



Nanostructured Hard Materials for Sensing and Detection: Material for Gas Sensor, Biosensor and Chemical Sensor

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Keywords

Biosensor, Chemical sensor, Gas sensor, Nanomaterial, Fabrication Techniques.

Abstract

Nanostructured hard materials (NSMs) have gained prominence in technological advancements due to their flexible physical, chemical and biological properties with enhanced performance over their bulk counterparts. NSMs are categorized depending on their size, composition, shape, and origin. The ability to predict the unique properties of NSMs increases the value of each classification. The aim of this chapter is to comprehensively examines the utilization of nanostructured hard materials in sensing and detection applications, specifically focusing on gas sensors, biosensors, and chemical sensors. Studying into the fundamental aspects, the paper explores the principles, basics and mechanisms of gas sensor, biosensor, and the chemical sensor. It provides a detailed overview of various types of gas sensors, emphasizing the important role played by nanostructures in enhancing sensing capabilities. Additionally, the integration of nanostructured hard materials in biosensors is discussed, with a spotlight on biomedical applications. The chapter also addresses their application in chemical sensors, highlighting the mechanisms involved and exploring emerging trends. The synthesis methods, characterization techniques, challenges, and opportunities associated with the fabrication of nanostructured materials are precisely examined. Through case studies, real-world applications are showcased, underscoring the successes and innovations achieved. This chapter concludes by summarizing the important role of nanostructured hard materials in sensing and detection, offering insights into future developments within the field.

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Article Info

Received: 25 April 2026, Received in revised form: 08 October 2026, Accepted: 08 October 2026, Available online: 18 October 2026; Volume: 2; Issue: 3; Pages: 390-407.

ISSN: 3049-2955/The authors © 2026, under exclusive license to the Sprout Publication

DOI: [10.63785/cpr.2026.2.3.390407](https://doi.org/10.63785/cpr.2026.2.3.390407)

1. Introduction

Nanotechnology, an emerging scientific field, focuses on synthesizing diverse nanomaterials. Presently, various metallic nanomaterials like copper, zinc, titanium, magnesium, gold, alginate, and silver are actively produced. These materials boast exceptional properties, propelling their continual advancement

across various fields such as chemical processes, environmental monitoring, agriculture, smart materials, sensors, biostructures, energy storage, fabrication, electronics, optics, and biomedicine. Nanostructured materials encompass nanoparticles (NPs), nanotubes (NTs), nanocomposites (NCMs), and

nanowires (NWs). Notably, nanoparticle technologies hold immense potential in converting biologically active substances, initially poorly soluble or absorbed, into viable and promising deliverable substances [1].

Nanostructured (NS) materials consist of polycrystalline structures characterized by grain sizes usually <100 nm (1 nm = 10^{-9} m). Due to the

diminutive grain size, a substantial portion of atoms resides in grain boundaries, imparting unique characteristics. Consequently, NS materials demonstrate exceptional strength, heightened diffusivity, lower sintering temperatures, advantageous catalytic properties, and appealing physical attributes [2].

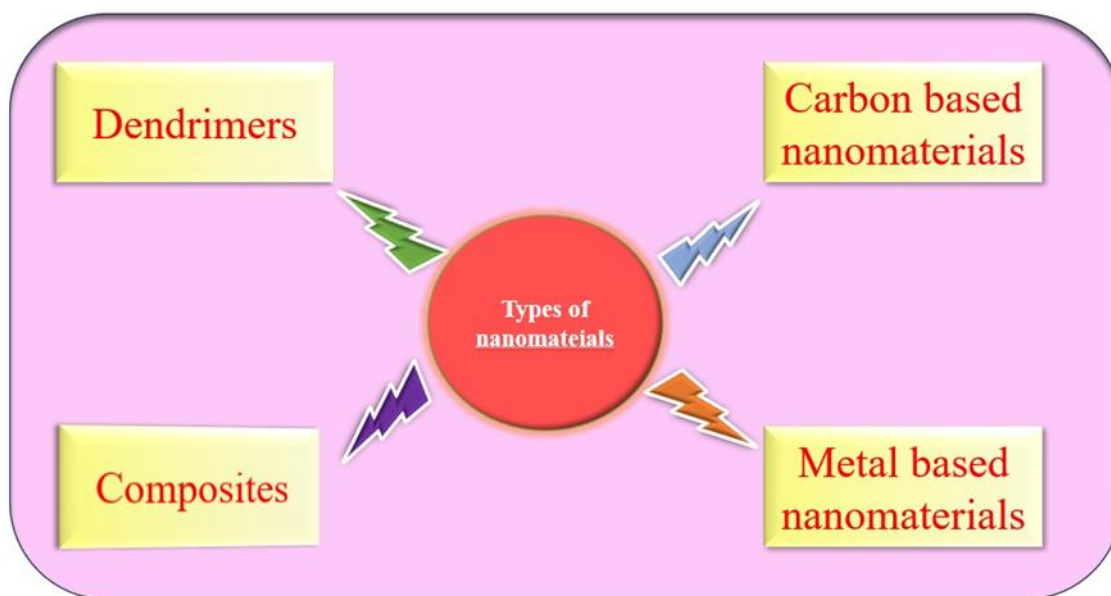


Figure 1: Different types of nanomaterials according to their composition.

2. Types and Classification of Nanomaterials

Presently, most nanoparticles (NPs) and nanostructured materials (NSMs) can be broadly classified into four major material-based categories, as illustrated in Figure 1. Carbon-based nanomaterials primarily consist of carbon and exhibit diverse morphologies, including hollow tubes, ellipsoids, and spherical structures. This group includes fullerenes (C₆₀), carbon nanotubes (CNTs), carbon nanofibers, carbon black, graphene (Gr), and carbon onions. Except for carbon black, these materials are commonly fabricated using techniques such as laser ablation, arc discharge, and chemical vapor deposition (CVD). Inorganic-based nanomaterials comprise metal and metal oxide NPs and NSMs, including noble metals such as gold (Au) and silver (Ag), metal oxides such as titanium dioxide (TiO₂) and zinc oxide (ZnO), as well as semiconductor and ceramic materials such as silicon. Organic-based nanomaterials are composed predominantly of organic components and are distinguished from carbon-based and inorganic nanomaterials by their reliance on noncovalent interactions for molecular assembly and structural organization. Representative examples include dendrimers, micelles, liposomes, and polymeric nanoparticles. Finally, composite-based nanomaterials consist of multiphase systems in which at least one phase has dimensions within the nanoscale range. These materials may involve combinations of

nanoparticles with other nanoparticles, nanoparticles integrated with larger or bulk materials such as hybrid nanofibers, or more complex architectures such as metal–organic frameworks (MOFs). Composite nanomaterials can therefore integrate carbon-based, metal-based, or organic nanomaterials with metallic, ceramic, or polymeric bulk components, enabling the development of multifunctional nanosystems [3].

2.1. Classification of Nanomaterials Based on Their Dimensions

The production of conventional products at the nanoscale presently and in the future significantly contributes to the economic advancement of numerous nations. A large number of reported NPs and NSMs exist, with predictions indicating the emergence of various other types. Consequently, the necessity for their systematic classification has become apparent. Initially the first idea for NM classification [4], the first NM classification based on crystalline forms and chemical composition lacked consideration for dimensionality [5]. In 2007, Pokropivny and Skorokhod introduced a new classification scheme shown in Figure 2 encompassing 0D, 1D, 2D, and 3D NMs, including the latest composite developments [6]. This classification relies heavily on electron movement within NM dimensions. For example, 0D NMs capture electrons within a dimensionless space, while 1D NMs allow electron

movement along a single axis (e.g., x-axis within 100 nm). Similarly, 2D and 3D NMs permit electron movement along the x–y-axis and x, y, z-axis, respectively. This scheme fundamentally outlines the

electron mobility characteristics within these nanostructures, aiding in a more comprehensive classification of nanomaterials.

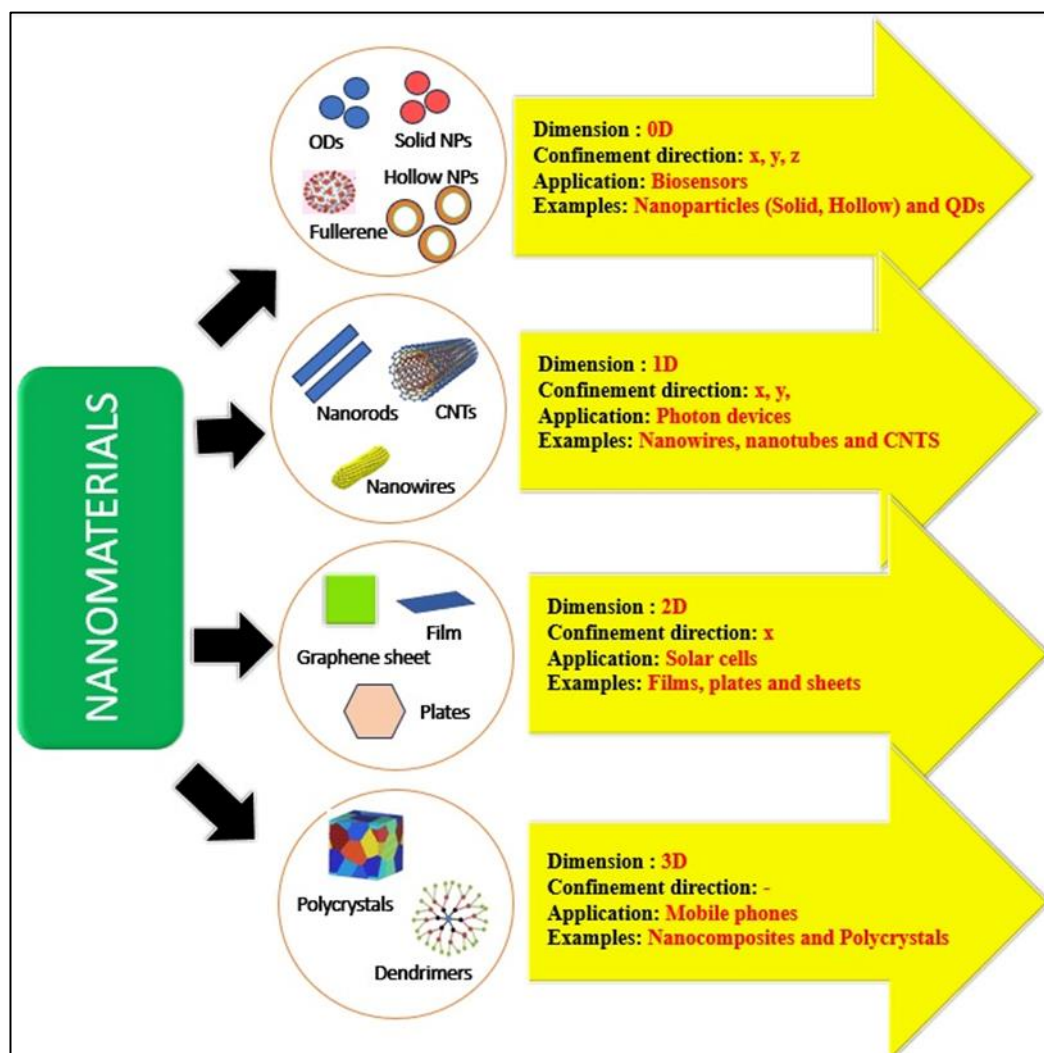


Figure 2: Classification of nanomaterials according to their dimension.

2.2. Classification of Nanomaterials Based on Their Origin

Nanoparticles (NPs) and nanostructured materials (NSMs) are further classified as natural or synthetic based on their origin and production methods. Natural nanomaterials originate from biological sources or occur due to natural processes and human activities. These materials form naturally across Earth's spheres hydrosphere, atmosphere, lithosphere, and biosphere regardless of human intervention. They exist in various environmental domains, including the atmosphere (encompassing the troposphere), hydrosphere (found in oceans, lakes, rivers, and hydrothermal vents), lithosphere (comprising rocks, soils, and evolving magma or lava), and biosphere (encompassing microorganisms, higher organisms, and humans) [7].

Synthetic or engineered nanomaterials result from mechanical grinding, engine emissions, or deliberate

synthesis via physical, chemical, biological, or hybrid methods. The increased manufacturing and release of these engineered NMs into consumer products and industries have raised concerns about risk assessment strategies. Understanding their behaviour and fate in different environmental settings becomes pivotal. Assessing the potential risks involves forecasting their behaviour, which poses a challenge due to the need to discern whether these engineered NMs behave similarly to natural NMs or exhibit distinct environmental behaviors. Current production methods for engineered NMs draw from diverse sources aligned with their intended applications [8]. The differentiation between natural and synthetic NMs is crucial for understanding their implications, environmental impact, and potential risks in various applications.

2.3. Sources of Nanomaterials

Nanomaterial sources stem from three primary

categories: (i) incidental nanomaterials, produced unintentionally in industrial or natural processes like vehicle exhaust, welding fumes, combustion, and forest fires; (ii) engineered nanomaterials, deliberately crafted by humans to suit specific applications; and (iii) naturally occurring nanomaterials, found in organisms, plants, animals, and human bodies. However, distinctions between these categories natural, incidental, and manufactured NPs can sometimes blur, with incidental NMs considered a subset of natural NMs in certain cases. Atoms, the fundamental building blocks of molecules found in all natural organisms, have been manipulated to form intricate nanoparticles (NPs) and nanostructured materials (NSMs), continuously contributing to life on Earth. Incidental and naturally occurring NMs are consistently generated and dispersed in ground and surface water, oceans, soil, and the atmosphere. Notably, engineered NMs offer greater control over morphology compared to incidental ones. Engineered NMs are intentionally designed to harness unique attributes from their small size. Metal NPs can spontaneously arise from synthetic objects, signifying prolonged human interaction with synthetic NMs. This suggests that both humans and macroscale objects potentially serve as sources of incidental nanoparticles in the environment, emphasizing the diverse sources and interactions of nanomaterials [3].

3. Biosensors

In recent years, biosensors have emerged as integral devices merging receptors and transducers, enabling the conversion of biological responses into electrical signals. Their development has garnered substantial interest among researchers and scientists due to their diverse applications in healthcare, disease identification, environmental monitoring, and upholding water and food quality [9].

According to the International Union of Pure and Applied Chemistry, a biosensor represents a self-contained analytical apparatus wherein a biological recognition component such as enzymes, antibodies, antigens, peptides, DNA, aptamers, or living cells directly interfaces with a transduction element, including electrochemical, optical, or mechanical transducers. Initially conceived for point-of-care (POC) testing, biosensors aimed to extend clinical analyses beyond specialized laboratories, reaching settings such as hospitals, nonhospital nursing facilities, and even households. Despite the creation of diverse biosensors facilitating sensitive and specific detection of disease-related molecules, challenges persist in effectively integrating and downsizing biosensors into portable devices, impeding their widespread adoption [10].

3.1. Design and Principle

A biosensor is a fusion of a biological component, such as an enzyme or antibody, with an electronic element, resulting in the production of a measurable signal. This electronic segment is responsible for identifying, recording, and transmitting information regarding physiological alterations or the presence of various chemical or biological substances within the environment. Biosensors exhibit diversity in their dimensions and configurations, possessing the capability to detect and measure even minute concentrations of specific pathogens, toxic substances, and pH levels. Generally, a biosensor comprises (a) an analyte, (b) a bioreceptor, (c) a transducer, (d) electronics, and (e) a display. (a) Analyte: Refers to the substance under scrutiny, whose constituents are being identified or detected, such as glucose, ammonia, alcohol, or lactose. (b) Bioreceptor: Designates a biomolecule or biological entity capable of recognizing the target substrate (analyte). Examples encompass enzymes, cells, aptamers, DNA or RNA, and antibodies. The interaction between the bioreceptor and analyte, culminating in signal production (e.g., light, heat, pH, charge or mass alteration, plant or animal tissue, and microbial products), is known as biorecognition. (c) Transducer: Serves as a crucial component within biosensors, responsible for converting energy from one form to another. It transforms the biorecognition event into a quantifiable electrical signal that correlates with the quantity or existence of a chemical or biological target. This energy conversion process is termed signalization. Transducers generate either optical or electrical signals commensurate with the number of analyte-bioreceptor interactions. They are broadly classified into electrochemical, optical, thermal, electronic, and gravimetric transducers based on their operational principles. (d) Electronics: Engages in processing the transduced signal for display. Electrical signals derived from the transducer undergo amplification and conversion into a digital format. The processed signals are then quantified by the display unit. (e) Display: Constituting a user interpretation system such as a computer or printer, the display unit furnishes output for user comprehension. The output may manifest as numerical, graphical, or tabular values or figures, contingent upon the specific requirements of the end-user [11].

3.2. Characteristics of a Biosensor

For the development of a viable biosensor system tailored for commercial use, adherence to specific static and dynamic criteria is imperative. These defined specifications serve as the cornerstone for optimizing biosensor performance, ensuring suitability for commercial applications. (a) Selectivity: The choice of a bioreceptor within a biosensor hinge

upon its selectivity, enabling the identification of a specific target analyte amidst a sample comprising diverse species and unwanted contaminants. (b) Sensitivity: Sensitivity denotes the capability to accurately detect minute amounts of analyte in a few steps and at low concentrations (ng/mL or fg/mL), affirming the presence of the analyte in the sample. (c) Linearity: The accuracy of measured results is influenced by linearity, where a higher degree of linearity (depicted by a straight line) augments the detection of substrate concentrations. (d) Response Time: This metric refers to the duration required to attain 95% of the final results. (e) Reproducibility: Reproducibility encompasses precision (consistency of output across multiple measurements of the same sample) and accuracy (the sensor's ability to converge on a mean value closer to the true value with each measurement of the same sample). It underscores the biosensor's ability to consistently produce results when measuring the same sample repeatedly. (f) Stability: In contexts demanding continual monitoring, stability holds paramount importance. It encapsulates the biosensor's susceptibility to environmental disturbances both within and outside the biosensing device. Factors influencing stability include the bioreceptor's affinity (the extent of analyte binding to the bioreceptor) and the bioreceptor's degradation over time [10].

3.3. Nanomaterial-Based Biosensors

The advancement of nanotechnology has sparked a diverse and adaptable approach to biosensor research and development. This progress involves exploring various nanomaterials (NMs), such as metal- and oxide-based nanoparticles (NPs), nanowires (NWs),

nanorods (NRs), carbon nanotubes (CNTs), quantum dots (QDs), and nanocomposites like dendrimers, leveraging their unique characteristics to potentially enhance biosensor performance and expand detection capabilities through size and morphology control. An illustrative depiction of diverse nanobiosensors, stemming from these nanomaterials, is presented in the Figure 3. Nanobiosensors fundamentally operate in alignment with traditional macro- and micro-counterparts but integrate nanoscale components for signal or data transformation. Their dimensional versatility bestows distinct advantages over conventional counterparts, facilitating multidisciplinary applications. In nanotechnology, nanobiosensors serve pivotal roles by (a) monitoring physical and chemical phenomena in inaccessible areas, (b) detecting biochemicals within cellular organelles for medical diagnostic purposes, (c) quantifying nanoscale particles in industrial and environmental domains, and (d) identifying exceedingly low concentrations of potentially harmful substances. The integration of diverse nanomaterials in augmenting biosensing mechanisms has been extensively explored based on their classifications. For instance, biosensors leveraging metallic nanoparticles (NPs) as signal enhancers fall into the category of NP-based biosensors. Similarly, nanotube-based biosensors, particularly those utilizing carbon nanotubes (CNTs), enhance reaction specificity and efficiency. Biosensors employing nanowires (NWs) serve as charge transporters and carriers and are recognized as NW biosensors. Additionally, sensors employing quantum dots (QDs) as contrast agents to improve optical responses are classified as QD-based sensors [11].

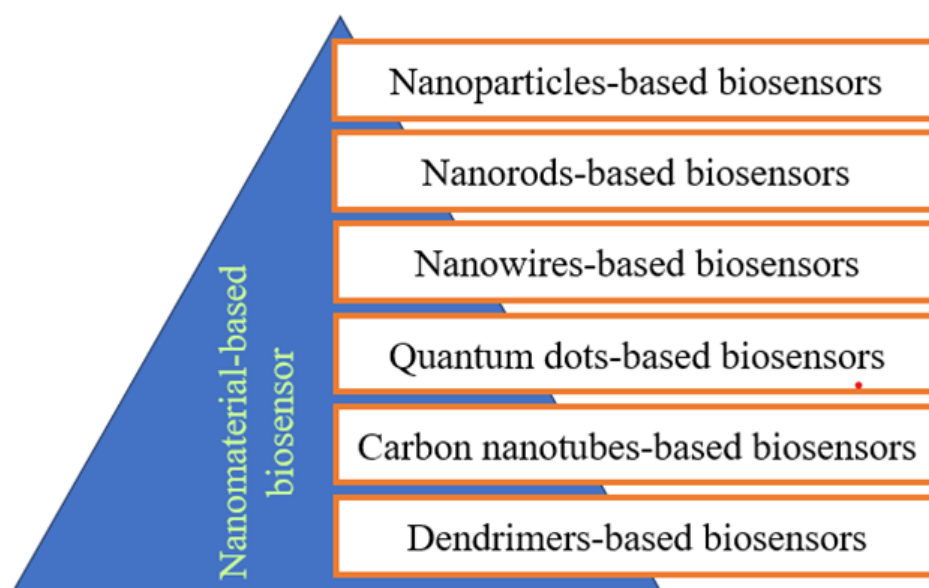


Figure 3: Types of nanomaterial based biosensors (nanobiosensors).

3.4. Nanoparticle-Based Biosensors

Nanoparticles (NPs) have become instrumental in various biomedical applications within biosensors, serving purposes in diagnostics, imaging, drug delivery, and therapy owing to their size-dependent properties influenced by biomolecule binding [12]. In electrochemical catalysis, they notably enhance electrode sensitivity and specificity [13]. Transition metal oxide NMs function as nanoenzymes, catalyzing biochemical reactions on biosensors. Notably, gold, silver, platinum, palladium, cobalt, iron, copper, and metal oxide NPs, such as ZnO, TiO₂, SnO₂, and MnO₂, possess a spectrum of diverse properties. To optimize performance, modified NP biosensing involves coatings such as metal oxides, silica, polymers, graphene, fibers, and dendrimers [14].

Gold nanoparticles (NPs), classified as noble metal NPs, hold a prominent position in biomedical research due to their distinctive optical, electronic, and physicochemical traits. They offer numerous advantages, including facile synthesis, simple fabrication, excellent chemical stability, biocompatibility, a broad electrochemical potential range, high catalytic activity, and diverse nanocomposite forms [15]. Demonstrations of their utility include development of a gold NP-based electrochemical sensor for uranyl detection in natural water, achieving a range of 2.4 to 480 $\mu\text{g L}^{-1}$, with a 0.3 $\mu\text{g L}^{-1}$ detection limit [16]. A graphene quantum dots (GQDs) and gold NPs-based fluorescent sensor detecting Pb²⁺ from 50 nm to 4 μm , boasting a 16.7 nm detection limit [17]. A novel glucose sensor utilizing gold-nickel bimetallic NPs doped aluminosilicate framework from agro-waste, offering a broad linear glucose range (1–1900 μM) and a low 0.063 μM detection limit [18].

Silver nanoparticles (Ag NPs) exhibit substantial interest in biomedical applications due to their exceptional surface-enhanced Raman scattering (SERS), biocompatibility, high conductivity, enhanced electrochemical signals, and catalytic activity [19, 20]. Researchers have engineered an optical fibre sensor utilizing localized surface plasmon resonance (LSPR) and lossy-mode resonance (LMR) with Ag NPs, displaying high sensitivity (0.943 nm per RH %), a wide dynamic range (42.4 nm for RH changes of 25–70%), and rapid response times (476 ms rise, 447 ms fall), suitable for human breathing monitoring [21]. A versatile colorimetric probe using biosynthesized AgNPs for Fe²⁺, H₂O₂, and glucose detection, achieving low detection limits: Fe²⁺ (0.54 μM), H₂O₂ (0.032 μM), and glucose (0.29 μM) based on the Fenton reaction [22].

Platinum nanoparticles (Pt NPs) have gained attention

in electrochemical biosensors for biomedical use due to their distinct electronic and electro-catalytic traits. A Pt NP/a-IGZO ammonia sensor exhibiting a high sensing response (SR) of 1467 (at 1000 ppm NH₃/air, 250 °C) and swift sensing speed [23]. A Pt and zinc oxide NPs-modified graphitic carbon nitride for non-enzymatic glucose sensing, featuring a broad linear detection range of 250 μM to 110 mM, reusable up to four times in whole blood and eight times in blood serum [24].

Palladium nanoparticles (Pd NPs) stand out in biomedical applications due to their robust catalytic and sensing capabilities, coupled with Pd's cost-effectiveness and greater abundance compared to Au and Pt metals. Tailored Pd NPs exhibit exceptional electro-catalytic and sensing traits for various analytes [25]. Pd/Co-NCNTs' superior electrocatalytic performance for hydrazine oxidation, boasting high sensitivity (343.909 $\mu\text{A mM}^{-1}$) and a low detection limit (0.007 μM) [26]. A novel 3D Pd-decorated crumple reduced graphene oxide ball (Pd-CGB) nanocomposite for H₂ detection in air, showing sensitivity in the range of 0.0025–2% H₂ with response values, response, and recovery times of 14.8%, 73s, and 126s at 2% H₂ [140]. A Pd/CNF/[M₃OA]⁺[NTF₂][−] modified sensor for sensitive determination of the anticancer drug pemetrexed, detecting concentrations from 1.00 to 35.0 nM with a 0.33 nM detection limit via square wave voltammetry (SWV) [27].

Copper (Cu) has emerged as an intriguing sensing material in biomedical applications due to its remarkable electrical conductivity, stability, cost-effectiveness, and electrocatalytic properties compared to noble metals. Electrochemical glucose sensors using copper nanoparticles (Cu NPs) on a flexible graphite sheet, achieving a low detection limit of 1.05 $\mu\text{mol L}^{-1}$ and high sensitivity (7254.1 $\mu\text{A mM}^{-1}\text{cm}^{-2}$). These sensors demonstrated excellent anti-interference properties against various substances [28]. A CuNPs-based sensor for H₂O₂ detection using an MWCNTs/IL/Chit/Rutin nanocomposite film, showing a linear detection range of 0.35 μM to 2500 μM and a 0.11 μM detection limit [29]. A Cu/rGO decorated buckypaper electrode for glucose detection, offering a linear range of 0.1–2 mM and an 11 μM detection limit [30].

3.5. Metal Oxide-Based Nanoparticles in Biosensors

Metal oxide-based nanomaterials have gained widespread application in electrochemistry, magnetism, catalysis, and sensors, thanks to their diverse electrical, chemical, and physical properties. These materials prove efficient as electrocatalysts for

biological and biomedical sensing, offering robust electrocatalytic activity, affordability, and organic capture capabilities. Commonly utilized metal oxide nanoparticles include CuO, NiO, Fe₂O₃, Co₃O₄, MnO₂, ZnO, TiO₂, SnO₂, CdO, MoO₃, and CeO₂ [31].

Nickel oxide nanoparticles (NiO NPs) exhibit remarkable electrical, magnetic, optical, thermal, catalytic, and mechanical properties, finding applications as catalysts, sensors, and additives in gases and ceramics. Functioning as p-type semiconductors with a direct bandgap of 3.56 eV, they display super-paramagnetic or superanti-ferromagnetic traits, contingent on size and oxidation states [32]. High-performance FET glucose biosensors using Ni/Cu metal organic frameworks, showcasing a low 0.51 μM detection limit within a linear range of 1 μM –20 mM [33]. Fabricated electroluminescence (ECL) glucose biosensors employing NiO NP-modified nickel foam, featuring a wide linear range (2.7×10^{-9} to 4.5×10^{-3} M) and a low 5.0×10^{-10} M detection limit in phosphate buffer solution (pH 7.4) [34].

Cobalt oxide-based nanoparticles (Co₃O₄ NPs) attract interest due to their diverse physical, magnetic, optical, electronic, and chemical properties, finding utility in catalysts, gas sensors, batteries, supercapacitors, and more [35]. A glutamate biosensor chip employing porous Co₃O₄ nanocubic crystals, exhibiting high sensitivity (20.12 $\mu\text{A mM}^{-1} \text{cm}^{-2}$), a wide linear range (10 to 600 μM), and a 10 μM detection limit [36]. A potentiometric urea biosensor on glass filter paper using cobalt oxide-chitosan nanocomposite, displaying good sensing ability over urea concentrations (1×10^{-4} to 8×10^{-2} M) with a linear slope curve of 45 mV/decade [37]. A Co₃O₄-Au polyhedron-based photoelectrochemical (PEC) biosensor detecting miRNA-141 with a 1 pM to 50 nM linear range and a 0.2 pM detection limit [38].

Iron oxide (Fe₂O₃) and manganese oxide (MnO₂) nanoparticles are recognized magnetic nanomaterials for bioanalytical applications and efficient electron transfer rates, making them promising for electrochemical biosensors [39]. The magneto-reactance effect in a nanohole-patterned soft ferromagnetic amorphous ribbon to develop a highly sensitive biosensor for anticancer drug quantification tagged to super-paramagnetic NPs [40]. A rapid and specific LF-NMR biosensor directly detecting Salmonella without sample pretreatment, achieving a detection limit of 2.6×10^4 CFU mL^{-1} [41]. A disposable biosensor using graphene nanoribbons supported by MnO₂ NPs, exhibiting a 0.05 mmol L^{-1} detection limit and high sensitivity (56.32 $\mu\text{A mmol}^{-1}\text{cm}^{-2}$) [42].

3.6. Quantum Dot-Based Biosensors

Quantum dots (QDs), zero-dimensional nanocrystals, possess distinctive optical traits encompassing broad excitation, size-tunable emission spectra, high stability, and minimal photo-bleaching [43]. Highly relevant in optical biosensor development for various organic compounds, pharmaceuticals, nucleic acids, proteins, and cancer detection, QDs serve as valuable fluorophore alternatives. Their sensitivity, specificity, cost-effectiveness, and size-dependent emission render them pivotal in multiplexed bioanalysis [44].

An efficient electrochemical sensor for Cu (II) utilizing GQDs and graphene, achieving a low 1.34 nM detection limit over a broad linear range (0.015 μM to 8.775 μM) [45]. Fluorescent turn-on biosensors using biofunctionalized GQDs and AuNPs for ultrasensitive small cell lung cancer biomarker detection, exhibiting a rapid response (16 min), a wide linear range (0.1 pg mL^{-1} to 1000 ng mL^{-1}), and a 0.09 pg mL^{-1} detection limit [46]. CdTe/CdS/ZnS core/shell/shell QDs-based biosensors for L-ascorbic acid detection in a range of 8.0×10^{-9} to 1.0×10^{-7} M with a 1.8×10^{-9} M detection limit [47]. A "turn-on" magnetic fluorescent biosensor employing GQDs, Fe₃O₄, and MoS₂ nanosheets for EpCAM detection, offering a 2–64 nM linear range and a 1.19 nM detection limit, enabling rapid and sensitive detection of circulating tumor cells (CTCs) [48].

3.7. Nanowire-Based Biosensors

Nanowires (NWs) represent an optimal platform for robust, sensitive, and selective electrical detectors of biological binding events, showcasing reproducible optical and electrical traits [49]. Their diameters, akin to the sensed biological or chemical species, enable excellent transduction, interfacing with macroscopic instruments and providing label-free electrical readouts due to tunable conducting properties [50]. Operating akin to ion-selective FETs, NW-based sensors leverage charge interactions within semiconductors, heightening sensitivity at low ionic strength [50].

A fiber optic sensor utilizing ZnO NWs and AuNPs for highly sensitive plasmonic biosensing [51]. Illustrated a label-free, PCR-free silicon NW-based biosensor, detecting genomes with a 2-copy detection limit for synthetic genomes and 20-copy detection for human blood-extracted genomes [52]. A silicon NW-based biosensor employing molecular gate control, detecting Dengue virus DNA with a 2.0 fM detection limit and high sensitivity (45.0 $\mu\text{A M}^{-1}$) [53].

3.8. Nanorods-Based Biosensors

Nanorods, derived from materials like gold, graphene, manganese, zinc, or iron oxide, serve as effective

electrochemical modifiers and are commonly used in detecting nucleic acids, glucose, and hydrogen peroxide [53]. A CDs/Au nanorod assembly-based FRET sensor for lead ion detection, achieving a linear range of 0 to 155 μM with a 0.05 μM detection limit [54]. A ZnO nanorods-based FET biosensor for continuous glucose monitoring using AC frequency mixing, displaying high sensitivity (1.6 $\text{mA } \mu\text{M}^{-1} \text{cm}^{-2}$) and a 1 μM concentration detection limit, with excellent stability over 38 hours [55]. Enhanced the sensitivity of an SPR biosensor for bovine IgG detection using GNRs and graphene oxide (GO), detecting concentrations within 0.075–40.0 $\mu\text{g mL}^{-1}$ [56]. A vertically grown ZnO nanorods-based FET biosensor for phosphate detection, boasting high sensitivity (80.57 $\mu\text{A mM}^{-1} \text{cm}^{-2}$) within a wide linear range (0.1 μM –7.0 mM) [57].

3.9. Carbon Nanotubes-Based Biosensors

Carbon nanotubes (CNTs), distinguished 1D nanomaterials, hold significant applications in biosensors, diagnostics, tissue engineering, drug delivery, and biomolecular studies [58]. Comprising single, double, or multiple concentric graphite layers, they possess unique structures and exceptional properties, including remarkable electrical and mechanical traits, high thermal conductivity, chemical stability, and electrocatalytic activity. Notably, their high surface-to-volume ratio and distinct electron transport characteristics make them highly sensitive to minor surface alterations, crucial in CNT-based biosensing across healthcare, industries, environmental monitoring, and food quality analysis [43]. These nanotubes excel in electrochemical sensing, detecting various biomolecules such as glucose, fructose, neurotransmitters, proteins, hormones, DNA, and cancer biomarkers. A wearable amperometric biosensor integrated into gloves for lactate detection. A CNT-based biosensor with a 2.89 ng mL^{-1} detection limit for bovine serum albumin (BSA). Elucidated SWNT-DNA binding mechanisms for future biotechnology applications, Improved sensor response by increasing floating electrodes in metallic floating electrode-based DNA sensors. A CNT-based biosensor system-on-a-chip integrated with CMOS chips for detecting neurotransmitters, beneficial in biomedical applications like lab-on-a-chip systems for neuronal culture [59].

3.10. Dendrimer-Based Biosensors

Dendrimers, nano-sized 3D macromolecules akin in size to average proteins, exhibit a hyper-branched, mono-dispersed, and star-shaped structure with a dense array of surface functional groups. Their structure provides ample surface area for conjugating biologically active molecules, comprising a core, interior dendron, and exterior surface with terminal

functional groups. These dendrimers find extensive use in biosensors, diagnostics, and drug delivery, leveraging electrochemistry, fluorescence, SERC, impedimetry, and SPR techniques. They enhance sensitivity, stability, and reproducibility in biosensors while minimizing nonspecific interactions. A PAMAM dendrimer integrated tapered optical fiber sensor for dengue detection, achieving a resolution of 19.53 nM^{-1} and a 1 pM detection limit within the concentration range of 0.1 pM to 1 μM . An SPR sensor using self-assembled monolayer/reduced graphene oxide-polyamidoamine dendrimer (SAM/NH₂rGO/PAMAM) thin films to detect DENV-2 E-proteins, detecting concentrations from 0.08 pM to 0.5 pM with a detection limit of 0.08 pM [60].

4. Gas sensor

The human nose contains approximately 400 scent receptors, allowing detection of about 1 trillion odors. However, our olfactory abilities do not extend to identifying gas type or concentration in the atmosphere. Sensors bridge this gap by measuring various parameters, with gas sensors particularly crucial for detecting fluctuations in toxic gases, ensuring system safety, and alerting against potential threats. These sensors are diverse and capable of detecting gases like oxygen, carbon dioxide, nitrogen, methane, among others. They are used in devices for gas leak detection and monitoring air quality in industries and offices [61].

Gas sensors operate by detecting the presence or concentration of gases. They modify the material resistance within the sensor, leading to a corresponding change in potential difference or output voltage. This voltage variation aids in estimating the gas type and concentration. The detection capabilities of the sensor rely on the embedded sensing material. Typically, available as modules with comparators, these sensors allow for the establishment of specific gas concentration thresholds. When the gas concentration exceeds the threshold, the digital pin triggers an alert, while the analog pin measures gas concentration levels, providing a comprehensive gas monitoring solution [62].

4.1. Different types of gas sensor

Gas sensors can be categorized according to the sensing element incorporated into the sensor system. Based on the sensing principle and sensing element, commonly used gas sensors include metal oxide-based gas sensors, optical gas sensors, electrochemical gas sensors, capacitance-based gas sensors, calorimetric gas sensors, and acoustic-based gas sensors. Each category operates through a distinct sensing mechanism and offers specific advantages in terms of sensitivity, selectivity, response time, stability, and

suitability for particular gas-detection applications [63].

4.2. Gas sensor construction

Among the above-mentioned types, metal oxide semiconductor-based gas sensors are the most widely used because of their high sensitivity, simple construction, low cost, and rapid response. A typical metal oxide semiconductor gas sensor consists of several essential components that collectively facilitate gas detection, as illustrated in Figure 4. These components include a gas-sensing layer, heater coil, electrode line, tubular ceramic substrate, and electrodes. The gas-sensing layer interacts with the target gas, while the heater coil maintains the required operating temperature for the sensing reaction. The electrode line and electrodes provide electrical connectivity and enable the measurement of changes in the electrical properties of the sensing layer, whereas the tubular ceramic substrate provides mechanical support and thermal stability to the sensor assembly [64].

The gas sensor consists of several essential components that collectively contribute to efficient and reliable gas detection. The gas-sensing layer is the primary sensing element and detects variations in gas concentration by changing its electrical resistance. It is

commonly composed of tin dioxide (SnO_2), which exhibits measurable resistance changes upon exposure to toxic gases, thereby allowing gas concentration to be determined through corresponding changes in electrical current. The heater coil, typically fabricated from nickel–chromium (Ni–Cr), provides uniform and controlled heating to the sensing layer, thereby improving its sensitivity and operational efficiency while withstanding elevated temperatures because of its high melting point. The electrode line, generally made of platinum wires, facilitates the transmission of the small electrical currents generated by the sensing element during gas exposure. The electrode, commonly composed of gold (Au), electrically connects the sensing layer to the electrode line and enables efficient transfer of the output signal to the terminal. A tubular ceramic substrate, usually prepared from aluminium oxide (Al_2O_3), is positioned between the heater coil and the sensing layer and provides thermal insulation, structural support, and suitable burn-in conditions required for stable sensor operation. In addition, a protective metal mesh covering encloses the sensing assembly and protects the sensing layer and other internal components from physical damage, dust, and corrosive particulate contaminants while allowing the target gas to reach the sensing surface [65].

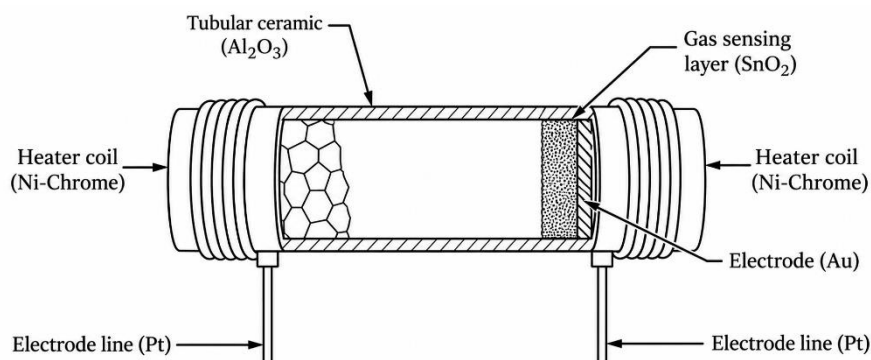


Figure 4: Illustrates the parts present in a metal oxide gas sensor.

4.3. Gas Sensor Working

A gas sensor's efficacy hinges on the chemiresistor ability to facilitate current flow. Tin Dioxide (SnO_2) serves as the predominant chemiresistor, functioning as an n-type semiconductor with free electrons (donors). Typically, atmospheric conditions entail higher oxygen levels than combustible gases. Oxygen particles attract and relocate the SnO_2 free electrons to its surface, resulting in a lack of free electrons and zero output current. The visual representation below illustrates how oxygen molecules (depicted in blue) draw in and restrict the free electrons (depicted in black) within the SnO_2 , hindering their ability to conduct current [66].

However, when the sensor encounters a toxic or combustible gas environment, these reducing gases (depicted in orange) interact with adsorbed oxygen particles, severing the chemical bond between oxygen and free electrons. This action releases the previously immobilized free electrons, allowing them to resume their original positions and conduct current. The extent of this conduction directly corresponds to the quantity of free electrons available in the SnO_2 ; higher toxicity levels yield increased free electrons, intensifying current conductivity [67].

Among the various nanostructured hard materials, metal oxides such as zinc oxide (ZnO), tin dioxide (SnO_2), titanium dioxide (TiO_2), and tungsten oxide

(WO₃) have garnered substantial attention for gas sensing applications. These metal oxides exhibit excellent properties, including high stability, sensitivity, and selectivity, making them ideal candidates for gas sensors [68].

4.4. Zinc Oxide

Zinc oxide (ZnO) nanoparticles, possess exceptional electrical and optical properties, making them suitable for gas sensing. The surface defects and oxygen vacancies in ZnO nanostructures play an important role in gas adsorption and desorption processes, influencing the sensor's response [69]. Zinc oxide nanostructured materials have gathered significant attention in gas sensing applications due to their exceptional properties, including high sensitivity, selectivity, and stability. These materials, with their unique nanostructures, exhibit promising capabilities in detecting and sensing various gases, contributing to advancements in environmental monitoring, industrial safety, healthcare, and beyond [70].

4.5. Properties of Zinc Oxide Nanostructures

Zinc oxide can be synthesized into various nanostructures, including nanoparticles, nanorods, nanowires, nanosheets, and nanotubes. These nanostructures offer a high surface area-to-volume ratio, providing an extensive surface for gas interactions. The morphology, size, and surface properties of these nanostructures significantly influence their gas sensing performance. ZnO nanostructures possess a high density of surface defects, oxygen vacancies, and active sites. These surface features play a crucial role in gas adsorption and desorption processes, affecting the sensor's response. Gas molecules interact with these active sites, leading to changes in the material's electrical, optical, or structural properties, which are then translated into measurable signals. Zinc oxide exhibits excellent electrical conductivity and semiconducting behaviour. When exposed to target gases, ZnO's electrical conductivity changes due to alterations in the charge carrier concentration or mobility. Additionally, ZnO's optical properties, such as light absorption and emission characteristics, can also be modulated by gas interactions, enabling optical-based gas sensing [71].

4.6. Gas Sensing Mechanisms

In resistive gas sensors based on ZnO nanostructures, changes in electrical resistance occur upon exposure to gases. Typically, these sensors operate by measuring the resistance change in a ZnO-based thin film or a network of ZnO nanostructures. The interaction between gas molecules and the ZnO surface alters the conductivity, resulting in a measurable change in resistance, which is correlated with the gas

concentration. Gas molecules, upon contact with the ZnO surface, chemisorb or physisorb, leading to modifications in the electronic structure of the material. This interaction causes a shift in the Fermi level or charge transfer between the gas and ZnO surface, affecting the material's conductivity. For instance, oxidizing gases tend to donate electrons to ZnO, while reducing gases extract electrons, influencing the electrical conductivity. ZnO nanostructured gas sensors can exhibit selectivity towards specific gases based on their surface properties and the nature of gas-surface interactions. The selectivity arises from the varying affinity of different gases towards ZnO and their distinctive influence on the material's electrical properties. This selectivity is advantageous for identifying and quantifying specific gases within a mixture [72].

4.7. Fabrication Techniques

The sol-gel technique involves the formation of a colloidal solution (sol) followed by gelation to create a solid material. ZnO nanostructures can be synthesized using this method by controlling parameters such as precursor concentration, temperature, and pH, enabling the fabrication of thin films, nanoparticles, or nanowires. Hydrothermal synthesis involves the growth of ZnO nanostructures under high-temperature and high-pressure aqueous conditions. This method allows the controlled synthesis of various nanostructures by adjusting parameters such as temperature, time, and reactant concentrations. Chemical Vapor Deposition (CVD) and Atomic Layer Deposition (ALD) techniques enable precise control over the growth of ZnO nanostructures on substrates. These methods offer excellent uniformity and scalability, producing high-quality thin films or coatings suitable for gas sensing applications [73].

4.8. Applications and Advancements

ZnO-based gas sensors find applications in environmental monitoring systems for detecting pollutants like nitrogen dioxide (NO₂), ozone (O₃), carbon monoxide (CO), and volatile organic compounds (VOCs). They contribute to assessing air quality in urban environments and industrial settings. In industrial settings, ZnO-based gas sensors are employed for detecting hazardous gases, ensuring workplace safety. These sensors can monitor gases like hydrogen sulfide (H₂S), ammonia (NH₃), and methane (CH₄), providing early warning systems against potential leaks or exposure. ZnO nanostructured sensors have potential applications in healthcare for monitoring gases related to diseases or metabolic processes, such as monitoring acetone levels for diabetes management or detecting biomarkers for early disease diagnosis. Ongoing research focuses on enhancing the performance of ZnO-based gas sensors

by optimizing nanostructure morphology, surface functionalization, and exploring novel device architectures. Integration with nanomaterials, such as graphene or metal nanoparticles, is being explored to further improve sensitivity and selectivity. Zinc oxide nanostructured materials have revolutionized gas sensing technology, offering high sensitivity, selectivity, and stability. Their unique properties and gas-sensing mechanisms enable the detection and quantification of various gases, contributing significantly to diverse fields like environmental monitoring, industrial safety, healthcare, and beyond. Ongoing research aims to overcome challenges, further improve performance, and facilitate the integration of ZnO-based gas sensors into everyday applications, enhancing safety and quality of life [73].

5. Tin Dioxide

Tin dioxide (SnO_2) nanostructured materials have emerged as a promising candidate for gas sensing applications due to their remarkable properties, including high sensitivity, selectivity, and stability. These nanostructured materials have been extensively researched and applied in gas sensors for detecting various gases, contributing significantly to fields like environmental monitoring, industrial safety, healthcare, and more [74].

5.1. Properties of Tin Dioxide Nanostructures

Tin dioxide can be synthesized into diverse nanostructures such as nanoparticles, nanowires, nanorods, nanotubes, and thin films. These nanostructures possess a high surface area-to-volume ratio, providing ample active sites for gas interactions. The morphology and size of these nanostructures play a crucial role in determining the gas sensing performance. SnO_2 nanostructures exhibit a large number of surface defects, oxygen vacancies, and active sites. These features significantly influence the gas adsorption and desorption processes, impacting the sensor's response. Gas molecules interact with these active sites, leading to changes in the material's electrical, optical, or structural properties, which are then translated into measurable signals [74]. Tin dioxide is a semiconductor with excellent electrical conductivity. Upon exposure to target gases, the conductivity of SnO_2 nanostructures changes due to modifications in charge carrier concentration or mobility. Additionally, SnO_2 optical properties, such as light absorption and emission characteristics, can be altered by gas interactions, enabling optical-based gas sensing applications [74].

5.2. Gas Sensing Mechanisms

SnO_2 nanostructured gas sensors primarily operate based on changes in electrical resistance upon exposure to gases. These sensors usually consist of

thin films or networks of SnO_2 nanostructures. Gas molecules interacting with the SnO_2 surface modify its conductivity, resulting in a measurable change in resistance, which is correlated with the gas concentration. Gas molecules adhere to the surface of SnO_2 through chemisorption or physisorption processes, leading to modifications in the material's electronic structure. This interaction induces a shift in the Fermi level or facilitates charge transfer between the gas and SnO_2 surface, altering the material's conductivity. For instance, oxidizing gases tend to donate electrons to SnO_2 , while reducing gases extract electrons, influencing the electrical properties. SnO_2 nanostructured gas sensors often exhibit selectivity towards specific gases based on their surface properties and the nature of gas-surface interactions. Different gases have varying affinities towards SnO_2 , resulting in distinct effects on the material's electrical properties. This selectivity is advantageous for identifying and quantifying specific gases within complex gas mixtures [75].

5.3. Fabrication Techniques

Chemical Vapor Deposition (CVD) and Physical Vapor Deposition (PVD) methods enable the controlled growth of SnO_2 nanostructures on substrates. These techniques offer precise control over the morphology and structure of the resulting materials, producing high-quality thin films or coatings suitable for gas sensing applications. Sol-gel and hydrothermal synthesis routes are commonly employed to fabricate SnO_2 nanostructures. These methods involve controlling reaction parameters like temperature, time, and precursor concentrations to synthesize nanoparticles, nanowires, or other nanostructured forms of SnO_2 [76].

5.4. Applications and Advancements:

SnO_2 -based gas sensors are extensively used for environmental monitoring, detecting pollutants like nitrogen dioxide (NO_2), carbon monoxide (CO), volatile organic compounds (VOCs), and ozone (O_3). They play a crucial role in assessing air quality in urban environments and industrial zones. In industrial settings, SnO_2 -based gas sensors are employed for detecting hazardous gases such as hydrogen sulphide (H_2S), ammonia (NH_3), methane (CH_4), and other volatile substances. These sensors provide early warning systems against potential leaks or exposure, ensuring workplace safety. SnO_2 nanostructured sensors have potential applications in healthcare for monitoring gases related to diseases or metabolic processes. They could be used for monitoring acetone levels for diabetes management or detecting specific biomarkers for early disease diagnosis. Ongoing research focuses on enhancing the performance of SnO_2 -based gas sensors by optimizing

nanostructure morphology, surface functionalization, and exploring novel device architectures. Integration with other nanomaterials, such as graphene or metal nanoparticles, is being explored to further improve sensitivity and selectivity. Tin dioxide nanostructured materials have exhibited exceptional potential in gas sensing technology, offering high sensitivity, selectivity, and stability. Their unique properties and gas-sensing mechanisms enable the detection and quantification of various gases, contributing significantly to diverse fields like environmental monitoring, industrial safety, healthcare, and more. Ongoing research aims to address challenges, enhance performance, and facilitate the integration of SnO_2 -based gas sensors into everyday applications, thereby improving safety and quality of life [76].

6. Chemical Sensor

Chemical sensors serve the critical function of translating chemical information into electrical signals, providing qualitative or quantitative insights into specific components. These sensors exhibit diverse properties such as conductivities, potentials, capacities, heats, masses, or optical constants, which undergo alterations upon interaction with chemical species. An array of sensor types exists, encompassing amperometric CO -sensors for assessing air quality, Lambda-probes adept at detecting oxygen in car exhaust, Taguchi SnO_2 sensors measuring oxide conductance for gas warnings, and pellistors monitoring reducible gases through reaction heats. While chemical sensors might lack the high selectivity and quantitative precision of laboratory equipment,

they are compact, cost-effective, and widely available. Modern sensors heavily rely on thin films and nanostructures, which act as both functional and structural materials. The evolution of microelectromechanical systems (MEMS) showcases the utilization of submicron materials in versatile functions for advanced devices, highlighting the expanding utilization of confined materials in cutting-edge technologies. An accompanying schematic diagram depicts the chemical sensor in Figure 5 [77].

The advent of nanostructured hard materials has transformed chemical sensing and detection technologies owing to their outstanding properties, offering heightened sensitivity, selectivity, and stability. These materials, characterized by their nanoscale dimensions and distinctive structures, have significantly contributed to chemical sensors, enabling precise and efficient detection of various chemicals and analytes across diverse applications. Carbon-based nanomaterials, like graphene and carbon nanotubes (CNTs), possess remarkable electrical, mechanical, and chemical attributes. With high surface area, exceptional conductivity, and unique interactions with target molecules, these materials are well-suited for chemical sensing applications. Functionalized graphene and CNT-based sensors exhibit exceptional sensitivity toward diverse analytes, including biomolecules, gases, and environmental pollutants. Their adaptable design allows for customized sensor architectures, enhancing efficiency and specificity in detection [78].

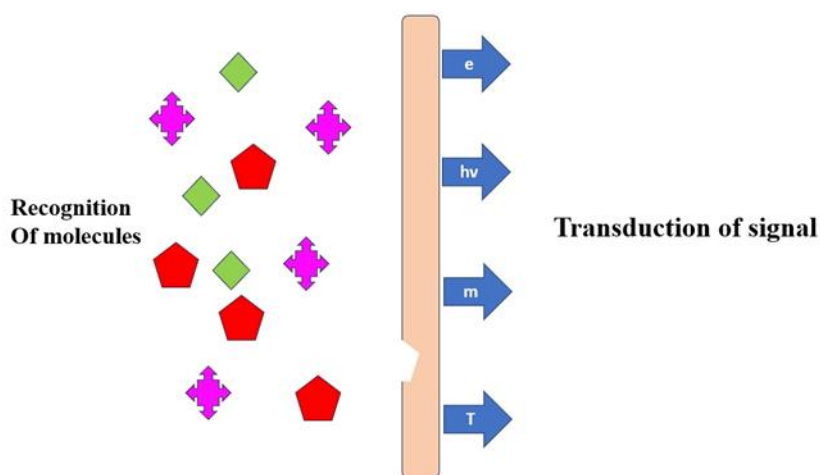


Figure 5: Schematic diagram of a chemical sensor.

6.1. CNTs

The discovery of carbon nanotubes (CNTs) in 1991 by Iijima sparked significant scientific and technological interest in the field of nanotechnology. CNTs, resembling rolled graphite sheets, exist primarily in two forms: single-wall carbon nanotubes (SWCNTs) and multi-wall CNTs (MWCNTs). These structures,

ranging in diameter from fractions of nanometers to tens of nanometers and extending several centimetres in length, typically possess fullerene-like structures at both ends [79]. Their nanoscale nature endows these structures with exceptional properties that have garnered attention in the materials realm, particularly in the realm of conductive polymers and composite

applications. The integration of CNTs into polymer matrices has been a focal point for researchers aiming to create advanced materials with diverse functionalities. These efforts concentrate on atting polymers, thereby producing conductive polymer composites. In chemical sensing applications, CNTs offer appealing attributes due to their cylindrical carbon structure, high aspect ratio, impressive electrical conductivity, and extensive surface area. These characteristics enable sensitive and selective detection of gases, volatile organic compounds (VOCs), and various analytes, promising widespread applications in environmental monitoring, industrial safety, healthcare, and beyond. The physical and catalytic properties of CNTs make them ideal candidates for use in chemical sensors. Their structured composition and high aspect ratio contribute to outstanding chemical, thermal, and mechanical characteristics, including stiffness, Young's modulus, flexibility, and electrical conductivity [80]. These exceptional attributes facilitate the development of nanoscale devices and multifunctional composite materials, showcasing the versatile applications of SWCNTs and MWCNTs across various scientific and technological domains [81].

6.1. Chemical sensing mechanism

When exposed to target molecules or gases, these substances interact with the surface of carbon nanotubes through physical adsorption or chemical interactions. This interaction can cause a change in the electronic structure near the nanotube surface, leading to alterations in the nanotube's conductance or other electrical properties. The adsorption or attachment of molecules onto the surface of the nanotube alters its electronic structure, leading to modifications in its conductance. This change in conductance can be measured using various techniques like electrical measurements or field-effect transistors (FETs) based on carbon nanotubes. The specificity of the sensing mechanism depends on the type of functional groups or the nature of molecules attached to the nanotube surface. This selectivity allows for the detection of specific gases or molecules. Additionally, the high surface-to-volume ratio of CNTs contributes to their sensitivity, enabling detection at very low concentrations [82].

6.2. Fabrication

Two primary strategies exist for incorporating carbon nanotubes (CNTs) into electric devices: utilizing as-grown CNT films or depositing purified CNTs. As-grown CNT film fabrication involves high-temperature chemical vapor deposition onto prepatterned electrodes, ensuring robust electrode/CNT connections and minimizing bundling and inter-CNT

effects. However, it presents challenges in controlling CNT growth angles, resulting in low device yield, particularly for longer channel lengths. Moreover, limitations exist in controlling CNT diameter distributions and chiralities, hindering on-device purification steps. Techniques disrupting metallic CNTs such as electrical breakdown plasma etching enhance CNT transistor performance [83].

Alternatively, fabrication approaches employing preformed CNT deposition leverage solution-based functionalization and purification methods, enriching specific CNT characteristics. Post-deposition treatments further enhance transistor performance, sensitivity, and response time. Strategies involving prepatterned electrode deposition hold CNTs weakly, potentially leading to variable contact resistance and device performance drift. In contrast, postdeposition of metal electrodes onto CNTs ensures stronger contact and lower resistance [84]. Various deposition methods like inkjet printing, spray coating, spin coating, drop casting, or doctor blading secure CNTs in place by solvent removal or external forces, yielding robust sensing materials [85].

Layer-by-layer assembly or alternating current dielectrophoretic (DEP) techniques enable repeatable and aligned CNT deposition, resulting in enhanced device performance compared to random network configurations. Exploration into solvent-free deposition methods, such as abrasive deposition using compressed CNT pellets, offers simplicity and rapid fabrication suitable for teaching laboratories and prototyping [86]. Adhesive deposition using viscous CNT-containing mixtures like "bucky gels" with ionic or deep eutectic liquids shows promise in commercial chemiresistive sensor production, despite limitations in mechanical integrity and substrate requirements [87]. These diverse strategies offer distinct advantages and limitations in effectively incorporating CNTs into diverse electronic devices and sensor applications.

6.3. Applications and Advancements

CNT-based sensors demonstrate high sensitivity and selectivity in detecting toxic gases such as ammonia, nitrogen dioxide, carbon monoxide, and various volatile organic compounds (VOCs). They offer rapid and precise detection even at low concentrations, crucial in environmental monitoring and industrial safety. CNT sensors are employed in environmental monitoring to detect pollutants, greenhouse gases, and air quality. Their sensitivity enables real-time monitoring of environmental changes, aiding in pollution control and management. Functionalized CNTs are used in biosensors for detecting biomolecules like DNA, proteins, and other biological markers. Their high specificity and sensitivity make

them valuable in medical diagnostics, disease detection, and biomedical research. CNT-based sensors are capable of detecting chemical warfare agents due to their sensitivity to specific molecules. This application is critical in defence and security sectors for early detection and protection against chemical threats. In industrial settings, CNT-based sensors are used for quality control purposes, particularly in the semiconductor and electronics industries. They aid in monitoring gas concentrations during manufacturing processes to ensure product quality and safety. CNT sensors play a role in leak detection systems, identifying gas leaks in pipelines, storage facilities, or industrial equipment. Their sensitivity allows for the early detection of leaks, preventing potential hazards [77].

7. Future Directions and Potential Breakthroughs

The future of nanostructured hard materials in sensing and detection holds advancement across various fields due to their unique properties and potential for innovation. Researchers, delving deeper into nanotechnology, anticipate several directions and potential advancements. Further refinement in nanostructured materials is expected to lead to sensors with heightened sensitivity and selectivity, capable of detecting extremely low concentrations of analytes, even at the single-molecule level. The integration of multiple nanostructured materials or multifunctional nanocomposites may cover the way for sensors capable of simultaneously detecting and analyzing multiple parameters, providing comprehensive and real-time monitoring of complex environments. Advancements in nanostructuring techniques are likely to contribute to sensor miniaturization, facilitating integration into wearable devices. These compact, flexible, and lightweight sensors could reorganize personalized healthcare and safety monitoring by offering continuous, non-invasive monitoring of health parameters, environmental conditions, or toxic gas exposure. Nanostructured materials are expected to play an important role in the development of smart sensing technologies, contributing to real-time data collection and analysis for smart cities, intelligent transportation systems, and efficient environmental monitoring. Future advancements may focus on developing self-powered nanosensors that harvest energy from their environment or utilize energy-efficient mechanisms for sustained operation. The development of biocompatible and biodegradable nanostructured materials is likely to lead to sensors suitable for biomedical applications, ensuring compatibility with biological systems and enabling continuous health monitoring or drug delivery. Additionally, nanostructured sensors could significantly contribute

to environmental monitoring and sustainability efforts by detecting pollutants, monitoring climate-related parameters, and enabling precision agriculture. Despite these promising prospects, challenges such as standardization, scalability, cost-effectiveness, and potential environmental and health impacts of nanostructured materials will require continued attention. Interdisciplinary collaborations, technological innovation, and sustained research efforts will be crucial in shaping the landscape of sensing and detection technologies with nanostructured hard materials [88].

8. Limitations of Nanostructured Materials in Sensing

While nanostructured hard materials hold innovating potential in sensing and detection, several limitations impede their widespread adoption. Challenges include complex and costly synthesis processes, making upscaling for large-scale manufacturing is difficult. Ensuring consistent sensor performance across different material batches remains a challenge due to variability in synthesis methods. High production costs, associated with expensive raw materials and intricate fabrication techniques, limit accessibility, particularly in lack of resource settings. Achieving stable functionalization of nanostructures and ensuring long-term stability hold challenges, impacting sensor performance over time. Despite high sensitivity, achieving exceptional specificity and selectivity for target analytes proves challenging, leading to potential inaccuracies in detection. In complex matrices, nanostructured sensors may face interference, affecting accurate target analyte detection. Durability issues, including degradation and structural changes, impact sensor stability and reliability, especially under harsh conditions. Some nanostructured materials, like metal-based nanoparticles, raise concerns about toxicity, emphasizing the need for biocompatibility in biomedical and environmental sensor applications. Integration challenges, requiring specialized instrumentation, and regulatory and ethical considerations further complicate widespread adoption. Addressing these limitations necessitates interdisciplinary efforts in materials science and engineering, emphasizing continued research to unlock the full potential of nanostructured hard materials in sensing and detection across diverse applications [88].

Conclusion

In the wide field of sensing and detection, the introduction of nanostructured hard materials marks a progressive era, presenting unique opportunities in gas sensors, biosensors, and chemical sensors. These materials, with their tiny size, extensive surface area,

and distinctive physical and chemical properties, have become crucial components in modifying sensor technology. Gas sensors, utilizing nanostructured materials like metal oxides, carbon-based nanomaterials, and semiconductor nanoparticles, demonstrate exceptional sensitivity and selectivity in detecting various gases and volatile organic compounds. They play a vital role in monitoring environmental pollutants and ensuring industrial safety, becoming indispensable for protecting both human health and the environment. In the field of biosensors, nanostructured materials have opened new frontiers, enabling precise and sensitive detection of biomolecules, viruses, and pathogens. Quantum dots, gold nanoparticles, and carbon nanotubes modified with specific biomolecules have paved the way for advanced diagnostics, disease monitoring, and biomedical research, promising breakthroughs in personalized healthcare and disease management. Additionally, nanostructured materials have redefined chemical sensing, providing diverse opportunities, including the detection of chemical species, environmental parameter monitoring, and ensuring food safety. These sensors leverage the unique properties of nanomaterials, such as high surface-to-volume ratio, to achieve heightened sensitivity, selectivity, and reliability. While the potential of nanostructured hard materials in sensing and detection is enormous, challenges such as synthesis complexity, scalability issues, and cost constraints pose obstacles to widespread commercialization. Addressing standardization, reproducibility, and stability concerns requires collaborative efforts in materials science and engineering to ensure consistent and reliable sensor performance. Despite these challenges, the future holds promise for advancements, with innovations in nanomaterial synthesis techniques, functionalization strategies, and sensor integration expected to overcome existing limitations. Miniaturization and wearable sensors

enabled smart sensing systems are anticipated to thrive, providing real-time, high-fidelity data for personalized health monitoring, environmental surveillance, and smart city initiatives. Ethical and regulatory considerations related to nanomaterials necessitate a balanced approach, emphasizing safety, sustainability, and ethical deployment in sensor technologies. Collaborative efforts across scientific disciplines, academia, industry, and regulatory bodies will play a crucial role in guiding nanostructured hard materials toward responsible and impactful applications in sensing and detection. In conclusion, nanostructured hard materials are leading the way in sensing and detection technologies, poised to redefine innovation boundaries. Their multifaceted applications in gas sensors, biosensors, and chemical sensors signal a future where precision, sensitivity, and reliability converge to tackle critical societal and environmental challenges, ushering in an era of transformative sensor technology.

Acknowledgement

Thankful to Narayan Institute of Pharmaceutical Sciences, Gopal Narayan Singh University, Jamuhar, Sasaram, 821305, Bihar, INDIA, for their support throughout writing this article.

Author Contribution

SK: Study Conception and Design; **AKP:** Data Collection; **DK:** Manuscript Drafting

Consent for publication

Not applicable.

Funding

None.

Conflict of interest

The author declared no conflict of interest.

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