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Recent advances in nanowires-based field-effect transistors for biological sensor applications

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ABSTRACT

Nanowires (NWs)-based field-effect transistors (FETs) have attracted considerable interest to develop innovative biosensors using NWs of different materials (i.e. semiconductors, polymers, etc.). NWs-based FETs provide significant advantages over the other bulk or non-NWs nanomaterials-based FETs. As the building blocks for FET-based biosensors, one-dimensional NWs offer excellent surface-to-volume ratio and are more suitable and sensitive for sensing applications. During the past decade, FET-based biosensors are smartly designed and used due to their great specificity, sensitivity, and high selectivity. Additionally, they have the advantage of low weight, low cost of mass production, small size and compatible with commercial planar processes for large-scale circuitry. In this respect, we summarize the recent advances of NWs-based FET biosensors for different biomolecule detection i.e. glucose, cholesterol, uric acid, urea, hormone, proteins, nucleotide, biomarkers, etc. A comparative sensing performance, present challenges, and future prospects of NWs-based FET biosensors are discussed in detail.

1. Introduction

The rapid development of nanoscience and nanotechnology has created an overwhelming stream of opportunities to manufacture nanosized systems that perform specific electrical, mechanical, biological, chemical, or computing tasks (Huang et al., 2011b; Monopoli et al., 2012). It is well known, when the materials size are brought to nanoscale sizes they suddenly display very different properties compared to their original properties as a bulky material (Vigneshvar et al., 2016). A variety of nanomaterials has been synthesized using different preparation methods (Yang et al., 2015; Sadeghian et al., 2017; Ahmad et al., 2017a, 2017b, 2017c; Ashley et al., 2017; Luong and Vashist, 2017; Shrestha et al., 2017). Among diverse nanomaterials architectures, NWs are highly functional structures and offer unique properties due to their one dimensionalities. Especially, the electrical conductivity through NWs is greatly affected by the biological/chemical species adsorbed on their surface. Hence, NWs are effectively used to develop nanoscale devices with enhanced sensing performances.

NWs have been used for the integration/immobilization on biosensing devices for clinical, environmental, and industrial applications, which generates novel interfaces that offer improved sensitivity and efficiency to target analytes. Bioanalysis in general and biosensor fields in particular are showing special interest in NWs due to rapid response, small size, and high sensitivity and portability. Moreover, newer NWs with particularly impressive, robust and economically feasible platforms may provide high current amplification and sustain an enhanced signal-to-noise ratio among all the detection methodologies owing to their excellent sensitivity, label-free, real-time response for bio- and chemical molecule detection (Turner, 2013; Citartan et al., 2013; Sang et al., 2015). Other nanomaterials (bulk or non-NWs) nanostructures are also used for the fabrication of FET-based sensing devices. However, such devices made of bulk or non-NWs materials offer poor sensitivity due to the high dimensionality and lower surface-to-volume ratio.

The FET-based biosensors are advantageous over other methods due to the accumulation of charge on the nanomaterials channel between source-drain (S-D) electrodes, which gets affected by external fields and allow rapid analysis of different analytes with great specificity, sensitivity, and high selectivity (Han et al., 2017; Majd et al., 2017; Kaisti, 2017). Recently, FET-based biosensing devices were reported with high sensitivity and easy fabrication process, compared to other biosensing devices (Chen et al., 2011b; Rubtsova et al., 2017; Arya et al., 2015; Huang et al., 2015; Zheng et al., 2015; Zhang et al., 2016; Piccinini

Abbreviations: IGZO, Indium gallium ZnO; CMOS, Complementary metal-oxide semiconductor; PAC, Polymer-like amorphous carbon; AFP, Anti-α-feptoprotein; PSA, Prostate specific antigen; cTnT, Cardiac troponin T; CEA, Carcinoembryonic antigen; PNA, Peptide nucleic acid; APTES, 3-aminopropyltriethoxysilane; BSA, Bovine serum albumin; ALD, Atomic layer deposition; PEDOT, Poly(ethylene dioxythiophene); PSMA, Prostate-specific membrane antigen; AMPs, Antibody mimic proteins

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et al., 2017; Jin et al., 2015; Lee et al., 2015b; Tran et al., 2016; Mao et al., 2016; Kim et al., 2016; Minami et al., 2016; Tan et al., 2015; Park et al., 2016; Puchnin et al., 2017). Additionally, FET-based biosensing devices have the advantage of low-weight, low-cost of mass production, small size and compatible with commercial planar processes for large-scale circuitry. During biological fragments analysis, these biosensing devices directly concert the biological actions into electronic signals, which can be the shortest route of detection. Therefore, development of new nanostructured materials for FET-based biosensor fabrication drew more attentions. In this context, this review summarizes the recent advances of NWs-based FET biosensors for different biomolecule detection. Utilization of various materials NW, comparative sensing performance, limitations, present challenges, and future prospects of NWs-based FET biosensors are also discussed.

2. FET-based biosensor

Since the development of first FET in 1970, there has been the major drive to utilize FET-based biosensor devices for different analytes detection (Bergveld, 1970; Balasubramanian, 2010; Cella et al., 2010; Artiles et al., 2011). In these biosensors, current flows along a semiconductor path (the channel) that is connected to two electrodes, S-D. When charged molecules exist on the surface of the FET biosensors, the channel conductance between S-D can be controlled by a third (gate) electrode that is capacitively coupled through a thin dielectric layer (Liu and Guo, 2012; Shoorideh and Chui, 2014). In such devices for insulation, an oxide is used as a gate dielectric, such as silicon dioxide (SiO_2) (Scheme 1a). It also contains a p-type silicon substrate (bulk). Where the negative gate potential leads to the accumulation of holes (majority charge carriers), resulting in an increase of the channel conductance, while the positive gate potential leads to the depletion of holes and hence decrease the conductance. The adsorption of molecules on the surface of the semiconducting channel either changes its local surface potential or directly dopes the channel, resulting in the change of FET conductance. This makes the FET a promising sensing device with easily adaptable configuration, enhanced sensitivity and real-time capability. Additionally, the nonspecific absorption problem is solved using smart chemistry to prevent the fouling of the surface when device is exposed to complex media i.e. human serum/blood (Cheran et al., 2014).

However, in solution-gated FET biosensors, the analytes are detected in an aqueous environment (Scheme 1b). From the scheme, the semiconducting NWs channels are immersed in a flow or sensing chamber, which is used to confine the solution. In such FET biosensors, the source and electrodes are insulated to prevent current leakage from ionic conduction using insulators i.e. poly(methyl methacrylate), poly (dimethylsiloxane)/silicone rubber, SiO_2 thin film, SU8 passivation, and silicone rubber (Yang and Zhang, 2014; Huang et al., 2010, 2011a; Kergoat et al., 2012; Chen et al., 2013; Feigel et al., 2011; Sudibya et al., 2011). The gate electrode (Ag/AgCl or Pt) is immersed in the solution. Due to the small size of devices, use of a conventional reference electrode limits seriously. Therefore, the development of a miniature reference electrode is necessary. At the channel/solution interface, the gate potential is applied through thin electric double layer capacitance. The sensing performance of FET biosensors depends on the variety and thickness of the gate insulators. The ionic strength of solution determines the double-layer thickness (or Debye length), which is typically within 1 nm. Maehashi et al. (2013) have demonstrated a graphene-based FET for the detection of K/Na ions in solution. In this report, the solution-gated FET was over two orders of magnitude more sensitive than the typical back-gate FET.

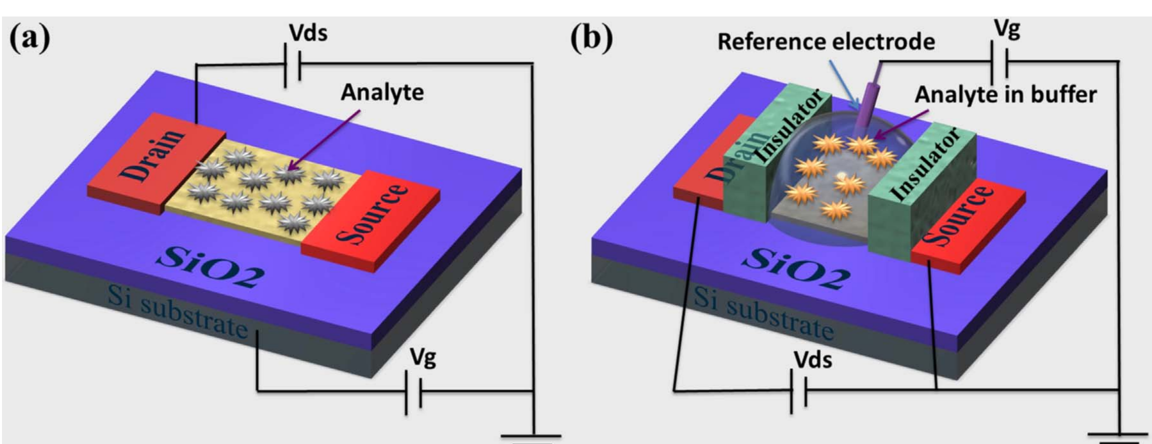
3. NWs-based FET biosensor

Wide range of nanomaterials has been used as channel materials to fabricate metal-oxide semiconductor FET, ion-selective FET, and NWs-based FET biosensors, where prepared channel remain in direct contact with the environment, and this gives better control over the surface charge (Shavanova et al., 2016; Wang et al., 2014; Jiang, 2011; Sarkar et al., 2014; Liu and Guo, 2012). Thus far, considerable efforts have been made to develop better FET architecture by incorporating different metals (Ag, Pt, Au, and Cu), semiconductor (ZnO, SnO_2, Si, GaN, TiO_2, In_2O_3, InP, etc.), and polymer NWs to study biomolecular interactions and overcome the physical limitations of FET technology. These NWs fabrication processes are mainly categorized into bottom-up and top-down techniques (Hobbs et al., 2012; Namdari et al., 2016). Scheme 2 is showing the schematic representation of bottom-up and top-down technologies have been demonstrated using different methods. The top-down approach is important as it can accurately align and control identical precise directions of NWs. However, it cannot achieve as good down-scaling as bottom-up approach. Importantly, NWs-based FET biosensors have been reported to tackle multiple limitations, and thus, they are most effectively used for FET-based biosensors fabrication. We reviewed semiconductor and polymer NWs-based FETs in the following sections and presented a brief comparison of semiconductor and polymer NWs-based FETs biosensors in Table 1.

3.1. Semiconductor NWs-based FET biosensor

3.1.1. Zinc oxide NWs-based FET biosensor

Zinc oxide (ZnO) is one of the most exciting materials for FET-based biosensors fabrication due to its versatile properties (Hahn, 2011; Shen et al., 2016; Ahmad et al., 2015; Drobek et al., 2016; Sinha et al., 2016; Asif et al., 2009; Wang et al., 2016; Ye et al., 2016). The high



Scheme 1. Schematic illustration of (a) a typical back-gated and (b) solution-gated FET biosensors used in chemical and biological sensing applications.