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Study on Enhancing Sensor Sensitivity through Material Modification

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Abstract: The sensing capability of sensors is directly determined by sensitivity indicators, and intrinsic performance limitations of sensitive materials can restrict the sensor's signal response level. Material modification is a mainstream approach to enhancing sensing performance, enabling adjustments to the electronic structure, micro-morphology, and interface states of materials, thereby addressing practical issues such as insufficient active sites and low carrier transport efficiency in raw materials. This paper systematically identifies three core factors influencing sensor sensitivity and summarizes material modification strategies from four perspectives: elemental doping, nanostructuring, hetero-compositing, and surface functionalization. It further analyzes key process parameters during the modification and fabrication stages and introduces orthogonal experimental design to optimize process combinations.

1. Introduction

Modern detection scenarios demand higher performance from sensors in terms of detection limits and signal resolution, making it difficult for conventional sensing materials to simultaneously meet the requirements of high sensitivity and stable output. The electronic state, particle morphology, and interlayer contact conditions of the material itself all influence the sensor's response to target analytes or external physical signals. Relying solely on device structural improvements has become insufficient to surpass current sensitivity ceilings, prompting increasing focus on material-level modification and optimization in sensor research. Material modification—achieved through chemical or physical means—can alter the intrinsic properties of sensitive materials without requiring a complete replacement of the base material, thereby enhancing sensor performance. Numerous studies have demonstrated that techniques such as doping, nanostructuring, compositing, and surface functionalization can effectively improve the response characteristics of gas, electrochemical, and pressure sensors. However, there is currently no unified standard for selecting modification process parameters; deviations in processing conditions may directly offset the performance gains achieved through modification, and some treatments may even compromise sensor stability. To clarify the underlying relationship between modification strategies and sensitivity enhancement, this paper systematically examines key material factors, summarizes the mechanisms of various modification methods, outlines critical process control points during fabrication, and analyzes optimization approaches under multiple influencing factors, providing technical guidance for future advancements in sensitive material modification and sensor

performance improvement.[1]

2. Analysis of Factors Affecting Sensor Sensitivity

Sensor sensitivity represents the degree to which the device's output signal varies in response to changes in the measured signal. The sensitive material serves as the core medium for signal transduction in sensors, and the sensor's sensitivity level is jointly determined by the material's intrinsic properties, microstructural morphology, and interfacial contact conditions.

2.1. The influence of intrinsic properties of sensitive materials on sensitivity

The intrinsic properties of sensitive materials include band structure, carrier concentration, electron mobility, and surface inherent activity. The bandgap of the matrix material directly determines the difficulty of electronic transitions; when the bandgap is too large, internal charge carriers find it difficult to move, resulting in smaller changes in sensor output signals and reduced sensitivity. Meanwhile, the intrinsic number of defects and oxygen vacancies within the material affects the efficiency of carrier generation and recombination. For unmodified matrix materials, electron transport capability is fixed; when a target signal interacts with the material surface, insufficient carrier concentration makes it difficult to generate noticeable electrical signal changes. Some intrinsic materials exhibit weak surface chemical activity, leading to limited adsorption of target analytes, which hinders the sensor's ability to detect subtle external stimuli and restricts overall device sensitivity. Since these intrinsic characteristics are inherent to the material, modifications are required to alter the electronic distribution and overcome the performance limitations of the original material.[2]

2.2. The Influence of Material Microstructure on Sensitivity

Microstructure encompasses grain size, pore state, specific surface area, and particle arrangement. For sensitive materials with relatively large grain sizes, the number of reactive sites available per unit volume is limited, restricting interactions of the analyte to only a few locations and resulting in minimal signal changes. The internal pore structure determines how easily the analyte can diffuse into the material; dense, non-porous structures hinder penetration, preventing most of the internal material from participating in sensing reactions and thereby reducing overall material utilization efficiency. A higher specific surface area means more surface regions are available for reaction, enabling greater numbers of active sites. This allows even weak external signals to induce significant changes in electrical parameters. However, finer microstructures are not always better—excessive grain refinement can lead to material agglomeration. Once particles aggregate, the effective surface area may actually decrease, while internal resistance increases, negatively affecting sensitivity. Therefore, the goal of microstructure engineering is to design highly active micro- and nanostructures while avoiding agglomeration.[3]

2.3. The Influence of Interface Contact Characteristics on Sensitivity

The interface consists of the internal interface between sensitive material particles and the external interface between the sensitive layer and the electrodes. The contact state among particles determines the charge carrier transport pathways within the sensitive material; insufficient particle contact leads to a significant increase in contact resistance, hinders charge transfer, and causes attenuation of the sensing signal. The interface condition between the sensitive material film and the electrode substrate is also critical—poor adhesion results in numerous contact defects, causing

charge loss at the interface and preventing the complete conversion of external input signals into detectable electrical signals. When heterogeneous materials are combined, a potential barrier forms at their interface, and adjusting the barrier height can modulate carrier flow. Inappropriate interface contact conditions directly negate performance improvements achieved through material modification, resulting in actual device sensitivity falling short of theoretical expectations.[4]

3. Approaches to Enhancing Sensitivity through Material Modification

3.1. Band structure modulation through element doping

Elemental doping introduces heteroatoms into the crystal lattice of the host material, where these foreign atoms either replace existing lattice atoms or occupy interstitial sites, thereby altering the original band structure of the material. Doped atoms create defect sites within the lattice, which can act as carrier trapping centers and modify the concentrations of electrons and holes inside the host material. Doping enables adjustment of the bandgap without changing the main phase composition of the material; appropriate dopant components can reduce the energy required for electronic transitions, allowing even weak external stimuli to trigger changes in carrier concentration. Doping also generates oxygen vacancies, which are highly active sites that enhance the surface reactivity of the material. However, it is important to control the doping ratio within a reasonable range. Insufficient doping results in minimal lattice modification and limited improvement in sensitivity, while excessive doping causes severe lattice distortion, compromises the material's structural stability, increases carrier recombination probability, and ultimately degrades sensor performance.

3.2. Nanoscaling increases active sites

Nano-scale modification transforms conventional bulk or coarse-grained materials into nanoparticles, nanosheets, or porous nano-network structures. After nanostructuring, the overall specific surface area of the material increases, allowing a greater number of surface sites to be exposed per unit mass, thereby enabling thorough contact between the analyte and the sensing material. In practice, at the nanoscale, the proportion of surface atoms significantly increases, and these surface atoms are incompletely coordinated, leading to enhanced chemical reactivity. Even small external stimuli can trigger reactions across numerous active sites, resulting in a larger output signal change. Porous nanostructures further shorten the diffusion path for analytes, enabling target molecules to rapidly reach internal sites within the material and participate in the sensing response. At the same time, it is essential to suppress particle aggregation during nano-scale modification. Due to their high surface energy, nanoparticles tend to agglomerate during synthesis. Aggregation reduces the specific surface area and encloses active sites within clusters, thereby diminishing the beneficial effects of the modification.[5]

3.3. Heterogeneous Composite for Interface Barrier Construction

Heterogeneous composites combine two or more different sensitive materials, each possessing its own distinct Fermi level. Upon contact, charge carriers migrate at the interface between the phases until the Fermi levels equilibrate, forming a space-charge region and establishing a stable interfacial barrier. When an external signal to be detected acts on the composite surface, the height of this interfacial barrier changes accordingly, directly altering the conductivity state of the conduction pathway. Even minor external perturbations can lead to significant changes in resistance or capacitance, thereby enhancing sensitivity. Moreover, the different components can complement each other: one material provides abundant adsorption sites, while the other enables rapid charge

transport, resulting in synergistic performance gains. In practice, effective heterogeneous composites require thorough interfacial contact; if large gaps exist at the interface or the phases are merely physically mixed without proper interaction, an effective heterojunction cannot form, and the interfacial charge modulation mechanism fails to function.

3.4. Surface modification to enhance adsorption capacity

Surface modification involves altering only the outer layer of sensitive materials without significantly changing their internal crystal structure. This method employs physical adsorption or chemical bonding to load metal particles, organic functional groups, or introduce other active components onto the material surface. The modifying components can act as catalytic active centers, reducing the activation energy required for adsorption reactions of target analytes and thereby enhancing the material's ability to capture the target substances. After introducing specific functional groups on the surface, the material's selective adsorption capability toward particular analytes is strengthened, enabling even trace concentrations of the target substances to react effectively on the surface, resulting in more pronounced sensor signal changes. However, surface modification also has an optimal loading range; excessive loading of modifying components may cover the original active sites of the base material and hinder the diffusion of the analyte into the material interior, leading to reduced sensitivity.

4. Key Points for Material Modification Process Optimization

The final modification effect is not determined solely by the modification method; process conditions during synthesis and preparation can alter the material's microstructure, defect density, and interfacial bonding quality. If process parameters deviate from optimal ranges, even with the correct modification approach, high-sensitivity materials cannot be achieved. Below, key process control points are analyzed.

4.1. Precise control of doping ratio

The doping ratio is the primary control parameter in doping modification, as the proportion of dopant directly determines the number of lattice defects generated. During the experimental phase, multiple gradient compositions should be designed to observe changes in the material's phase structure and electrical properties, thereby identifying an optimal doping range. Additionally, uneven dispersion of doping precursors can lead to locally high doping concentrations, resulting in inconsistent internal material performance and increased variability among sensor devices. Therefore, thorough mixing and stirring of the precursors during preparation are essential to ensure uniform distribution of the dopant components. The final structure consists of multiple square-crossed metallic resonant structures, a PDMS thin-film substrate, and a metal layer coated on the bottom surface of the PDMS film. The metal layer is made of copper with a conductivity of 5.88×10^{7} S/m, while the PDMS substrate has a relative permittivity of 2.7 and a loss tangent of 0.04.

4.2. Optimization of calcination temperature and holding time

Calcination is used to remove residual solvents and impurities from the precursor while completing crystallization of the grains. If the calcination temperature is too low, the material will not crystallize sufficiently, leaving a large amount of residual impurities inside that interfere with carrier transport. Conversely, if the temperature is too high, the grains grow rapidly, reducing the

specific surface area and decreasing the number of active sites, which hinders sensitivity improvement. Holding time is directly related to grain growth: insufficient holding time leads to incomplete crystallization, whereas excessive holding time causes continuous grain coarsening. Therefore, the calcination process must balance crystallization quality and grain size, optimizing the relationship between crystallinity and microstructure.

4.3. Precursor concentration and pH control

The concentration of the precursor solution affects the nucleation rate of product crystals. Excessively high concentrations lead to rapid nucleation, causing easy aggregation of the product; conversely, low concentrations result in insufficient nucleation, leading to low product yield and large variations in crystal size distribution. The pH value of the system alters the hydrolysis and precipitation behavior of precursor ions, thereby influencing the nucleation and growth processes of particles. Changes in pH result in significant differences in the morphology and pore structure of the product crystals, further affecting the material's specific surface area and surface functional group characteristics. In hydrothermal and sol-gel modification processes, pH is an indispensable control parameter.

4.4. Control of Annealing Atmosphere and Cooling Rate

The annealing atmosphere can regulate the types of vacancies and defects within the material. The number of oxygen vacancies in materials obtained under inert, reducing, and oxidizing atmospheres differs significantly, with reducing atmospheres favoring the formation of oxygen vacancy defects. A moderate amount of oxygen vacancies is beneficial for sensor response; however, excessive defects may reduce the material's chemical stability. Additionally, cooling rate affects residual stress inside the material. Rapid cooling induces high internal stress, making thin-film samples prone to cracking, compromising the integrity of the sensitive layer, deteriorating interfacial contact quality, and reducing device stability. Therefore, it is essential to select appropriate annealing atmospheres and cooling protocols based on the properties of the substrate material. The modified preparation process involves multiple influencing parameters, which interact with each other. In practical fabrication, constraints must be imposed on various process variables, as detailed in Table 1.

Table 1 Physical Parameters of Modified Preparation Process

Process parameters	Parameter range	Control of physical quantities
Doping mole fraction	0.5% 10%-	Lattice distortion degree
Calcination temperature	300800 °C-	Crystallinity
Holding time	1-6 h	Grain size
Precursor concentration	0.0105 mol/L-	Nucleation rate
System pH	2-12	Settling rate
Cooling rate	1-20 ℃/min	Residual stress

(5) Orthogonal Experiment to Determine the Optimal Process Combination

The modification preparation process involves multiple influencing parameters, and there are interactions among various process conditions. Single-factor experiments can only yield locally optimal parameters, making it difficult to obtain the globally optimal combination of processes. The orthogonal experimental method selects representative test groups from all possible parameter combinations, enabling determination of the relative importance of each process factor on material

performance with fewer trials. In practice, doping ratio, calcination temperature, holding time, and pH value should be selected as orthogonal experimental factors, each set at three to four levels. Sensor sensitivity is used as the evaluation criterion. After conducting the orthogonal experiment, the influence weights of each factor are calculated from the results, allowing identification of the optimal process combination. This approach reduces blind trial-and-error efforts and improves the efficiency of modified material preparation.

5. Conclusion

In summary, enhancing sensitivity is the core objective in optimizing sensor performance, with the intrinsic properties, microstructure, and interface contact state of sensitive materials collectively determining the sensor's response level. Material modification through four approaches—elemental doping, nanoscaling, hetero-compositing, and surface functionalization—improves sensitive material performance by modifying electronic band structures, active sites, interfacial barriers, and surface adsorption capacity, thereby achieving higher sensor sensitivity. The effectiveness of these modifications strongly depends on fabrication processes; factors such as doping concentration, calcination conditions, precursor characteristics, and annealing environment can significantly alter the final material’s phase composition and microstructure. Interactions among multiple process parameters make it difficult to identify optimal conditions using single-factor experiments alone, whereas orthogonal experimental designs enable efficient multi-parameter synergistic optimization. Each modification method has an optimal parameter range; exceeding this range may lead to adverse effects such as grain agglomeration, lattice distortion, or coverage of active sites, ultimately degrading sensing performance. Future research should further clarify the quantitative relationships between modification mechanisms and processing parameters, minimize stability losses associated with modification, and accelerate the practical application of high-sensitivity modified sensing materials in real devices.

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