SYNTHESIS, MECHANISM AND APPLICATIONS OF GAS SENSORS-A COMPREHENSIVE STUDY

Abstract

An overview of Gas sensors is presented in the present chapter. The scientific community has recently conducted in-depth study from theory to practice on the optimum sensor. We address gas sensors for high-volume applications. This industry mostly consists of semiconductor sensors, although comparisons between rival products highlight their advantages. Spectroscopic data and molecular calculations shed light on chemical and physical function. As examples of significant applications, monitoring of combustibles, particularly methane, and the early detection of fires are provided. The development of electronic noses has been accelerated by advancements in microelectronics. This paper examines the current state of the art for electrical gas sensors using carbon nanomaterials, discusses the barriers to their commercialization, and also highlights some recent developments. In light of the foregoing, this review article concentrates on new materials and technologies that can be used for applications involving environmental monitoring, Indoor Air Quality, Automative applications, medical applications and other plentiful Applications.

Keywords: Gas sensors, Spectroscopic data, Nanomaterials, Indoor Air Quality, Automative applications.

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I. INTRODUCTION

In general, Sensors are intricate devices designed to perceive and measure various physical attributes within our environment. These attributes encompass a wide range of phenomena, such as temperature, pressure, light intensity, and more. The collected measurements can be interpreted directly or transformed into signals, which can then undergo processing by electrical, hydraulic, or pneumatic systems, enabling us to gain valuable insights and make informed decisions based on the gathered data. Gas sensors are devices that allow us to understand both the amount of gas in the environment and the natural dispersion patterns of the gas [1]. Moreover, Gas sensors use electrical impulses to determine the kind of gas composition, the amount of gas present. Gas sensors can be used in a variety of fields, including the food, cosmetic, and medical industries. Different selectivity and sensitivity to various gases are needed for each application. The sensors must be versatile for this. This subject has been communicated through a comprehensive approach encompassing various disciplines, including chemistry, biology, medicine, nano-material synthesis, and applications. The emphasis is on highlighting the significant scientific and technological progress achieved within this field over the years. A review of developments in basic and applied research that have resulted in the creation of real high-performance devices is given [2]. Additionally, methods for creating novel semiconducting materials with unheard-of nanostructures and gas-sensing capabilities could be revealed. Future uses of gas sensors and perspectives on new technology have also been emphasized. Using solid state sensors to detect and monitor gases has become a common practice. There are now three main types of solid-state gas sensors that are widely used, and several other designs that are currently under development may one day be used commercially. Here, the existing sensor kinds are discussed, and some of the emerging technologies are briefly introduced. Additionally, sensors employing oxide-free semiconductors hold significant promise. The potential for achieving highly selective sensors far surpasses that of MOS sensors. Moreover, these sensors commonly function at ambient temperatures, unlike MOS sensors, which usually require operation at temperatures ranging from 300°C to 500°C [3].

II. DISCUSSION

From our perspective, the future advancement of semiconductor sensor technology will be centered on non-oxide semiconductor sensors, particularly those incorporating layers of carbon nanotubes (CNTs) and graphene. This progress will be facilitated by the growing mastery of technology and the enhanced accessibility of carbon nanomaterials employed in their fabrication.

Solid-state gas sensors are devices that can detect the presence and concentration of specific gases in the environment. These sensors use solid materials as their sensing elements, and they are widely used in various applications. Three principle classifications of solid-state gas sensors that are widely used are, [4].

1. **Metal Oxide Gas Sensors:** Metal oxide gas sensors are among the most commonly used solid-state gas sensors. They operate based on the principle that certain metal oxides change their electrical conductivity in the occurence of specific gases. When a target gas interacts with the metal oxide surface, it causes a change in resistance that could be measured and correlated to the gas concentration. These sensors are sensitive to a wide

range of gases, including combustible gases (such as methane and propane) and harmful gases (such as carbon monoxide and nitrogen dioxide) [5, 6].

2. **Conducting Polymer Gas Sensors:** Conducting polymer gas sensors are alternative category of solid-state gas sensors. These sensors use organic polymers that can conduct electricity when exposed to specific gases. The engagement between the gas molecules and the polymer's structure causes changes in its electrical properties, allowing for gas detection. Conducting polymer sensors are used for detecting gases like ammonia, volatile organic compounds (VOCs), and various other analytes [7].

3. **Catalytic Gas Sensors:** Catalytic gas sensors are designed to detect combustible gases. They consist of a catalytic material that promotes the oxidation or reduction of a target gas. When the gas reacts with the catalytic material, heat is generated; this leads to a change in resistance or another measurable parameter. These sensors find frequent use in industrial contexts for the purpose of detecting the existence of combustible gases [8].

   Each of the above discussed types of solid-state gas sensors has its advantages and limitations, and their suitability for specific applications depends on factors such as sensitivity, selectivity, stability, and cost. Advances in materials science and sensor technology continue to drive improvements in the performance and applicability of Solid-State gas sensors.

   Creating novel semiconducting materials with unique nanostructures and gas-sensing capabilities involves a combination of innovative techniques, materials engineering, and a deep understanding of both semiconductor physics and gas-surface interactions. Brief outline of methods used is discussed in the below sections.

4. **Computational Modeling and Design:** Commence by employing sophisticated computational techniques like density functional theory (DFT) and molecular dynamics simulations to forecast the characteristics and actions of diverse nanostructures. Begin by utilizing advanced computational tools such as density functional theory (DFT) and molecular dynamics simulations to predict the properties and behaviors of various nanostructures. Design and simulate the interactions between the chosen gas molecules and the proposed nanostructures to understand their potential gas-sensing capabilities [9].

   - **Bottom-Up Synthesis Techniques:** Employ bottom-up synthesis methods as chemical vapor deposition (CVD), molecular beam epitaxy (MBE), or solution-phase techniques to precisely control the growth of nanostructures with atomic precision. Tailor growth parameters such as temperature, pressure, and precursor concentrations to create specific nanostructures with desired properties [10, 11].

   - **Nanomaterials Fabrication:** Explore techniques like self-assembly, nanolithography, and atomic layer deposition to construct intricate and controlled nanostructures, such as nanowires, nanotubes, and quantum dots [12]. These techniques enable the fabrication of materials with tuned band gaps and surface properties, which are crucial for gas sensing.

- **Hybrid and Composite Materials:** Combine different materials, such as semiconductors, metals, and oxides, to form hybrid or composite structures. These can offer synergistic properties that enhance gas-sensing capabilities. For example, hybrid nanocomposites of graphene and metal oxides have shown improved gas adsorption and sensitivity [13].

- **Surface Functionalization:** Modify the surface of the nanostructures through techniques like doping, chemical functionalization, or surface coatings to enhance gas adsorption and selectivity. Introducing specific functional groups can improve interaction with target gases, leading to more accurate and sensitive gas sensing [14].

- **Innovative Sensor Designs:** Experiment with diverse sensor configurations, including field-effect transistors (FETs), nanowire sensors, and surface acoustic wave (SAW) devices. Diverse sensor configurations present differing levels of sensitivity, reaction speeds, and discriminations, contingent on the interplay between gas molecules and the semiconductor surface.

- **Real-Time Monitoring and Data Analysis:**Develop advanced measurement setups to enable real-time monitoring of gas interactions with nanostructured materials. Implement sophisticated data analysis techniques, such as machine learning algorithms, to extract meaningful patterns from sensor responses and improve gas identification accuracy.

- **Characterization Techniques:** Employ advanced characterization techniques like X-ray diffraction, transmission electron microscopy (TEM), and scanning probe microscopy to analyze structural and electronic properties of the created materials [15].

- **Iterative Optimization:** Continuously iterate through the design, fabrication, and testing processes, optimizing the material composition, nanostructure geometry, and sensor configuration based on experimental results.

- **Collaborative Research:** Collaborate with experts from various fields, including materials science, chemistry, physics, and engineering, to gain diverse perspectives and insights into creating novel materials with exceptional gas-sensing capabilities. Remember that creating such novel materials requires a combination of creativity, scientific expertise, and technological innovation. It's also important to stay updated with the latest advancements in nanotechnology, materials science, and gas sensing techniques.

III. GAS SENSING MECHANISMS OF METAL OXIDE SEMICONDUCTORS:

For conductivity in MOS, electrons and holes serve as the primary charge carriers. N-type MOS are materials that bear more electrons than holes in accordance with variations in their relative contents, whereas p-type MOS have internal carriers that are more abundant in relative terms [16, 17]. Some oxidizing gases, such as O_2, have the ability to pull electrons away from the MOS surface when their electronic affinities are greater than the latter's work function. As a result, ionized oxygen anions, such as O_2, O will develop at different temperatures when this happens. Furthermore, in cases where the electrical attraction of gas molecules is less than the work function of the MOS surface, electrons from these gas molecules might be released, giving rise to cations like reducing gases (CO) on the surface. As a result, when an n-type MOS is unmasked to an oxidizing gas, electrons are drawn in and merged with the gas molecules, creating an electron depletion layer on the material's facet and creating an electrical core-shell structure as shown in Figure (1), that has a high resistance property. Adsorbed oxygen ions in an n-type MOS can be oxidized when it is exposed to a reducing atmosphere. Subsequently, entrapped electrons will reintegrate into the MOS surface, amplifying the density of charge carriers and consequently reducing the resistance of the sensor. A recognized functional correlation exists between the gas concentration and the response of the MOS gas sensor [18- 23]. This makes it useful for quantitative gas analysis.

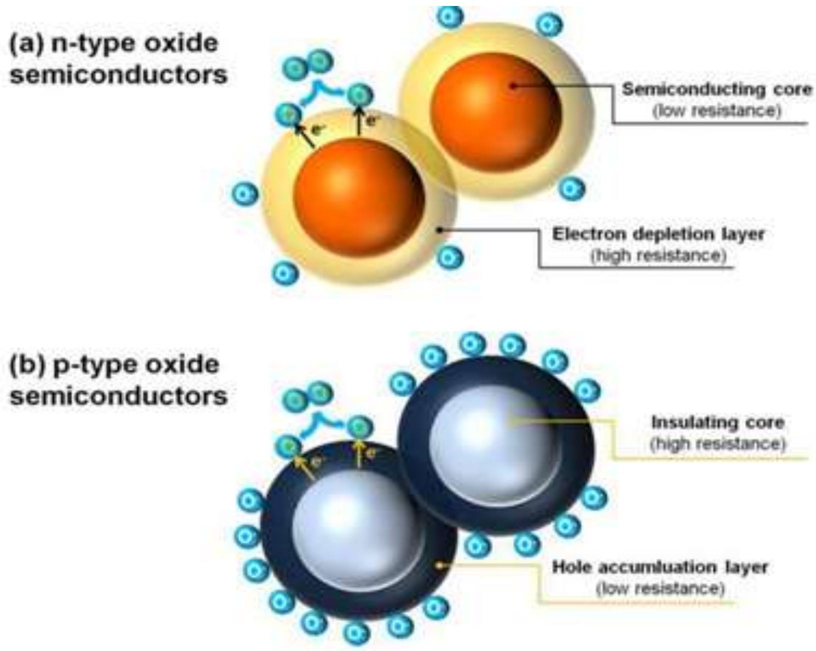

Figure 1: Formation of core–shell structures of charge carriers [17].

In case of p-type MOS, the predominant charge carriers are holes, which accumulate on the semiconductor's surface, creating a low-resistance hole accumulation layer. In contrast, MOS displays a high-resistance trait, giving rise to the core-shell structure. In this setup, upon adsorption of reducing gases, these gases interact with ionized oxygen anions on the material's surface, liberating electrons to the MOS. As a consequence, the concentration of holes in the shell layer diminishes, leading to an increase in material resistance [24].

IV. SYNOPSIS OF SYNTHESIS METHODS

As study of metal-oxide-based heterostructures has progressed, many fabrication techniques have been used to create these materials. Synthesis techniques have developed quickly as a result of the requirements for the preparation of these heterostructures, which include structural affinity and chemical uniformity. As a result of the investigation's introduction of some widely used production methods, it will be possible to combine multiple MOS material types to create a variety of hetero-structural nanomaterials.

1. **Sol-Gel Method:** The sol-gel technique stands as one of the highly favored methods for crafting heterostructures based on MOS. This involves introducing a surface-active agent to a blend of highly reactive compound precursors, resulting in the development of a stable and transparent sol system through internal chemical processes. Gradual polymerization that follows causes the gel to become stationary. Finally, drying and sintering techniques can be used to create nanostructured materials. Using the sol-gel technique, Jiang et al. investigated impact of polyethylene glycol on the microstructures of thin films of TiO_2 [25]. They stated that when more polyethylene glycol is added or when polyethylene glycol has a high molecular weight, porous and fine-grained TiO_2 films can form. They came to the conclusion that they could control the size and shape using the sol-gel approach [26].

2. **Vapor Deposition Method:** Physical vapor deposition (PVD) or chemical vapor deposition (CVD) make up majority of this technique. In CVD technology, films are created on the substrate surface by chemical reactions between one or more gaseous compounds or basic substances encasing film ingredients. The CVD process can be used to deposit monocrystal, polycrystal, glassy inorganic films, and other types of crystals as well as to build new crystals from raw materials. Vapor deposition is a method for accurately controlling the physical characteristics of materials. Additionally, by carefully controlling the vapor deposition process, including the operating temperature, reactor pressure, template material, and gas-phase composition [27], high purity samples with various structures and morphologies can be produced. Recently, SnO_2/ZnO super lattice nanowires were produced [28].

   PVD is another established method for creating new heterostructures. To enhance the nucleation of oxide materials, several catalyst layers could be put on substrates. Materials created with PVD process have a different morphology depending on the type of catalyst used, the patterned framework, the furnace's temperature and pressure, the carrier gas composition along with its flow [29]. Low dimensional metal oxide heterostructures are obtained using the PVD process, which is commonly employed under elevated temperatures within a high-vacuum or inert-gas atmosphere. Choi et al. successfully constructed the ZnO-SnO_2 nanofiber-nanowire stem-branch heterostructure by depositing a small layer of Au on the outer layer of ZnO nanofiber stems to encourage the expansion of SnO_2 nanowires using PVD technique [30].

3. **Electro Spinning Method:** liquid droplets.The micro flow of polymer will be expelled from the solution surface when the surface charge repulsion force is larger than the surface tension. Electric field force causes liquid flow to be stretched and dragged, followed by the solvent volatilizing and solidifying before the sample is deposed on ready substrate to create polymer fiber [31]. By electro spinning, nano polymer filaments can be created. By using the electro spinning technique, Feng et al. [32] created TiO_2-SnO_2 composite hetero junction materials exhibiting core-shell nanofiber architecture.

V. MECHANISMS OF GAS SENSING IMPROVEMENT WITH HETEROSTRUCTURES

Incorporating heterostructures into gas sensors leverages the unique properties of different materials to create more sensitive, selective, and efficient sensing platforms. Understanding the mechanisms driving the enhancement enables researchers to design and optimize novel gas sensors for an extensive variety of applications. Gas sensing enhancement with heterostructures involves the integration of different materials to create interfaces that optimize the interaction between the sensing material and the target gas molecules. Here are some points on the mechanisms behind the gas sensing enhancement achieved through heterostructures [33].

1. **Synergistic Sensing Effects:** Heterostructures combine materials with complementary properties, such as different work functions, band gaps, and surface chemistry. The resulting synergistic effects at the interfaces enhance gas adsorption, charge transfer, and reactivity, leading to improved sensitivity and selectivity [34].

2. **Band Alignment and Charge Transfer:** In heterostructures, energy band alignment at the interfaces can facilitate charge transfer between different materials. This charge transfer enhances the separation and migration of charge carriers, which affects the electrical conductivity and response of sensor to gas molecules [35].

3. **Enhanced Surface Area:** Heterostructures often create a high surface-to-volume ratio due to the presence of additional interfaces and nanostructures. The increased surface area provides more active sites for gas adsorption, amplifying the sensor's response to trace amounts of gas.

4. **Surface Functionalization:** Different materials within heterostructures can be functionalized to create specific binding sites for target gas molecules. This functionalization improves the affinity of the sensor for particular gases, leading to higher sensitivity and selectivity [36].

5. **Band Gap and Energy Levels:** Heterostructures enable manipulation of material properties, including band gap and energy levels, which influence sensor's response to different gases. By engineering these properties, the sensor can be optimized for detecting specific gases.

6. **Carrier Concentration Modulation:** The presence of hetero junctions can alter the carrier concentration and mobility in the sensing material. This modulation affects the sensor's electrical conductivity and response time, improving its ability to detect and recover from gas exposure. Heterostructures can modify the kinetics of gas adsorption and desorption due to variations in surface energies and binding strengths. Faster adsorption and desorption kinetics enhance sensor’s response and recovery times [37].

VI. APPLICATIONS OF GAS SENSORS

1. **Industrial Safety and Occupational Health:** Gas sensors are extensively used in industrial settings to monitor the presence of toxic or flammable gases, ensuring the safety of workers. They are employed in environments where gases like hydrogen sulfide (H_2S), carbon monoxide (CO), ammonia (NH_3), and volatile organic compounds (VOCs) can pose health risks.

2. **Environmental Monitoring:** Gas sensors are utilized to monitor air quality and detect pollutants in the atmosphere. This is crucial for assessing environmental impact, measuring pollution levels, and complying with air quality regulations. They can detect

gases such as nitrogen dioxide (NO_2), ozone (O_3), sulfur dioxide (SO_2), and other fine particles.

3. **Indoor Air Quality (IAQ):** Gas sensors are integrated into buildings to monitor indoor air quality, ensuring a healthy and comfortable environment for occupants. They detect indoor pollutants like CO_2, VOCs, and radon, helping to control ventilation and improve well-being.

4. **Automotive Applications:** Gas sensors are a vital component of vehicle emissions control systems, helping to minimize exhaust emissions and comply with emissions standards. They detect gases like oxygen (O_2), nitrogen oxides (NOx), and hydrocarbons, contributing to efficient combustion and reduced pollution.

5. **Leak Detection:** Gas sensors are used for detecting leaks of gases such as natural gas, propane, and refrigerants. They prevent hazardous situations, reduce waste, and conserve resources. In homes and industries, they can help prevent gas leaks that could lead to fires, explosions, or environmental contamination.

6. **Food and Beverage Industry:** Gas sensors are employed for monitoring the freshness of perishable goods. For instance, they can detect gases produced during spoilage, helping with quality control and shelf-life extension.

7. **Medical Applications:** Gas sensors are employed in medical equipment to track the concentration of gases like oxygen and anesthetic agents during surgeries and patient care. They also find applications in breath analysis for disease diagnosis and monitoring.

8. **Fire Detection:** Gas sensors can detect smoke and combustion gases early, providing crucial time for evacuation and minimizing property damage in case of fires.

9. **Mining and Oil Exploration:** In mining and oil industries, gas sensors are utilized to continuously observe the levels of explosive or toxic gases in confined spaces, protecting workers and equipment.

10. **Agriculture:** Gas sensors can be employed in agriculture to monitor the levels of gases emitted by plants, soil, and livestock, aiding in disease detection, pest management, and environmental monitoring.

11. **Wastewater Treatment:** Gas sensors assist in monitoring and controlling the gases produced during biological wastewater treatment processes, ensuring efficient treatment and preventing odour issues.

12. **Security Systems:** Gas sensors are integrated into security systems to detect unauthorized entry by sensing specific gases used to breach secured areas [38-40].

These are just a few examples of the diverse applications of gas sensors across different industries and sectors. The technology continues to advance, enabling more accurate and versatile detection of various gases for improved safety, efficiency, and environmental protection.

VII. CONCLUSION

In order to mitigate the environmental and human health concern, there has been a great deal of extensive research in recent decades on various sensing methods for gas detection. Solid State sensing techniques, including mechanical oxide and polymer conducting sensors, which have remarkable applications due to their outstanding advantages over other sensor methods such as simple and cost effective, are among the most commonly used Gas Sensing Methods. Furthermore, a comprehensive assessment and summarization were executed on the recent advancements in the field of advanced gas sensors.

VIII. CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests.

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