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Exploring Semiconductor Gas Sensors : A Detailed Analysis

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Abstract:

In the present research work, significant improvements in TiO_2 semiconductor metal oxide-based gas sensors are reviewed, which are utilized to detect the contaminants and hazardous gases. In everyday life, the utilization of gas sensors has been growing quickly because of potential benefits. Due to its intrinsic physical and chemical characteristics, Semiconductor Metal Oxide (SMO) have emerged as the prominent material for creating economical, stable, and extremely sensitive gas sensors for real-world applications. These sensors play a crucial role in various sectors, including environmental monitoring, industrial safety.

Key words: Semiconductor Metal Oxide (SMO), TiO_2, Gas Sensor.

Introduction:

The primary objective of this review is to analyse the various types of synthesis method of TiO2 thin films and implementation of these films in different environments. The sensing properties of TiO_2 thin films are influenced by factors such as crystal structure, operating temperature, and doping with other semiconductor oxides. It has been observed that TiO_2 thin-film sensors generally exhibit reduced sensitivity at elevated temperatures. Key parameters investigated include operating temperature, detection range and response time particularly within the range of 40 °C - 200 °C. Gas sensitivity in these films is typically assessed through changes in electrical resistance upon gas exposure. Alternatively, it can be quantified as the ratio of the film's resistance in air to its stabilized resistance in the presence of a target gas.

TiO_2 Morphology:

Titanium dioxide (TiO_2) primarily exists in three major crystalline phases: brookite (orthorhombic), anatase (tetragonal), and rutile (tetragonal). These phases exhibit energy band gaps of approximately 2.96 eV, 3.2 eV, and 3.02 eV, respectively.

Among all the polymorphs, rutile is the most thermodynamically stable phase under standard conditions. However, at the nanoscale, anatase and brookite tend to be more stable due to their lower surface energies [1]. The crystalline phase of TiO_2 significantly influences the properties of thin films, especially in gas sensing applications. This phase can be controlled by tuning synthesis parameters such as annealing time, preparation temperature, solution pH, and other structural growth conditions. As a result, anatase and rutile phases are particularly well-studied for their potential in sensing technologies [2].

TiO_2 has gained significant attention in gas sensing due to its versatility in nanostructured forms. Its sensing mechanism is primarily based on surface interactions with oxidizing or reducing gases, which in turn affect the electrical conductivity of the material. When exposed to ultraviolet (UV) light, TiO_2 absorbs photons, leading to the generation of electron–hole pairs. These charge carriers facilitate redox reactions on the surface, which not only contribute to gas sensing but also enable the breakdown of organic pollutants into harmless byproducts like CO_2 and H_2O.

Furthermore, TiO_2 films exhibit a unique photoinduced wettability transition—they can shift from hydrophobic to hydrophilic surfaces upon UV irradiation. This, along with their strong photocatalytic activity, makes them excellent candidates for self-cleaning and antifogging applications [3].

TiO_2 was selected as a thin-film material in this study due to its high electrical resistivity, which makes it a good electrical insulator. However, sub-stoichiometric TiO_2—where the material is slightly titanium-rich acts as an n-type semiconductor with distinct electronic properties. These properties are largely influenced by oxygen vacancies and deviations in the Ti/O stoichiometric ratio, which play a crucial role in determining its electrical behavior [4].

Gas Detection:

Gas detection in semiconductor metal oxide (SMOX) sensors typically operates within the temperature range of 150 °C to 400 °C. At these temperatures, oxygen molecules from the ambient environment are adsorbed onto the surface of the metal oxide, where they capture free electrons—primarily the charge carriers. This process leads to an increase in resistance for n-type semiconductors or a decrease in resistance for p-type semiconductors [5].

The change in electrical resistance is primarily due to the interaction between the target gas and the adsorbed oxygen species on the sensor surface. This interaction results in a measurable electrical signal, which directly reflects variations in gas concentration [6]. The intensity of this signal is proportional to the concentration of the detected gas.

To develop highly sensitive gas sensors, it is crucial to understand two key aspects: (1) the chemical reaction between the gas molecules and the sensing material surface and (2) how effectively this reaction is translated into measurable changes in the material's electrical resistance [7].

The sensing mechanism of metal oxide-based sensors is fundamentally surface-driven, relying on variations in conductivity caused by gas-surface interactions under specific atmospheric conditions. For p-type semiconductors, exposure to oxidizing gases leads to oxygen adsorption, which can be described through well-established surface reaction equations [5].

When oxidizing gases are removed, the previously trapped electrons are released back into the conduction band of the semiconductor, either partially or completely. This leads to a reduction in resistance and an increase in electrical conductivity. In contrast, when the sensor is exposed to a reducing gas, the process is reversed, resulting in higher resistance. For n-type semiconductors, these effects are reversed compared to p-type materials [8–11].

Research has shown that the sensing performance of TiO_2-based gas sensors is strongly influenced by factors such as surface morphology and the concentration of dopants incorporated into the thin films.

B. Comert [12] reported that TiO_2 thin-film sensors fabricated at elevated temperatures tend to exhibit low sensitivity. This reduction in sensitivity was attributed to relatively large grain sizes, which limit the available surface area for gas adsorption—particularly for detecting gases like methane.

In a related study, Joy Tan et al. [13] investigated both undoped and gold-doped TiO_2 thin films with a thickness of 100 nm. Their findings indicated that the incorporation of gold significantly enhanced the sensor's sensitivity to carbon monoxide. This improvement was primarily due to the catalytic role played by gold atoms on the film surface, which promoted more effective gas-surface interactions.

Titanium dioxide (TiO_2) has been widely utilized in gas sensing applications, including in medical monitoring systems, environmental surveillance, and material characterization techniques. Although traditional single gas sensors often struggle to manage complex detection tasks, advanced multi-sensor systems, such as electronic noses, have been developed. These systems typically incorporate multiple TiO_2-based sensors, each operating on different signal transduction mechanisms, to collectively analyze and identify various gases [15].

Despite their innovation, these sensor arrays still face limitations when compared to established analytical techniques like gas chromatography–mass spectrometry (GC-MS). The challenges mainly arise from issues such as signal drift, limited sensitivity, and restricted selectivity, meaning these sensors often detect only specific classes of gas molecules [20]. These constraints highlight the need for further development to enhance their reliability and performance in practical applications.

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