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Original Article

Synthesis and Characterization of Pure ZnO Thin Films by Spray Pyrolysis for Greenhouse Gas Sensing

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Abstract

The rapid expansion of Artificial Intelligence (AI) and digital infrastructures has markedly enhanced economic growth and governance efficiency; however, it has concurrently engendered considerable environmental externalities, notably characterized by elevated energy consumption, carbon emissions, and resource-intensive data ecosystems. This research rigorously analyzes the notion of "Green AI" in the context of sustainable development, emphasizing the convergence of digital governance, environmental sustainability, and data privacy in India. This analysis examines how new AI technologies, particularly large-scale data processing systems and cloud-based infrastructures, contribute to ecological stress, prompting a reassessment of policy and regulatory frameworks. The study assesses the impact of India's Digital Personal Data Protection Act, 2023, in conjunction with current environmental and digital governance rules, on mitigating the sustainability problems presented by AI-driven systems. It identifies critical regulatory deficiencies, including the lack of environmental accountability within data governance frameworks and the absence of established sustainability indicators for AI implementation. The study presents a normative framework for incorporating environmental issues into digital governance by employing an interdisciplinary approach that merges legal analysis, policy assessment, and sustainability discourse. The paper advocates for the establishment of a "Green AI regulatory model" that integrates principles of energy efficiency, carbon accountability, and ethical data management. It additionally advocates for legislative interventions like green data center standards, ESG-linked digital governance, and incentives for sustainable innovation. The report ultimately enhances the ongoing dialogue regarding the alignment of technological progress with environmental sustainability, providing practical recommendations for policymakers, regulators, and stakeholders within India's digital ecosystem.

***Keywords**: Green AI, Sustainable Development, Digital Governance, Data Protection, DPDP Act 2023, Energy Consumption, Environmental Sustainability, ESG.*

Introduction

Greenhouse gases (GHGs) such as carbon dioxide (CO2) and methane (CH4) are primary contributors to global warming, making their detection and monitoring crucial [1]. Metal oxide semiconductors, particularly zinc oxide (ZnO), have been extensively studied for gas-sensing applications due to their chemical stability, wide band gap (≈ 3.3 eV), and large exciton binding energy [2]. While several deposition techniques have been utilized for ZnO thin films, including sol-gel [3], puls ed laser deposition [4], and sputtering [5], spray pyrolysis has emerged as a simple, cost-effective, and scalable technique for producing high-quality films [6]. This study focuses on the synthesis of pure ZnO thin films using spray pyrolysis to evaluate their structural and morphological properties for environmental monitoring applications.

Experimental Methods

1. *Materials and Preparation*

ZnO thin films were synthesized via spray pyrolysis using a 0.1 M zinc acetate dihydrate [$Zn(CH_3COO)_2.2H_2O$] precursor solution in methanol [7, 8]. The precursor was atomized using a pneumatic spray nozzle and deposited onto glass substrates preheated to 400°C at a spray rate of 2 mL/min [10, 11]. After deposition, the films were annealed at 450°C to 500°C for one hour to enhance crystallinity and reduce structural defects [7, 9].

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Results and Discussion

1. ***Structural and Elemental Analysis (XRD and EDS)***

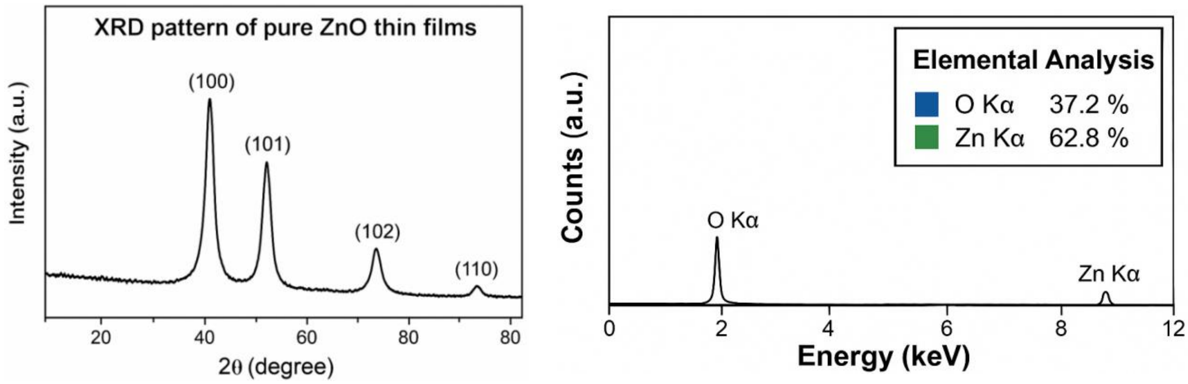

Fig.1. (a) XRD, (b) EDS spectrum of ZnO thin films synthesized by spray pyrolysis Technique.

The XRD pattern (Fig. 1a) reveals main peaks at 2θ≈35.14⁰, 43.79⁰, 61.29⁰, and 76.78⁰, corresponding to the (100), (101), (110), and (102) planes of the hexagonal wurtzite structure [13]. The calculated lattice constants are a ≈2.98 A⁰ and c ≈3.44 A⁰, with an average crystallite size of approximately 2.0 nm determined by the Scherrer equation. EDS analysis (Fig. 1b) confirms high purity, showing dominant peaks for O Kα (37.2%) and Zn Kα (62.8%). This indicates a slightly Zn-rich composition, which often provides the native defects necessary for n-type conductivity in gas sensors [12].

2. ***Morphological Study (FE-SEM and SAED)***

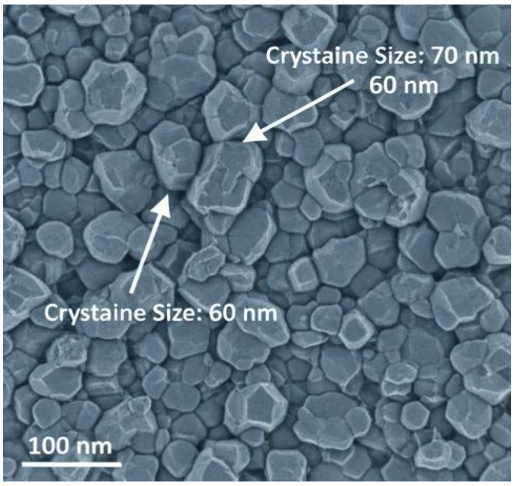

Fig.2. (a)

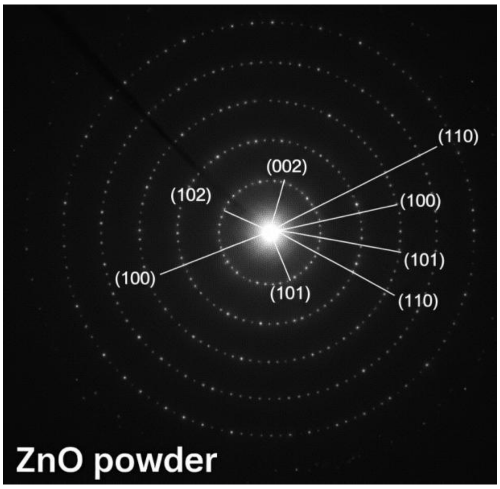

Fig.2. (b)

Fig. 2: (a) FE-SEM image of spray pyrolized ZnO thin film showing densely packed polygonal grains (~60–70 nm) with high surface area. (b) SAED pattern of ZnO confirming polycrystalline wurtzite structure with indexed rings (100, 002, 101, 102, 110).

FE-SEM imagery (Fig. 2a) displays a highly uniform surface composed of densely packed polygonal grains ranging from 60 nm to 70 nm [12]. This nanostructured morphology provides a high surface-to-volume ratio, essential for the effective adsorption of target gases [14, 15]. The SAED pattern (Fig. 2b) exhibits concentric indexed rings, (100), (002), (101), (102), and (110) validating the polycrystalline nature and wurtzite phase of the ZnO material [16, 17,18].

3. Gas Sensing Properties

1. Selectivity and Sensitivity

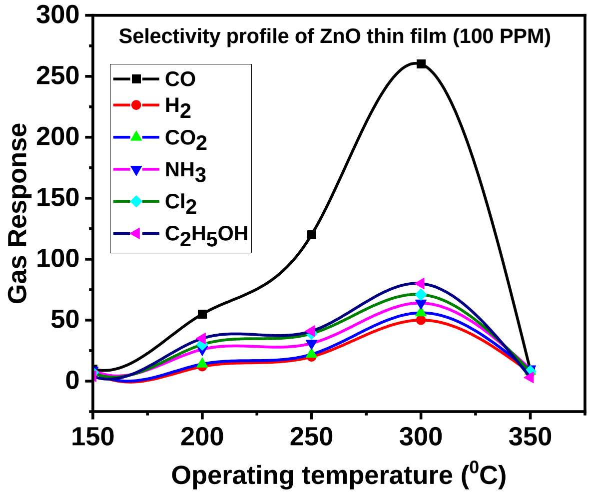

Fig.3. (a)

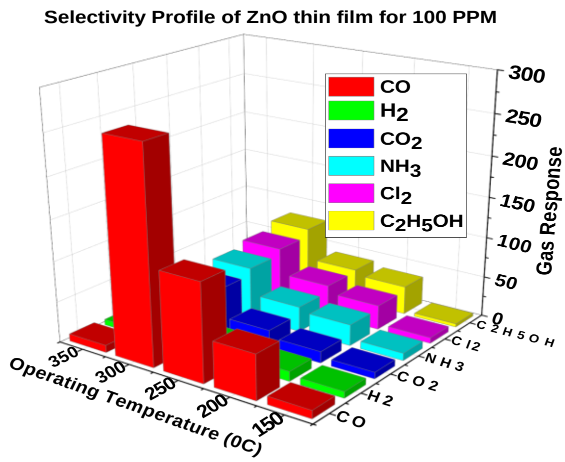

Fig.3. (b)

Fig.3. Selectivity profile of ZnO thin film prepared by spray pyrolysis technique for greenhouse gas sensing.Fig.5. Histogram of ZnO thin films prepared by spray pyrolysis technique for greenhouse gas sensing.

The selectivity profile (Fig.3(a)) indicates that the ZnO thin film differentiates between various analytes (CO, H_2, CO_2, NH_3, Cl_2, and C_2H_5OH). Enhanced sensitivity toward NH_3 and CO_2 is attributed to strong molecular interactions with oxygen vacancies [19,20]. Furthermore, the histogram (Fig.3(b)) demonstrates a pronounced response to CO, likely due to its strong reducing nature and effective interaction with adsorbed oxygen species (O^-) [21, 22].

3. **Response and Recovery**

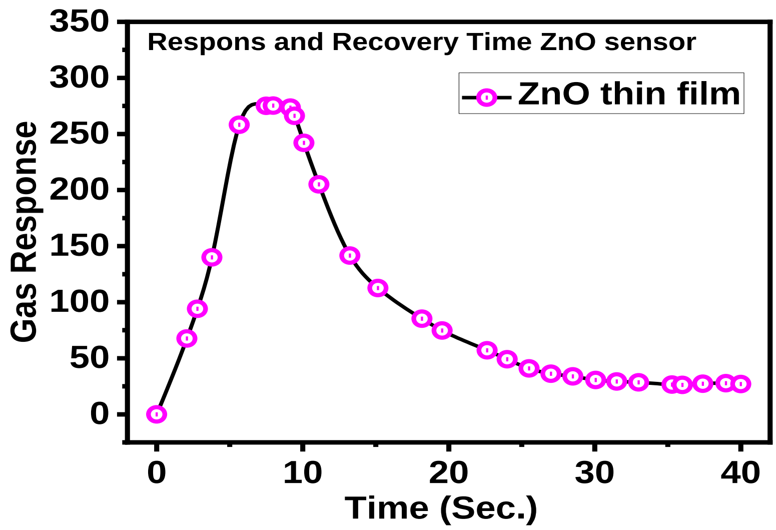

Fig.4.The response and recovery transients of a spray pyrolysis-deposited ZnO thin film sensor upon exposure to a greenhouse gas

Transient studies (Fig. 4) show a fast response time, indicating rapid gas adsorption [23]. The slower recovery time suggests that the desorption of gas molecules is more difficult, likely due to strong chemisorption interactions on the nanocrystalline surface [24,25].

4. ***Gas Sensing Mechanism***

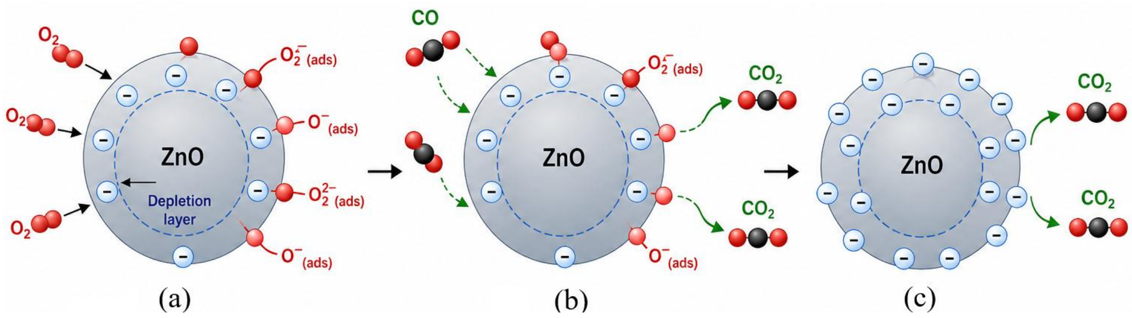

Fig.5.: Schematic illustration of the CO gas sensing mechanism of a ZnO sensor showing (a) oxygen adsorption on the ZnO surface in air leading to depletion layer formation and high resistance, (b) reaction of CO gas with adsorbed oxygen species releasing electrons, and (c) decrease in resistance due to increased electron concentration after CO exposure (sensing signal).

The figure explains how a ZnO gas sensor detects CO gas in three steps. In fig (a), which shows the condition "In Air Oxygen Adsorption (High Resistance State)," oxygen (O_2) from the air sticks to the surface of the ZnO particle. These oxygen molecules take away electrons from ZnO and become charged oxygen ions (like O_2^- and O^-). Because electrons are removed, a "depletion layer" is formed around the surface, and the sensor has very few free electrons to carry current. This makes the resistance high.

In fig (b), labeled "Exposure to CO Gas (Surface Reaction)," carbon monoxide (CO) gas comes in and reaches the ZnO surface. The CO reacts with the adsorbed oxygen ions. During this reaction, CO combines with oxygen to form carbon dioxide (CO_2), which leaves the surface. At the same time, the electrons that were earlier taken by oxygen are released back into ZnO. So, electrons start coming back into the material.

In fig (c), called "Resistance Change – Sensing Signal (Low Resistance State)," the returned electrons increase the number of charge carriers in ZnO. This reduces the depletion layer and allows electricity to flow more easily. As a result, the resistance becomes low. The sensor detects CO gas by measuring this change from high resistance (in air) to low resistance (in CO gas).

Conclusion

Nanocrystalline ZnO thin films were successfully fabricated via a cost-effective spray pyrolysis technique. The films exhibited a hexagonal wurtzite structure with uniform grain distribution, providing a robust platform for greenhouse gas detection. The high selectivity toward CO and CO_2 underscores the potential of these films for environmental monitoring. Future work will focus on doping strategies to further enhance sensitivity and lower the operating temperature.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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