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Nanosensors in Contemporary Sciences

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ABSTRACT

Nanosensors are one type of sensors. Others include bio-sensors, catalytic sensors, electrochemical sensors. Nanosensors are nanoscale devices that are constructed to identify a particular molecule, biological, medicinal or environmental component and operate within the nanoscale dimensions. Nanosensors convert chemical data such as the concentration of a single sample component to complete composition analysis into an analytically usuable signal. Nanosensors are quite superior to conventional sensor and possess several advantages over conventional sensors. These include amongst others: greater adsorptive capacity due to large surface area to volume ratio, greater modulation of electrical properties such as capacitance, resistance etc. upon exposure to analytes, exceptional electrical conductivity and compatibility with biological systems. Nanosensors have found applications in several realms such as agriculture, biology, chemistry, physics, medicines, environmental, gas sensing, industrially, in the aerospace and defence industry. Research in nano sensor technology is proliferating.

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Introduction

A chemical sensor is a device that converts chemical data such as the concentration of a single sample component to complete composition analysis, into an analytically usuable signal [1]. It consists basicallty of two components: a receptor which receive the signals and a physicochemical transducer. The receptors can take various form and range from activated or doped surfaces to complex macromolecules that are engaged with specific interactions with the analyte. Figure 1.0 shows a schematic representation of a chemical sensor.

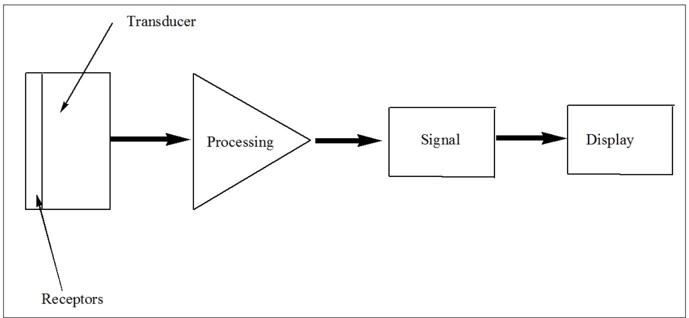

Figure 1.0: Schematic Representation of a Chemical Sensor

Requirements of Sensors

A chemical sensor must maintain a high degree of specificity for the intended analyte in the presence of potentially interfering chemical species to avoid false positive outcomes. A chemical sensor must also have a transducer, responsible for converting the signal created by the receptor-analyte interactions in a readable and recognizable one. Another aspect is that sampling is often overlooked. An analyte cannot accurately be detected if its not delivered to the transducer in a functional form. Fouling of a sensor by other macromolecular or reactive species can be an issue. An advantage of chemical sensing is that the sensor interface can be frequently refreshed or replaced. Monitoring of the recognition events can be performed via several methods, depending on the type of transducer utilized. These include optical, gravimetric or electrochemical [2].

Classification of Chemical Sensors

Chemical sensors can be classified into various types. These include:

1. Bio-sensors
2. Catalytic sensors
3. Electrochemical sensors
4. Nanosensors

Applications of Nanosensors

Nanosensors are nanoscale devices that are constructed to identify a particular molecule, biological, medicinal or environmental component. They collect information from numerous sources and transform them into signals that are detectable and analyzable. Nanosensors are highly specific, cost-effective and can detect at a level much lower compared to macro-sacle sensors. Nanosensors are currently used in several fields. These include medical science, agriculture, environmental pollution control, pathogen detection, medical diagnoses, explosive detection, virology etc.

In agriculture, nanosensors have great application. They are used for monitoring soil or plant conditions and this would lead to more efficient usage of fertilisers, herbicide, pesticides and insecticides. They are also used to facilitate real time monitoring of crop, field condition, crop growth, pest attack, plant disease, environmental stressors and pesticide residue. Nanosensors can convert the conventional agriculture practices into smart agriculture, which are more energy efficient, environmentally friendly and leads to sustainable agriculture practices. In agriculture, nano biosensors can monitor parameters such as temperature, humidity and soil composition to reduce water usage and minimize chemical use at specific times and locations [3, 4]. In Entomology, gas nanosensors are used to detect insect pheromones. For example, silicon oxide based nanosensors are used to detect sex pheromone of Helicoverpa armigera.

The fundamental components of a bio-nanosensor, including the signal transduction elements and target selective receptors such as low molecular weight synthetic moieties or organic molecules such as DNA, enzyme, antibody etc. have been reported [5]. Nanosensors provide an opportunity to measure ultra-low concentrations (< nML-1) of target analytes. This allows for improved understanding of complex biological processes. These nanosensors can allow for early detection of diseases, containment of infections and viral propagation, monitoring biodata, food quality control and elucidating high resolution genome phenome relationships.

A nanosensor for Vitamin D monitoring in the body has been reported [6]. This sensor can detect and quantify vitamin D metabolites in the blood or urine. This would allow individuals to take the necessary measures to maintain the required level of vitamin D in the diet.

Nanobiosensors have been reported to detect pesticide and herbicide residues and controlling fertilizer application, pesticide and herbicide application, nutrient deficiency, soil quality and good soil health optimization etc. Holistically, this improves crop production yield [7].

Nanomaterial sensors are being designed for high-efficiency, multiplex-functionality and high-flexibility sensing applications. Many existing nanosensors have the inherent capacity to achieve such goals. However, they require further development into consumer and operator-friendly tools with the ability to detect analytes in previously inaccessible locations, as well as at a greater scale than possible. Nanotechnology-enabled sensors have great promise to provide widespread and potentially low-cost monitoring of chemicals, microbes and other analytes in drinking water [8].

The fabrication of a gas nanosensor for detecting ammonia gas in air that is unaffected by humidity has been reported. The manufacturing of a nanostructured material sensor for the detection of ammonia gas can be tuned to eliminate interference from water vapor. This was achieved by precisely functionalizing single-walled carbon nanotube (SWNT) networks with camphorsulfonic acid doped polyaniline (PANI (CSA). This resulted in the opposite electrical responses toward humid air of CSA doped PANI and SWNTs which cancelled the humidity interference. The appropriate selection of nanomaterials and fine tuning of the synthesis conditions can overcome some of the limitations encountered by nanosensors [9].

The development of carbon nanotube (CNT) as components of gas sensors and sensor arrays has been attracting increasing attention because of their potential for the selective and rapid detection of various gaseous species. This calls for a modification of the nanostructures of carbon nanotubes. The detection of biological and chemical species in the atmosphere or process gas is of utmost importance as it relates to environmental pollution, industrial emission monitoring, process control, medical diagnosis, agriculture, public security etc [9]. Nanoengineered materials such as nanowires, nanobelts, nanotubes, nanoribbons etc. are attractive candidate for the development of miniaturized chemical and biological sensors. This is due to the following:

(a) Greater adsorptive capacity due to large surface area to volume ratio
(b) Greater modulation of electrical properties such as capacitance, resistance etc upon exposure to analytes.
(c) Ability to tune electrical properties of the nanostructures, by adjusting the composition and size.
(d) The ease of configuration as chemiresistors and field effect transistors (FETs)
(e) Potential to integrate with low-power microelectronics to form complete systems with microprocessor and wireless communication units [10].
(f) Quantum confinement effects
Tailorable surface chemistry
Nanomaterials can sense a range of substrates via optical, electrochemical and other transduction principles depending on the nanomaterial and analyte of interest.
(h) Exceptional electrical conductivity and compatibility with biological systems
(i) They offer precise detection capabilities for sensing physical parameters, CBRN (chemical, biological, radiological, and nuclear) agents
(j) Nanosensors are tiny and portable, allowing their suitability for high throughput applications

Chemiresistors and chemical field effect transitors are the most promising types of gas sensors. These sensors have their electrical properties dramatically changed when exposed to the target gas analytes.

Carbon nanotubes (CNTs) are graphene sheets of covalently bonded carbon molecules rolled into hallow cylinders. There are two types of CNT: Single walled carbon nanotubes (SWNTs) consisting of a single carbon layer with a diameter of 1-5 nm and multi-walled carbon nanotubes (MWNTs), consisting of multiple layers of carbon (with an interlayer spacing of 3.4 A, concentrically connected together [11].

In the health realm, Nanomaterial infused nanosensors are finding increasing application in healthcare and biomedical fields. They have demonstrated high profiency in identifying tumor specific biomarkers, circulating tumor cells and extracellular vesicles discharged by tumors. This facilitates intelligent cancer detection and enchance patient prognosis [12]. The exploration of carbon nanotubes (CNTs) for glucose detection in urine has been noteworthy. CNTs dissolved in an aqueous solution of the biopolymer chitosan (CS) has enabled precise glucose measurements in urine, with a detection threshold reaching a value of 3M [13].

In environmental monitoring, nanosensors offer several advantages over traditional sensors in detecting pollutants for environmental monitoring. These include: Cost effectiveness and excellent detection potential and selectivity. Based on these properties, they have successfully detected contaminants such as ethanol, 2,6-dimethoxyphenol Nanosensors can transform environmental monitoring by providing real-time air and water quality information [14, 15]. They can detect and monitor changes in chemicals found in water, soil and the environment. Thus, identifying pollutants and toxins and address water quality. They ensure the safety of water resources by identifying chemicals and bacteria that threaten aquatic life and human health [14, 15].

Industrially, nanosensors can be integrated with nanoelectronics, allowing for real time monitoring and control. For example in the manufacturing process, nanosensors can detect early products defects, allowing for adjustments, before large quantities are produced. This saves time and reduce cost [14].

Nanosensors have significant applications in the aerospace and defence industries. In the aerospace industries, they are used for real-time structural monitoring of aerospace components, allowing for its integrity, safety and minimize maintenance cost. Nanosensors also improve fuel efficiency and flight safety.

In the defence industry, nanosensors are used for threat detection and surveillance. They can detect CBRN threats. This allows for crucial situational awareness and protection of military personnel. They can be used in explosives detection, camouflage technology and unmanned aerial vehicles (UAVs) for surveillance [15].

Table 1.0. shows diverse nanomaterial, exploiting various transduction mechanisms. The detection mechanism, the type of analyte & detection range are all quoted [16-18].

Table 1.0: Diverse Nanomaterial Exploiting Various Transduction Mechanisms

Nanomaterial	Detection mechanism	Analyte	Detection range
Graphene quantum dots (GQDs) and acid functionalized multiwall carbon nanotubes (MWCNTs)	Electrochemical	Dopamine	0.25-250 uM
Gold and silver nanoparticles	Colorimetric sensing platform	Target DNAs and target proteins (thrombin and platelet-derived growth factor)	15-40 nM
Graphene	Prism-coupled surface plasmon resonance (SPR) biosensor	Glucose	25-175 mg dl^{-1}
Quantum dots	Electrochemiluminescence (ECL)	Alpha-fetoprotein (AFP) and carcinoembryonic antigen (CEA)	0.001-0.1 pg mL^{-1}
Graphene oxide	Fluoresecent aptasensor	Aflatoxin B1	0 ng mL-1-3ng mL^{-1}
Silica nanoparticles	pH responsive fluorescent	pH	pH 5.5 to 9.0
Chitosan, graphene and titanium dioxide (CS/RGO/TiO^2)	Electrochemical sensing	Lead ions (Pb^{2+})	1 ng L^{-1} to 1000 ngL^{-1}
Titanium dioxide nanotubes (TNTs) and silver nanoparticles (AgNPs)	Electrochemical biosensing	Heat shock protein 70 (HSP70)	0.1 to 100 ng mL^{-1}

Conclusion

Fabrication of nanosensors is a rapidly growing area in nanotechnology. Nanosensors are superior to conventional sensors and have found application in many realms: agriculture, bio-chemical sciences, medicines, environment, gas sensing, industrially, aerospace and defence industry amongst others. Amongst nanomaterials modified to use as nanosensors include: metal oxides, fullerenes, carbon nanotubes (Single walled and multi walled), graphene, graphene oxide, nanodiamond, gold nanoparticles, silver nanoparticles, platinum nanoparticles, silicon etc. Research in the design and fabrication of nanosensors should continue to proliferate in response to a rapidly advanced world and the treat of new emerging diseases, especially those that are virally based.

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