

Nanostructures Containing Zinc Oxide as Sensors for Health Monitoring

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Abstract

Nanotechnology has had a revolutionary impact on biomedicine and has seen tremendous progress over the past several decades. Nanostructures have dimensions from 1 to 100 nm. At this nanoscale, materials like Zinc oxide (ZnO) exhibit distinct physical, chemical, and electronic properties that are not present in their bulk counterparts. ZnO nanostructures, including nanocombs, nanorings, nanowires, and nanocages, take advantage of these unique properties, making them promising candidates for various applications, especially in health monitoring. Semiconducting, optical, and piezoelectric properties of ZnO nanomaterials make them very suitable for biosensor applications. These biosensors are distinguished by their high specificity and sensitivity, fast response time, portability, low cost, and minimal power requirement. The use of ZnO nanostructures in health monitoring can lead to the development of innovative diagnostic tools that provide real-time data, improve patient care, and empower individuals with better health insights. In summary, this research emphasizes the importance of ZnO nanostructures in the realm of health monitoring sensors and highlights their unique properties and their potential impact on biomedical technologies.

Keywords: “Nanostructure, Zinc oxide, Sensors, Health monitoring”

Introduction

Extensive research in nanotechnology has been conducted to investigate new behaviours and properties of materials with nanoscale dimensions. Nanostructured including nanoparticles, nanofibers, thin films, and bulk materials be with at least one nanometer-scale dimension. In recent years, they have attracted much attention in different fields due to their extraordinary physical, chemical, mechanical, and electrical properties. For example, in nanobiomedicals, nanostructures can be effective as sensors for health monitoring. In recent years, with the recognition of the properties of nanoscale materials, a wide range of bioceramics such as zinc oxide (ZnO), have been introduced as biosensors. ZnO can be used as a pressure sensor to measure various parameters such as artery pulse signals, slight movement of the muscle (trachea, esophagus), movements of joints due to its physical properties like piezoelectricity [1, 2]. Piezoelectric sensors for healthcare monitoring can measure, in real time, the physiological functions of human organisms via dynamic measurements. These flexible sensors can be attached to clothing or directly mounted on the human skin for the real-time monitoring of human activities and physiological measurements with high efficiency [3]. Over the last few years, non-invasive nano biosensors demonstrated unique capabilities for physiological signal monitoring, disease diagnosis, and health assessment. In this research, we introduce nanostructures. Since ZnO is a suitable nanosensor for physiological signal monitoring, we will introduce it and review the recent research with the approach of using ZnO nanoparticles in sensors for health monitoring.

Nanostructure

Nanomaterials are known as small materials that are in where at least one of their dimensions must be less than 100 nm. They exhibit many unique advantages, such as extremely small size, and large specific surface area, which greatly expand their application prospects in biomedicine. The main reason for the fascination with nanostructures is their interesting properties, which are not found in the bulk materials. The peculiar dimensionality of nanostructure gives rise to quantum confinement phenomena, which modify the bulk materials' structural, optical, chemical, and electronic properties. In bulk materials, only a small percentage of atoms will be at the surface or interface, while in nanostructures, the small feature size ensures that many atoms, half or more, will be near interfaces. Therefore, surface properties, such as energy levels, electronic structure, and reactivity can be quite different from interior states or bulk structures, thus causing different material properties [4, 5].

A variety of methods have been developed to fabricate high-quality bio-piezoelectric nano- platforms, such as solvothermal, hydrothermal, electrostatic spinning, and mechanical exfoliation. In general, according to their dimension (D), nanomaterials include 0D, 1D, 2D, and 3D (Fig. 1). 0D nanomaterials generally refer to nano- particles, nanoclusters, and quantum dots. The characteristics of 0D nanomaterials include large surface area. 0D is used as therapeutic nanocarriers, especially in cancer chemotherapeutics. They offer advantages such as easy delivery and reduced toxicity. Today, 0D bio-piezoelectric nanomaterials are used in polymer or ceramic scaffolds to improve piezoelectric properties. 1D nanomaterials are often used as nanowires, nanobelts, nanotubes, nanorods, and nanofibers. Compared with 0D bio-piezoelectric nanomaterials, exhibit a higher charge transfer efficiency due to their morphology, and can overcome the shortcomings of agglomeration that exist. 1D nanomaterials due to excellent processability, high sensitivity, good biocompatibility, and good flexibility, allowing them to be widely used in biosensors, smart textiles, and electronic skins (e-skin). 2D nanomaterials due to a nanometer thickness, can lose their centrosymmetry in one direction. 2D forms such as nanoplatelets, nanoplates, nanosheets, or nanoflowers [6, 7].

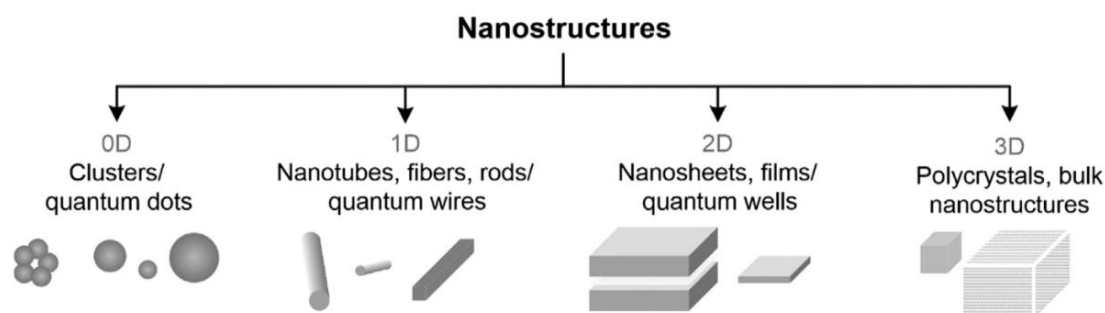


Figure 1: Nanomaterial classification according to dimensionality[5]

The geometry of nanostructures becomes more complicated for composites and multicomponent materials. The desire for multifunctionality, enhancement of properties, and improvement of characteristics of materials has given rise to nanocomposites, where at least one of their dimensions must be less than 100 nm. Naturally occurring structures, such as bone, are hierarchical nanocomposites that are built from ceramic and polymer biomaterials. Mimicking nature and based on the demands of building new materials that can serve several functions at the same time, scientists have been devising synthetic strategies to produce different nanocomposites such as metal-ceramics, polymer-ceramic, and biologically inspired nanocomposites, which can be used in tissue engineering, biosensors and drug release [8].

Zinc Oxide

Zinc oxide (ZnO) is the second most abundant metal oxide after iron and is found in the Earth's crust as the mineral zincite. ZnO has a slew of unique chemical and physical properties, like high chemical stability, high electrochemical coupling coefficient, a broad range of radiation absorption, and high photostability, which make it among all metal oxides a key technological material and confer upon it its wide applications in varied fields. Zinc oxide (ZnO) is a unique material that exhibits semiconducting, piezoelectric, and pyroelectric multiple properties [9]. This bioceramic has been widely used as an additive in nanocomposites. Also, ZnO nanoparticles have recently attracted attention owing to their unique features including antimicrobial and anticancer activities in biomedical applications like drug delivery and wound healing.

A range of precursors and a variety of conditions such as temperature, time, concentration of reactants, and so forth can be employed for the chemical synthesis of ZnO nanoparticles. These chemical techniques by virtue of adjustment of the various aforesaid parameters allow better control of morphology in terms of size and geometry. ZnO NPs can be chemically synthesized using the following techniques: the mechanochemical process, controlled precipitation, sol-gel method, vapor transport method, solvothermal and hydrothermal methods, and methods using emulsion and micro-emulsion environments (Fig. 2) [1].

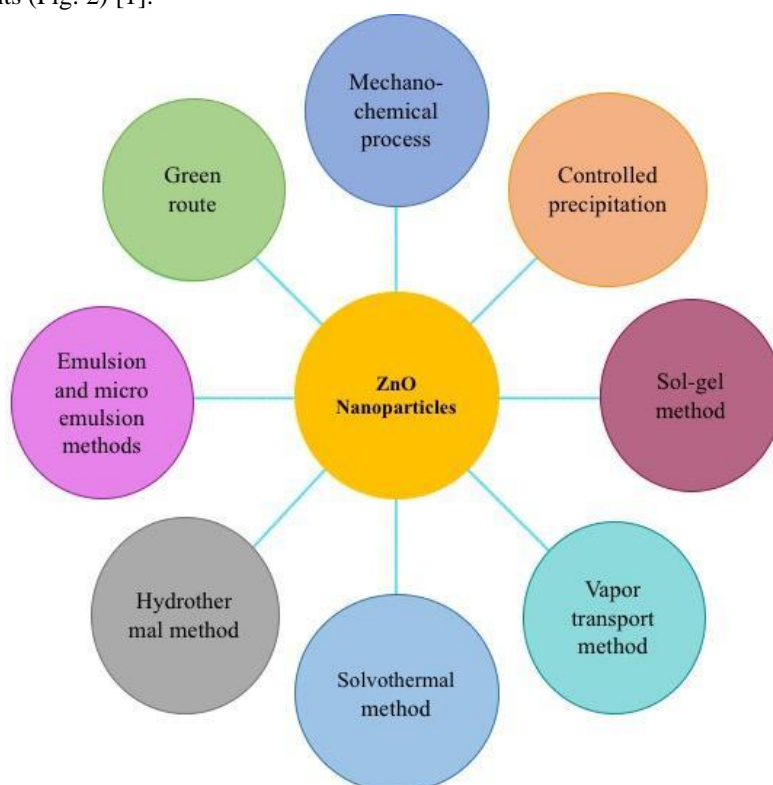


Figure 2: Various strategies for the fabrication of ZnO NPs [1]

Investigation of the properties including mechanical, piezoelectric, electrical, optical, magnetic and chemical of individual ZnO nanostructures is essential for developing their potential as the building blocks for future nanoscale devices. ZnO can have three possible polymorphs, rock salt, wurtzite, and zinc blende. The rock salt polymorph exists under conditions of high pressure and is therefore very rare. At ambient pressure and temperature, ZnO has a

hexagonal wurtzite crystal structure that have the piezoelectric behavior [10]. Wurtzite is which belongs to a hexagonal crystal system with a tetrahedral coordination AB- type composition. In this type of crystal structure, the A atoms are in a hexagonal configuration and the B atoms occupy the tetrahedral void. The oxygen atoms and zinc atoms are tetrahedrally bonded. In such a non centrosymmetric structure, the center of positive charge and negative charge can be displaced due to external pressure induced lattice distortion (Fig. 3). This displacement results in local dipole moments, thus a macroscopic dipole moments appears over the whole crystal. In fact, among the tetrahedrally bonded semiconductors, ZnO has the highest piezoelectric tensor which provides a large electro-mechanical coupling. The results showed that ZnO is biocompatibility and with piezoelectric properties can be used as nanogenerators for tissue engineering, and biosensors [4, 10, 11].

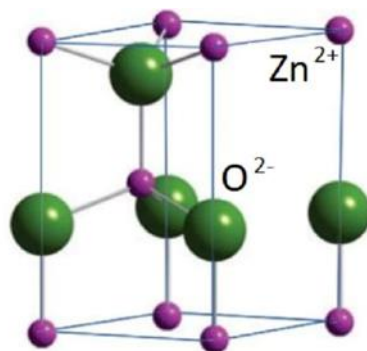


Figure 3: Wurtzite structure of ZnO

The piezoelectric effect was first discovered in 1880 by the Curie brothers. Accordingly, piezoelectricity can be translated as “pressure-induced electricity.” From the perspective of crystallography, piezoelectric materials have a specific form (non-centrosymmetric, asymmetrical structure) that has no center of symmetry in the crystal structure or molecular chains of the material. Deformation results in the asymmetric shift of ions or charges within unit cells in piezoelectric materials, which induces a change in the electric polarization. This phenomenon leads to the loss of the center of symmetry and induces the accumulation of charge through an ordered dipole distribution. Applying mechanical energy to piezoelectric material deforms its crystal structure, and generates an electrical moment (direct piezoelectric effect), and vice versa (inverse piezoelectric effect) [12, 13].

Sensors for Health Monitoring

Nanomaterials, alone or in combination with biologically active substances, are attracting ever-increasing attention since they can provide a suitable platform for the development of high performance biosensors due to their unique properties. Biosensors e.g. photometric, calorimetric, electrochemical, piezoelectric, are widely used in healthcare and monitoring, and chemical/biological analysis. Overall, real-time body sensing and communication of comprehensive physiological information via wearable biosensing technologies offer significant promise to enhance personal healthcare and performance monitoring with the potential to have a broad impact on our daily lives. Early efforts in this area focused on physical sensors that monitored mobility and vital signs, such as steps, burned calories, or heart rate. The face of wearable devices has changed rapidly in recent years with researchers branching out from tracking physical exercise activity to focus on tackling major challenges in healthcare applications, such as the management of diabetes or remote monitoring of the elderly. Wearable monitoring platforms can shed useful insights into dynamic biochemical processes in these biofluids by enabling continuous, real-time monitoring of biomarkers, which can be related to a wearer’s health and performance. Such real-time monitoring can provide information on wellness and health, enhance the management of chronic diseases and alert the user or medical professionals of abnormal or unforeseen situations. Wearable biosensors can obviate painful and risky blood sampling procedures and can be readily blended with a wearer’s daily routine [15]. Such body compliance can be achieved through use of advanced materials and smart designs that provide the necessary flexibility and stretchability. Continuous multidisciplinary development of new biosensing technologies (and corresponding new materials and energy sources) has led to numerous proof-of concept demonstrations and has driven growing efforts towards the commercialization activity of wearable sensors.

Wearable biosensors are attractive due to their potential to provide continuous, real-time physiological information in an array of healthcare-related applications, and dynamic non-invasive measurements. The increased accuracy, effectiveness and utility of modern wearable biosensing platforms are enhancing both reliability and commercial impact. In addition, both an expanded set of on-body bioaffinity bioassays and additional sensing strategies will be required to expand the scope and type of biomarkers accessible to monitoring. Further improvements in biosensor accuracy and stability in uncontrolled conditions, along with reproducible sample transport, will be required for improved sensor reliability [15-17]. The concept of a biosensor was first proposed by Professor Leland C. Clark Jr. in 1962. Over the past decade, biosensors have gone through rapid development with wearable, portable, and appropriate for potential commercialization. Piezoelectric effects offer a linear relationship between stress/strain and electricity, for detecting physiological signals of humans, such as heart rate, pulse, and body movement. Real-time biomedical monitoring systems have provided Great medical progress in modern lifestyle because they can recognize physiological signals and medical diagnoses, instantaneously. Monitoring human physiological signals is considered to be an effective way for disease diagnosis and health assessment. In recent years, flexible, wearable, and biocompatible pressure sensors have played an important role in biomedical, computing, health care monitoring, electronic skin (e-skin), and robotics applications. The research showed it is possible Various human gestures monitoring, such as wrist bending, neck stretching, arm compressions, throat movements during drink, coughing, heart pulse, and swallowing, by using sensors. The emergence of wearable devices could potentially improve the quality of human life owing to their applications for healthcare monitoring, smart fabrics, motion tracking, roll-up displays, and wearable heaters [19]. Table 1 provides an overview of the research on zinc oxide nanoparticles as sensors with piezoelectric properties for Health Monitoring.

Table 1: An overview of the research on zinc oxide nanoparticles as sensors for Health Monitoring

Material	Description	Result	Refs
PVDF/ZnO	Core-shell nanofiber Respiration, wrist pulse, and muscle behavior	Sensitivity 3.12 mV k Pa ⁻¹ Response time 53-55 ms	[3]
PVDF / ZnO	Self-powered piezoelec Nanowires ZnO	Suitable for continuous monitoring and sensing	[20]
PVDF/ZnO	Nanofibers Cowpea-structured	Sensitivity up to 0.33 V kPa ⁻¹ during pressing and bending	[21]
P(VDF-HFP) /ZnO	Nanofibers Sandwich structure	Air permeability 24.97 mm/s Antibacterial properties over 98%	[22]
PLLA/ZnO	Nanofibers	Voltage (VOC) of 7.9 V Current (SCS) of 286nA Power density of 1.25 mW cm ⁻³	[23]
ZnO	Nanowire with diameter 50 nm	Sensitivity -6.8 kPa ⁻¹ Working within 0.3 kPa pressure	[24]
PVDF/ZnO	Nanofilm Working with 57 bending angle Relative oxygen concentration range: 20-50% Relative humidity range: 45-85%	Linear response to oxygen concentration and relative humidity	[25]
PVDF-HFP/ CNC/ Fe-doped ZnO	Nanocomposite fibers double layers As piezoelectric nanogenerator (PENG)	This ferroelectric composite exhibited peak-to-peak output voltage of 12 V and a current density of 1.9 μAcm^{-2} Finger tapping generated peak-to-peak output voltage of 6.5 V, and elbow movements generated voltage of 5.5 V	[26]

Conclutions

Nanotechnology has had a revolutionary impact on biomedicine and witnessed tremendous advancement over the last several decades. With sizes less than a few hundred nm, nanomaterials can exhibit properties distinct from both molecules and bulk solids. ZnO nanomaterials are excellent candidates as sensor for health monitoring due to phizical and chemical properties. Biosensors hold considerable promise due to their high specificity, speed, portability, low cost and low power requirements. In this research, we introduced nanostructures, unique properties of zinc oxide in nano dimensions and its application as a sensor in health monitoring. It is expected that research in ZnO nanomaterials will continue to flourish over the next decade, and will be driven growing efforts towards the commercialization activity of sensors.

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