Future Sensor Technology with Nanomaterials

Shashi P. Karna
U.S. Army Research Laboratory
Weapons and Materials Research Directorate
ATTN: AMSRD-ARL-WM-BD
Aberdeen Proving Ground, MD 21005-5069
USA

Rudolph G. Buser
RGB & Associates
2051 Baileys Corner Road
Wall, NJ 07719
USA

ABSTRACT

Materials at nanometer scale exhibit unique properties that are different from their atomic or bulk counterparts. Nano-scale materials also exhibit specific responses to external electrical, optical, magnetic, chemical, and biological stimuli that are unique to the material-stimulus interaction and can be used for a wide range of sensing applications. Among the nano-scale materials, atomic nanoclusters, also known as nanoparticles or quantum dots, nanowires, and nanotubes have been extensively studied for their chemical and biological sensing applications. In this paper, we present a brief overview of the recent advances and future scope of sensing technologies with nanomaterials focusing on quantum dots, nanowires, and nanotubes.

I. INTRODUCTION

Materials with nanometer-size dimension exhibit unique electronic, physical, and chemical properties [1]. At nano-scale, electron confinement and tunneling become dominant phenomena, which provide completely new electronic properties of materials that are often different from their atomic or bulk counterparts. Confinement of electrons and their interaction with photons and other physical and chemical stimuli, and a high degree of correlation between electron spins lead to various novel phenomena that, while providing new information on the richness of physics at nano-scale, are also useful for numerous technological applications including advanced electronics, photonics, medicine, and sensing. Due to these reasons, there has been considerable interest in Nanomaterials synthesis and properties explorations in the past two decades. Recent advancements in the scaled-up production of nanomaterials, sophisticated instrumentations for property characterization, and successful assembly and fabrication of useful device architectures at nano-scale have further intensified the interest in nano-scale electronics and sensors [2].

Nanomaterials are materials with at least one dimension in the nanometer scale, i.e. from one to tens of nanometers. Thus for example, atomic nanoparticles (NPs) also sometimes referred as quantum dots (QDs) are naturally nanomaterials as their diameters are in the nanometers. Other examples of nanomaterials are nanowires (NWs) and nanotubes (NTs), with diameters typically in the nanometer scale. Superlattices and

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ordered thin films with a thickness in the nanometer scale are also often included in the nanomaterials category, as their key functional properties are controlled by the nano-scale dimensions. Here we present an overview of the sensing applications of nanomaterials, focusing on QDs, NWs, and NTs.

II. SENSING APPLICATIONS OF QD NANOMATERIALS

Due to the atom-like quantized energy levels [3], QDs exhibit narrow-band, if not discrete, absorption and emission spectra that can be tuned by controlling the size of the particle. Furthermore, a change in the electronic structure or the surface charge distribution changes the optical properties of the QDs. This size and electronic structure-dependent absorption and emission from QDs have led to their applications as optical sensors, especially for biological molecules. The bio-sensing applications also result from the fact that QDs can be easily surface functionalized by or encapsulated in organic/biological molecular assemblies, which, while acting as surfactants, serve the purpose of a typical receptor. The optical properties of the encapsulated QDs get modified when organic receptor molecules bind with a target analyte. Since receptor-analyte bindings for biological molecules are highly specific, the colorimetric sensing of biomolecules using biofunctionalized QDs is a very reliable and promising technique.

In the past several years, a number of experiments have demonstrated the biosensing applications of encapsulated Au [4-7] and silica NPs [8].

The advantages of NP/QD-based chemical and biological sensors involve (a) ease in their synthesis and functionalization by specific receptors, (b) tunability of size and spectral features, (c) high degree of selectivity and enhanced sensitivity, and (d) low cost of production. However, by virtue of the fact that the sensing, which generally involves colorimetry, requires chemical binding between the receptor and the analyte, the QD-based sensors, in general, have slow response time, cannot be reused, and are limited to point detection. It is anticipated that advances in using characteristic optical emission to transduce electrical signals and the development of adjustable and reusable QD-based receptors would lead to real-time chemical and biological sensing with nanoparticles.

III. SENSING APPLICATIONS OF NW AND NT NANOMATERIALS

The NWs and NTs can behave as metals, semiconductors and/or insulators depending upon their morphology and atomic structure. Furthermore, their electrical properties (conductivity/resistivity) exhibit very high degree of sensitivity to their electronic structure and surface charge distribution. A combination of the unique electrical characteristics and their sensitivity to the surface charge make the NWs and NTs an excellent candidate as electronic sensors of chemical and biological species. Recently, Si NWs have been used to show [9] electronic sensing of chemical and biological species. Similar to the QD receptor-analyte binding event as the transducer, the NW biosensors use specific receptors to bind with target analyte. For example, the Si NW biosensors [9] were demonstrated by modifying the NW surface by biotin receptors to detect straptavidin as an analyte. The high degree of specificity is achieved by the biotin-straptividin binding. The receptor-analyte binding modifies the surface charge on Si surface and hence the electrical conductivity of the NW. This allows the electronic sensing of biological species using NWs.

Very recently, ZnO nanowires have been used to demonstrate electronic sensing of chemical species, such as NO_2 and NH_3 gases at room temperature [10, 11]. ZnO nanowires have semiconducting property, which makes them an excellent candidate as channels in nano-scale field effect transistors (FETs) [12]. For sensing applications, the ZnO nanowires are used as open channel and the gate is generally at the back of the transistors. Sensing is performed by measuring the change in the current (*I*)-voltage (*V*) characteristics of the FETs upon adsorption of chemical species on the open nanowire channels, as shown by Fan et al [10, 11].

Carbon nanotubes (CNTs) [13-16] are arguably the most extensively investigated nano-scale material for realizing nano- and molecular-scale electronics and sensor devices [17-19]. CNT-based electronic devices, such as interconnects [20, 21], junction rectifiers [22-24] field-effect transistors [25, 26] and logic gates [27] have been successfully demonstrated in recent experiments. More recently, experiments demonstrating the use of single-walled carbon nanotubes (SWNT) as the active channel in metal-oxide-semiconductor (MOS) FETs have also been reported [28], which opens the possibility for a wide-range of integrated CNT-complementary (C)MOS nanoelectronics and sensors platform.

Recently, there have also been reports [29, 30] of dense arrays of high throughput CNT FETs that take advantage of multiple parallel nanotube channels between metal *source* and *drain* contacts. This opens the possibility of high-density electronics and sensors.

Similar to the NW FETs, the CNT FETs exhibit observable change in the *I-V* properties upon change in the surface charge distribution on CNT sidewalls. Since a variety of chemical and biological species can adsorb at CNT sidewalls, inducing changes in charge distribution, the event and possibly the chemical nature of the adsorbing molecules can be sensed electronically by the CNT FETs. This mechanism has been used to demonstrate the sensing of gaseous species, such as O_2 [31], NO_2 and NH_3 [32] using unmodified SWNT FETs. Recently, sidewall-functionalized CNT devices [33] have been used to electronically sense gaseous species.

Another mechanism of chemical sensing by CNTs is the ionization of target molecules at the tip of vertically aligned tubes [34]. The ionization characteristics provide a fingerprint of the ionizing gas, allowing a reliable sensing mechanism.

While chemical sensing by CNTs in different configurations has been demonstrated in several experiments, the biosensing application of CNT FETs has only been recently realized. A major reason for the slow progress in CNT-based biosensing has been the relatively inert nature of CNT side walls. Since biosensing utilize receptor-analyte binding, the difficulty in attaching receptors to the CNT sidewalls has been a real bottleneck toward CNT-based biosensors. Recently, several groups [35, 36] have developed methods to functionalize CNT sidewalls by chemical and biological species, which has opened the way for the fabrication of CNT-based receptor-analyte sensors. This has enabled the fabrication of CNT-based electronic sensors for sensing biological species, such as proteins [37], DNA [38] and single viruses [39].

IV. FUTURE OUTLOOK

Nano-scale materials offer a unique opportunity to develop low-power, high-sensitivity, multifunctional future sensors technologies. Due to their nanometer size, these materials also offer a very-high density of devices in small area and very light-weight systems. Furthermore, since Nanomaterials preserve their electronic and optical properties in different environment, they can be embedded in a wide-variety of platform, including light-weight flexible platform, such as thin-film polymers fiber structures. These favorable materials properties combined with high electrical and optical sensitivity make them the materials of choice for future sensors as well as electronics technologies.

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