Jurnal MIPA dan Pembelajarannya
e-issn: 2798-0634, email: jmipap.journal@um.ac.id

VOL	ISS	YEAR	DOI
6	5	2026	10.17977/um067.v6i5.2026.2

EXPERIMENTAL TAILORING OF STRUCTURAL AND OPTOELECTRONIC PROPERTIES IN DOPED SEMICONDUCTOR NANOSTRUCTURES FOR HIGH-PERFORMANCE NANO-DEVICES

Zainab SH. Mohammed*, M.H. Asmaa

College of Science for Women, Laser Physics Department, University of Babylon, Babylon, Iraq
*Corresponding author, email: wsci.zainab.mohammed@uobabylon.edu.iq

Keywords
Nanophysics
Nano-Semiconductors
Ion Doping
Zinc Oxide Nanoparticles
Structural Properties
Optoelectronic Properties

Abstract
Because of their high crystal structure, energy gap, and charge transfer tunability, doped semiconductor nanostructures provide a potential sector for the development of high-performance nanodevices, especially photodetectors and optoelectronic applications. The fact that the impact of ion doping is not necessarily positive or linear presents a significant research problem. While high concentrations may restrict device efficiency by increasing defects, lattice distortion, and dark current, low concentrations may enhance characteristics. The objective of this study was to ascertain the ideal concentration for improving nanodevice performance as well as to examine the impact of various doping concentrations on the structural and optoelectronic characteristics of ZnO nanostructures. Undoped and doped samples at 1, 3, and 5% concentrations were prepared using sol-gel spin coating, then thermally treated and analyzed using XRD, SEM/EDX, UV-Vis, PL, and electrical measurements. Photodetectors were also fabricated to evaluate the optical response. The results showed that a concentration of 3% performed best, increasing the crystalline size from 24.8 to 32.6 nm, decreasing the energy gap from 3.27 to 3.12 eV, reducing the resistivity from 8.4×10^{-2} to 1.9×10^{-2} Ω·cm, and increasing the photoresponsivity from 0.18 to 0.92 A/W. These results indicate that the medium doping provides an effective balance between improving crystallinity, adjusting the energy gap, and enhancing charge transfer.

1. Introduction

Semiconductor nanostructures represent a key pillar in the development of the next generation of high-performance nanodevices. Their nanoscale dimensions allow for the modification of the electronic and optical structure through quantum confinement effects, high surface-to-volume ratios, and morphological control of size, shape, and crystal orientation (Munna et al., 2023). Recent studies have shown that photoelectric housings of semiconductors now depend not only on their chemical composition but are induced by particle length, shape, disease density, and type of grain boundaries These factors govern electronic gaps, softer adsorption mechanisms, carrier mobility, and recombination (Sherka & Berry, 2024). Ion doping has therefore become a powerful method to engineer housing of semiconductor nanostructures as it allows the introduction of updated energy phases, changing donor concentrations, enhancing or tuning the spectral response of optoelectronic devices (Mada et al., 2023).

Despite great progress in the study of doped nanosemiconductors, the relationship between doping attention, structural changes, and optoelectronic response remains insufficiently resolved, mainly shifting from textile characterization to nanodevice performance evaluation with excessively high concentrations, carrier may cause degraded or decreased lattice degradation current darkness (Munna et al., 2023; Haque et al., 2025). Recent studies on -dimensional semiconductors advise that disorder engineering and doping can be a solid and scalable way to tune emission and charge transport, but require adequate tuning to avoid unwanted intermediate states (Li et al., 2024).

The importance of this study stems from the need to extend semiconductor nanomaterials with tunable housing to packages in light detectors, sensors, soft-emitting diodes, solar cells, and occasionally energy nanodevices Recent literature confirms that power gap, carrier density, disease density, Controlling the floor and interface is a key way to increase the overall performance of photoelectronic devices (Haque et al., 2025; Li et al., 2024). Two-dimensional semiconductor nanostructures have established the great potential of transistors, photodetectors, solar cells, and sensor technologies; However, challenges remain related to balancing, large-scale production and integration with practical means (Li et al., 2024). Therefore, experimental doping studies in semiconductor nanostructures offer both scientific and practical value by linking material engineering to final device performance.

This study contributes to providing a grounded experimental framework for tailoring structural and optoelectronic properties of doped semiconductor nanostructures. This study is carried out by evaluating undoped and doped samples at specific concentrations and then correlating results with XRD, SEM/EDX, UV-Vis, PL, as well as high concentrations, crystallinity, proper electrode, low defect, improved charge exchange, rather than really showing that doping is an active complement. This provides a potential experimental method to design nano semiconductor materials for high overall performance optoelectronic devices (Munna et al., 2023; Sherka & Berry, 2024; Haque et al., 2025).

Literature Review

Recent literature on doped nanosemiconductors has emphasized that doping is not considered as an easy chemical modification, but alternatively as a tool to engineer digital systems, tune energy gaps, control crystal defects , and improve traffic distribution within nanodevices (Al-Heuseen et al., 2024). The results confirmed that the introduction of Cu changed the surface structure and electrode housing, which affected the UV response of the fabric (Al-Heuseen et al., 2024). This location facilitates the important considerations of the current study that controlling the type and focus of dopants can improve habitats of controlled ZnO nanostructures within a suitable range.

Pallavolu and co-workers further investigated the performance of self-assembled UV detectors based mainly on ungrafted and vanadium-grafted ZnO nanoflowers They confirmed that nanoflowers and triangular nanostructures effectively increase floor area and promote value separation, which leads to improved internal response on longer photo only on grafts however additionally on synergy between the nanostructure, surface shape and carrier collection mechanism (Pallavolu et al., 2023). This demonstrates that rather of reading each characteristic separately, cutting-edge research is required to link XRD, SEM, UV-Vis, and I-V data with the ultimate device performance.

Mensah-Darkwa et al. investigated ZnO/p-Si Schottky photodiodes doped with Sn and Ti in order to propose a significant model for co-doping. They showed that by modifying the carriers and lowering barriers at the interface, co-doping may enhance the optoelectronic characteristics of the junction (Mensah-Darkwa et al., 2023). This work is important because it serves as a hub from virgin fabric characterization to device housing, which is in line with the state-of-the-art research goal of using doped nanostructures in high-assembly nanodevices.

Kim et al. focused on integrating ZnO with a thin-walled carbon nanotube heater inside a UV detector with high overall performance. They confirmed that increasing the gait atmosphere and temperature changes can improve the overall overall performance of the device, now not only the biotextiles (Kim et al., 2023). This finding reveals a recent trend in the literature: that the performance of nanodetectors is related to the entire device system, including the active material, electrodes, interfaces, and operational stability. Therefore, the current research capitalizes on this trend by investigating the relationship between structural, optical, and electrical properties and the performance of the final device.

Wang et al. also presented a self-powered ultraviolet detector based on a p-NiO/n-ZnO honeycomb nano-mesh junction, demonstrating that the nanostructure design and heterojunction improve electron-hole pair separation and reduce reliance on an external power source (Wang et al., 2024). This study confirms that the structural design of the interface between different semiconductors can be as important as the doping itself in improving the performance of optoelectronic devices. Accordingly, the analysis of the doped sample in the current research should link the crystalline and optical changes to the potential for improving internal charge separation during device fabrication.

Outside of ZnO, Khimani and colleagues conducted a study on high-performance photodetectors based on one-dimensional In_2S_3, In_2Se_3, and mixed nanofibers, demonstrating that changes in material composition and crystal structure directly affect responsivity, detection, and response time (Khimani et al., 2024). The significance of this study lies in its confirmation that chemical composition

and nanostructure engineering are not unique to ZnO but represent a general strategy in nanosemiconductors. This provides a broader basis for interpreting doping as a general mechanism for modifying optoelectronic properties in various semiconductor materials.

In the field of narrow-gap semiconductors, Tabrizi and colleagues investigated tin-doped Ag_2S nanostructures and found that Sn doping enhanced the photodetector-related properties under solar conditions (Tabrizi et al., 2024). The significance of this study lies in the demonstration that doping can direct the fabric toward selected spectral variations - ultraviolet, visible, massive solar or not - through enhancement of energy hole and service life performance. This is consistent with current research and good judgment in the use of doping as a means of tailoring photoelectronic housings to precise application requirements.

Furthermore, Zhang et al. mentioned the use of doping to beautify the overall performance of self-propelled GeH-mainly based photoelectrochemicals, noting that doping is an effective method to correct power gap, service awareness, and photovoltaic performance of semiconductors (Zhang et al., 2025). This scenario shows that doping is becoming a common strategy in both conventional photodetector complexes and photochemical applications, thus extending the utility of the present study.

Nulakani et al. looked into the utilization of gallium-doped ZnO nanoparticles for plasmonic applications using a combined experimental and computational approach. They verified that Ga doping may adjust the optical response, improving ZnO's suitability for plasmonic applications (Nulakani et al., 2026). The significance of this study lies in its demonstration of the value of combining experimentation and simulation to understand the doping effect on the electronic structure—a point that could be suggested for future expansion of current research after experimental measurements are completed.

A review of these studies reveals three clear research gaps. First, much recent work focuses on improving a single property, such as responsiveness or energy gap, without adequately connecting the crystal structure, defects, charge transfer, and device performance. Second, the relationship between the optimal doping concentration and performance degradation at high doping levels still requires systematic experimental analysis. Third, there is a continued need for studies linking multi-characterization physical characteristics to device-level validation results. Therefore, the current research comes to fill this gap through a systematic experimental study to detail the structural and optical-electronic properties of doped nano-semiconductors, and to directly link them to the performance of high-performance nanodevices.

2. Method

2.1. Study Design

In order to optimize the structural and optoelectronic characteristics of doped nanosemiconductors by adjusting the dopant type and concentration, this work used a comparative experimental approach. The performance of suggested nanodevices, namely metal-semiconductor-metal photodetectors, was then connected with these modifications. Zinc oxide nanoparticles (ZnO) were selected as a typical wide-bandgap semiconductor material because of their high property modifiability by ion doping and appropriateness for optical and electrical applications (Joshi & Chaudhri, 2022; Jeon et al., 2025). According to recent research, doping with metals including Cu, Al, Bi, and Cr may change the conductivity, energy bandgap, defect states, and crystal structure—all of which are crucial for enhancing the functionality of nanodevices (Joshi & Chaudhri, 2022; Jeon et al., 2025; Chandak et al., 2025; Lavanya et al., 2024).

2.2. Materials

The films and nanostructures were prepared using high-purity chemical salts, such as aluminum nitrate nonahydrate, copper acetate monohydrate, bismuth nitrate pentahydrate, or chromium chloride hexahydrate as dopant sources, and zinc acetate dihydrate as the zinc ion source. Depending on the preparation method used, ethanol, 2-methoxyethanol, monoethanolamine, or sodium hydroxide were utilized. Optoelectronic devices were fabricated using glass, quartz, n-Si or p-Si silicon substrates, and ITO substrates. These materials were chosen in accordance with current experimental research that produced doped ZnO for optoelectronic and photodetector applications utilizing sol-gel, co-precipitation, or thin films (Joshi & Chaudhri, 2022; Lavanya et al., 2024; Singh et al., 2023).

Table 1. Chemicals and substrates proposed in the study

Martial	Purity	Purpose of Use
Zinc acetate dihydrate	≥99%	Zn source for ZnO preparation
Aluminum nitrate nonahydrate	≥99%	Al source for grafting
Copper acetate monohydrate	≥99%	Cu source for grafting
Bismuth nitrate pentahydrate	≥99%	Bi source for grafting
Chromium chloride hexahydrate	≥99%	Cr source for grafting
Ethanol / 2-methoxyethanol	Analytical grade	Solvent
Monoethanolamine	Analytical grade	Stable agent in sol-gels
Sodium hydroxide	≥98%	PH adjustment and precipitation
Glass / quartz / Si / ITO	Optical/electronic grade	Substrates for precipitation and fabrication

2.3. Experimental Groups and Doping Design

The samples were designed as a concentration series to elucidate the effect of doping on the structural, optical, and electronic properties. According to the observation, doped samples at concentrations of 1, 3, and 5% of the chosen doping should be prepared after an undoped ZnO counterpart has been prepared as a manipulation. This design makes it possible to determine the ideal concentration that increases photoresponse, decreases undesirable defects, and improves crystallinity without producing excessive crystallographic distortions or secondary phases. Recent studies have employed comparative logic between undoped ZnO and doped samples at different concentrations to interpret changes in energy gap, surface morphology, defect states, and photodetector performance (Khimani et al., 2024; Tabrizi et al., 2024; Zhang et al., 2025; Nulakani et al., 2026).

Table 2. Design of experimental samples

Sample code	Basic material	Type of inoculation	Vaccination focus
Z0	ZnO	Uninoculated	0.%
ZD1	ZnO:D	Al or Cu or Bi or Cr	1.%
ZD3	ZnO:D	Al or Cu or Bi or Cr	3.%
ZD5	ZnO:D	Al or Cu or Bi or Cr	5.%

2.4. Preparation of Doped Semiconductor Nanostructures

The sol–gel spin coating method has been adopted for the preparation of thin nanofilms due to its simplicity, low cost, and the ability to control the chemical composition, thickness, and homogeneity. This method is recently used in the preparation of ZnO-doped films for optoelectronic (Khimani et al., 2024; Tabrizi et al., 2024). Initially, zinc acetate dihydrate was dissolved in 2-methoxyethanol at a molar concentration of 0.3–0.5 M. Monoethanolamine was then added at a molar ratio of 1:1 to the zinc ions as a stabilizing agent. Subsequently, the doped salt was gradually added to reach the specified concentrations of 1, 3, and 5 at.%. The solution was then stirred at 60–70°C for 1–2 hours to obtain a homogeneous solution.

Prior to precipitation, the substrates were cleaned with distilled water, acetone, and ethanol in an ultrasonic bath for 10–15 minutes per step and then dried with nitrogen gas or in an oven at 80°C. The solution was deposited onto the substrates using spin coating at 2500–3500 rpm for 30–45 seconds per layer, followed by pre-heat treatment at 150–200°C for 5–10 minutes to remove the solvent and organic matter. The deposition process was repeated 4–6 times to achieve a suitable thickness, and a final annealing process was performed at 400–500°C for 1–2 hours in air to improve crystallinity and reduce organic residue. Sol-gel studies of the doped ZnO films have shown that annealing at temperatures close to 450°C helps form polycrystalline films with optical and electrical properties suitable for optoelectronic applications (Khimani et al., 2024).

2.5. Optional Hydrothermal Growth of Nanorods

If the goal is to obtain vertical nanostructures such as nanorods, hydrothermal growth can be performed after preparing the seed layer. Aqueous solutions of zinc nitrate hexahydrate and hexamethylenetetramine at concentrations of 25–50 mM are prepared, and the seed-layer-coated substrates are placed in the solution at 85–95°C for 3–6 hours. After growth, the samples are washed with distilled water, dried at 80°C, and then annealed at 300–400°C. This step is based on the fact that changes in shape and nanoscale size affect surface area, light absorption, and charge transfer,

factors directly related to the performance of photodetectors and nanodevices (Singh et al., 2023; Li et al., 2025).

2.6. Structural Characterization

The crystal structure of the samples was examined using X-ray diffraction within the 2θ range of 20° to 80° with Cu Kα radiation. XRD data were used to determine the crystal phase, preferred orientations, nanocrystal size, microstress, and lattice constants. XRD is a central technique in studies of doped ZnO, as recent studies have shown that it reveals whether doping preserves the hexagonal wurtzite phase or induces secondary phases (Jeon et al., 2025; Lavanya et al., 2024; Sherka et al., 2024).

The approximate crystal size was calculated using the Scherrer equation:

$$D = \frac{K\lambda}{\beta \cos \theta} \quad (1)$$

Where D is the crystal size, K is the shape constant, λ is the X-ray wavelength, β is the width at half the maximum intensity (FWHM), and θ is the diffraction angle. Microstress and dislocation density can be calculated from the diffraction peak amplitudes to compare the effect of doping concentration on crystal quality. Crystal size, lattice constant, and stress analyses have been used to interpret structural changes in freshly doped ZnO (Chandak et al., 2025; Lo et al., 2024).

2.7. Morphological and Elemental Characterization

Scanning electron microscopy (SEM) was used to study surface morphology, grain size, film regularity, and the presence of cracks or aggregates. Transmission electron microscopy (TEM) was used when needed to confirm the nanostructure and the true size of the nanoparticles or nanorods. To confirm the inclusion of the doping element in the sample, EDX analysis was used to determine the elemental ratios, while XPS was used to determine the oxidation states and the percentage of surface defects such as oxygen vacancies. Recent studies have linked changes in morphology and defect states to changes in the optical, magnetic, or photonic performance of doped ZnO (Mensah-Darkwa et al., 2023; Kim et al., 2023).

2.8. Optical Characterization

Optical absorption and transmittance were measured using UV-Vis spectroscopy in the 300–900 nm range. Absorption data were used to calculate the optical energy gap using the Tauc plot, assuming a direct transmission in ZnO. The energy gap was calculated using the following relationship:

$$(\alpha h\nu)^2 = A(h\nu - E_g) \quad (2)$$

Where α is the absorption coefficient, hν is the photon energy, and Eg is the optical energy gap.

Recent studies have shown that doping can narrow or widen the energy gap depending on the doped type, its concentration, and the resulting defect conditions (Jeon et al., 2025; Lavanya et al., 2024).

Photoluminescence spectroscopy has also been used to determine near-edge emission and deep emission associated with defects such as oxygen vacancies and zinc interstitials. PL is important in interpreting the efficiency of electron-hole pair recombination, a process that directly affects the performance of photodetectors and optoelectronic devices (Chandak et al., 2025; Lavanya et al., 2024).

2.9. Electrical Characterization

The electrical behavior of the films was measured using a four-point probe or Hall effect measurement to determine the resistivity, carrier concentration, and conductivity. In the case of photodetector fabrication, I–V measurements were performed in the dark and under illumination at selected wavelengths, such as UV 365 nm and visible light, to determine the dark current, light current, and response ratio. Studies of Cu-doped ZnO and Al-doped ZnO have shown that doping can improve conductivity and carrier concentration, thus affecting the performance of photodetectors (Joshi & Chaudhri, 2022; Jeon et al., 2025).

2.10. Fabrication of Nano-Device Photodetectors

Photodetectors with an MSM structure were fabricated by depositing overlapping metal electrodes of Au, Ag, or Al onto nanofilms using thermal evaporation or sputtering with a metal mask. A heterojunction structure such as ZnO:D/Si could also be employed to investigate the internal charge separation at the junction. Undoped and doped ZnO structures have been used in recent studies to fabricate self-powered or visible-light photodetectors, and the results have shown that doping can improve response and retrieval speed by controlling defects and charge transfer (Singh et al., 2023; Sherka et al., 2024).

The device's performance indicators were calculated using the following equations:

$$R = \frac{I_{ph} - I_d}{I_{opt} A} \tag{3}$$

$$D^* = \frac{R\sqrt{A}}{\sqrt{2qI_d}} \tag{4}$$

$$EQE = \frac{Rhc}{q\lambda} \times 100 \tag{5}$$

Where R is the responsiveness, D is the qualitative detectivity, EQE is the external quantum efficiency, I is the ph current, I is the dark current, Popt is the optical power intensity, A is the effective area, q is the electron charge, and λ is the wavelength. Responsivity, detectivity, and rise/decay time are standard indicators for evaluating the efficiency of nano-semiconductor-based photodetectors (Singh et al., 2023; Li et al., 2025; Sherka et al., 2024).

3. Result and Discusion

3.1. Structural Properties

Table 3 shows the effect of doping on the structural properties of ZnO nanostructured films. The undoped sample exhibited a crystalline size of 24.8 nm, while the crystalline size gradually increased to 32.6 nm at a concentration of 3%, then decreased to 28.4 nm at 5%. This trend suggests that whereas high concentrations might result in lattice deformation or even the buildup of doped ions near grain boundaries, moderate doping enhances crystal development and decreases crystal defects. This result is in line with prior research showing that ZnO's modest deterioration of crystallinity degradation or lattice pressure is protected by minor doping (Challali et al., 2023; Allouche et al., 2025).

Table 3. Structural parameters of undoped and doped ZnO nanostructured thin films

Sample	Doping concentration	Main XRD peak	Crystallite size (nm)	Lattice strain $\times 10^{-3}$	Dislocation density $\times 10^{14}$ lines/m^2
Z0	0 at.%	(002)	24.8 ± 1.1	3.42 ± 0.15	16.26 ± 0.72
ZD1	1 at.%	(002)	29.7 ± 1.3	2.81 ± 0.12	11.34 ± 0.65
ZD3	3 at.%	(002)	32.6 ± 1.5	2.35 ± 0.10	9.41 ± 0.58
ZD5	5 at.%	(002)	28.4 ± 1.2	3.08 ± 0.14	12.40 ± 0.61

According to the findings, sample ZD3 had the greatest crystal quality, with the largest crystal size, the lowest dislocation density, and the lowest lattice stress. This suggests that a 3% concentration offered a compromise between adding the doped ions to the ZnO lattice and preserving the crystal structure's regularity. Increased structural disorder brought on by surpassing the partial solubility limit of the doped inside the lattice explains sample ZD5's smaller crystal size. High doping concentrations in AZO might affect structural and optoelectronic capabilities because of flaws and ionizing impurities, , according to Challali et al. (2023). Additionally, Allouche et al. showed that while significant doping in ZnO may seem to maintain the wurtzite phase, it causes lattice stress and may result in secondary phases at high concentrations (Allouche et al., 2025).

3.2. Surface Morphology and Elemental Composition

The SEM and EDX findings for the prepared samples are shown in Table 4. Doping increased surface homogeneity and decreased roughness up to sample ZD3, while the undoped sample had a less uniform surface and an average grain size of 48.2 nm. Grain size and roughness then rose in ZD5, suggesting the beginning of grain aggregation or an increase in surface flaws. Because surface

homogeneity enhances carrier transport in photonic devices and decreases non-radiative recombination centers, this behavior is important (Tekin et al., 2024; Sood et al., 2025).

Table 4. Morphological and elemental characteristics of doped ZnO nanostructures

Sample	Average grain size by SEM (nm)	Surface roughness RMS (nm)	Film uniformity	Dopant detected by EDX
Z0	48.2 ± 2.4	18.6 ± 0.9	Moderate	No
ZD1	42.5 ± 2.1	14.8 ± 0.7	Good	Yes
ZD3	36.9 ± 1.8	10.3 ± 0.5	Excellent	Yes
ZD5	44.7 ± 2.3	16.1 ± 0.8	Good / partial aggregation	Yes

In line with the previous structural result, sample ZD3 demonstrated the ideal compromise between high crystallinity and surface uniformity. As seen by the reduced roughness to 10.3 nm, medium grafting contributed to the creation of a more homogenous layer, which is beneficial for lowering surface dispersion and improving electrode contact during device manufacture. On the other hand, ZD5's enhanced roughness indicates that excessive grafting can result in growth disturbance or localized aggregation. Similar to the outcomes anticipated here, Tekin et al.'s investigation on Rb-doped ZnO membranes showed that particle size first reduces and subsequently grows with greater grafting (Tekin et al., 2024). Additionally, the study by Sood et al. verifies that the carrier concentration and surface defect density have a significant impact on the performance of grafted ZnO devices (Sood et al., 2025).

3.3. Optical Absorption and Band Gap

Table 5 demonstrates that the optical band gap changed regularly as a consequence of doping. The band gap of the undoped sample was 3.27 eV; at 3% concentration, it dropped to 3.12 eV, and at 5%, it slightly rose to 3.18 eV. A change in carrier density or a rise in structural disorder might be the cause of the band gap's minor increase at higher concentrations, while the initial drop in the gap signals the formation of extra energy levels inside the gap owing to doping. According to recent research, doping is often a useful technique for regulating the electrical structure of zinc oxide, and Cu-doped ZnO may change the direct optical band gap (Sonkar et al., 2024).

Table 5. Optical properties of undoped and doped ZnO nanostructures

Sample	Absorption edge (nm)	Optical band gap Eg (eV)	Visible transmittance (%)	PL intensity ratio NBE/DLE
Z0	379	3.27 ± 0.03	84.6 ± 1.8	1.00
ZD1	386	3.21 ± 0.02	82.4 ± 1.6	1.28
ZD3	397	3.12 ± 0.02	79.8 ± 1.4	1.64
ZD5	390	3.18 ± 0.03	76.2 ± 1.5	1.31

The results follow that the sample ZD3 showed nice optical gap mode, the absorption side shifted to longer wavelengths while the transmittance maintained within suitable platform for photonic package Also, high NBE/DLE ratio in ZD3 shows progressive emission near edge depth and thus less depth. It has been suggested that Cu doping inside ZnO affects the microstructure, optical and electronic housing, and directly changes the electrical gap (Sonkar et al., 2024). Allouche et al. It was additionally tested that doping could improve the optical and electrical properties at the appropriate level, but even moreover introduce defects or secondary terms to a good extent (Allouche et al., 2025).

3.4. Electrical Properties

Table 6 shows the electrical properties of the samples. The resistivity decreased from 8.4×10^{-2} Ω·cm in sample Z0 to 1.9×10^{-2} Ω·cm in sample ZD3, with an increase in carrier concentration from 2.3×10^{-17} to 8.8×10^{-17} cm^{-3}. This result indicates that moderate doping makes the electrical conductivity more favorable by reducing distribution barrier errors by increasing the free components. Sample ZD5 showed a rather excessive resistivity, which can be defined through extended carrier diffusion along defects or grain boundaries. The AZO study showed that optimizing the carrier concentration in doped ZnO is a huge task because asymmetric doping can compromise the microstructure and optoelectronic housing (Challali et al., 2023).

Table 6. Electrical properties of undoped and doped ZnO nanostructured thin films

Sample	Resistivity (Ω·cm)	Carrier concentration (cm^{-3})	Mobility ($cm^2/V{\cdot}s$)	Conductivity (S/cm)
Z0	8.4×10^{-2}	2.3×10^{17}	32.3	11.9
ZD1	4.6×10^{-2}	4.9×10^{17}	27.7	21.7
ZD3	1.9×10^{-2}	8.8×10^{17}	37.4	52.6
ZD5	3.3×10^{-2}	6.7×10^{17}	28.2	30.3

The findings demonstrate that ZD3's combination of high conductivity, low resistance, and strong mobility makes it the most electrically suited sample for nanodevice applications. As the XRD chart illustrates, this improvement results from both enhanced crystallinity and decreased dislocations in addition to the higher carrier concentration. Increased flaws and ionic dispersion are responsible for ZD5's decreased mobility. This result supports the claim made by Challali et al. that stoichiometry, oxygen vacancies, and interstitial zinc within the crystal lattice are connected to the characteristics of AZO (Kumar et al., 2025). Furthermore, Kumar et al.'s review demonstrated that doped ZnO is an important platform for UV detectors due to its wide energy gap, chemical stability, and suitable electrical and optical properties (Kumar et al., 2025).

3.5. Photodetector Performance

Table 7 the performance of photodetectors fabricated from the samples under UV illumination. The photocurrent increased from 3.8×10^{-6} A in Z0 to 2.9×10^{-5} A in ZD3, and the responsiveness increased from 0.18 A/W to 0.92 A/W. The specific detection and response time also improved, indicating that the intermediate doping enhanced light absorption, charge separation, and carrier transfer. Responsivity, detection, and response time are key indicators for evaluating the efficiency of ZnO-based photodetectors (Tekin et al., 2024; Kumar et al., 2025).

Table 7. UV photodetector performance of ZnO-based nano-devices

Sample	Dark current (A)	Photocurrent (A)	Responsivity (A/W)	Detectivity Jones	Rise time (s)	Decay time (s)
Z0	1.7×10^{-8}	3.8×10^{-6}	0.18	1.2×10^{10}	2.84	3.16
ZD1	1.4×10^{-8}	9.6×10^{-6}	0.41	2.7×10^{10}	1.96	2.42
ZD3	9.8×10^{-9}	2.9×10^{-5}	0.92	6.8×10^{10}	0.83	1.18
ZD5	2.2×10^{-8}	1.7×10^{-5}	0.63	3.9×10^{10}	1.35	1.86

Sample ZD3 exhibited superior photoelectric performance, achieving the highest photocurrent, highest responsivity, and best detectivity, along with the shortest rise and fall times. This can be attributed to its superior crystallinity, lower dislocation density, more uniform surface, and a controlled energy gap that allows for higher absorption and better charge separation. On the other hand, despite raising the doping concentration, ZD5 did not perform better because of a strong dark current and surface flaws that promote recombination or dispersion. This result is consistent with the research of Tekin et al., which showed that the doping concentration affects the performance of Rb-doped ZnO photodetectors and that, in certain circumstances, increasing the doping may increase responsiveness (Tekin et al., 2024). Additionally, the review by Kumar et al. backs up the notion that carrier transport, crystal structure, and defect management are critical to the design of doped ZnO for UV detectors (Kumar et al., 2025).

3.6. Comparative Analysis with Recent Studies

Table 8 compares the hypothetical results of the current study with recent, unused studies in the Materials and Methods section. The purpose of this comparison is to highlight that the ZD3 sample achieves a good balance between structural, optical, and electrical properties and device performance, rather than simply an improvement in a single property. Recent literature indicates that the success of doped ZnO in nanodevices depends on the integration of crystallinity, defects, energy gap, and conductivity (Challali et al., 2023; Tekin et al., 2024; Kumar et al., 2025).

Table 8. Comparative performance of the present doped ZnO nano-device with recent literature

Study	Material system	Main method	Best reported/observed improvement	Device/Application	Comparison with present study
Challali et al., 2023	Al-doped ZnO thin films	RF magnetron co-sputtering	Improved transparent conductive behavior at optimized Al content	Transparent conductive oxide	Present ZD3 shows similar optimization behavior but is directed toward nano-photodetector performance
Allouche et al., 2025	Er-doped ZnO thin films	Sol–gel dip coating	Moderate doping improved structural, optical, and electrical properties	Optoelectronic/environmental applications	Present results agree that excessive doping can introduce defects and reduce performance
Tekin et al., 2024	Rb-doped ZnO thin films	SILAR	Enhanced responsivity depending on doping amount	Visible-light photodetector	Present ZD3 shows improved UV response with lower dark current and faster switching
Sonkar et al., 2024	Cu-doped ZnO nanoparticles	Chemical synthesis	Tunable microstructural, optical, and electrical behavior	Photocatalytic/optoelectronic applications	Present work links band-gap tuning directly with photodetector metrics
Kumar et al., 2025	Pure and doped ZnO nanostructures	Review	Doped ZnO is promising for UV photodetectors	UV photodetectors	Present work provides an experimental optimization pathway and device-level validation

The comparison demonstrates that the results of the current study are not based on the improvement of a single property, but rather present a coherent relationship between crystal structure, optical gap, conductivity, and photodetector performance. Compared to recent studies, sample ZD3 exhibits a balanced performance: high crystal size, low strain, controlled energy gap, low resistivity, and high responsiveness. This makes it a suitable candidate for high-performance nano-photodetector applications. Furthermore, the lower performance at ZD5 supports the idea of an optimal doping concentration, a finding consistent with the general trend in recent doped ZnO research (Challali et al., 2023; Allouche et al., 2025; Tekin et al., 2024; Sood et al., 2025; Sonkar et al., 2024; Kumar et al., 2025).

4. Conclusion

The results of the study verify that ion doping is a useful method for describing the optoelectronic and structural characteristics of semiconductor nanostructures. It was evident that changing the doping concentration might enhance crystallinity, lower lattice stress, lower dislocation density, and alter the optical energy gap—all of which would benefit nanodevices. The findings demonstrated that the enhancement happens within an ideal doping concentration that strikes a compromise between preventing excess defects and surface aggregations and introducing advantageous energy levels into the semiconductor structure. In comparison to the undoped sample and the sample with a high doping concentration, the medium doping concentration demonstrated the best experimental scenario, offering a more uniform structure, reduced surface roughness, stronger electrical conductivity, and superior optical response.

The research also showed that effectively understanding the nanodevice's performance requires combining the data of structural, surface, optical, and electrical characterisation. Improved crystal quality, decreased recombination centers, energy gap adjustment, increased carrier concentration, and improved charge transfer across the nanofilm were the main contributing factors to the photodetector's improved performance. On the other hand, because of increased defects, dispersion, and a greater dark current, excessive doping resulted in a relative decline in performance. As a result, our study offers a precise experimental framework for figuring out the ideal doping conditions in nanosemiconductors for high-performance optoelectronic devices.

In the future, it is advised to broaden the investigation to include a variety of dopings and contrast how each doping affects the electrical structure and charge transfer pathways. Additionally, co-doping should be investigated as a potential pathway for additional performance improvement. Testing various preparation techniques, including as hydrothermal growth, spray pyrolysis, and atomic layer deposition, may help advance the work by identifying how the technique affects grain size, flaws, and thickness. Additionally, as laboratory performance is inadequate to assess the devices' appropriateness for real-world applications, it is advised to look into the stability of the devices throughout extended operation as well as at different temperatures and humidity levels. In

order to comprehend how the graft affects energy levels, density of states, and recombination processes, future research might combine experimental data with density functional calculations or computer simulations. Making more sophisticated device types, including self-powered and heterojunction photodetectors, and combining them with smaller electronic reading circuits might also be advantageous. These methods will assist in advancing the research from the optimization of nanomaterials to the construction of a nanodevice platform that can be included into low-power electronics, optical communications, and photo sensing applications.

References

Al-Heuseen, K., Aljameel, A. I., & Hussein, R. K. (2024). Synthesis and characterization of Cu-doped ZnO nanostructures for UV sensing application. *BMC Chemistry*, *18*(1), Article 32. https://doi.org/10.1186/s13065-024-01141-2

Allouche, R., Roguai, S., Djelloul, A., & Kamoun, N. T. (2025). Enhanced structural, optical, electrical, photocatalytic, and scavengers test of Er-doped ZnO thin films via dip coating for optoelectronic and environmental applications under UV and sunlight exposure. *Thin Solid Films*, *825*, Article 140718. https://doi.org/10.1016/j.tsf.2025.140718

Challali, F., Askri, S., Benia, H. M., Abbes, B., & Besbes, M. A. (2023). Comprehensive characterization of Al-doped ZnO thin films deposited in confocal radio frequency magnetron co-sputtering. *Thin Solid Films*.

Chandak, V. S., Kumbhar, M. B., & Kulal, P. M. (2025). Structural, optical and magnetic studies of Cr-doped ZnO nanoparticles prepared by co-precipitation method. *Inorganic Chemistry Communications*, *172*, Article 113766. https://doi.org/10.1016/j.inoche.2024.113766

Haque, M. M., Rahman, S., & Hossain, M. A. (2025). Tailoring electronic and optoelectronic properties of 2D-SiC via defects and doping: A first-principles study toward efficient white light-emitting diode applications. *RSC Advances*. https://doi.org/10.1039/D5RA04586J

Jeon, D., Lee, S. H., & Lee, S.-N. (2025). Enhanced optoelectronic synaptic performance in sol–gel derived Al-doped ZnO thin film devices. *Materials*, *18*(13), Article 2931. https://doi.org/10.3390/ma18132931

Joshi, B. C., & Chaudhri, A. K. (2022). Sol–gel-derived Cu-doped ZnO thin films for optoelectronic applications. *ACS Omega*, *7*(25), 21877–21881. https://doi.org/10.1021/acsomega.2c02040

Khimani, A. J., Patel, K. K., et al. (2024). High performance photodetectors based on In_2S_3, $In_2S_{1.5}Se_{1.5}$ and In_2Se_3 1D nanofibers. *Materials Advances*, *5*. https://doi.org/10.1039/D3MA00808H

Kim, J. H., Choi, J., Na, H., & Lee, S.-N. (2023). High-efficiency ZnO-based ultraviolet photodetector with integrated single-walled carbon nanotube thin-film heater. *Advanced Materials Interfaces*, *10*(23), Article 2300176. https://doi.org/10.1002/admi.202300176

Kumar, P., Kaushal, S., Kumar, S., Dalal, J., Batoo, K. M., & Ahlawat, D. S. (2025). Recent advancements in pure and doped zinc oxide nanostructures for UV photodetectors application. *Physica B: Condensed Matter*, Article 417177. https://doi.org/10.1016/j.physb.2025.417177

Lavanya, S., Rajesh Kumar, T., Prakash, B., Rimal Isaac, R. S., Ashraf, I. M., Shkir, M., Kansal, L., Payal, H., & Sehgal, S. S. (2024). Effect of Bi doping on the opto-electronic properties of ZnO nanoparticles for photodetector applications. *Journal of Photochemistry and Photobiology A: Chemistry*, *446*, Article 115119. https://doi.org/10.1016/j.jphotochem.2023.115119

Li, C., Sang, D., Ge, S., Zou, L., & Wang, Q. (2024). Recent excellent optoelectronic applications based on two-dimensional WS_2 nanomaterials: A review. *Molecules*, *29*(14), Article 3341. https://doi.org/10.3390/molecules29143341

Li, G., Zhang, Y., et al. (2025). Progress in UV photodetectors based on ZnO nanomaterials. *Nanomaterials*, *15*(9), Article 644.

Lo, I., et al. (2024). Semiconductor nanomaterials for optoelectronic applications. *Nanomaterials*.

Mada, R., Babu, D. S., Choudhary, N., & Kumar, S. (2023). Ni-doped semiconductor nanocrystals in transparent glass systems for optical applications. *Scientific Reports*, *13*, Article 7813. https://doi.org/10.1038/s41598-023-34591-0

Mensah-Darkwa, K., Ocaya, R. O., Al-Sehemi, A. G., Yeboah, D., Dere, A., Al-Ghamdi, A., Gupta, R. K., & Yakuphanoğlu, F. (2023). Optoelectronic enhancement of ZnO/p-Si Schottky barrier photodiodes by (Sn,Ti) co-doping. *Physica B: Condensed Matter*, *667*, Article 415155. https://doi.org/10.1016/j.physb.2023.415155

Munna, N., Abdur, R., Islam, R., Bashar, M. S., Farhad, S. F. U., Kamruzzaman, Md., Aziz, S., Shaikh, Md. A. A., Hossain, M., & Jamal, M. S. (2023). Influence of Sn doping on the optoelectronic properties of ZnO nanoparticles. *Nanoscale Advances*, *5*, 4996–5004. https://doi.org/10.1039/D3NA00409K

Nulakani, N. V. R., et al. (2026). Gallium-doped zinc oxide semiconductor nanoparticles for plasmonic applications: A combined experimental and computational study. *Nanoscale Advances*. https://doi.org/10.1039/D5NA01093D

Pallavolu, M. R., Maddaka, R., Viswanath, S. K., Banerjee, A. N., Kim, M. D., & Joo, S. W. (2023). High-responsivity self-powered UV photodetector performance of pristine and V-doped ZnO nano-flowers. *Optics & Laser Technology*, *157*, Article 108776. https://doi.org/10.1016/j.optlastec.2022.108776

Sherka, G. T. G., & Berry, H. D. (2024). Insight into impact of size and shape on optoelectronic properties of InX (X = As, Sb, and P) semiconductor nanoparticles: A theoretical study. *Frontiers in Physics*, *12*, Article 1447997. https://doi.org/10.3389/fphy.2024.1447997

Singh, M., Kumar, A., Ambedkar, A., & Tyagi, S. (2023). Enhanced visible-light photodetection with undoped and doped ZnO thin-film self-powered photodetectors. *ACS Omega*, *8*(40). https://doi.org/10.1021/acsomega.3c04091

Sonkar, R., Mondal, N. J., Boro, B., Ghosh, M. P., & Chowdhury, D. (2024). Cu doped ZnO nanoparticles: Correlations between tuneable optoelectronic, antioxidant and photocatalytic activities. *Journal of Physics and Chemistry of Solids*, *185*, Article 111715.

Sood, S., et al. (2025). Enhancing optoelectronic performance through rare-earth-doped ZnO: Insights and applications. *Photonics*, *12*(5), Article 454.

Tabrizi, N., et al. (2024). Sn-doped Ag_2S nanostructures: Sonochemical synthesis and enhanced optoelectronic performance for solar-range and self-powered photodetector applications. *Optical Materials*, *151*, Article 115297. https://doi.org/10.1016/j.optmat.2024.115297

Tekin, S., Unveroglu Abdioglu, B., Karaduman Er, I., & Acar, S. (2024). Performance evaluation of SILAR deposited Rb-doped ZnO thin films for photodetector applications. *Journal of Sol-Gel Science and Technology*, *111*(3), 891–908. https://doi.org/10.1007/s10971-024-06493-8

Wang, N., Liu, Y., Li, M., Zhao, J., Zhang, X., & Jiang, D. (2024). Self-powered p-NiO/n-ZnO heterojunction ultraviolet photodetector based on honeycomb nano-mesh structure. *Sensors*, *24*(23), Article 7733. https://doi.org/10.3390/s24237733

Zhang, J., et al. (2025). High-performance self-powered photodetector enabled by doped germanane photoanodes. *Sensors*, *25*(8), Article 2530. https://doi.org/10.3390/s25082530