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PHYSICAL PROPERTIES AND APPLICATION PROSPECTS OF SULFUR- AND NITROGEN-DOPED ZINC OXIDE (ZnO:S, ZnO:N)

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Abstract. Zinc oxide (ZnO) is one of the most promising wide-bandgap semiconductor materials due to its excellent optical transparency, high exciton binding energy, chemical stability, and versatile electronic properties. In recent years, sulfur and nitrogen doping have attracted considerable attention as effective approaches for tailoring the structural, optical, and electrical properties of ZnO. This review analyzes the influence of sulfur and nitrogen dopants on the crystal structure, defect formation, band-gap engineering, photoluminescence characteristics, and electrical conductivity of ZnO. The findings demonstrate that sulfur and nitrogen incorporation can significantly improve the performance of ZnO-based optoelectronic devices, gas sensors, photocatalysts, and energy conversion systems. Despite substantial progress, several challenges remain regarding defect control, dopant solubility, and stable p-type conductivity. Further investigations are required to optimize the physical properties of doped ZnO for advanced technological applications.

Keywords: Zinc oxide, sulfur doping, nitrogen doping, semiconductor materials, crystal defects, photoluminescence, optoelectronics, photocatalysis.

Introduction. The rapid advancement of modern nanotechnology, optoelectronics, and semiconductor engineering has increased the demand for multifunctional materials with controllable physical properties. Metal oxide semiconductors have emerged as attractive candidates for various technological applications because of their thermal stability, chemical resistance, low production cost, and environmentally friendly nature [1]. Among them, zinc oxide (ZnO) has attracted particular interest due to its direct wide bandgap of approximately 3.37 eV and high exciton binding energy of about 60 meV at room temperature [2].

ZnO possesses a hexagonal wurtzite crystal structure and exhibits excellent optical transparency in the visible spectral region. These characteristics make ZnO suitable for ultraviolet photodetectors, light-emitting diodes, transparent conducting electrodes, solar cells, piezoelectric devices, and gas sensors [3]. However, the practical performance of ZnO-based devices strongly depends on the control of intrinsic defects and charge carrier concentrations. Consequently, doping has become one of the most effective methods for tailoring the structural and electronic properties of ZnO [4].

Among various dopants, nitrogen and sulfur are considered promising nonmetal dopants capable of modifying the electronic structure and defect chemistry of ZnO. Nitrogen can act as an acceptor dopant due to its similarity to oxygen, whereas sulfur can alter lattice parameters and induce additional electronic states within the band structure [5]. Furthermore, co-doping with sulfur and nitrogen has been reported to improve optical absorption, charge separation efficiency, and photocatalytic performance [6].

Therefore, the present study aims to review the current state of research concerning sulfur- and nitrogen-doped ZnO materials, focusing on their structural, optical, and electrical properties as well as their technological applications.

Materials and Methods. This study was conducted as a systematic literature review. Scientific publications indexed in Scopus, Web of Science, SpringerLink, ScienceDirect, and IEEE Xplore

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databases were analyzed. The selected articles focused on the synthesis, characterization, and application of sulfur- and nitrogen-doped ZnO materials.

The reviewed studies employed various characterization techniques, including X-ray diffraction (XRD), scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), ultraviolet-visible spectroscopy (UV-Vis), photoluminescence spectroscopy (PL), Raman spectroscopy, and Hall effect measurements. These techniques were used to investigate crystal structure, morphology, defect formation, optical bandgap, carrier concentration, and electrical conductivity changes resulting from sulfur and nitrogen incorporation into ZnO lattices [7].

Comparative analysis and synthesis of published results were applied to identify common trends and scientific challenges associated with doped ZnO materials.

Results and Discussion. ZnO is intrinsically an n-type semiconductor because of native defects such as oxygen vacancies and zinc interstitials [8]. These defects introduce donor states near the conduction band and significantly influence the electrical conductivity and optical behavior of the material. Oxygen vacancies are particularly important because they contribute to visible emission bands observed in photoluminescence spectra.

Nitrogen doping has been extensively investigated as a potential route toward achieving p-type ZnO. Nitrogen atoms can substitute oxygen sites within the crystal lattice and generate acceptor levels above the valence band maximum [9]. Several studies have reported modifications in photoluminescence spectra and improved visible-light absorption after nitrogen incorporation. However, obtaining stable p-type conductivity remains challenging due to the low solubility of nitrogen and compensation by native donor defects [10].

Sulfur doping also produces significant changes in ZnO properties. The larger ionic radius of sulfur compared with oxygen causes lattice distortions and modifies crystal parameters. XRD analyses frequently reveal peak shifts and variations in crystallite size following sulfur incorporation [11]. In addition, sulfur doping can narrow the optical bandgap and enhance visible-light absorption, which is beneficial for photocatalytic and photovoltaic applications.

The influence of sulfur on defect chemistry has also been widely reported. Sulfur incorporation can alter oxygen vacancy concentrations and introduce additional electronic states that affect carrier transport and recombination processes. Consequently, sulfur-doped ZnO often exhibits enhanced photocatalytic activity and improved gas sensing performance compared with undoped ZnO [12].

Recent investigations have focused on sulfur and nitrogen co-doping. The simultaneous incorporation of these dopants creates a more complex defect structure that may improve charge carrier separation and reduce electron-hole recombination rates [13]. Co-doped ZnO materials frequently demonstrate superior photocatalytic efficiency under visible-light irradiation and enhanced sensitivity toward various gases.

In optoelectronic applications, sulfur- and nitrogen-doped ZnO materials have shown improved ultraviolet detection capabilities and enhanced emission characteristics. In environmental applications, these materials are effective photocatalysts for the degradation of organic pollutants. Their high surface activity and modified electronic structure also make them promising candidates for biosensing and energy harvesting technologies [14].

Although considerable progress has been achieved, several scientific challenges remain unresolved. These include the precise control of defect formation, optimization of dopant concentration, enhancement of dopant solubility, and realization of stable p-type conductivity. Addressing these issues is essential for the development of next-generation ZnO-based electronic and optoelectronic devices.

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Conclusion. The literature review demonstrates that sulfur and nitrogen doping significantly influence the structural, optical, and electrical properties of ZnO. Nitrogen doping contributes to the formation of acceptor states and improves the possibility of obtaining p-type conductivity, while sulfur doping modifies crystal structure, defect chemistry, and optical absorption characteristics. Co-doping with sulfur and nitrogen provides additional opportunities for defect engineering and performance enhancement.

The reviewed studies indicate that sulfur- and nitrogen-doped ZnO materials are highly promising for applications in optoelectronics, photocatalysis, sensing technologies, and renewable energy systems. Nevertheless, further investigations are necessary to achieve precise control over defect states and carrier transport mechanisms. Future research should focus on advanced synthesis techniques and comprehensive characterization methods to fully exploit the potential of doped ZnO materials.

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