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Semiconductor Nanostructures and Ferrocene; Pillars of Bioelectronics and Biomedicine

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Abstract

The semiconductor nanostructures are studied due to their fascinating new property in the perspective of nanotechnology. The properties of semiconductor structures can be altered by external rheological conditions. This article presents an overview of semiconductor nanostructures and their properties, such as electrical, magnetic, and optical properties of semiconductors. Moreover, it presents an intuitive description of a variety of semiconductor nanostructures and ferrocene. The quests for medical and electronic applications of such nanostructures enable exploration of their characteristic properties, including biocompatibility, sensitivity; surface area to volume ratio, piezoelectricity, and strain-induced electrical properties. An intuitive description of size, dimension, and generations of nanomaterials is also presented. The research explores the properties and applications of semiconductor nanostructures, including nanoparticles, nanocomposite, and ferrocene. Moreover, emphasis is given to the essentials of three semiconducting layers, namely monolayer, bilayer, and multilayer, and their pivotal role in bioelectronics and medical applications. Article, therefore, summarizes the potential of applications of semiconductor nanostructure on the basis of their dimension, generations, size, and layers for bioelectronics and biomedicine.

Keywords: Semiconductor, nanostructures, nanocomposite, bioelectronics, biomedicine

INTRODUCTION

Nanotechnology is one of the most top three emerging technologies namely 3D print & digital, artificial intelligence, and nanotechnology. Nanotechnology is not only about the materials at Nanoscale but includes nanodevices, nanostructures, and manipulating properties of matter at Nanoscale. Nanotechnology can be regarded as the 3rd industrial revolution. It encompasses the use of nanobiosensor, Nano syringes, Nanosyrnix, mini surgeons, nanorobotics, and Nanozymes for nanomedicine. It involves special techniques and advanced laboratories which efficiently manipulate and characterize matter at Nanoscale.

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Nanotechnology is the spice of nanomedicine. Nanotechnology provides new methods for synthesis and characterization techniques that improve the quality, sensitivity, reactivity, biocompatibility, and quality of nanomaterials. Nanotechnology provides drugs with enhanced bio-reactivity and catalytic activity. It enables the fabrication of nano needles, nano syringes, and Nanosyrnix which are painless injection tools.

Nanotechnology fosters tissue engineering by providing disulfide scaffolds that repair dam graphene, nanotube, and molybdenum-aged tissue in the area of nanomedicine. For example, Graphene can interact with biomolecules, such as DNA, enzymes, proteins, and peptides. This interaction is a pillar in tuning graphene nanodots for regenerative medicine and tissue engineering. Nanotechnologies enhance the efficiency of biosensors which allow clinicians to detect cancer in the earliest stages and enable it for the long-term diagnosis, imaging, and cancer therapy. It provides real-time assessments of therapeutic and surgical efficacy for accelerating novel methods to manage the symptoms of cancer troubles life standard.

Nanoscience extends its branches to Nanobiotechnology which is the integration of nanotechnology and biotechnology. It also entails leveraging the sound application of nanomaterials and their composites for biotechnology, regenerative medicine, tissue engineering, cell therapy, and gene therapy. Nanobiotechnology inculcates an in-depth understanding of the engineering of molecules, atoms, and their specific characteristics at the genetic level. As the size of nanomaterials decreases to the nanometer scale, they can cross biological membranes, cells, tissues, and organs more easily than macro particles.

The research is focused on nanostructures due to emerging new properties and applications in various sectors. This is due to the fact nanostructures, such as Zn-doped iron oxide nanoparticles, are biocompatible and can easily interact with human and animal tissues. They also act as sensors for detecting organic matters, such as glucose, bioorganisms, and cell labels. Iron-containing nanocomposites like $Zn_xFe_{2-x}O_3$ nanoparticles are important for biomarkers, immunoassays, immunosensors, and medical imaging devices. In order to achieve such requirements first the various nanostructures with varied synthesis and characterization methods, crystal structure, and magnetic properties, are discussed. Then its diverse applications, including biomedicine, bioelectronics, and nanobiosensors are discussed. To this end, this research is aimed to investigate the functional properties, mechanisms, and applications of nanostructures.

NANOSTRUCTURES

Nanoscience and nanotechnology open doors for a new era of research, which aims to investigate the new properties of matter and characterization techniques at Nanoscale. Nanoscience and technology process requires both skilled, specialized human power, and intelligent devices in order to control surfaces, interfaces, and crystal morphologies.

Semiconductor nanostructures can be synthesized by biological methods. Semiconductor nanostructures, such as ZnO nanoparticles, Fe_2O_3 nanoparticles, quantum dots, etc. can be synthesized by biological methods. This method is an ecofriendly synthesis method, cost-effective, and even productive. The biological method incorporates green leaves, magnetotactic bacteria, viruses, fungi, and domestic peels for the synthesis of nanostructure with desired biophysical properties. For exemplification, nanoparticles and nanocomposite of Fe_2O_3 can be synthesized by using magnetotactic bacteria.

Advanced applications of nanotechnology are manifested in the ability of Nanorobotics to perform complex tasks, such as writing on the keyboard. It also involves processing, generating, and characterizing meaningful data for high-grade quality. Therefore, it is important to invest in both capital resources and instruments for fabricating high-grade nanomaterials. Therefore, ZnO and Fe_2O_3 are quite suitable in environmental remediation, biomedical applications, and for photo-catalytic applications in neutral environments. They are regarded as safety materials for human body tissues and the natural environment. For these reasons, $Zn_xFe_{2-x}O_3$ nanoparticles are the focus of this research. For the need to fully understand its nanoscale applications and function, assessing, analyzing, and specifying its bio-chemo-physical properties is primarily important. Nanostructures that fit this requirement are diluted magnetic semiconductors, metal nanoparticles, quantum dots, quantum wires, quantum wells, silica nanoparticles, nanowires, Nanopowders, supermolecules, and fullerene, C_{60}.

Dimension, Size, and Generation of Nanomaterials

Nanostructures exhibit size-dependent electrical and optical properties, which are in the realm of nanoscience. Even in nanoscale, most of the properties of matter are size dependent. Decreasing materials to a nanoscale increase not only its efficiency but also the biological activity of the system. Metal oxide nanoparticles can exist in various shapes and sizes, such as nanorods, nanowires, nanocubes, and nanofiber.

As the size of the material decrease, (i) a pronounced change in surface area to volume ratio appears, (ii) a change in the band gap occurs, (iii) a change in reactivity, sensitivity, biocompatibility, and biodegradability occurs, and (iv) changes in optical, magnetic, electrical, and thermal properties occurs. This property inevitably changes the functionality of the nanomaterials. With reduced sizes, it is easier to control mechanical, thermodynamic, and magnetic properties by determining the strain (bulk modulus), pressure, temperature, and magnetization. As the size of materials decreases from micro-scale to nanoscale, both surface area to volume ratio and band gap increase. The first is mostly observed in almost all nanomaterials. However, the second change is significant in most semiconductor materials which are applicable in nanoelectronics and optoelectronics.

Compared to macromolecules, nanomolecules, have desired biological, chemical, and physical characteristics. Particularly, magnetic nanoparticles and nanocomposites can interact readily with body fluids, cells, and tissues. This interaction improves immunity and immuno system. These properties make ZnO nanostructures, Fe_2O_3 nanostructures, and lipid nanoparticles suitable for magnetic nanosensor, cell imaging, immunotherapy, and drug delivery. Fabricating nanomedicine and medical tools using nanomaterials (nanoparticles) enables the design of devices at automatic risk operations. Due to their high mechanical strain and flexibility, these devices efficiently improve the diagnosis and imaging process.

Based on their compositions, zero-dimensional (0D) nanoparticles are classified as metal oxides, noble metals nanoparticles, magnetic oxides, magnetic nanoparticles, semiconductor nanoparticles, and quantum dots. In 0D nanomaterials like Quantum Dots, a 3D quantization occurs. 0D noble metal nanoparticles, such as Au/Ag nanoparticles are used in optical transduction, theranostics, and tumor detection.

In 1D nanomaterial-like nanorods, a 2D quantization occurs. Research by Luci Piraux, 2020 [1] indicates that 1D-nanowire systems are advantageous over conventional magnetic multilayers made by vacuum deposition. In 2D nanomaterials, such as carbon nanotube, a 1D quantization is preserved. The properties of 2D nanomaterials, such as nanolayers, nano disks, and 2D crystal are determined by Bragg diffraction condition rather than total internal reflection. As Chaves, A. et al. 2020 [2] discussed, 2D materials are characterized by a layered crystal structure with strong in-plane bonds, where layers are coupled together by weak van der Waals forces.

3D nanomaterials are materials that project in 3D crystals namely $\hat{x}_1$, $\hat{x}_2$, and $\hat{x}_3$. 3D nanomaterials include proteins, metallic oxides, α-Fe_2O_3, carbon black, TiO_2, $Zn_xFe_{2-x}O_3$, and ZnMnO nanoparticles. $Zn_xFe_{2-x}O_3$ has different dimensions and structures which depend on synthesis methods, natures, size of dopant, and type of rheology. Fe nanoparticles can be obtained by reduction of 3D $Zn_xFe_{2-x}O_3$ nanocrystals. These nanoparticles can be used in 3D printing technology. It is also used in chemical reactors and catalysts. In general, as compared to ZnO, Fe_2O_3, and $Zn_xFe_{2-x}O_3$, Fe_2O_3-ZnO nanocomposite exhibits better photocatalytic activity, photodetector, biosensing, and cancer immunotherapy.

In the thermite reaction, Fe_2O_3 reacts with aluminum to form aluminum oxide and molten iron; 2 Al (s) + Fe_2O_3(s) = 2 Fe (l) + Al_2O_3(s). This is important in welding railway tracks and generating heat for in situ applications. $Zn_xFe_{2-x}O_3$ enables the fabricating of multifunctional and multimodal biomedical tools. Sayed Ameenuddin Irfan et al. 2019 [3] had shown that nanoparticles and nanofluid enhance the efficiency of the oil recovery process.

Nanomaterials have shown four progressive generations. These are first-generation, second-generation, third-generation, and the fourth-generation nanomaterials. These nanomaterials are briefly illustrated in the following diagram (Figure 1). The second generation's nanomaterials are specialized for medical applications, such as diagnosis, drug delivery, imaging, nanosensors, and actuators.

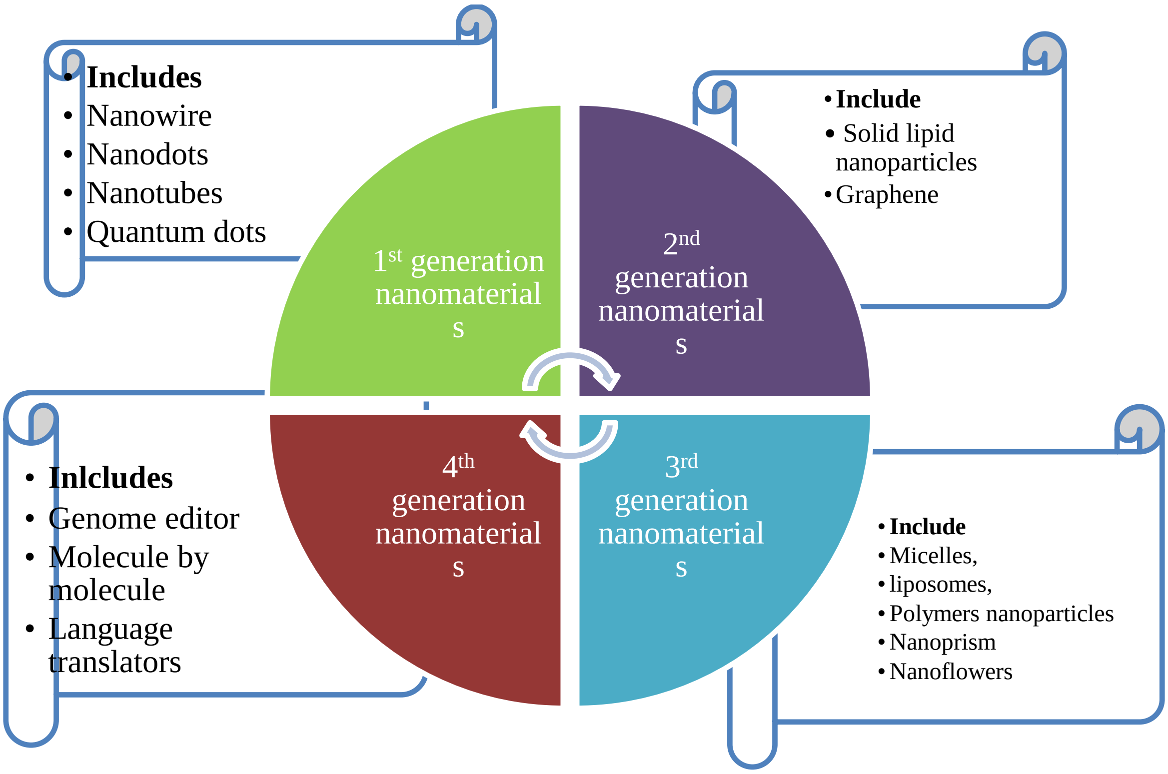

Figure 1. Evolution of nanomaterials: generations and key components.

The third-generation nanomaterials are synthesized for nanorobotics, 3D networks, 7-8G networking, and guided assembles. The fourth-generation nanomaterials are engineered to perform specific tasks e.g. artificially intelligent device which includes genomics editor, internet of things (IoTs), molecule-by-molecule devices, language translators, and self-assembled devices. In the subsequent sections, semiconductor monolayer, bilayer, and multilayer are presented with their functional properties.

Monolayer's

Monolayers are quantum well structures that are atomically thin. It extends indefinitely in two dimensions (2D). Monolayers include nanowires, nanorodes, and representatives of one-dimensional nanostructures. Hui Zheng et al. 2015 [4] noticed that 2D semiconductor monolayer, such as BeO, MgO, CaO, ZnO, CdO, CaS, SrS, SrSe, BaTe, and HgTe honeycomb mono layers have good dynamic stability. These monolayers possess band gaps and are in the ultraviolet electromagnetic spectrum. This tunable band gap and wavelength make them suitable nanomaterials in optical engineering.

Monolayer has been used to dope semiconductor materials to achieve desired electronic properties. As Ye, L. et al. 2017 [5] discussed, monolayer doping of semiconductors avoids the crystal damage during ion implantation and is capable of doping 3D structures. Robert J. Hammers, 2008 [6] revealed that thin monolayer's can act either as dielectric or conductive layers depending on the nature of the bond. On the other hand, the organic monolayer in the interface of semiconductors and biomolecules can directly detect biomolecules, such as DNA, gene, antibodies, and bioorganism.

Crystalline $Zn_xFe_{2-x}O_3$ can be synthesized on hydrophilic self-assembled organic mono layers, such as citric acid and carboxylic acids. Self-assembled monolayers can be used to create nanoscale carriers for targeted drug delivery. Self-assembled monolayer with specific nanocarriers, such as carbon nanotubes, can be bound to targeted cells or body tissues. By improving the biocompatibility, cytotoxicity, and efficacy of magnetic nanoparticles or polymer nanoparticles, they can be used to reduce the negative impacts of high-dose radiation therapy.

Bilayer/Multilayer

Scientists are able to discover an extremely useful technology that functions at the cellular level. The advancement in semiconductor technology incorporating proteins and lipids can meet such requirements. $Zn_xFe_{2-x}O$ bi-layers are solutions for such requirements. $Zn_xFe_{2-x}O_3$ bilayer is a semiconductor that forms either p-type or n-type conductivity depending on the amount of dopant. Increasing Zn dopant decreases their resistivity while its conductivity increases. Using a simple and low-cost fabrication method, such as an anodic alumina template, a double-walled hematite nanotube can be prepared with good crystal morphology. This nanotube can be used in lightweight materials with high quality and enhanced photo-catalytic activity. $Zn_xFe_{2-x}O$ can serve as constituent nanomaterials in the lipid bilayer to regulate salt concentration and PH values. $Zn_xFe_{2-x}O$ bilayer has potential applications in immunosensors and tissue imaging.

Multi-layer includes superlattices, which are top tactical and single crystal layers. They are characterized by periodic arrays and constant lattice parameters. Semiconductor multilayer’s can also be obtained by surface coating of magnetic nanoparticles and semiconductor nanostructures with DNA, carbon nanotube, or polymers, such as Chitosan. As Neda Nasser et al. 2017 [7] noted, synthetic and natural hydrophilic polymeric coating have less impact on the immunologic response. However, DR Paul and LM Robeson, 2008 [8] have revealed that the electron spinning of biodegradable polymer solution enhances nanofiber scaffolds for tissue engineering.

The physio-chemical property of metal oxide nanoparticles is sophisticated due to biomolecular dynamics. For this reason, polymetallic oxides are preferred for biological applications due to their synergistic effects. Moreover, the nature of interactions with biomolecules, such as hemoglobin, proteins, and DNA contributes to their binding energy and growth of zeta potential. Complementary structures and polytypism in metal oxide nanoparticles influence the sensitivity, cytotoxicity, and antibacterial activity of metal oxide nanoparticles. As Slavica Stankic et al. 2016 [9] verified that polymetallic oxides have a synergistic effect on antibacterial and non-cytotoxic effects.

Magnetic Nanocomposite

Nanocomposite represents a hybrid nanostructure, which exploits physio-chemical properties, with improved crystal structure. The magnetic nanocomposite is a heterogeneous system in which each constituent ion is physically assembled at different levels of organization. Magnetic nanocomposite, such as iron oxide with polymers, offers higher mechanical, thermal, and magnetic properties. The smart nanocomposite is resistant to corrosion, vibrations, and solicitations. As clarified by Anca Armaselu, 2018 [10] nanocomposites comprise fluorescent and magnetic particles which are the basis for multiplexed nano-probe designs. They can be used for forming ferrofluid, magnetic refrigeration, nanosensors, and actuators inside their layers. These properties make magnetic nanoparticles useful in the demand of Boeing aeroplanes for weight ratio.

Magnetic nanoparticles have a multitude of applications, including biotechnology, bioelectronics, nanobiosensor, nanoneedles, nanorobotics, nanomedicine, and super magnets. According to Sarkar

Siddique et al. 2020 [11] nanomaterials, such as nanoparticles, nanorods, nanospheres, nanoshells, and nanostars are widely used in biomedical imaging and cancer therapy. Magnetic nanostructures, such as $Zn_xFe_{2-x}O_3$ nanoparticles are predominantly, used in photo catalysts, nanotherapy, bio-imaging, regenerative nanomedicine, drug delivery, etc.

The Fe_2O_3-ZnO nanocomposite has been known for removing dyes and photocatalytic activity. Ying Zhang et al. 2019 [12] verified the photocatalytic activity of γ-Fe_2O_3-ZnO biochar nanocomposite synthesized by thermal decomposition method. Mohammadreza Kamali et al. 2022 [13] have also shown that ZnO/γ-Fe_2O_3/Bentonite can be synthesized by two-step method. Moreover, Hassan Pour A. et al. 2013 [14] have shown that nanopowders of Fe_3O_4-ZnO composite can be prepared from zinc acetate and di-ethanol-amine via the sol–gel method. The prepared nanocomposite in all methods exhibits better photocatalytic activities, light sensitivity, and magnetic fluid hyperthermia. Joseph Govan and Yuri K. Gun'ko, 2014 [15] revealed that magnetic nanocomposite coated with Zeolite are good catalyst for a flow reaction system. As Yuyun Yang et al. 2023 [16] discussed, nanocomposite offers significant applications in diagnosis, therapeutic, theranostics, anticancer, and antimicrobial. Nanocomposite-based sensors are candidates for clinical diagnosis, environmental remediation, food safety, and security surveillance.

FERROCENE

Ferrocene is a relatively stable solid with an orange color. It is a flammable solid when exposed to heat. As the Katja Heinze and Heinrich Lang 2023 [17] report indicates, Ferrocene was independently discovered in 1951 by Kealy, Paulson, and Miller. It is significantly used in the production of stable and heat-resistant nanomaterials. It can be purified from its host by crystallization and chromatographic process.

The largest synthetically made Nanosized macromolecule with an atomically defined structure is the dendrimer. As demonstrated by Sarkar Siddique et al. 2020 [11] dendrimers have potential applications in medical imaging, such as cell tracking, lymph node imaging, blood pool imaging, and tumor-targeted theranostics. Ferrocene containing dendrimers is represented by $Fe(C_5H_5)_2$. Ferrocene-containing dendrimers can be used in the synthesis of iron-based magnetic nanoparticles.

The best strategy to turn ferrocene for medical applications is modification of its magnetic properties. Free ferrocene are diamagnetic materials. However, polymer conjugated ferrocene exhibits paramagnetic/ferromagnetism. Magnetic nanoparticles can make composites Ferrocene since magnetic nanoparticles and ferrocene can be characterized by spectroscopic techniques, such as FT-IR spectroscopy, NMR-imaging spectroscopy, and UV-visible spectroscopes. In ferrocene, π-bonding extends in the iron atom's d-orbital enabling easier electron sharing between magnetic nanoparticles, such as ZnO and Fe_2O_3. Both ferrocene and magnetic nanoparticles can also be characterized by Apreo-chemi-SEM with improved quality in a short time.

As Hmyene, M. 1992 [18] noticed, the magnetic properties and stability of ferricenium can be modified by hybridizing with high spin polymer. Ferrocene alone can exhibit anticancer, antibacterial, and antifungal activity. This evidence suggests that the biomedical activity of magnetic nanoparticles, such as Fe_2O_3 and TiO_2, can be improved by hybridizing these with ferrocene.

SEMICONDUCTOR NANOSTRUCTURES IN BIOELECTRONICS AND BIOMEDICINE

Semiconductor nanostructures are endowed with many important size-dependent biophysical properties. These can be tailored for stable, flexible, and highly efficient bioelectronics devices and medical utensils.

One of the fundamental principles of bioelectronics is the integration of biomaterials with electronics. Magnetic nanocomposite, such as GO-Fe_3O_4 nanocomposite is used for attracting enzymes toward the electrodes. These enzymes enable electron immobilization and increase the conductivity of bioelectronics and nanoscale transistors. In the GO-Fe_3O_4 hybrid system, graphene oxide (GO) part provides conduction electrons while Fe_3O_4 maintains smooth current flow by inducing thermal energy which helps to increase the kinetic energy of electrons. Ferrocene is a useful Organometallics material in electronics. In electronics, multilayers is investigated for their resonant tunneling, anomalous Hall Effect, and flux quantization. Hence, they are ideal materials in bioelectronics.

Ferrocene is an electrode material. It increases the rate of carrier transfer rate. As a component of bioelectronics, semiconductor nanostructures are used in biotechnology as Forensics, genetic figure print, diagnosis, and Gene therapy. Silicon nanowires and carbon nanodots are used for the nanosensor for sensing biomolecules.

Due to their unique optical and dielectric properties, semiconductor nanocolloids are widely used in biosensors, bio labels, and biomarkers. As Zhang A & Lieber CM (2015) [19] revealed the development of bioelectronics enables blood glucose sensors, cardiac pacemakers, and deep-brain stimulators.

CONCLUSIONS

As the research revealed different semiconductor nanostructures have emerged with different properties and applications. Semiconductor nanostructures have different energy band gaps, density of states, and effective mass. The physiochemical properties of semiconductor nanoparticles, such as Fe_2O_3 and TiO_2, can be improved by hybridizing, with biomolecules, such as DNA, protein, and ferrocene. It is seen that such hybrid nanostructures exhibit improved biocompatibility, stability, and adaptability to body cells and tissues. Their unique characteristics and properties enable them quite useful in electronics, biotechnology, biomedicine, Forensics, and smart healthcare systems. They are pillars of nanomedicine, regenerative medicine, biosensors, and bioelectronics. Semiconductor nanostructures have shown improved anticancer, antibacterial, antifungal activity, and therapeutic applications. The application of semiconductor nanostructures is not limited to electronics and medicine but also contributes significantly to surveillance and sustainability. Although semiconductor nanostructures, such as nanoparticles, monolayers, semiconductor bilayers, multilayer, and binary semiconductors hybridized with ferrocene are quite essential in biomedicine and bioelectronics, it is important to examine the health risk effects related with dose, toxicity, and particle agglomeration. Hence, pre-tests, examinations, and AI-based detection, evaluations, and monitory systems are important.

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