Principles of Biomimetic solid-state nanopores and the application to biosensors

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Abstract. The wide application of biomimetic solid-state nanopores in biosensors has made them a high-profile research area. It can be applied in several fields such as genomics, proteomics, biomedicine, and environmental monitoring. Bionic solid-state nanopores have demonstrated the capability to detect biomolecules and creatures, including proteins, nucleic acids, cells, and microbes, with a notable degree of sensitivity and selectivity. Biomimetic solid-state nanopores offer several advantages over conventional biosensors. An innovative kind of biosensor is called biomimetic solid state nanopores. This study provides a comprehensive overview of the principle, construction, and use of the bionic solid state nanopore sensor. Bionic solid-state nanopores are of significant importance within the realm of biosensors. Firstly, it has micrometer or nanometer scale, which can effectively capture and control target molecules; Additionally, the dimensions of the biomimetic solid-state nanopores can be modified, along with the surface functionalization, in order to enhance the performance of the sensor and expand its potential applications. In addition, the structural stability and reusability of biomimetic solid-state nanopores also guarantee the long-term application of biosensors. Through in-depth research and development, it is expected to promote the technological progress in the field of biosensors, and provide more accurate and reliable detection methods for life science, medical diagnosis, environmental protection and other fields.

Keywords: Biomedicine, testing, biomimetic solid-state nanopores, biosensors.

1. Introduction

As an important technical tool, biosensors have been widely used in medical diagnosis and environmental monitoring. Traditional biosensors usually use the specific interaction of the biometric molecule with the target molecule to achieve detection and analysis. However, conventional biosensors have some limitations in terms of sensitivity, selectivity, and real-time monitoring [1].

To overcome the limitations of traditional biosensors, researchers have begun to focus on biomimetic solid-state nanopores, a novel biosensor technology[2]. By replicating the pore structure and function seen in biological systems, biomimetic solid-state nanopores can be designed that are very sensitive and selective in their ability to detect biomolecules and organisms.

The field of biosensors has witnessed significant interest in biomimetic solid-state nanopores due to the rapid advancements in nanotechnology and materials science. The principle is based on the formation of a solid material matrix and the specific interaction of target molecules with biological recognition molecules. Achieving highly sensitive detection of target molecules can be accomplished by manipulating the dimensions, morphology, and surface characteristics of nanopores.

The application of bionic solid-state nanopores in biosensors has also been increasingly studied. The application of this technology has demonstrated success in diverse domains, including biomedicine and environmental monitoring. Bionic solid-state nanopores possess the ability to selectively and in real-time detect various biomolecules and creatures, including proteins, nucleic acids, cells, and microbes.

In this paper, we will delve into the principles of bionic solid-state nanopores and their applications in biosensors [1]. This study will primarily concentrate on the particular instances where biomimetic solid-state nanopores have been employed in the domains of biomedicine, environmental monitoring, and related professions. Additionally, we will explore the anticipated directions for future advancements in this area. By understanding and studying biomimetic solid-state nanopores, hoping to promote innovation in the field of biosensors, making the diagnosis of biosensor in life science, medical and environmental protection and other fields to play a bigger role.

2. Biomimetic solid state nanopores

2.1. Principle

Biomimetic solid nanopore is a kind of nanopore, which is inspired by biological ion channels to construct bionic intelligent nanopore with similar functions as biological ion channels. The principle of biomimetic solid-state nanopores is based on the function of ion channels in living organisms. Ion channel is a kind of protein channel that has the function of selective ion transport in organism. Selective ion transport can be achieved through the manipulation of the channel's pore size and shape. Solid-state nanopores that mimic ion channels by manipulating surface modifications and material properties are known as "biomimetic solid-state nanopores"[1].

2.2. Film Material

The creation of biomimetic solid state nanopores relies heavily on thin film materials, and the choice of these materials is directly influenced by their properties. By selecting appropriate film materials, the size, shape and properties of nanopores can be controlled, so as to realize the functions of bionic solid nanopores in different fields. There are many kinds of thin film materials, such as polymer film, metal film, ceramic film and other thin film materials.

2.2.1. Polymer film

The polymer exhibits remarkable flexibility and processability, while the dimensions and configuration of the nanopore can be manipulated through modifications to the polymer's composition and structure. Common polymer films are polyether sulfide (PES) film, polystyrene (PS) film, polyimide (PI) film [2], polycarbonate (PC) film and polyester (PET) film. These polymer films also have good biocompatibility and can be used in fields such as biosensing and drug delivery.

2.2.2. Metal film

Among the biomimetic solid nanopore thin film materials, metal thin film is also a common one. These metal films are often used as carriers for the preparation of biomimetic solid nanopore films or as part of the films to enhance the mechanical properties of the films or to provide electrical conductivity. Aluminum, copper, silver, titanium, and platinum are common metal film constituents. Aluminum film is one of the most commonly used metal carriers for the preparation of solid nanoporous films. Aluminum has good workability and conductivity, and is relatively cheap, so it is widely used in the preparation of large area solid nanoporous films [2].

2.2.3. Ceramic film

Ceramic films are also a common type of film materials for bionic solid state nanopores. Ceramic materials are composed of non-metallic elements, such as alumina, silicon oxide, silicon nitride, etc., which have excellent heat resistance, corrosion resistance and hardness, and are suitable for some special environment applications [3].

2.2.4. Other thin film

In addition to polymer, metal, and ceramic thin films, there are several other materials that can be applied to biomimetic solid-state nanopores. For example, some two-dimensional (2D) layered materials like graphene, mica [4]. The remarkable in-plane conductivity of graphene enables it to have a diverse array of uses. Mica is very suitable for biomimetic solid state nanopore technology due to its chemical inertia, insulation and electric heating.

2.3. Fabrication and Surface Modification

The manufacture and surface modification of biomimetic solid-state nanopores play a crucial role in preparing these structures for their diverse applications in many sectors. Through the study of preparation methods, bionic solid nanopores with controllable size and stable structure can be successfully prepared. At the same time, through the optimization of the surface modification method, the surface properties of the bionic solid nanopores can be adjusted to further improve their application performance.

The common preparation methods of bionic solid-state nanopores include template method, ion beam etching method and self-assembly method. The template approach is a frequently employed technique in the fabrication of biomimetic solid-state nanopores. In this method, the pore structure of the template material is used as a template to deposit nanomaterials on its surface, followed by the removal of the template to obtain solid nanopores [5]. Common template materials include barrier membranes, porous silicon and metal-organic frameworks. The control of bionic solid-state nanopore size and structure can be achieved by modifying the pore size and form of the template. Ion beam etching is a method of forming nanopores on the surface of materials by bombarding them with ion beams. This method takes advantage of the high energy and small beam diameter of the ion beam, which can form nanoscale pores on the surface of the material [3]. The form and size of bionic solid-state nanopores can be controlled by adjusting the ion beam energy, density, and other parameters. The self-assembly technique, which utilizes intermolecular interactions to organize nanopores in a self-assembling manner, has been extensively employed in the production of unique functional materials and ion channel constituents [3].

There are also many surface modification methods. Chemical modification is a commonly used method for surface modification. By introducing chemical modification groups on the surface of bionic solid nanopores, the surface properties and functions of nanopores can be controlled. The commonly used chemical modification methods include self-assembling monolayers, surface polymerization, and chemical modification reactions [6]. By selecting different chemical modification groups and reaction conditions, the surface properties of nanopores such as hydrophilicity, hydrophobicity, charge and biocompatibility can be regulated. Metal anodization is a powerful method for the formation of dense nanotubule-like anodized films by modifying the anodization conditions appropriately to modify the surface of the formed oxide [3]. Biomodification is a method to modify biomimetic solid-state nanopores using biomolecules. Using the specificity and selectivity of biomolecules, applications such as biological recognition of nanopores and biomolecule separation can be realized [7]. Commonly used biological modification methods include antibody modification and enzyme modification. Efficient biological recognition and biological separation of biomimetic solid-state nanopores can be achieved by selecting appropriate biomolecules and modification strategies.

3. Biomimetic solid-state nanopore biosensors

3.1. Principle

The underlying idea of biosensors utilizing bionic solid-state nanopores is the transportation of ions in the electrolyte solution through the nanopores upon the application of voltage across both ends of the nanopores. Selective interaction between a target molecule or ion and biomolecules can be achieved when the former traverses a biomimetic solid-state nanopore, facilitated by surface modification of stated nanopore. For example, appropriate biomolecular recognition elements such as antibodies, DNA probes, or enzymes can be introduced on the nanopore surface. When target biomolecules interact with surface-modified nanopores, the properties of ion transport can be altered, leading to changes in the current signal. These changes can be captured and recorded by sensor devices, and information about the target substance can be obtained by analyzing these signals.

3.2. Application

As an emerging sensor technology, biomimetic solid-state nanopore biosensor has the characteristics of high sensitivity, high selectivity and high stability, and has shown broad application prospects in many fields.

In the fields of genomics and proteomics, bionic solid-state nanopore sensors can be used for efficient and high-precision DNA sequencing and protein analysis and identification. The passage of DNA molecules through nanopores elicits a modification in electrical current. According to the characteristics of the current signal, the base sequence of DNA can be determined and DNA sequencing can be realized [8]. Protein molecules can also pass through nanopores, and different protein molecules will produce different current signals [6]. By analyzing the pattern of current signals, the species and structure of proteins can be determined.

Biomimetic solid-state nanopore biosensors have great potential for medical detection. It can be used to detect various disease markers in organisms, such as tumor markers, heart disease markers, and infectious pathogens markers. Using the special structure and sensitivity of nanopores, sensors can detect low concentrations of markers to help doctors diagnose and monitor diseases at an early stage. Bionic solid-state nanopore biosensors have the capability to detect mutations in DNA sequences as well [9]. Through nanopore conductance measurements or changes in current characteristics, base mutations or gene deletions or rearrangements in DNA sequences can be detected, thereby helping doctors to diagnose genetic diseases and genotype analysis. Bionic solid-state nanopore biosensors can also analyze various components in blood, such as proteins, cells, metabolites, etc. Through the selective identification and response characteristics of nanopores, the concentration or characteristics of different components in blood can be quantitatively measured, providing important information for disease diagnosis and treatment [10]. It can also be used to monitor drug metabolism in the human body. Sensors can detect the transport behavior of drugs and their metabolites in nanopores to evaluate the rate of drug metabolism in vivo, the generation of metabolites. This is very important for the formulation of drug efficacy and drug use regimens.

Bionic solid-state nanopore sensors has a diverse array of potential uses within the realm of environmental studies. Biomimetic solid-state nanopore biosensors can be used to monitor pollutants and environmental indicators in water bodies. Sensors can detect heavy metals, organic pollutants, microorganisms, etc. in water and provide rapid and accurate water quality assessment. This is essential for safe drinking water, environmental monitoring and water resource management. In addition, it can also detect air pollution and soil pollution, which plays a great role in protecting the ecosystem. In addition, bionic solid-state nanopore sensors can also be used for seawater desalination by using nanoporous monolayer graphene to effectively desalinate seawater [4]. It may even solve the world's fresh water shortage in the future.

4. Summary

Biomimetic solid-state nanopores are a biosensor technology that exhibits a diverse array of possible applications. Bionic solid-state nanopores have the potential to provide exceptional sensitivity and selectivity in detecting biomolecules and organisms by replicating the pore shape and functionality found in biological systems. In the field of biosensor, it has been successfully applied in biomedicine and environmental monitoring.

By deeply understanding and exploring the principles of bionic solid-state nanopores, we can find their uniqueness. The micrometer or nanometer scale of biomimetic solid-state nanopores can trap and control target molecules. In addition, the sensor performance and application range can be further optimized by adjusting the pore size and surface functionalization. Its structural stability and reusability also increase the feasibility of long-term applications of biosensors.

By applying bionic solid-state nanopores in biosensors, we can achieve rapid, accurate and reliable detection of target molecules such as proteins, nucleic acids, cells and microorganisms. In the biomedical field, this can help early disease diagnosis and personalized treatment, while in the environmental monitoring, it can provide timely and effective detection and monitoring means.

Despite the significant advancements achieved in the realm of biosensors through the utilization of biomimetic solid-state nanopores, there remain a number of obstacles and prospects that warrant attention. Future research should focus on further optimizing nanopore performance, improving sensitivity and selectivity, achieving multiple target detection, and achieving better integration and automation techniques. Through continuous innovation and development, bionic solid-state nanopores are expected to bring revolutionary progress to the field of biosensors and make important contributions to the development of many other fields.

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