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Impact of pH on Room-Temperature Synthesis of Zinc Oxide Nanoparticles for Developing Flexible Gas Sensors

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ABSTRACT

This study explores the room-temperature (RT) synthesis of zinc oxide nanoparticles (ZnO NPs) and their integration into flexible gas sensors for environmental applications. ZnO, a group II-VI semiconductor with a wide bandgap (3.0–3.37 eV), is highly sensitive, stable, and cost-effective, making it ideal for gas sensing. However, traditional synthesis methods often require high temperatures and energy-intensive processes, limiting their use in flexible technologies. To address this, we developed an efficient RT synthesis method by varying solution pH to optimize ZnO NP properties, enabling their practical application in flexible sensors.

ZnO NPs were synthesized using bath sonication at different pH levels (neutral to highly basic). This RT approach eliminates the need for high-temperature processes, reducing energy consumption and environmental impact. The NPs were characterized for size, structure, surface area, and thermal stability, with some calcinated at 500 °C to study the effects on gas-sensing performance. NPs synthesized at high basicity (pH $\approx$ 13) showed minimal organic residue (4.2 wt%), high crystallinity, and narrow size distribution (30–80 nm), as confirmed by thermogravimetric analysis (TGA), scanning electron microscopy (SEM), and X-ray diffraction (XRD). In contrast, neutral pH synthesis resulted in impurities and less uniformity, highlighting the importance of pH control.

The NPs were incorporated into flexible gas sensors using the doctor blade technique, depositing nanocomposite pastes onto carbon electrodes on polyethylene terephthalate (PET) substrates. These sensors exhibited excellent mechanical flexibility and stability under bending. Gas sensing tests under ambient conditions revealed that pre-calcinated ZnO NPs (RT.pH13) were highly sensitive to styrene and acetic acid, while post-calcinated NPs (RT.pH13.C) showed improved selectivity for benzene, acetone, and ethanol. Calcination enhanced specificity by removing organic residues, improving stability and reversibility. RT.pH13 sensors exhibited partial recovery after styrene exposure, suggesting chemical interactions, whereas RT.pH13.C sensors showed reversible responses, indicating physical sorption.

The sensors' performance under varying temperature and humidity conditions demonstrated the calcination process's role in enhancing stability. RT.pH13.C sensors maintained consistent performance, making them suitable for industrial applications, while RT.pH13 sensors were more sensitive to environmental fluctuations due to residual organic materials.

This study highlights the potential of RT-synthesized ZnO NPs as a cost-effective, scalable, and eco-friendly alternative to traditional methods. Their integration into flexible sensors opens avenues for IoT applications in environmental monitoring, healthcare, and industrial safety. Future work will explore further modifications to enhance sensor performance, bridging the gap between nanomaterial synthesis and real-world applications.