

“Spray Pyrolysis: A Green Approach to Thin-Film-Based Pollution Detection”

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Abstract

Green thin-film technologies prepared by spray pyrolysis offer promising solutions for pollution detection, environmental protection, and sustainable development. This paper reviews the potential of semiconductor thin films deposited using spray pyrolysis for monitoring and controlling environmental pollutants. Metal oxide thin films and their nanocomposites exhibit distinctive electrical, optical, and catalytic properties, making them suitable for detecting harmful gases, volatile organic compounds, and other contaminants. Spray pyrolysis is a simple, cost-effective, and scalable deposition technique that enables the fabrication of uniform thin films with controlled composition and tunable properties. The influence of precursor concentration, substrate temperature, spray rate, and doping on film structure, morphology, and functional performance is discussed. Applications in gas sensors, photocatalytic systems, and environmental monitoring are highlighted. The integration of green precursors and energy-efficient processing can further reduce environmental impacts. These developments support pollution prevention, resource conservation, and the achievement of relevant Sustainable Development Goals.

Keywords: Green thin films; Spray pyrolysis; Pollution detection; Environmental remediation; Sustainable development.

1. Introduction

Environmental pollution caused by toxic gases, volatile organic compounds (VOCs), and other hazardous pollutants has increased the demand for reliable, economical, and environmentally sustainable monitoring technologies. Semiconductor metal-oxide thin films are widely investigated for pollution detection because their surface chemistry, electrical conductivity, and sensing response can be strongly influenced by interactions with target gases [1,2].

Among different thin-film fabrication methods, spray pyrolysis has emerged as a simple, versatile, low-cost, and scalable technique. In this process, a precursor solution is atomized into fine droplets and transported towards a heated substrate, where solvent evaporation and thermal decomposition lead to the formation of a thin film. The technique does not require a vacuum system and can be adapted for large-area deposition [3,4].

An important advantage of spray pyrolysis is the ability to control film properties by adjusting parameters such as substrate temperature, precursor concentration, spray rate, deposition time, and nozzle-to-substrate distance. These parameters influence crystallinity, grain size, morphology, porosity, and surface area, thereby affecting sensor sensitivity, selectivity, response, and recovery characteristics [4,5]. Metal oxides such as ZnO, SnO₂, TiO₂, WO₃, and CuO prepared by spray pyrolysis have therefore attracted considerable attention for detecting pollutants and hazardous gases [1,2].

Thus, spray pyrolysis provides an attractive route for developing environmentally compatible thin-film sensors. This approach combines simple processing, compositional flexibility, and scalability, making it promising for low-cost pollution monitoring and sustainable environmental technologies [6-10].

2. Materials and Methods

Thin films of selected metal oxides were prepared using the chemical spray pyrolysis technique. Analytical-grade metal salts were used as precursor materials, and distilled water or a suitable solvent was employed to prepare homogeneous precursor solutions of the required concentration. Clean glass substrates were ultrasonically cleaned

successively with detergent, distilled water, and alcohol, followed by drying. The precursor solution was atomized through a spray nozzle and directed onto a preheated substrate maintained at an optimized temperature. The spray rate, nozzle-to-substrate distance, precursor concentration, and deposition time were carefully controlled to obtain uniform and adherent films. During deposition, the solvent evaporated and the precursor underwent thermal decomposition, resulting in the formation of the desired metal-oxide thin film. The deposited films were allowed to cool naturally and were subsequently subjected to structural, morphological, optical, and electrical characterization. The prepared films were finally evaluated for their gas-sensing response toward selected environmental pollutants. The experimental parameters were optimized to achieve good crystallinity, surface morphology, stability, and sensing performance.

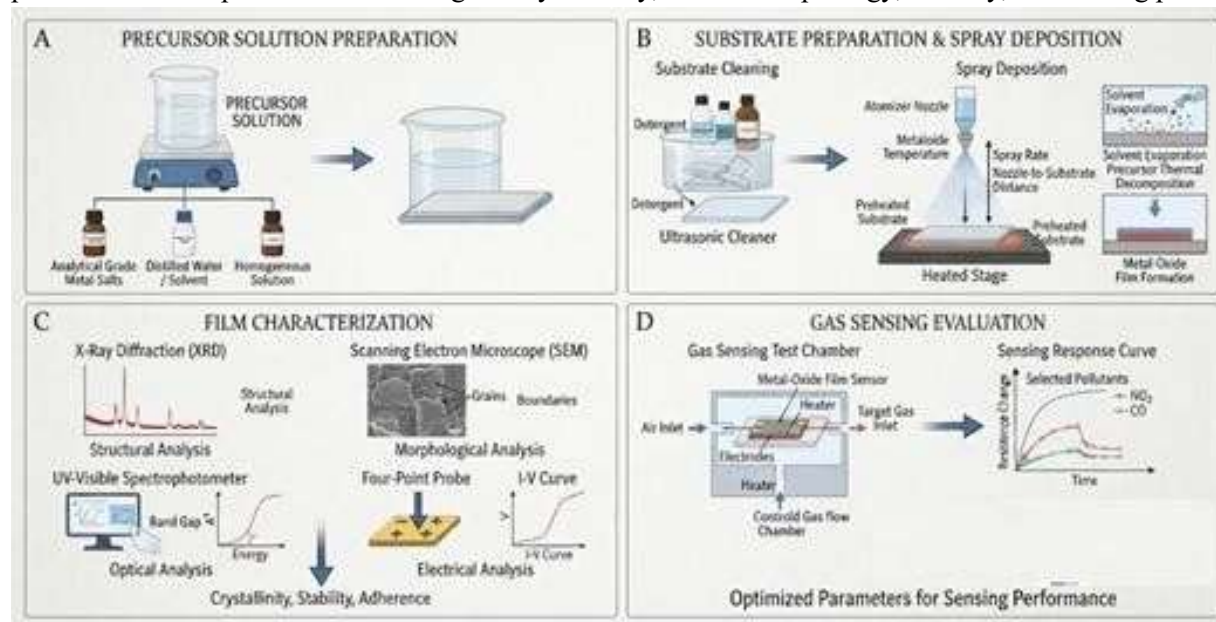


Figure 1: Schematic overview of the chemical spray pyrolysis synthesis, structural and functional characterization, and gas-sensing evaluation of metal-oxide thin films.

3. Results and Discussion

The reviewed literature demonstrates that spray pyrolysis is a versatile and effective technique for fabricating nanostructured thin films for gas-sensing and environmental pollution monitoring. Its major advantages include low processing cost, simple equipment, atmospheric-pressure operation, high deposition rate, large-area coating capability, and scalability. Unlike several vacuum-based deposition methods, spray pyrolysis allows the precursor solution to be directly converted into a functional thin film through aerosol generation and thermal decomposition.

A major finding from the literature is that the properties of spray-pyrolyzed films are strongly governed by deposition parameters. Substrate temperature, precursor concentration, solution flow rate, deposition time, nozzle-to-substrate distance, solvent type, and carrier-gas conditions significantly influence nucleation, crystal growth, crystallographic orientation, grain size, porosity, and surface morphology. Appropriate optimization of these parameters can produce nanorods, nanowires, nanospheres, nanoflowers, porous structures, and other desirable morphologies. Such morphological control is particularly important for gas sensors because a high surface-to-volume ratio provides more active sites for interaction with gas molecules [1].

The reviewed studies further indicate that metal-oxide semiconductor thin films prepared by spray pyrolysis exhibit promising sensing responses toward both oxidizing and reducing gases. Changes in electrical resistance resulting from adsorption and desorption of gas molecules are commonly utilized for resistive gas detection. Nanostructured morphologies can improve sensitivity, response rate, and recovery behaviour by enhancing gas-surface interactions. In addition, elemental doping and the formation of heterojunctions have been reported as effective strategies for modifying charge-carrier concentration, surface defects, and adsorption sites, thereby improving sensing performance [11].

Overall, the literature suggests that spray pyrolysis provides considerable flexibility for optimizing thin-film gas sensors.

However, challenges remain regarding long-term stability, humidity effects, selectivity in mixed-gas environments, reproducibility, and reliable detection at very low concentrations. Future research should therefore focus on systematic parameter optimization, advanced nanostructure engineering, low-temperature operation, and integration of spray-pyrolyzed sensors with portable monitoring systems.

4. Conclusion

Spray pyrolysis has emerged as a promising green and versatile approach for the fabrication of functional thin films for pollution detection and environmental monitoring. The reviewed studies demonstrate that its simple operation, low cost, atmospheric-pressure processing, scalability, and compositional flexibility provide significant advantages over several conventional thin-film deposition techniques. The ability to control precursor concentration, substrate temperature, spray rate, deposition time, and nozzle-to-substrate distance enables effective tailoring of film structure, morphology, and functional properties. Nanostructured metal-oxide films prepared by this technique have shown considerable potential for detecting toxic gases, volatile organic compounds, and other environmental pollutants. Doping, nanostructure engineering, and heterojunction formation further provide opportunities to enhance sensitivity, selectivity, response, recovery, and stability. Despite these advantages, challenges associated with humidity interference, long-term stability, reproducibility, and low-concentration detection remain. Future efforts should emphasize green precursors, energy-efficient deposition, flexible substrates, low-temperature operation, and integration with portable sensing platforms. Such developments can contribute significantly to sustainable pollution monitoring and environmental protection.

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