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Mini Review

Nanowire-Based Biosensors for the Recognition of Diverse Bioagents

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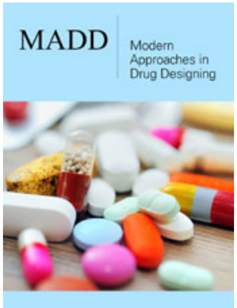

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Abstract

Nanowires (NWs) are one-dimensional nanomaterials with a very high surface-area-to-volume ratio, as well as good durability, which have attracted researchers for use in sensing materials. The advancement of nanowire manufacturing processes and modification methods have made nanowire-based biosensors viable in a wide variety of research fields, counting protein biomarker discovery, metal ion detection, and drug discovery. Nanowires are best suited for biomedical sensors due to their high sensitivity, homogeneity, reproducibility, scalability, and easy fabrication process. This review evaluates an array of nanowire-based biosensors suitable for detecting a wide range of biological compounds. We expect to see more advancements in nanowire research and biosensor development in near future.

Keywords: Biosensors; Nanowires; Sensors; Nanotechnology; Vivo-sensing

Introduction

The quantification and interpretation of biological processes are crucial for biomedical applications and cellular programming research. However, due to the constraints of coupling electronic equipment into a biological environment, transferring biological information into an electronic signal is difficult. Among the applications of biomedical sensors are the detection and characterization of chemical and biological species, including those used in diagnosis and drug discovery. A nanowire (NW) is an anisotropic, one-dimensional structure with a high surface-to-volume ratio [1]. A nanowire biosensor is a sensor or measuring device composed primarily of a nanowire or nanofiber formed by a biological molecule, such as DNA, polypeptides, fibrin proteins, or filamentous bacteria. Nanowires with distinct optical, magnetic, and electrical properties are well suited to biomedicine's primary functions [2,3] Nanostructures made of nanowires are the best choice for biomedical sensors because they are highly sensitive, consistent, reproducible, scalable, and the production process is simple. NWs have a wide range of uses, including drug delivery [4], sensors, magnetic storage [5], biomedicine [6], water purification [7], and electronics. This review will concentrate on biosensors made from nanowires and employed in the detection of various ailments.

Proteins

In proteomics and genomics research, many new biomarkers have been identified which are nanowires based [8-10]. Several nanowire-based platforms have been developed to simultaneously detect multiple disease markers, including nanowire array-based platforms that could help in diagnosing diseases [11-13]. The detection of multiple biomarkers is also essential for the treatment of cancer, as they can identify the stage of the disease [14,15]. Furthermore, a broader range of biomarkers, such as cardiac biomarkers, can now be detected [16]. Additionally, nanostructured sensing platforms have been demonstrated to be capable of detecting many proteins without using labels, making it possible to diagnose pregnancy [17] and diseases such as diabetes [18], Parkinson's [19,20] and atherothrombosis. Maya and her colleagues demonstrated a label-free and effective technique for determining prostate-specific antigens in human serum using a Nanowire Field-Effect Transistor (NW FET) [21]. Their biosensors produce better electrical performance and pH sensitivity by adding GNPs to increase the surface-to-volume ratio of silicon nanowires. By using linear voltammograms with silicon nanowire arrays coated with Au nanoparticles, we demonstrated a promising biosensor that can readily be controlled and manufactured into electrodes for detecting BSA in PBS solution [22]. Because of the upgraded silicon nanowire arrays' robust sorption ability and high electrical conductivity, the sensor displayed superior linear response and high sensitivity. Using a SiNW-FET, Zheng et al. developed a new protein detection technology that involves electrical measurements of frequency (f) domains. In buffer solution measurements of antibody-functionalized SiNW-FET devices antibody receptor, the power spectral density of voltage or the presence of protein not specific to the antibody receptor, from a current biased SiNW-FET displays 1/f-dependence in the frequency domain. In the presence of the protein (antigen), the frequency spectrum has a Lorentzian form with a characteristic frequency of several kHz that may be detected uniquely by the antibody-functionalized SiNW-FET. The binding events were tracked and a detection limit was calculated using the frequency spectrum structure. A novel technology for frequency-domain measurements has been reported to increase detection sensitivity by tenfold. There have been recent developments in the development of nanowire-on-a-chip platforms for the detection of biomolecules, in which nanowires execute preconcentration, separation, filtering, and detection, allowing the rapid and practical clinical application.

DNA/RNA

Nanowire sensors can detect specific DNA and RNA sequences [23,24]. Silicon nanowires are composed of single-stranded sequences of PNAs organized to function as receptors. Nanowires are also capable of detecting the bonding between proteins and DNA in addition to detecting individual strands of DNA. A label-free method for detecting virus genes has also been developed with nanowire biosensors. Using exonuclease III to recycle the target, Huang et al. [25] achieved a LOD (Limit of Detection) of 3.6pM by amplification of the detected signal [25]. Nanowires-based DNA sensors could be used to detect and treat cancer-based on monitoring telomerase and carcinoembryonic antigen at the DNA level [26]. A bio-sensing configuration is suggested for analyzing hepatitis B virus deoxyribonucleic acid (HBV DNA) diagnosis, including swift screening and Field-Effect Effect Transistor (FET) in the label-free assay [27].

Viruses

Since many viruses cause serious human diseases and can be used to create biological weapons, nanowire sensors are critical for keeping our societies safe and healthy. Several dangerous viruses have been detected using Si nanowire sensors, including Dengue [28-30], influenza A H3N2, H1N1 [31,32], and HIV. Shen et al discovered that using a nanowire-based biosensor, as many as 29 influenza viruses/μL could be detected from Exhaled Breath Condensate (EBC) samples [33]. As a point-of-care diagnostic tool, nanowire biosensors are expected to play an increasingly crucial role due to their ease of use, accuracy, and rapidity.

Vivo sensing

Nanowires are predominantly used in vitro for traditional applications. However, in recent times, there has been a growing interest in measuring bio-signals continuously *in vivo*. Nanowires are not stable when used with cells, according to early studies. Zhou et al. [26] developed a method for coating nanowires to enhance their long-term stability [34]. This coating method was successful for Si nanowire as well as Si-Ge and InAs complexes, although nanowire sensitivity decreased with increasing shell thickness. In any case, this approach improves the long-term stability of nanowires in complex environments, thereby giving rise to the idea of using nanowires for *in vivo* injectable electronics in the future. To create a chemiresistive biosensor for sensing Bacillus globigii, a bioterrorism agent simulant, polypyrene nanowires (Ppy) were assembled onto microfabricated gold interdigitated microelectrodes [35]. An effective biosensor with a 1 CFU/mL detection limit and a dynamic range of 100 CFU/mL was created using PB 10mM. Ni nanowires can damage DNA, change genes, and oxidize cells. However, these negative effects were not directly correlated with cytotoxicity or mutagenesis. As a result, existing studies suggest that nanowires and cells interact very sophisticatedly. It is therefore critical that additional studies be conducted to understand and minimize potential toxicity induced by nanowires *in vivo*.

Glucose detection

Glucose monitoring with high precision, superior selectivity, and high throughput remain a barrier in food quality management (such as red wine and beverages) and human blood, despite significant advances in glucose monitoring. Many nanomaterials, notably in the recent decade, have been employed to build glucose biosensors due to their large specific surface area and exceptional physical and chemical properties. Using silver nanowires (AgNWs), this paper reported the development of an amperometric glucose biosensor [36]. Glucose oxidase (GOx) was immobilized onto a linker coupled to ZnO nanowires to develop ZnO-nanowire-based glucose biosensors [37]. To evaluate the influence of the coupling agent, they measured the amount of GOx immobilized on ZnO nanowires, the performance and sensitivity of each biosensor, as well as its Michaelis-Menten constant and electron transfer resistance via the biosensor. Analyzing glucose by amperometry using orientated nanowires and magnetic switching of a bio-electrochemical process has also been done [38]. The biosensor that resulted had a good amperometric response to glucose in PBS and human blood serum. It also has several other appealing characteristics, such as quick reaction, long-term storage stability, excellent repeatability, and satisfactory anti-interference ability. Rafiee and their coworkers presented the modification of ZnO nanowires through the inclusion of Graphene Nanoplates (GNPs) beneath the ZnO NWs to develop a high-performance glucose biosensor [39]. By implanting graphene nanoplates beneath the ZnO NWs, the sensitivity to glucose at room temperature was improved dramatically. In comparison to the ZnO NWs-based glucose biosensor, the suggested graphene-based ZnO NWs glucose biosensor has a shorter response time, higher responsiveness, and superior stability. Researchers have developed glucose biosensors using Carbon Nanotubes (CNTs) and Reduced Graphene Oxide (rGO) nanosheets coupled with gold nanowire arrays (AuNWAs) for glucose detection [40]. Because of the integration of CNTs and rGO nanosheets, glucose biosensors obtained good sensitivity and a wide linear range at a low working potential of -0.2V vs Ag/AgCl. Graphene foam/hematite (GF/-Fe_2O_3) nanowire arrays hetero-structured nanocomposite electrodes were developed for the detection of glucose [41]. Graphene foam is used as an active backing layer because it has a large surface area, which allows high electron transfer rates and greater electrochemical responsiveness. Large quantities of glucose oxidase were immobilized by increasing the surface area of the electrode.

Additional detections

WO3 nanowires with a high length-diameter ratio was synthesized using just a straightforward synthetic approach with no additives and then used to create mediator-free biosensors for NO_2-sensing [42]. Biosensors made of WO_3 nanowires perform better due to their unique morphology and properties. WO_3 nanowires could trap Hb by forming a web of tightly woven nets on the electrode, as well as promote direct electron transport. This study used pseudobienzyme cascade amplification and direct electron transfer of multifunctional hemin/G-quadruplex nanowires to construct an electrochemical biosensor for exceptionally sensitive Pb^{2+} detection [43]. The hemin/G-quadruplex nanowires improved the electrochemical signal by allowing electron transport to the electrode while also acting as NADH oxidase and HRP-mimicking DNA zymes. Using palladium-copper nanowires (Pd-Cu NWs), an electrochemical biosensor for acetylcholinesterase (AChE) analysis of organophosphate pesticides (OPs) in vegetables and fruits has been developed [44]. Furthermore, the OPs biosensor has been used to analyze malathion in commercial vegetable and fruit samples, with exceptional recoveries ranging from 98.5 to 113.5 percent. For noninvasive lactate monitoring in human sweat, the use of Ag Nanowires (AgNWs) and Molecularly Imprinted Polymers (MIPs) on screen-printed electrodes has been proposed [45]. Additionally, the sensors exhibited superior stability and reproducibility, with sensitivity recovery of 99.8 percent to 1.7% after 7 months in a dark plastic box at ambient temperature. Furthermore, after being bent and twisted 200 times, the flexible electrodes displayed a steady electrochemical response. Based on aptamer-modified sandwich-structured ZnCuInSe/Au/TiO_2 nanowires, a highly selective and sensitive Photoelectrochemical (PEC) sensing platform for the kanamycin test was established [46]. The suggested sensing platform had a linear response range of 0.2 to 250nm. and high selectivity based on kanamycin test results. A new sensor platform based on silicon nanowires/reduced graphene oxide nanocomposite for the detection of cyclohexane and formaldehyde has been developed [47]. The developed sensor was utilized to identify biomarkers of infectious diseases in a simple, low-cost and non-invasive manner.

Conclusion

Nano biosensors are biosensors that utilize nanostructures and have remarkable performance and responsiveness due to their high level of sample stability. It is extremely advantageous to utilize nanowires in the construction of electrochemical sensors and biosensors due to their mechanical stability, low weight, current augmentation, and potential reduction characteristics. Nanowire sensors with customized receptors have shown significant potential in medical and biological diagnostics. A nanowire sensor is intrinsically beneficial if the platform is constructed in such a way that it supports the interrogation of the entire sample volume. It is, however, their ability to detect limit ranges, sensitivity, and other features that make sensors successful, all of which are bolstered by nanowire-modified electrodes. Researchers and industry will rely heavily on nanowire sensors in the next few years.

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