Research of Biosensors Based on Nanomaterials

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Abstract. With the continuous advancement of science and technology, the application of nanomaterials in the field of biosensors is becoming increasingly widespread. Nanobiosensors are widely used due to their high sensitivity, selectivity, small size, and low cost, finding applications in medical diagnostics, environmental monitoring, biotechnology, and industrial automation, among others. This paper primarily discusses the research progress of biosensors based on nanomaterials and their applications in biological detection and medical diagnosis. It introduces the working principles of nanomaterial-based biosensors, provides practical application cases of nanomaterial biosensors in various fields, such as protein detection, DNA detection and pathogen detection. And this paper also looks forward to the prospects, as well as the advantages and disadvantages, of nanomaterial-based biosensors. With the deepening of nanomaterial research and the continuous innovation of technology, biosensors based on nanomaterials are expected to play an increasingly important role in biological detection, medical diagnosis, and biomedical research. Simultaneously, they also hold the potential for widespread application in clinical diagnosis, biosecurity, and environmental protection.

Keywords: Nanomaterials, Biosensors, DNA detection, Pathogen detection, Protein detection.

1. Introduction

In recent years, nanomaterials have been widely applied in numerous fields due to their unique physical and chemical properties, one of which is the biosensing field. Biosensors have played an extremely important role in various industries since their inception, but traditional biosensors often suffer from low sensitivity, poor selectivity, and slow response speed, which limit their effectiveness in practical applications.

To address these issues, researchers have begun exploring the use of nanomaterials to enhance the performance of biosensors. Nanomaterials possess an extremely high specific surface area, excellent biocompatibility, and unique electronic properties, which have led to significant breakthroughs in the sensitivity, selectivity, and response speed of nanomaterial-based biosensors.

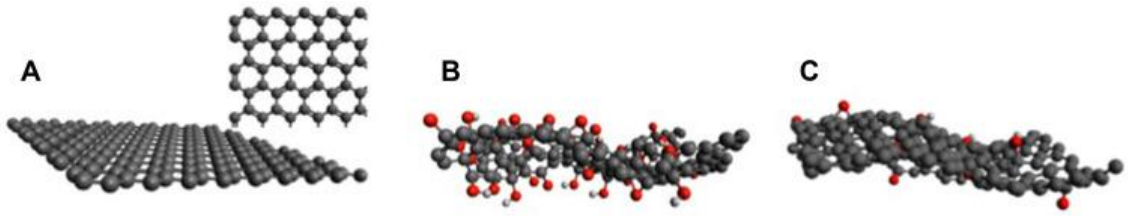


Figure 1. (A) Hexagonal array structure of graphene, (B) The disordered structure of graphene oxide, (C) Reduced GO [1]

As shown in Figure 1, the structure of GO is very specific. For example, a screen-printed, paper-based biosensor without labels has been developed for the detection of E. coli in water. This biosensor uses nanoarchitectured graphene oxide (GO), which acts as a fast electron-transfer platform, deposited on top of screen-printed graphene (G) on a hydrophobic paper. Lectin Concanavalin A (ConA) is then immobilized on this structure to act as a biorecognition element for the GGO_ConA biosensing electrode. Electrochemical characterization of GGO_ConA demonstrates rapid electron transfer, with a calculated electroactive surface area of 0.16 cm^2. The performance of this biosensor was evaluated using electrochemical impedance spectroscopy (EIS) in samples of sludge water and beach water, which are real-world samples. The charge-transfer resistance (Rct) of GGO_ConA was

found to increase in a linear fashion with the concentration of bacteria in the range of 10 to 10^8 CFU mL^-1, with an estimated limit of detection (LOD) of 10 CFU mL^-1. This indicates the high sensitivity of this biosensor, which is 100 times more sensitive than previous studies [1]. Two-dimensional quantum dots (2D-QDs) derived from planar structures have garnered significant attention due to their distinctive characteristics, including their expansive surface areas, numerous reactive sites, superior dispersibility in water, remarkable electrical properties, and facile surface modification capabilities. Researchers have synthesized numerous types of 2D-QDs utilizing diverse materials, such as graphene, black phosphorus, nitrides, transition metal dichalcogenides, transition metal oxides, and MXenes [2]. To review the research progress and application prospects of nanomaterial-based biosensors. The paper will introduce the working principle of nanobiosensors, provide several examples of their applications, and focus on introducing some nanomaterials such as graphene oxide and carbon nanotubes. Subsequently, we will analyze the development prospects and challenges and trends in the application of nanomaterial-based biosensors.

As an emerging research area, nanomaterial-based biosensors hold tremendous potential and broad application prospects. Through continuous exploration and innovation, we can further improve and perfect nanomaterial-based biosensors, contributing to social development and human health.

2. Working Principles of Nanomaterials Biosensors

(1) Biosurface Recognition and Binding

The attachment of specific biomolecular recognition layers (such as antibodies or DNA) to the surface of nanomaterials facilitates the highly selective capture and binding of target molecules, thereby creating a precise biomolecular recognition layer.

(2) Signal Transduction and Detection

Upon binding of the target molecule to the biorecognition layer, changes in the surface charge density, optical properties, or electrochemical properties of the nanomaterials can be detected by sensors and converted into readable information.

(3) Signal Amplification and Processing

Generally, biosensors apply signal amplification techniques to weak signals detected, enhancing the sensitivity and accuracy of the detection process.

3. Examples In Nanomaterials Biosensors

3.1. Protein Detection

Nanomaterials, serving as the foundational materials, exploit their high plasticity to facilitate the detection of specific proteins by modifying their surfaces with antibodies or other recognition elements. For instance, oxidized graphene can be modified with antibodies for the detection of tumor markers. Graphene is a very thin material with only one-atom-thick, which consisting of sp2-bonded carbon with a hexagonal honeycomb structure. Despite their exceptional properties, two-dimensional quantum dots (2D-QDs) derived from planar materials have limitations in sensing applications, such as the inertness of graphene in organic solvents and the lack of electrical conductivity in graphene oxide. To overcome these difficulties, scientists have developed numerous alteration methods. These methods aim to endow quantum dots with the required features for biological sensing. These modifications enhance the interaction between the QD surface and biomolecules, resulting in a bioconjugate that can serve as the core component of biosensors. 2D-QDs, when used as transducers, considerably boost the signal reaction in applications involving detection. Their vast expanse of surface and good compatibility with different biochemical substances provides the groundwork for a dependable biosensor, which is achieved by fixing a biological recognizer to the transducing substance.

The advancement of biosensors is vital in a multitude of domains, including but not limited to, environmental assessment, safety and protection concerns, guaranteeing food quality, the healthcare

sector, oceanographic research, biological sciences, and pharmaceutical innovation. Furthermore, biosensors find extensive application in plant biology to uncover the missing links in metabolic pathways [1]. Here the author introduced some examples about the application of oxidized graphene in nanomaterial-based biosensors. Widely adopted biosensors, including glucose meters for monitoring blood sugar levels, home pregnancy test strips, and rapid diagnostic kits for diseases like COVID-19, serve as prime instances of successful biosensor applications. These devices are highly acclaimed for their high degree of accuracy, which is made possible by incorporating selective biological recognition elements, and they provide these capabilities at a reduced cost. Electrochemical biosensor platforms stand out for their numerous advantages, such as their low cost, specificity, accuracy, speed, and portability. Furthermore, they can be integrated with smartphones and various analytical methods to enhance their sensitivity and improve a range of their properties [3]. For instance, as shown in Figure 2.

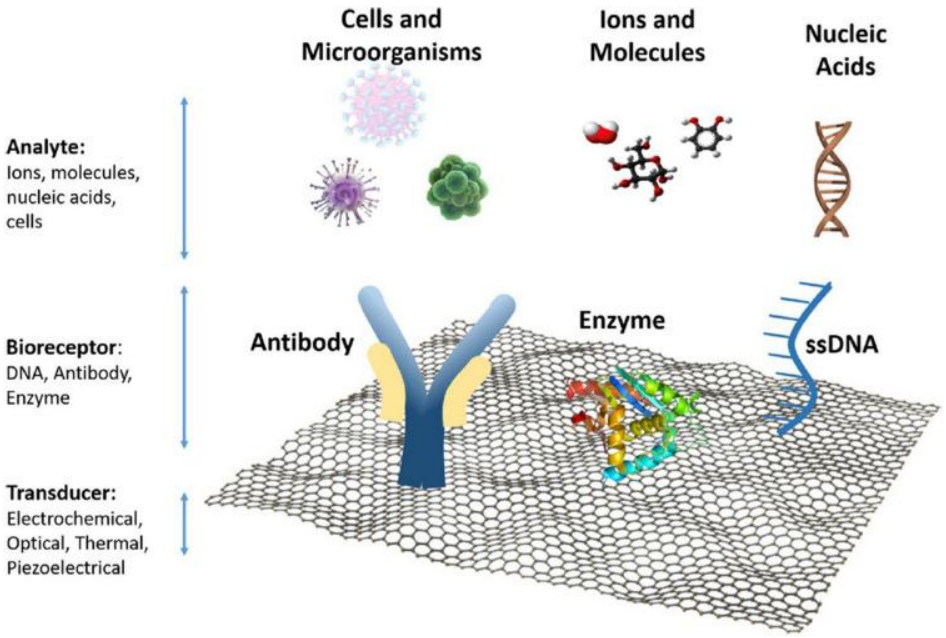


Figure 2. Graphene-based biosensors and their constituent parts [3]

The combination of graphene and optofluidic/electrochemical microfluidic systems is garnering significant interest in the realm of biomarker detection, particularly for its ability to enable highly sensitive and multiplexed sensing capabilities. Colleagues of Trau engineered a microfluidic system that harnesses graphene oxide (GO) and biochips made of gold for the precise detection of cellular and protein components within human serum samples. The GO employed in their setup features negatively charged oxygen-substituted groups at physiological pH, and its hexagonal, aromatic lattice encourages bonds via hydrogen bonds, electrostatic interactions, hydrophobic van der Waals attractions, and π–π stacking, allowing for the attachment to protein analytes. The GO-derived biochip showcased enhanced biomarker capture yields and diminished detection thresholds in serum, noting a novel progress. By employing functionalized GO on a gold surface as a potent sensing platform, the researchers managed to entrap and profile individual cells (at a concentration of 10–20 cells per mL) and proteins (down to 10 fg/mL) from human serum, indicating a potential early warning system for illnesses [4].

3.2. DNA Detection

The minuscule volume of nanomaterials allows for the detection of the presence and alterations in DNA sequences. Plasmonic nanomaterials, particularly those composed of gold (Au) and silver (Ag), have exhibited appealing physicochemical characteristics, including facile functionalization and the ability to tunes their optical absorption bands. The advancement of this dynamic field has cleared the path for the creation of sophisticated biosensing platforms. Recently, plasmonic nanomaterial-based

sensors have garnered extensive scholarly interest for their applicability in the diagnosis of genetic disorders, elucidation of biological mechanisms, augmentation of device functionality, and advancement of cellular imaging methodologies [5]. DNA probes, which upon binding to the target DNA sequence, can cause a change in solution color or alteration in optical signal. In this study, we introduce a novel reversible shearing DNA-based tension probe (RSDTP) that is capable of measuring molecular forces at the piconewton scale (4–60 pN) transmitted by cells. The RSDTP allows for the straightforward discrimination of force-bearing integrins without disrupting adhesion biology. Our findings indicate that a robust cluster of integrins bearing force can function as a 'mechanical pivot,' supporting the maintenance and maturation of focal adhesion architecture. The advantages of the RSDTP lie in its high dynamic range, reversibility, and single-molecule sensitivity, which collectively contribute to a deeper comprehension of the molecular underpinnings of mechanobiology [6].

3.3. Pathogen Detection

Nanomaterials are applicable in the detection of pathogens such as bacteria and viruses, enabling rapid and sensitive detection for prompt diagnosis. Here we can introduce the carbon nanomaterial. The presence of foodborne pathogens can pose significant risks to food safety and public health. Consequently, there is a critical need to establish rapid, sensitive, and cost-effective methods for the detection of these pathogens. Traditional detection methods are often characterized by their slowness, low efficiency, and high expenses, in contrast to electrochemical biosensors, which offer simplicity, speed, high sensitivity, miniaturization, and affordability. These attributes make them highly suitable for the rapid identification of foodborne pathogens. Over the past few years, carbon nanomaterials have increasingly been utilized in the development of electrochemical biosensors for the detection of foodborne pathogens, due to their excellent electrical conductivity, stability, and compatibility with biological systems [7]. So far, nanomaterial-based biosensors have many applications in pathogen detection. Nanomaterials can be broadly categorized into various shapes and structures, including 0D entities such as quantum dots and carbon dots, along with various types of nanoparticles. They also encompass 1D materials like nanotubes, nanowires, and nanorods. Further, there are 2D materials consisting of nanoplates, nanosheets, and nanodisks, as well as 3D materials which include nanoflowers, nanocones, and nanoballs.

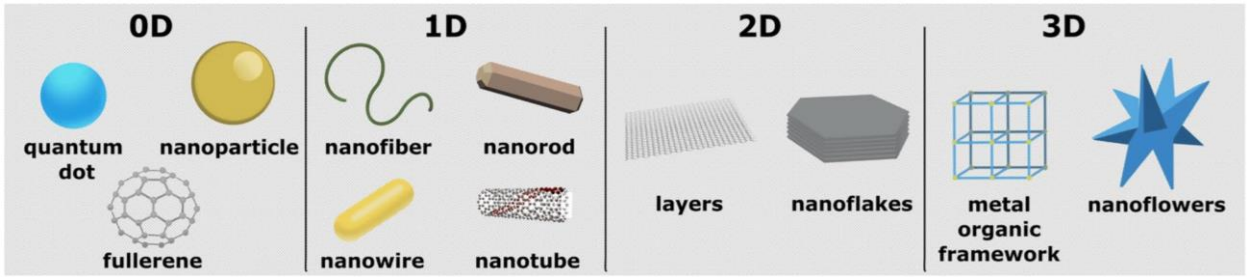


Figure 3. Explanation of some 0–3D nanostructured material morphologies [7]

Nanomaterials, as shown in Figure 3, spanning from 0D to 3D in structure, have extensively been integrated into the construction of electrodes in the electrochemical biosensors employed for the identification of some foodborne pathogens. In the 0D category, nanoparticles are prevalent, which often include metals or metal oxide nanoparticles, carbon dots, and quantum dots. Gold nanoparticles, in particular, are favored for their high conductivity and biocompatibility, along with their capability to retain biomolecule activity over time. Quantum dots, due to their small size and reliable stability, are promising for use in compact electrochemical sensing devices. Quantum dots are classified into three main types: metallic QDs, carbon dots (CDs), and graphene quantum dots (GQDs).

For electrochemical biosensing, one-dimensional (1D) nanomaterials like carbon nanotubes and metal oxides, which are produced as nanowires, nanotubes, or nanorods, are commonly used.

Since the discovery of graphene in 2004, two-dimensional (2D) nanomaterials have come to the forefront. They are known for their thin atomic layers and adjustable electronic properties, while also displaying good mechanical integrity and reactivity. Their high surface-to-volume ratio makes them

ideal for applications in electrochemical biosensing, gas sensing, energy conversion, and storage, among others in the biomedical field. In addition to graphene and its variations, research is also centered on the advancement of other emerging 2D nanomaterials such as boron nitride, graphitic carbon nitride, transition metal dichalcogenides, MXenes, black phosphorus, transition metal oxides, and more recently, heterostructures that incorporate at least one 2D nanomaterial. Metal oxides, when expanded into monolayers, can create a 2D oxide nanostructure.

In the realm of electrochemical biosensing for foodborne pathogens, the most prevalent 3D nanomaterial structures are metal oxides, frequently grown as nanoflowers or other 3D arrangements. Additionally, carbon allotropes like laser-induced graphene have gained attention recently. Nanomaterials with inherent conductivity, including metal oxides, carbonaceous materials, and metal nanoparticles, significantly improve the sensitivity and functionality of electrical signal-based sensing devices. Moreover, the combination of two or more 0–3D nanomaterials can lead to synergistic effects, resulting in a nanocomposite heterostructure on the same electrode surface, further improving biosensing capabilities [8].

4. Conclusion

In conclusion, all these biosensors are just a few examples of nanomaterial biosensors. The development prospect of biosensors based on nanomaterials is very broad. The high specific surface area and unique properties of nanomaterials enable the provision of more reactive sites compared to other materials, enhancing the interaction with biomolecules and thereby improving the detection sensitivity and selectivity of biosensors. The modulation and functionalization of nanostructures allow for precise capture and recognition of target biomolecules. About multifunctionality and integration, the high plasticity, or multifunctionality, of nanomaterials has led to the combination of various detection methods, such as optical, electrochemical, and biochemical techniques. Furthermore, nanomaterials can be integrated with other materials, such as microelectronic devices, to extend the functionality and of sensors. The rapid response speed and small size of nanomaterials make them suitable for rapid and portable detection applications. This contributes to real-time, prompt, and precise detection results in fields such as medical diagnosis, food safety monitoring, and environmental pollution detection, enhancing the efficiency and accuracy of detection. These properties show the rapid and portable detection of nanomaterials biosensors. Novel materials and infinite possibilities in structural design. The unique properties and structures of nanomaterials can be optimized through design, synthesis, and optimization to improve their efficiency and quality. For instance, the emergence of two-dimensional nanomaterials offers more possibilities for biosensors and broadens the application range and performance of sensors. Additionally, nanomaterials biosensors have wide range of applications. Areas like healthcare, food safety, environmental monitoring, and drug development benefit from nanomaterials in biosensors. About potential challenges, issues related to stability, biocompatibility, production cost, and working efficiency of nanomaterials in biosensors still need to be addressed. However, with technological advancements, these challenges are expected to be overcome.

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