM, ROX	5 pM	Exonuclease III amplification and multiplexed analysis	[22]
GO	Silver nanoclusters	0.5 nM	Multiplexed analysis	[23]
GO	Graphene quantum dots	75 pM	-	[24]
g-C ₃ N ₄	FAM, ROX	81 pM	Exonuclease III amplification	[25]
MoS ₂	FAM	0.5 nM	-	[26]
MoS ₂	FAM	15 pM	Hybridization chain reaction	[27]
WS ₂	TAMRA	60 pM	-	[28]
TaS ₂	FAM, Texas red	50 pM	Multiplexed analysis	[29]
Cu-TCPP MOF	Texas red, TET	20 pM	Multiplexed analysis	[30]
TPA-COF	Texas red	20 pM	Hybridization chain reaction	This work

Abbreviations: FAM, carboxyfluorescein; ROX, 6-carboxy-x-rhodamine; Cy5, cyanine 5; TET, tetrafluorescein; TAMRA, tetramethylrhodamine.

6.3 Conclusion

In summary, a novel 2D TPA-COF with highly ordered hexagonal network and sheet-like structure is prepared by Schiff-base condensation reaction based on two flexible organic building units. The obtained bulk TPA-COF has weak interaction between adjacent layers owing to the flexible nonplanar organic building blocks, leading to easy exfoliation of bulk TPA-COF into ultrathin 2D TPA-COF nanosheets in high yield by simple sonication-assisted liquid method. Taking the advantage of the low-dose TEM technique, the pore channels and organic building units on the pore walls of the as-prepared ultrathin 2D TPA-COF nanosheet are clearly visualized. Importantly, the TPA-COF nanosheets have excellent fluorescence quenching ability. This feature of TPA-COF nanosheets is used for fabrication of a new fluorescent DNA sensor. The proposed TPA-COF nanosheet-based fluorescence sensor exhibit high sensitivity and selectivity. It is believed that this approach can be used for designing and synthesis of other ultrathin 2D COF nanosheets, which may also have new other properties and functions.

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Chapter 7

Conclusion and Future Work

In this chapter, the threads of my thesis are drawn together. A series of 2D metalloporphyrinic MOF nanosheets with peroxidase-like activities are prepared and used as the sensing platform to fabricate colorimetric sensor. In addition, 2D metalloporphyrinic MOF-based composite nanosheets with peroxidase-like activities and glucose oxidase-like activities are prepared and used for fabrication of colorimetric sensor. Furthermore, novel 2D imine-linked COF nanosheets with good stability are prepared and used for development of fluorescent sensor. The structure tunability and large surface area of 2D MOF and COF nanosheets hold great promise for designing various MOF and COF nanosheets with diverse functionalities. The unique properties of MOF and COF nanosheets can make them ideal candidates for a wide range of applications. Future work based on my results in this thesis and current research status is suggested.

7.1 General Discussion

MOFs and COFs with tunable structure and diverse function can be prepared by deliberately designing and tailoring building units and the linking functional group as well as coordination mode.^[1,2] These features of MOFs and COFs have aroused a surge of interest in the preparation of enormous MOF and COF nanomaterials for a variety of applications. Among them, 2D MOF and COF nanosheets have been explored very recently, showing a wide range of applications in gas separation, catalysis, energy storage, sensor, drug delivery, and so on. However, it is still in their infancy. Therefore, new 2D MOF and COF nanosheets as well as 2D MOF-based composite nanosheets with unique properties need to be designed and prepared. For example, 2D MOF nanosheets are to be used as biomimetic enzyme with better catalytic performance compared with bulk MOF crystals. Incorporation of other nanomaterials into 2D MOF nanosheets is to be considered as the efficient way to prepare composite nanosheets with intriguing properties to mimic nature multi-enzymes. The yield of 2D COF nanosheets is to be improved by selecting flexible building units and new application of 2D COF nanosheets is to be explored. These hypotheses have been demonstrated as discussed in chapter 4, 5 and 6.

First, 2D metalloporphyrinic MOF nanosheets (Cu-TCPP(Fe), Cu-TCPP(Co) and Cu-TCPP(Mn)), in high yield and large scale with thickness of sub-10 nm, are prepared by selecting metalloporphyrins as organic building units and copper clusters as metal nodes via surfactant-assisted method. The obtained 2D metalloporphyrinic MOF nanosheets not only prevent the suicidal self-oxidation of metalloporphyrins but also give rise to highly efficient biomimetic catalysis. They are used as artificial enzymes to mimic peroxidase, exhibiting better catalytic performance compared to their bulk counterparts. The reason is due to the fact that the as-prepared 2D metalloporphyrinic MOF nanosheets have large surface area and ultrathin thickness as well as a huge number of accessible active sites on their surface, which facilitate more interaction between substrate molecules and active sites, leading to the enhanced catalytic performance. This feature of these 2D metalloporphyrinic MOF nanosheets inspires the great interest in exploring their potential

sensing application. Taking Cu-TCPP(Fe) nanosheets as example, Cu-TCPP(Fe) nanosheets catalyze the oxidation of TMB to generate oxTMB in the presence of H_2O_2 . It is noted that the concentration of H_2O_2 has an influence on the catalytic performance. According to this finding, a colorimetric sensor is developed to detect H_2O_2 . In addition, glucose oxidase can catalyze the oxidation of glucose to generate H_2O_2 . Therefore, the proposed Cu-TCPP(Fe) nanosheet-based colorimetric sensor is also utilized for detection of glucose. The result indicates that the developed sensor shows highly sensitive and selective. Moreover, the proposed sensor is used to detect glucose in serum samples.

Second, the aforementioned 2D metalloporphyrinic MOF nanosheets (Cu-TCPP(Fe) and Cu-TCPP(Co)) are used as templates for growth of Au NPs on their surface to prepare 2D MOF-based composite nanosheets (Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co)). The obtained Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) nanosheets combine the beneficial properties of individual components, exhibiting new property and function. As known, Au NPs can act as glucose oxidase, which can catalyze the oxidation of glucose in the presence of O_2 to generate H_2O_2 . In the above work, Cu-TCPP(Fe) and Cu-TCPP(Co) nanosheets have the peroxidase-like activity, which can catalyze the oxidation of TMB to produce oxTMB in the presence of H_2O_2 . Therefore, the as-prepared Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) nanosheets have the GOx-like activity and peroxidase-like activity, which can achieve enzymatic-mimic cascade reaction. The as-prepared Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) nanosheets catalyze the oxidation of glucose to produce H_2O_2 , and the obtained H_2O_2 is used for the oxidation of TMB catalyzed by Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) nanosheets, suggesting that the Au NP/Cu-TCPP(Fe) and Au NP/Cu-TCPP(Co) nanosheets can mimic nature multi-enzyme system. Since the concentration of glucose have an effect on the performance of this cascade reaction, a colorimetric sensor based on Au NP/Cu-TCPP(Fe) nanosheets is fabricated for detection of glucose without the help of natural enzyme.

Last, a novel 2D TPA-COF with hexagonal layered structure and sheet-like feature is prepared by elaborately designing and selecting two flexible molecules with C_{3v}

molecular symmetry as organic building units. The obtained 2D TPA-COF, showing weak interlayer stacking due to the flexible nonplanar building units, can be easily exfoliated into ultrathin 2D TPA-COF nanosheets. For the first time, the 2D TPA-COF nanosheets have been synthesized in large scale. It is reasonable that other ultrathin 2D COF nanosheets can also be prepared by choosing flexible molecules with suitable molecular symmetry as organic building units. Importantly, the low-dose TEM technique is used to observe the structure information including the pore channels and organic building units in TPA-COF nanosheets, which cannot be achieved by using conventional HRTEM due to the instability of ultrathin TPA-COF nanosheets under electron beam. Since ultrathin 2D TPA-COF nanosheets have large surface area and good stability in water as well as biocompatibility, they are used as fluorescence quenchers, which show strong fluorescence quenching ability to probe DNA. Thus, 2D TPA-COF nanosheets are used as sensing platform for fabrication of fluorescent DNA sensor, which exhibit good sensitivity and selectivity. The sensitivity of the fabricated fluorescence sensor is comparable with or even better than other 2D nanomaterial-based fluorescent DNA sensors. In addition, the obtained TPA-COF nanosheets are semiconductor materials, which may be also promising in electronic gas sensors.

7.2 Reconnaissance Work and Future Work

Although some works have been done in the field of 2D MOF and COF nanosheets, it is still in their infancy. Therefore, there are still vast opportunities for developing novel 2D MOF and COF nanosheets with different properties and new functions as well as outstanding applications. Based on the current status in the field of 2D MOF and COF nanosheets, the following future works are recommended.

7.2.1 2D COF nanosheet-based electrochemical sensor

2D COF nanosheet is a new member in the family of 2D nanomaterials. Compared to their bulk counterparts, 2D COF nanosheets have many unique properties. As discussed in chapter 6, 2D COF nanosheets show higher fluorescence quenching ability than that of

bulk COF. On the other hand, the diversity of organic building blocks and the various connection modes make it easy to tune the properties of 2D COF nanosheets. Therefore, it is possible to explore other novel 2D COF nanosheets with desirable properties and functions as well as applications. Until now, the sensing applications of 2D COF nanosheets are restricted in optical sensor. As known, there are rare reports on using 2D COF nanosheets as electrode nanomaterials for electrochemical sensors and biosensors, which are due to the fact that the reported 2D COF nanosheets have low conductivity. Therefore, it is expected to design and prepare new 2D COF nanosheets with high conductivity, which may be promising in the application of electrochemical sensors and biosensors.

It is noteworthy that the properties of 2D COF can be tailored by precisely designing and choosing functional organic building blocks and suitable condensation reaction. Thus, it is anticipated the redox-active building units may be incorporated into 2D COF backbone to prepare 2D redox-active COF with high conductivity. In addition, the 2D redox-active COF with ultrathin thickness may facilitate the diffusion of electron and the fully utilization of redox-active sites due to the active sites exposed on the surface. Taking advantage of this property, it is believed that 2D COF nanosheets with redox-active sites and good stability can be used as electrode materials for construction of electrochemical sensors and biosensors. Very recently, Wang et al. reported that few-layer COF nanosheets with redox-active sites were used as cathode materials for lithium-ion batteries.^[3] As shown in Figure 7.1, DAAQ-TFP-COF and DABQ-TFP-COF are prepared by integrating redox-active anthraquinone and benzoquinone moieties into COF backbone. Compared with their bulk counterparts, the exfoliated DAAQ-TFP-COF and DABQ-TFP-COF nanosheets with shorter ionic diffusion pathways and more active sites exhibited faster charge-discharge ability and superior rechargeability. Bearing this in mind, 2D anthraquinone-based COF, benzoquinone-based COF, and viologen-based COF nanosheets can be used as electrode materials for constructing electrochemical sensors and biosensors for detection of various targets, including small molecules, heavy metal ions, biomolecules, nucleic acid, and so on.

Figure 7.1 Structures of DAAQ-TFP-COF and DABQ-TFP-COF.^[3]

7.2.2 2D COF nanosheet-based composite nanosheets

2D composite nanostructures consist of two or several components, which have drawn increasing attention because of their excellent intriguing properties compared to their individual components. Previous studies have proved that some 2D nanomaterials (e.g. graphene, MoS₂, TiS₂, TaS₂ and C₃N₄) can be used as 2D nanotemplates for deposition of various nanomaterials including noble metal, metal oxide, carbon nanomaterials, and so on.^[4-7] The obtained composite nanosheets are efficient electrocatalysts, organic catalysts and electrode materials, which show promising applications in catalysis, energy storage/conversion, and electrochemical sensors. These results confirm that incorporation of various nanomaterials into 2D nanomaterials is a good approach to prepare composite nanomaterials with extraordinary properties. Therefore, it is reasonable that this concept can be further extended to fabricate 2D COF nanosheet-based composite nanosheets. As known, there are no reports on synthesis 2D COF nanosheet-based composite nanosheets.

In chapter 6, the TPA-COF nanosheets in large scale were synthesized. The as-prepared TPA-COF nanosheets would be utilized as promising templates for direct decoration of

noble metal nanostructures. Taking Pd NPs as example, Pd NPs may be directly decorated on the TPA-COF nanosheets by using in situ photochemical reduction route. Because of the porous structure of TPA-COF and the nitrogen atom on the surface of TPA-COF, Pd NPs on the surface of TPA-COF nanosheets may be small and uniform. If some parameters are optimized, Pd nanoclusters may be grown on the surface of TPA-COF nanosheets. As known, Pd NPs are excellent catalyst, which can catalyze a wide spectrum of organic reactions. In addition, TPA-COF nanosheets have basic sites, which can catalyze many organic reactions. Thus, the obtained composite nanosheets may be an ideal system to achieve a tandem reaction, such as Knoevenagel condensation reaction. 4-nitrobenzaldehyde and malononitrile would be condensed into 2-(4-nitrobenzylidene)malononitrile via alkaline TPA-COF, and then the $-\text{NO}_2$ group of 2-(4-nitrobenzylidene)malononitrile would be selectively hydrogenated by Pd NPs. After that, the final product, 2-(4-aminobenzylidene)malononitrile, which is an important intermediate in the preparation of dyes and antihypertensive drugs, would be obtained. In addition, the high conductivity of Pd NPs may enable the composite nanosheets to become sensing platform for electrochemical detection of various analytes. Besides Pd NPs, Au NPs and Pt NPs may also be deposited on 2D COF nanosheets surface, which might be used as electrode materials for construction of electrochemical sensor and biosensor for detection of biomolecules.

Additionally, the porous channel of 2D COF nanosheets is another important feature. On the one hand, ultrafine noble metal nanoparticles or nanoclusters can be encapsulated into the porous channel of 2D COF, preventing the aggregation of noble metal nanoparticles or nanoclusters. On the other hand, the porous structure can be designed and tailored by choosing functional organic linkers, making it easy to anchor metal precursors and control the growth of noble metal. On the basis of this design, noble metal nanoparticles or nanoclusters at high loading with narrow size distribution would be immobilized on the cavity of 2D COF. Therefore, the performance of sensor based on 2D COF composite will be further improved.

7.2.3 2D COF nanosheet-based electronic sensor

As known, ultrathin 2D nanomaterials can confine the electrons in two dimensions in ultrathin region, exhibiting interesting electronic properties. In the light of this, ultrathin 2D nanomaterials are considered as ideal candidates for fabrications of electronic devices. For example, graphene has ambipolar behavior and nanoelectronic conductance, which is of great importance in electronic sensor (field-effect transistor sensor and chemiresistor sensor).^[8] In addition, MoS₂ with semi-conductive property can be used as channel materials for development of electronic sensor, which can detect a wide spectrum of targets including NO₂, NO, NH₃, O₂, DNA, and so on.^[9] The success of graphene and MoS₂ in electronic sensor may simulate the preparation of ultrathin 2D COF nanosheets with semi-conductive property by precisely choosing organic building blocks and linkage motifs. Importantly, the porous property of ultrathin 2D COF nanosheets can enhance the selectivity of the 2D COF-based electronic sensor, which cannot be achieved in graphene-based or MoS₂-based electronic sensors. Based on this, 2D COF nanosheet-based electronic sensor may have excellent sensitivity and selectivity. Therefore, it is expected that ultrathin 2D COF nanosheets may be designed and prepared to fabricate electronic sensors for detection of various targets.

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