Sensors and Actuators B 207 (2015) 690–715

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

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

Review

Carbon nanotube based biosensors

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A R T I C L E I N F O

Article history:
Received 1 August 2014
Received in revised form 1 October 2014
Accepted 9 October 2014
Available online 18 October 2014

Keywords:
CNTs
Biosensors
Sensing mechanisms
CNT-based electrodes
CNT-field effect transistors

A B S T R A C T

Carbon nanotube (CNT) based biosensors are recognized to be a next generation building block for ultra-sensitive and ultra-fast biosensing systems. This article provides an overview on the recent expansion of research in the field of CNT-based biosensors. We start by first introducing the material structures and properties of CNTs. The basic and some new developed synthetic methods of CNTs are presented. This is followed by a collection of working principle and performance of different CNT-based biosensors. The roles and the processing methods of functionalized CNTs are summarized. After that, some of the practical applications and concerns in the field are addressed. What is more, the scientific and technological challenges in the field are discussed at the end of this review.

Contents

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http://dx.doi.org/10.1016/j.snb.2014.10.040
0925-4005/

1. Introduction

The detection of biomolecules is crucial for many areas of healthcare, clinical medicine, food safety, environmental monitoring and homeland security, ranging from uncovering and diagnosing disease to the discovery and screening of new drug molecules and to giving off early warning against health agents [1–3]. Hence, the development of reliable and inexpensive devices that enable direct, high sensitive/selective, and rapid analysis of these species could impact mankind to have a more healthy and reliable life [4]. Central to detection is the signal transduction with selective recognition of the biological species of interest. Biosensors, which combine a biological recognition with a chemical or physical transduction [5], have proved to be promising the advantage in the utilization, and especially commercialization to satisfy the demands of the above-mentioned areas. Ever since the discovery of the CNTs in 1991 [6,7], they have quickly become a global research activity due to their ultra-high specific surface area and outstanding electrical, mechanical and electrochemical properties. It is well known that the material properties (e.g. electrical or optical) of CNTs is very sensitive to be affected by exposure to biomolecules and this has led to the investigation, by a number of groups [6,8–10], of these materials as sensing elements for biosensors [11]. The high surface-to-volume ratio of the CNT makes it possible to obtain ultra fast detection of biological species at low concentrations. Thus, CNT-based biosensors are recognized to be a next generation building block for ultra-sensitive biosensing systems. Comparing with the most of the commercially available sensors, based usually on metal oxides, silicon and other materials, the CNT-based biosensors have the following great advantages: (i) high sensitivity, because of the large surface area ratio and hollow pipe, CNTs can be used to immobilized enzyme [12] which keep high biological activity; (ii) fast response time, CNTs have an outstanding ability to mediate fast electron-transfer kinetics hence promote the electron-transfer reactions like NADH and hydrogen peroxide [11]; (iii) lower potential of redox reaction and less surface fouling effects; (iv) highly stability and longer life time. These improved characteristics have stimulated the increasing research interest in the applications of CNTs as components for biosensors. Fig. 1 gives the number of papers referring of biosensor based on CNTs (searching from Google Scholar) in last 15 years. It is clearly seen that the study of CNT-based biosensor was in an explosive growth since 2007. A previous, a review has described the state of the art in this field up to the year 2006 [11]. Since CNT-based biosensors have been seen rapid development as well as a substantial increase in activities and in the number of papers on this topic from 2007. The present review focuses on these more recent efforts and considers the developments up to the year 2014.

Here, we first introduce the structures and properties of CNTs in Section 2. The basic and some new developed synthetic methods of CNTs are represented in Section 3. This is followed by a collection of working principle and performance of different CNT-based biosensors, such as the CNT-based electrodes (the detection of physical and chemical signals) and CNT-field effect transistors (FETs), in Section 4. Section 5 discusses the roles of functionalized CNTs and summarizes the methods for functionalizing CNTs. After that, some of the practical applications and concerns in the field are traced in Section 6. Finally, the challenges and future work on developing CNT-based biosensor are presented at the end of the review.

2. The structure and property of CNTs

CNTs can be thought of as the seamless hollow tubes composed of rolling graphite sheet, according to the layer number of graphite sheet, the CNTs can be divided into single-walled carbon nanotubes (SWCNTs) and multi-walled carbon nanotubes (MWCNTs) [13,14], as shown in Fig. 2a and b respectively. In general, SWCNT is a single molecular nanomaterial, which is formed of only a layer that rolls a single sheet of graphite (graphene) into a seamless molecular cylinder. Its diameter distribution and length are at the range of 0.75–3 nm and l–50 μm respectively. While MWCNT is composed of more than two layers of curly graphite sheet, and its diameter is at the range of 2–30 nm and some even more than l00 nm (Fig. 2b) [15], the distance between each layer is approximately 0.42 nm.

You can image the structure of SWCNTs that the graphene plane is mapped into the cylinder without the deformation of hexagon graphene layer as shown in Fig. 3. The vector from A to A' can be illustrated in Eq. (1)

$$\hat{C}_h = n\bar{a}_1 + m\bar{a}_2 \quad (1)$$

where $\hat{C}_h$ is a linear combination of the lattice basis vectors, $\bar{a}_1$ and $\bar{a}_2$ are lattice basis vectors, and n and m are positive integers which are known as the chiral indices. In the process of rolling graphene sheet, the carbon atom A overlaps the carbon atom A', thus forming CNTs. Once integers (n, m) are affirmed, the structure of CNTs is completely determined. All structural parameters of SWCNTs can be determined by (n, m) index [16,17].

According to the different direction of winding, SWCNTs are divided into three different types of structure: armchair type, zigzag type and chiral type respectively [18]. The structure types of CNTs are related to their chiral vector (n, m) and the spiral angle θ. As shown in Fig. 4, when $n = m$, spiral angle is equal to 30° between chiral vector $\hat{C}_h$ and lattice vector $\bar{a}_1$, the type of CNTs is called armchair; when $m = 0$, $\theta = 0°$, the type of CNTs is called zigzag; and when $0 < \theta < 30°$, the type of CNTs is called chiral. The electrical properties of SWCNTs strongly depends on diameter and chirality [19], and the diameter d is given by Eq. (2)

$$d = \frac{|C|}{\pi} = a(n^2 + nm + m^2)^{1/2} \quad (2)$$