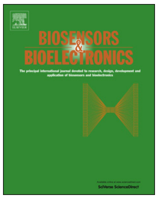
Contents lists available at ScienceDirect

Biosensors and Bioelectronics

journal homepage: www.elsevier.com/locate/bios



Two-dimensional graphitic carbon nitride nanosheets for biosensing applications

Mengyi Xiong[a], Qiming Rong[a], Hong-min Meng[a,b,c,d], Xiao-bing Zhang[a,*]

[a] State Key Laboratory for Chemo/Biosensing and Chemometrics, College of Chemistry and Chemical Engineering and College of Biology, Hunan University, Changsha 410082, People's Republic of China
[b] Collaborative Innovation Center of Henan Province for Green Manufacturing of Fine Chemicals, Xinxiang, Henan 453007, People's Republic of China
[c] Key Laboratory of Green Chemical Media and Reactions, Ministry of Education, Xinxiang, Henan 453007, People's Republic of China
[d] School of Chemistry and Chemical Engineering, Henan Normal University, Xinxiang, Henan 453007, People's Republic of China

ARTICLE INFO

Article history:
Received 30 November 2015
Received in revised form
20 February 2016
Accepted 17 March 2016

Keywords:
Two-dimensional material
Graphitic carbon nitride
Photoelectrochemistry biosensing
Electrochemiluminescence biosensing
Fluorescent biosensing

ABSTRACT

Two-dimensional graphitic carbon nitride nanosheets (CNNSs) with planar graphene-like structure have stimulated increasingly research interest in recent years due to their unique physicochemical properties. CNNSs possess superior stability, high fluorescence quantum yield, low-toxicity, excellent biocompatibility, unique electroluminescent and photoelectrochemical properties, which make them appropriate candidates for biosensing. In this review, we first introduce the preparation and unique properties of CNNSs, with emphasis on their superior properties for biosensing. Then, recent advances of CNNSs in photoelectrochemical biosensing, electrochemiluminescence biosensing and fluorescence biosensing are highlighted. An additional attention is paid to the marriage of CNNSs and nucleic acids, which exhibits great potentials in both biosensing and intracellular imaging. Finally, current challenges and opportunities of this 2D material are outlined. Inspired by the unique properties of CNNSs and their advantages in biological applications, we expect that more attention will be drawn to this promising 2D material and extensive applications can be found in bioanalysis and diseases diagnosis.

1. Introduction

Nanomaterials are, by definition, the natural or artificial materials possess at least one dimension in the size of nanoscale (Felix et al. 2013; Jiang et al. 2013; Nie, 2013). Their special optical, electronic, mechanical and thermal properties make them talented materials to construct fundamental devices that have been widely used in biosensing and biomedicine. The applications of nanomaterials in biosensing can be classified based on the topologies of those devices. For example, spherical nanoparticles (Quesada-Gonzalez and Merkoci, 2015; Sharma et al., 2015; Song and Yang, 2015; Wang et al., 2015; Wang and Gu, 2015; Zhao et al., 2013), nanowires (Nasr et al. 2015; Peng et al. 2013), nanotubes (Bai et al. 2010; Chen et al. 2009; Liu, 2007), nanosheets (Chen et al. 2015c; Ping et al. 2015) and nanocages (Chen et al., 2014a; Skrabalak et al., 2008; Yavuz et al., 2009). Among the profuse of nanomaterials, newly emerging two-dimensional (2D) nanomaterials with planar topography possess unique characteristics, including large special surface area, unique physicochemical properties (Chen et al., 2015c; Jaramillo et al., 2007; Kaul, 2014; Li et al., 2014a; Lui et al., 2009; Peng et al., 2014; Zhang and Xie, 2013), rapid electron transfer rate (Chen et al. 2012), optical properties (Ma et al., 2013; Xu et al., 2013), molecule adsorption capacities (Farid et al., 2015; Sun et al., 2008; X. Wang et al., 2015; Y. Wang et al., 2015; Yi et al., 2014; Yue et al., 2011), which render them potential tools for biological applications. As classic members of 2D nanomaterials, the graphene oxide (GO) and reduced graphene oxide (rGO) made up of sp^2 bonded carbon atoms completely have been reported to be outstanding candidates for biological applications, such as biosensing (Chen et al., 2015d; Cho et al., 2014; Li et al., 2014b; Qi et al., 2013; Qian et al., 2015; Zhao et al., 2011), nucleic acids (Jiao et al., 2013; Ke et al., 2014; Stobiecka and Chalupa, 2015) and drugs delivery (Sun et al., 2008; Yang et al., 2008; Zhang et al., 2010a), photothermal therapy (Robinson et al., 2011; Tian et al., 2011; Yang et al., 2010) due to the electron-rich conjugated structure of graphene to form strong interaction with cargos and efficient absorption of near-infrared light. Besides the graphene, various of 2D nanomaterials have been developed to build a library of current two-dimensional crystals (Geim and Grigorieva, 2013), which refer to as graphene analogs (GAs). The GAs are extensively used in some significant biological applications due to their graphene-like structures and special properties. For example, the nitrogenous graphene analogs (NGAs), boron nitride nanosheets (*h*-BN) which are referred to as “white graphenes” with relatively flexible

---

[*] Corresponding author.
E-mail address: xbzhang@hnu.edu.cn (X.-b. Zhang).

http://dx.doi.org/10.1016/j.bios.2016.03.043
0956-5663/© 2016 Elsevier B.V. All rights reserved.

Please cite this article as: Xiong, M., et al., Biosensors and Bioelectronics (2016), http://dx.doi.org/10.1016/j.bios.2016.03.043

interlayer space can accommodate various sized molecules, such as proteins, viruses, pesticides (Pakdel et al., 2014). The transition metal chalcogenides (MoS_2, WS_2, $MoSe_2$, WSe_2) and transition metal oxides (MoO_3, WO_3, MnO_2) have been extensively applied to cancer therapy and biological imaging, such as photothermal therapy (Cheng et al., 2014a; Chou et al., 2013), photoacoustic tomography (Cheng et al., 2014a), computed tomography (Yin et al., 2014; Yong et al., 2014) and magnetic resonance imaging (Chen et al., 2014b; Fan et al., 2015).

Among the plentiful GAs, the non-metallic covalent semiconductor carbon nitride nanosheets (CNNSs) with p-conjugated planar topography formed by sp^2 bonded carbon and nitrogen, have extensively attracted research interest of chemists, physicists, and material scientists due to their graphene-like structure and unique properties. They are known as polymeric photo-catalysts for solar and degradation, hydrogen production as well as oxygen reduction and evolution (Niu et al., 2012; Wang et al., 2012a, 2009a). In recent years, CNNSs exhibit great potential in biosensing due to their thermodynamic and chemical stability, superior optical properties, low toxicity and biocompatibility. In this review, the synthesis and properties of CNNSs will be introduced briefly and recent researches of CNNSs in biosensing will be highlighted. Furthermore, the deficiencies of CNNSs based sensors and potential applications of CNNSs combining with functional nucleic acids will be suggested. Our purpose is to draw more attention to this promising class of 2D nanomaterials and expand its applications in biotechnology.

2. Preparation and properties of CNNSs for biosensing

The discovery of C_3N_4 can date back to 1834 by Liebig (Thomas et al., 2008), and the structure of C_3N_4 was defined through theoretical calculation by Cohen and co-workers in 1989 (Liu and Cohen, 1989), which referred to as β-C_3N_4, and other allotropes of C_3N_4 such as α-C_3N_4, c-C_3N_4, pc-C_3N_4 and g-C_3N_4 were found subsequently. Due to the superior characteristics of g-C_3N_4, plenty of investigations were devoted to the synthesis, properties and applications of g-C_3N_4. It has been demonstrated that the atomic sheets of g-C_3N_4 show better physicochemical, optical and electrical properties than bulk g-C_3N_4, which render them more apposite candidates for biosensing. Therefore, the CNNSs that were prepared by exfoliating from bulk g-C_3N_4 through mechanical or chemical methods were utilized to act as important devices in biosensors. In this section, we will discuss the typical chemical approaches for the preparation of CNNSs and their properties for biological applications.

2.1. Synthesis of CNNSs

A variety of methods have been used to synthesize g-C_3N_4 such as solid-state reactions (Khabashesku et al., 2000; Zhang et al., 2001), solvothermal synthesis (Montigaud et al., 2000), electrodeposition (Li et al., 2004) and thermal decomposition (Lotsch and Schnick, 2006). Among them, the thermal decomposition is widely used for the preparation of bulk g-C_3N_4, in which the precursors polymerized when heated from ~90 to ~600 °C gradually. The condensation reactions of cyanamide to give discrete oligomers, polymers, and extended networks was illustrated in Fig. 1A. And it has been demonstrated that the type of precursors can determine the nitrogen content and properties of products, the precursors such as cyanamide, dicyandiamide, ammonium thiocyanate, urea and melamine (Cui et al., 2011; Li et al., 2007; Liu et al., 2011; Yan et al., 2009) tend to form the nitrogen-rich g-C_3N_4 bulk with the

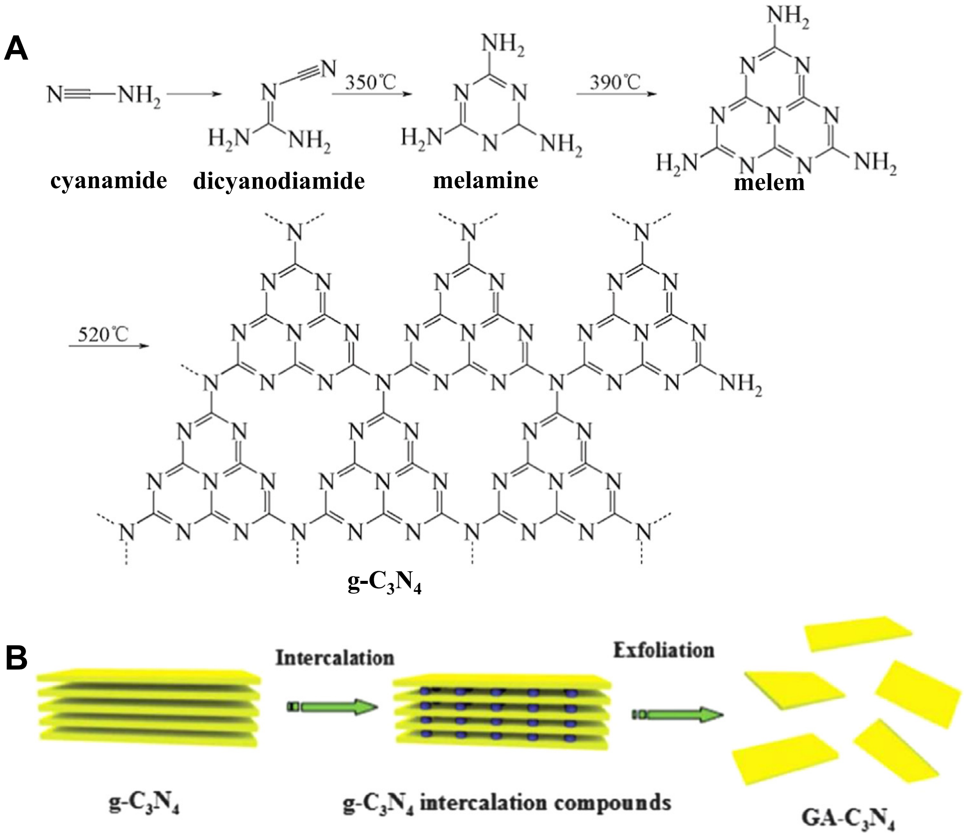


Fig. 1. (A) Condensation reactions of cyanamide to give discrete oligomers, polymers, and extended networks (Wang et al., 2012c). (B) Preparation of CNNSs from bulk g-C_3N_4 by exfoliation (Xu et al., 2014).

Please cite this article as: Xiong, M., et al., Biosensors and Bioelectronics (2016), http://dx.doi.org/10.1016/j.bios.2016.03.043