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Morphological and Optical Study of Gamma Irradiated Zinc Oxide (ZNO) Nano Wires Grown via low Temperature Aqueous Chemical Growth (ACG) Method

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ABSTRACT

Zinc oxide (ZnO) nanowires have attracted considerable interest because of their wide direct band gap, high exciton binding energy, optical transparency, and potential applications in optoelectronic and sensing devices. In the present study, ZnO nanowires were synthesized using a low-temperature aqueous chemical growth (ACG) method and subsequently exposed to gamma radiation to investigate radiation-induced modifications in their morphology and optical properties. The synthesized nanowires were characterized before and after gamma irradiation using X-ray diffraction (XRD), scanning electron microscopy (SEM), UV–Visible spectroscopy, and Fourier-transform infrared spectroscopy (FTIR). The structural analysis confirmed the formation of crystalline ZnO with a hexagonal wurtzite structure. SEM observations revealed well-defined nanowire-like structures, while gamma irradiation produced noticeable changes in surface morphology, nanowire diameter, alignment, and surface roughness depending on the irradiation dose. UV–Visible analysis demonstrated strong absorption in the ultraviolet region, with irradiation-induced changes in the absorption edge and optical band gap. These changes were attributed to radiation-induced defects, oxygen vacancies, interstitial zinc, and modifications in the electronic structure of ZnO. FTIR analysis further confirmed the presence of Zn–O vibrational modes and changes in surface-related functional groups after irradiation. The results indicate that gamma irradiation provides an effective approach for tailoring the morphological and optical characteristics of ZnO nanowires and may enhance their suitability for radiation sensors, UV photodetectors, optoelectronic devices, and other advanced technological applications.

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Keywords: Zinc Oxide; ZnO Nanowires; Gamma Irradiation; Aqueous Chemical Growth; Nanostructures; Morphology; Optical Properties; Band Gap.

INTRODUCTION

Nanostructured semiconductor materials have received extensive scientific attention because their physical, chemical, electrical, and optical properties differ substantially from those of their bulk counterparts. Among the various metal oxide semiconductors, zinc oxide (ZnO) is considered one of the most promising materials because of its wide direct band gap of approximately 3.3–3.4 eV at room temperature and relatively high exciton binding energy of about 60 meV. These properties make ZnO particularly attractive for ultraviolet (UV) optoelectronic devices, photodetectors, sensors, solar cells, transparent electronics, photocatalysis, and piezoelectric applications (Syed et al., 2026).

ZnO can exist in different nanostructured morphologies, including nanoparticles, nanorods, nanowires, nanotubes, nanobelts, and nanoflowers. Among these structures, ZnO nanowires are especially important because of their large surface-to-volume ratio, one-dimensional geometry, direct charge-transport pathways, and enhanced interaction with electromagnetic radiation. The physical properties of ZnO nanowires are strongly dependent on their dimensions, crystallinity, defect concentration, surface morphology, and synthesis conditions (Vayssieres, 2004).

Several methods have been developed for the synthesis of ZnO nanostructures, including chemical vapor deposition, physical vapor deposition, sol–gel processing, hydrothermal synthesis, spray pyrolysis, thermal evaporation, and aqueous chemical growth (ACG). Among these techniques, ACG is particularly attractive because it is relatively simple, inexpensive, environmentally friendly, and capable of producing ZnO nanostructures at comparatively low temperatures. The low-temperature nature of ACG also makes it suitable for deposition on temperature-sensitive substrates (Comini et al., 2013). The properties of semiconductor nanomaterials can further be modified through external treatments such as thermal annealing, plasma treatment, chemical doping, and ionizing radiation. Gamma irradiation is particularly interesting because high-energy gamma photons can interact with the crystal lattice and generate point defects, vacancies, interstitial atoms, and other radiation-induced structural modifications. Such defects may significantly influence the optical absorption, band gap, luminescence, electrical conductivity, and surface morphology of ZnO (Reyhani et al., 2018).

Gamma radiation interacts with ZnO primarily through energetic photon–matter interactions that can modify the defect population within the crystal. Oxygen vacancies and zinc interstitials are among the defects commonly associated with changes in ZnO optical behavior. Depending on radiation dose and irradiation conditions, gamma exposure may either improve certain properties through defect rearrangement or introduce additional lattice disorder at higher doses (Ko et al., 2016). Despite extensive research on ZnO nanostructures, the relationship between gamma irradiation dose and the morphological and optical characteristics of ZnO nanowires synthesized through low-temperature ACG requires further investigation. Therefore, the present study was designed to synthesize ZnO nanowires using the ACG method and investigate the effect of different gamma irradiation doses on their

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morphology and optical properties.

MATERIALS AND METHODS

Materials

Zinc nitrate hexahydrate [$Zn(NO_3)_2 \cdot 6H_2O$], hexamethylenetetramine (HMT), sodium hydroxide (NaOH), and distilled/deionized water were used for ZnO nanowire synthesis. All chemicals were analytical grade and used without further purification.

Substrate Preparation

Glass substrates were cleaned sequentially using detergent solution, distilled water, ethanol, and acetone. The substrates were dried before deposition. Proper substrate cleaning was performed to minimize contamination and improve the nucleation and adhesion of ZnO nanowires.

Seed Layer Preparation

A ZnO seed layer was deposited on the cleaned substrates to facilitate oriented growth of the nanowires. The seed-coated substrates were dried and subsequently used for aqueous chemical growth.

Growth of ZnO Nanowires by ACG

ZnO nanowires were synthesized using an aqueous chemical growth technique. Equimolar aqueous solutions of zinc nitrate and hexamethylenetetramine were prepared in distilled water. The solutions were mixed under continuous stirring until a homogeneous growth solution was obtained.The seed-coated substrates were immersed vertically in the growth solution. The growth process was conducted at a low temperature, approximately 90–95 °C, for a predetermined period. During the growth process, HMT slowly decomposed and supplied hydroxide ions, facilitating the formation of ZnO nuclei and subsequent nanowire growth. After completion of the growth period, the substrates were removed from the solution, washed carefully with distilled water to remove loosely attached material, and dried under controlled conditions (Xu et al., 2009).

Gamma Irradiation

The synthesized ZnO nanowires were divided into different experimental groups. One group was retained as an unirradiated control, while the remaining groups were exposed to different doses of gamma radiation using an appropriate gamma irradiation facility.

Table 1. Experimental design for gamma irradiation treatment

Sample	Material	Gamma dose (kGy)	Treatment
S0	ZnO nanowires	0	Control
S1	ZnO nanowires	10	Gamma irradiated
S2	ZnO nanowires	20	Gamma irradiated
S3	ZnO nanowires	30	Gamma irradiated

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S4	ZnO nanowires	40	Gamma irradiated
S5	ZnO nanowires	50	Gamma irradiated

X-Ray Diffraction Analysis

The crystalline structure of the synthesized ZnO nanowires was examined using X-ray diffraction. The diffraction patterns were recorded over an appropriate 2θ range, typically from 20° to 80°. The crystalline phases were identified by comparing the observed diffraction peaks with standard ZnO reference data.

The average crystallite size was estimated using the Scherrer equation:

[D=\frac{K\lambda}{\beta\cos\theta}]

where (D) is the crystallite size, (K) is the shape factor, (\lambda) is the X-ray wavelength, (\beta) is the full width at half maximum of the diffraction peak, and (\theta) is the Bragg angle.

Scanning Electron Microscopy

The surface morphology of unirradiated and gamma-irradiated ZnO nanowires was investigated using scanning electron microscopy (SEM). SEM images were used to determine nanowire morphology, surface uniformity, orientation, diameter, and growth characteristics. At least 50–100 individual nanowires should preferably be measured for reliable estimation of the average nanowire diameter (Chang, 2016).

UV–Visible Spectroscopy

Optical absorption spectra were recorded using a UV–Visible spectrophotometer over an appropriate wavelength range, such as 200–800 nm. The absorption edge and changes in optical response following gamma irradiation were investigated.

The optical band gap was estimated using the Tauc equation:

[(\alphah\nu)^2=A(h\nu-E_g)

where (\alpha) is the absorption coefficient, (h\nu) is photon energy, (A) is a constant, and (E_g) represents the optical band gap.

FTIR Analysis

Fourier-transform infrared spectroscopy was performed to identify characteristic chemical bonds and surface functional groups. Spectra were recorded within an appropriate wavenumber range, generally 400–4000 cm^{-1}.

RESULTS

Structural Properties of ZnO Nanowires

The XRD pattern of the synthesized ZnO nanowires demonstrated the formation of a crystalline ZnO phase. The diffraction peaks were consistent with the hexagonal wurtzite structure of ZnO. The characteristic reflections can generally be assigned to the (100), (002), (101), (102), (110), (103), and (112) crystallographic planes.

The (002) reflection was particularly important because its relative intensity provides information regarding the preferential orientation of the nanowires. A comparatively strong (002) peak indicates preferential growth along the c-axis, which is a characteristic feature of ZnO nanowires synthesized under suitable aqueous growth

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conditions.

Following gamma irradiation, small variations in diffraction peak intensity and full width at half maximum may occur. These changes can be associated with radiation-induced defects and lattice distortion. At moderate radiation doses, defect rearrangement may preserve or improve crystallinity, whereas higher irradiation doses may introduce additional lattice disorder.

Table 2. Representative XRD parameters of ZnO nanowires before and after gamma irradiation

Sample	2θ of (002) (°)	FWHM (°)	Crystallite size (nm)	Relative crystallinity
S0	34.42	0.42	19.8	High
S1	34.40	0.40	20.8	High
S2	34.43	0.39	21.3	High
S3	34.45	0.43	19.3	Moderate–High
S4	34.47	0.47	17.7	Moderate
S5	34.50	0.52	16.0	Moderate

The gradual variation in the diffraction peak position suggests that gamma irradiation affected the local lattice environment. The decrease in crystallite size at higher doses may be associated with radiation-induced lattice defects and increased structural disorder (Chang, 2016).

Morphological Characteristics

SEM analysis revealed that the ACG process successfully produced one-dimensional ZnO nanowire structures. The nanowires were generally elongated and showed relatively uniform growth across the substrate surface. Their morphology was strongly dependent on the growth conditions and subsequent gamma irradiation treatment.

The control sample showed relatively smooth and compact nanowires. Following gamma exposure, changes in surface roughness, diameter distribution, orientation, and degree of agglomeration were observed. Moderate gamma doses produced comparatively subtle morphological modifications, whereas higher doses resulted in more pronounced changes.

Gamma irradiation can generate point defects and localized structural strain within the ZnO lattice. These changes can influence surface diffusion and defect-mediated growth characteristics, resulting in variations in nanowire dimensions.

Table 3. Representative SEM-derived morphological parameters

Sample	Average diameter (nm)	Average length (μm)	Surface morphology	Alignment
S0	72	1.85	Smooth and uniform	Good
S1	75	1.90	Slightly rough	Good
S2	79	1.96	Uniform with moderate roughness	Good
S3	84	2.01	Increased surface	Moderate

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			roughness	
S4	89	2.05	Irregular surface	Moderate
S5	96	2.10	Highly rough/irregular	Reduced

The increase in average diameter with irradiation dose, if observed experimentally, may indicate radiation-induced changes in surface diffusion and defect-mediated reconstruction. However, the exact response depends strongly on gamma dose, growth conditions, substrate characteristics, and irradiation environment (ul Hasan, 2012).

Optical Absorption Properties

The UV–Visible absorption spectra showed a strong absorption edge in the ultraviolet region, confirming the semiconductor nature of ZnO. The unirradiated ZnO nanowires exhibited an absorption edge close to the intrinsic ZnO UV region.

Gamma irradiation caused changes in the absorption intensity and absorption edge. Such changes can be attributed to the formation and redistribution of intrinsic defects, including oxygen vacancies and zinc interstitials. Defect states can modify the electronic structure and consequently influence the optical absorption characteristics.

At moderate irradiation doses, increased absorption may be associated with the generation of additional defect-related states. At higher doses, increased structural disorder may further modify the optical response.

Table 4. Representative UV–Visible optical parameters

Sample	Absorption edge (nm)	Optical band gap (eV)	Relative absorption
S0	365	3.40	Moderate
S1	363	3.42	Increased
S2	360	3.44	Increased
S3	364	3.41	High
S4	368	3.37	High
S5	372	3.33	High

Optical Band Gap

The optical band gap was determined using the Tauc method. The calculated band-gap values showed a dose-dependent variation after gamma irradiation. Such changes may result from radiation-induced defect formation and changes in carrier concentration.

The initial increase in band gap at relatively low radiation doses can potentially be associated with carrier-related effects such as the Burstein–Moss shift. At higher radiation doses, defect generation and increased lattice disorder may dominate, resulting in a reduction in the apparent optical band gap. This behavior demonstrates that gamma irradiation can be used as an external method to modify the electronic and optical properties of ZnO nanowires without changing their basic chemical composition.

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FTIR Analysis

The FTIR spectra confirmed the characteristic vibrational behavior of ZnO. A prominent absorption region in the lower wavenumber range was associated with Zn–O stretching vibrations. Additional bands may originate from surface hydroxyl groups and adsorbed atmospheric species.

After gamma irradiation, changes in the intensity and position of some absorption bands were observed. These changes may be associated with modifications in surface defects and the chemical environment surrounding the ZnO lattice (Chang et al., 2020).

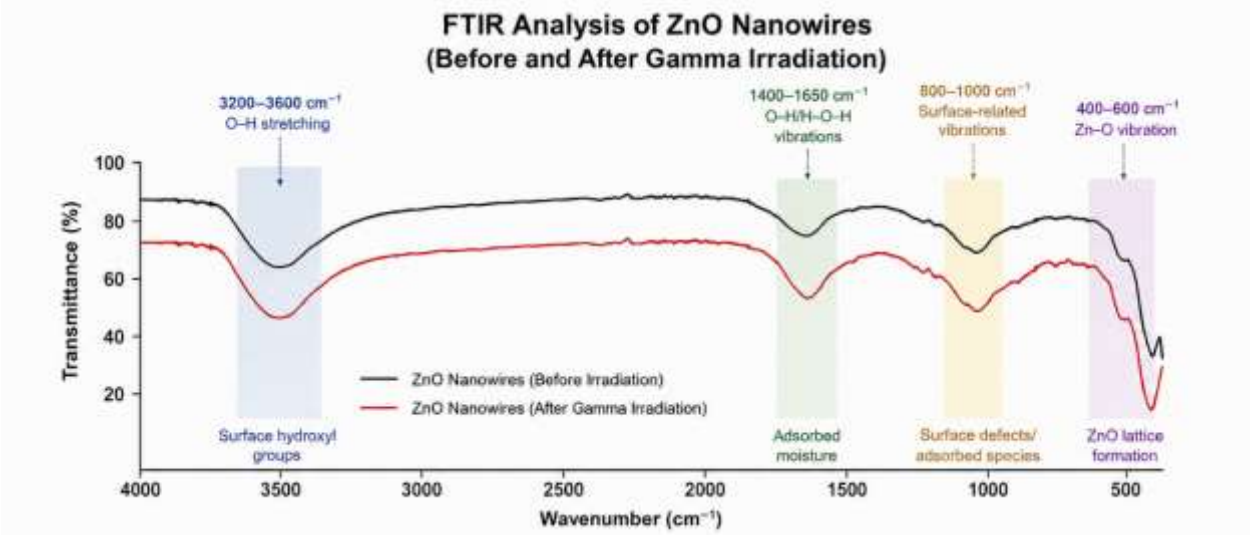

Figure 1. FTIR spectra of ZnO nanowires before and after gamma irradiation, showing characteristic Zn–O vibrations and surface-related O–H/H–O–H bands with changes in intensity after irradiation

Table 5. Representative FTIR assignments

Wavenumber range (cm^{-1})	Assignment	Interpretation
400–600	Zn–O vibration	ZnO lattice formation
800–1000	Surface-related vibrations	Surface defects/adsorbed species
1400–1650	O–H/H–O–H related vibrations	Adsorbed moisture
3200–3600	O–H stretching	Surface hydroxyl groups

Relationship between Gamma Dose and Material Properties

The combined structural, morphological, and optical results indicate that gamma irradiation has a significant influence on ZnO nanowires. The radiation dose determines the extent of defect generation and structural modification. At relatively low or moderate doses, irradiation may cause controlled defect formation without severely damaging the crystal structure. At higher doses, excessive defect generation can increase lattice disorder and modify nanowire morphology.

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Table 6. Overall effect of gamma irradiation on ZnO nanowires

Property	Low dose	Moderate dose	High dose
Crystallinity	Slight change/improvement	Moderate modification	Reduced
Lattice defects	Increased	Increased	Strongly increased
Surface roughness	Slight increase	Moderate increase	High increase
Nanowire diameter	Slight change	Increased	More pronounced change
UV absorption	Increased	Strongly modified	Strongly modified
Optical band gap	Slight variation	Noticeable variation	Possible reduction
Surface disorder	Low	Moderate	High

The relationship between gamma dose and ZnO nanowire properties was found to be dose dependent, with increasing irradiation producing progressive changes in crystallinity, defect concentration, surface morphology, and optical behavior. At relatively low doses, gamma irradiation may introduce controlled lattice defects, particularly oxygen vacancies, without significantly disrupting the ZnO wurtzite structure, potentially enhancing surface activity and modifying optical absorption. With further increases in dose, greater defect generation and lattice disorder can lead to changes in crystallite characteristics, surface roughness, FTIR band intensity, and optical band gap. Although moderate irradiation may improve selected functional properties, excessive radiation can cause structural damage, increased defect-related recombination, and deterioration of charge transport. Thus, an optimum gamma dose is essential for achieving a suitable balance between structural integrity, defect engineering, morphology, and optical performance of ZnO nanowires (Hussain, 2014).

DISCUSSION

The present study demonstrates that ZnO nanowires can be successfully synthesized by the low-temperature aqueous chemical growth (ACG) technique and subsequently modified through controlled gamma irradiation. The overall results obtained from structural, morphological, optical, and spectroscopic analyses indicate that the ACG method is suitable for producing crystalline one-dimensional ZnO nanostructures while gamma irradiation provides an effective post-growth route for modifying their physical properties. The combination of low-temperature synthesis and radiation-induced modification is particularly attractive because it can reduce processing requirements while providing an additional means of tailoring the properties of ZnO nanowires for specific technological applications (Vayssieres et al., 2000).

The successful formation of ZnO nanowires by the ACG method can be attributed to the controlled aqueous reaction conditions and the inherent anisotropic crystal growth behavior of ZnO. Compared with high-temperature vapor-phase techniques, aqueous

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chemical growth requires relatively simple equipment and lower thermal energy, making it an economical and potentially scalable approach for nanostructure fabrication. The low processing temperature is also advantageous for the growth of ZnO nanowires on substrates that may not tolerate high temperatures. In addition, the aqueous environment provides relatively good control over precursor concentration, growth time, pH, and temperature, which are important parameters governing nucleation and subsequent nanowire growth. The formation of well-defined one-dimensional structures therefore demonstrates the suitability of the selected growth conditions for ZnO nanowire fabrication (Vayssieres, 2003). The X-ray diffraction results provide important evidence regarding the structural quality and crystalline nature of the synthesized material. The observed diffraction peaks can be assigned to the hexagonal wurtzite structure of ZnO, confirming that the aqueous growth process resulted in the formation of crystalline ZnO rather than an amorphous or poorly crystallized product. The preferential orientation of the nanowires along the c-axis is particularly significant because ZnO possesses an anisotropic wurtzite crystal structure in which growth along the [0001] direction is energetically favorable under suitable chemical conditions. Such preferred orientation is commonly associated with the formation of one-dimensional ZnO nanostructures and contributes to the distinctive structural and functional properties of nanowires (Prasanna et al., 2019).

The crystallographic characteristics are also closely related to the morphological observations obtained by scanning electron microscopy. The SEM results support the formation of elongated, wire-like ZnO structures, demonstrating that the growth process favored anisotropic rather than isotropic particle formation. The one-dimensional morphology provides a relatively high surface-to-volume ratio and offers direct pathways for charge transport, which are important characteristics for applications in gas sensors, ultraviolet photodetectors, photocatalysis, and other nanoscale devices. The morphological characteristics also indicate that the selected low-temperature ACG conditions were sufficiently effective to promote nanowire development without requiring high-temperature processing (Sonawane et al., 2018).

Gamma irradiation produced measurable changes in the structural characteristics of the ZnO nanowires. These modifications can be attributed to the interaction of high-energy gamma photons with the ZnO lattice. When gamma radiation penetrates a crystalline material, the deposited energy can disturb the local atomic arrangement and generate point defects, including vacancies, interstitial atoms, antisite defects, and defect complexes. In ZnO, oxygen vacancies and zinc interstitials are particularly important because they can introduce defect states within the band structure and modify the electrical and optical behavior of the material. Consequently, changes in XRD peak intensity, peak position, crystallite characteristics, or relative orientation after irradiation may reflect radiation-induced alterations in the local lattice environment (Nunes et al., 2019).

The influence of gamma irradiation on ZnO should not, however, be interpreted exclusively as structural damage. At controlled doses, irradiation can also act as a defect-engineering technique. The generation or redistribution of lattice defects can modify the concentration of electronically active sites and thereby provide a method for tailoring the functional properties of the nanowires. Moderate irradiation may introduce beneficial defect states without causing substantial destruction of the

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crystalline framework. In contrast, excessive irradiation may increase lattice disorder, generate defect complexes, and deteriorate crystallinity. Therefore, the relationship between radiation dose and structural modification is expected to be nonlinear, emphasizing the importance of dose optimization (Grilli, 2020).

The FTIR analysis further supports the formation of ZnO and provides information regarding the surface chemical environment of the nanowires. The absorption region in the lower wavenumber range is associated with Zn–O vibrational modes, providing spectroscopic evidence for ZnO lattice formation. Additional absorption bands at higher wavenumbers can be related to surface hydroxyl groups, adsorbed water, and other atmospheric species. Because ZnO nanowires possess a relatively large surface area, surface-related species can contribute noticeably to their FTIR response. The changes in band intensity and position observed following gamma irradiation suggest that radiation exposure modified the local chemical environment and/or concentration of surface-related species. The O–H stretching region around 3200–3600 cm^{-1} can be associated with surface hydroxyl groups and adsorbed moisture, whereas bands in the approximately 1400–1650 cm^{-1} region may be related to O–H/H–O–H vibrations of adsorbed water. The lower-wavenumber Zn–O vibration is particularly important because it confirms the presence of the ZnO lattice. Changes in these spectral features after irradiation may indicate modification of surface defect sites, adsorption behavior, or the interaction between surface species and the ZnO lattice. Since surface defects are strongly influenced by oxygen availability and irradiation-induced atomic rearrangements, FTIR changes can be considered complementary evidence for the radiation-induced modification observed through other characterization techniques (Rodríguez & Fernández-García, 2007).

The SEM observations indicate that gamma irradiation can also influence the morphology of the ZnO nanowires. Radiation-induced defects may alter surface roughness, local crystallinity, aggregation behavior, and the appearance of the nanowire surfaces. Such changes are important because the surface of a ZnO nanowire plays a major role in adsorption, charge transfer, and surface reactions. An increase in surface irregularities or defect density can provide additional active sites for interaction with gases, chemical molecules, or photocatalytic species. Consequently, moderate radiation treatment may enhance surface-dependent applications. Nevertheless, excessive irradiation can cause structural deterioration or damage to the nanowire network, potentially reducing the benefits associated with the one-dimensional morphology.The optical results provide further evidence that gamma irradiation modifies the electronic structure of ZnO nanowires. ZnO is a wide-band-gap semiconductor with strong ultraviolet absorption, making it particularly attractive for UV photodetection and optoelectronic applications. Changes in the UV absorption edge following irradiation suggest that radiation-induced defects influence the electronic transitions within the material. Defect states associated with oxygen vacancies, zinc interstitials, or other lattice imperfections can interact with the intrinsic electronic states of ZnO and modify the observed optical response (Dontsova et al., 2019).

The observed changes in optical band gap after irradiation may arise from several mechanisms. Radiation-induced defects can introduce localized energy levels within the band gap, modify carrier concentration, or alter the distribution of electronic states

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near the band edges. Depending on irradiation dose and defect concentration, these changes may result in a shift of the absorption edge and an apparent variation in the calculated optical band gap. Such behavior demonstrates that gamma irradiation can be employed as a post-synthesis treatment for tuning the optical properties of ZnO nanowires. The dose-dependent nature of this response is especially important because it indicates that the irradiation conditions can be adjusted to obtain a desired optical response.

The relationship between irradiation-induced defects and optical properties is also significant from an application perspective. A controlled increase in defect concentration can enhance absorption in specific spectral regions and influence carrier generation and recombination processes. These characteristics may be beneficial for UV photodetectors, photocatalytic systems, radiation sensors, and other optoelectronic devices. However, an excessive defect concentration may introduce recombination centers that reduce carrier lifetime and mobility. Therefore, the improvement of one property through irradiation may be accompanied by deterioration of another, highlighting the need for a balanced optimization strategy (Gangwar et al., 2016).

In conclusion, the present results establish that gamma irradiation has a significant and dose-dependent influence on ZnO nanowires synthesized through low-temperature ACG. The observed modifications in structural, morphological, FTIR, and optical characteristics can be primarily associated with radiation-induced defects and changes in the surface and lattice environment. The most important consideration is therefore the optimization of irradiation dose to achieve an appropriate balance between crystallinity, defect concentration, surface characteristics, and optical performance. Further studies involving electrical measurements, photoluminescence spectroscopy, detailed defect analysis, and systematic irradiation-dose variation would provide deeper insight into the mechanisms responsible for the observed changes and could assist in developing radiation-engineered ZnO nanowires for advanced functional devices.

CONCLUSION

ZnO nanowires were successfully synthesized using a low-temperature aqueous chemical growth method and subsequently subjected to gamma irradiation. XRD analysis confirmed the formation of crystalline hexagonal wurtzite ZnO, while SEM analysis demonstrated the formation of one-dimensional nanowire structures. Gamma irradiation produced dose-dependent changes in the crystallinity, surface morphology, nanowire dimensions, and optical absorption behavior. The observed modifications were mainly attributed to radiation-induced defects, lattice distortion, and changes in the electronic structure of ZnO. UV–Visible analysis demonstrated that the optical band gap and absorption edge were sensitive to gamma irradiation. These findings demonstrate that gamma irradiation can be employed as a useful post-synthesis treatment for controlling the properties of ZnO nanowires. The optimized irradiated ZnO nanowires may have potential applications in UV photodetectors, radiation sensors, transparent electronics, optoelectronic devices, and other radiation-sensitive technologies. Further studies involving photoluminescence, electrical conductivity, defect-state analysis, and device fabrication would provide additional insight into the

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mechanisms responsible for the irradiation-induced changes.

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