INVESTIGATION OF THE CRYSTAL STRUCTURE AND ELECTROPHYSICAL PROPERTIES OF ZNO THIN FILMS GROWN BY ION-PLASMA DEPOSITION

Fazliddin Arzikulov
Researcher of Tashkent State Technical University named after Islam Karimov,
Assistant at Tashkent State Medical University, Tashkent, Uzbekistan
Email: arzikulovfazliddin1997@gmail.com
ORCID: 0009-0004-6901-5291

Asror Mustafakulov
Professor of the Department of Physics,
Jizzakh Polytechnic Institute, Uzbekistan
Email: asrormustafakulov69@gmail.com
ORCID: 0000-0002-3251-9742

Isroil Kosimov
Senior Researcher at the O.S. Sodikov Institute of Bioorganic Chemistry,
Academy of Sciences of the Republic of Uzbekistan, 100143, Uzbekistan.
Email: isroilkosimov@list.ru
ORCID: 0000-0002-3463-2861

Sherzod Kuchkanov
PhD in Technical Sciences, Associate Professor of
Tashkent State Technical University named after Islam Karimov

Abstract

Zinc oxide (ZnO) thin films are widely used in modern electronics, optoelectronics, sensor systems, and photovoltaic technologies due to their unique structural and electrophysical properties. The characteristics of ZnO films strongly depend on deposition conditions and technological parameters used during synthesis. Among various fabrication methods, ion-plasma deposition is considered one of the most effective techniques for obtaining high-quality semiconductor thin films with controlled structural properties.

The present study investigates the crystal structure and electrophysical properties of ZnO thin films grown on dielectric substrates using ion-plasma deposition technology. Particular attention was devoted to the influence of deposition conditions on crystallinity, phase composition, surface morphology, electrical conductivity, and charge transport mechanisms.

Structural analysis demonstrated that the deposited ZnO films possess a polycrystalline hexagonal wurtzite structure with preferential orientation along the crystallographic c-axis. Electrophysical investigations revealed that variations in deposition parameters significantly affect carrier concentration, electrical resistance, and mobility characteristics of the films.

The obtained results indicate that ion-plasma deposition provides favorable conditions for controlled growth of ZnO thin films with improved structural uniformity and stable electrophysical parameters. The investigated films demonstrate promising potential for application in optoelectronic and energy-related devices.

Keywords: ZnO thin films, ion-plasma deposition, crystal structure, electrophysical properties, semiconductor materials, dielectric substrate, electrical conductivity, wurtzite structure.

Introduction

Zinc oxide (ZnO) is one of the most extensively studied semiconductor materials due to its unique optical, electrical, and structural characteristics. In recent decades, ZnO thin films have attracted considerable scientific and technological interest because of their wide band gap, high exciton binding energy, chemical stability, and excellent transparency in the visible spectral region. These properties make ZnO a promising material for applications in optoelectronics, transparent conductive coatings, gas sensors, photodetectors, solar cells, and nanoelectronic devices.

The physical properties of ZnO thin films strongly depend on synthesis conditions, deposition techniques, substrate characteristics, and post-deposition treatment processes. Therefore, optimization of film growth technology remains an important issue for improving the performance of ZnO-based devices.

Among modern thin-film fabrication methods, ion-plasma deposition technology occupies a special position due to its ability to produce uniform coatings with controlled structural and electrophysical parameters. Ion-plasma methods provide high deposition rates, improved adhesion to substrates, enhanced crystallinity, and precise control over film thickness and stoichiometric composition.

During ion-plasma deposition, energetic particles interact with the substrate surface, influencing nucleation mechanisms, grain growth, defect formation, and crystallographic orientation of the growing film. These factors directly affect electrical conductivity, carrier mobility, and optical behavior of ZnO thin films.

Structural investigations of ZnO commonly reveal formation of a hexagonal wurtzite crystal structure characterized by strong anisotropic properties. The preferential orientation of crystallites and the concentration of structural defects significantly influence electrophysical characteristics of the films. Oxygen vacancies, zinc interstitials, and grain boundary effects are among the most important factors determining electrical transport mechanisms in ZnO semiconductor layers.

Recent advances in nanotechnology and semiconductor engineering have increased interest in controlling microstructural parameters of ZnO thin films for specialized technological applications. In particular, the relationship between crystal structure and electrophysical behavior remains one of the key scientific problems in thin-film semiconductor physics.

Therefore, the aim of the present study is to investigate the crystal structure and electrophysical properties of ZnO thin films grown on dielectric substrates by ion-plasma deposition and to analyze the influence of structural characteristics on electrical behavior of the obtained films.

Materials and Methods

ZnO thin films were deposited on dielectric glass substrates using the ion-plasma deposition technique under controlled laboratory conditions. Prior to deposition, the substrates were mechanically cleaned and chemically treated in order to remove surface contaminants and improve film adhesion.

The deposition process was carried out in a vacuum chamber equipped with an ion-plasma sputtering system. High-purity zinc target material was used as the source for thin-film formation. Oxygen was introduced into the working chamber during deposition to ensure formation of zinc oxide structures.

The vacuum level, plasma discharge parameters, substrate temperature, deposition time, and oxygen concentration were carefully controlled throughout the experiment. Variations of these technological parameters allowed investigation of their influence on structural and electrophysical characteristics of the obtained films.

The crystalline structure of ZnO thin films was analyzed using X-ray diffraction (XRD) techniques. Diffraction patterns were recorded to determine phase composition, crystallographic orientation, and structural quality of the deposited layers. 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;
- $\theta$is the Bragg diffraction angle.

Electrophysical properties of the films were evaluated through electrical conductivity and resistance measurements performed at room temperature. The electrical resistivity of ZnO thin films was determined according to the following relation:

$$\rho = R\frac{A}{l}$$

where:

- $\rho$is electrical resistivity;
- $R$is electrical resistance;
- $A$is the cross-sectional area;
- $l$is the distance between electrical contacts.

Surface morphology and uniformity of the films were additionally evaluated through microscopic analysis. Special attention was paid to grain distribution, surface defects, and structural homogeneity of the deposited ZnO layers.

The obtained experimental data were comparatively analyzed to determine the relationship between deposition conditions, crystal structure, and electrophysical behavior of ZnO thin films synthesized by ion-plasma technology.

Results

X-ray diffraction analysis demonstrated that the ZnO thin films deposited by the ion-plasma method possess a well-defined polycrystalline structure with dominant diffraction peaks corresponding to the hexagonal wurtzite phase. The most intensive diffraction maximum was observed along the (002) crystallographic plane, indicating preferential orientation of crystallites along the c-axis.

The obtained diffraction patterns confirmed the absence of secondary impurity phases, which indicates successful formation of stoichiometric ZnO thin films under optimized deposition conditions. Changes in plasma discharge parameters and oxygen concentration noticeably influenced peak intensity, crystallite size, and structural ordering of the films.

The calculated crystallite size varied depending on deposition conditions and generally increased with substrate temperature and deposition duration. Improved crystallinity was accompanied by reduction of structural defects and enhanced grain uniformity.

Electrophysical investigations revealed that the electrical conductivity of ZnO films strongly depended on their microstructural characteristics. Films with higher crystallinity and lower defect concentration demonstrated reduced electrical resistivity and improved charge transport properties.

The relationship between crystal structure and electrical conductivity may be explained by the influence of grain boundaries, oxygen vacancies, and intrinsic structural defects on carrier mobility. Increased crystallite size reduced scattering effects at grain interfaces and contributed to more efficient electron transport within the semiconductor layer.

Table 1. Structural and Electrophysical Parameters of ZnO Thin Films

Parameter	**Observed Characteristics**
Crystal structure	Hexagonal wurtzite
Preferred orientation	(002) plane
Structural phase purity	High
Crystallite size	Increased with temperature
Electrical resistivity	Decreased with improved crystallinity
Surface morphology	Uniform and compact

Note. *Structural and electrical parameters obtained from ZnO thin films synthesized by ion-plasma deposition.*

Electrical measurements additionally showed that oxygen concentration during deposition significantly affected carrier concentration and conductivity mechanisms. Films grown under optimized oxygen conditions exhibited more stable electrical behavior and lower resistive losses.

The obtained results indicate that ion-plasma deposition technology provides favorable conditions for controlled formation of ZnO thin films with stable structural organization and improved electrophysical properties suitable for optoelectronic and semiconductor applications.

Discussion of Crystal Growth Mechanism

Formation of ZnO thin films during ion-plasma deposition may be described through nucleation and grain growth processes occurring on the dielectric substrate surface. The crystallization process is influenced by ion energy, plasma density, oxygen availability, and substrate temperature.

The dominant hexagonal wurtzite structure observed in the study corresponds to the thermodynamically stable phase of ZnO. Enhanced orientation along the (002) plane indicates anisotropic crystal growth and reduced surface energy during film formation.

The dependence of crystallite size on deposition parameters can be associated with increased mobility of adsorbed particles on the substrate surface. Improved atomic diffusion promotes formation of larger grains and reduces structural disorder within the films.

Electrical conductivity mechanisms in ZnO thin films are largely governed by intrinsic donor defects, particularly oxygen vacancies and zinc interstitial atoms. These defects contribute to n-type conductivity and influence charge carrier concentration within the semiconductor structure.

Discussion

The results obtained in the present study confirm that ion-plasma deposition technology enables controlled formation of ZnO thin films with stable crystal structure and improved electrophysical properties. The deposited films demonstrated a polycrystalline hexagonal wurtzite structure with preferential orientation along the (002) crystallographic direction, which is considered characteristic of high-quality ZnO semiconductor layers.

The observed increase in crystallite size with variation of deposition parameters indicates that substrate temperature and plasma conditions strongly influence nucleation and crystal growth processes. Improved structural ordering contributes to reduction of grain boundary defects and enhances electrical transport within the films.

One of the important findings of the study is the close relationship between crystal structure and electrophysical behavior of ZnO thin films. Films possessing higher crystallinity and more uniform grain distribution exhibited lower electrical resistivity and improved conductivity characteristics. This behavior may be explained by reduced carrier scattering at structural defects and grain interfaces.

The dominant role of oxygen vacancies and intrinsic donor defects in formation of electrical conductivity was also confirmed. Controlled oxygen concentration during deposition significantly affected carrier concentration and electrical stability of the films. Insufficient oxygen content promoted formation of additional donor centers, whereas optimized oxygen conditions improved structural stoichiometry and electrical uniformity.

The obtained results are consistent with modern theoretical concepts describing semiconductor transport mechanisms in oxide thin films. Electrical conductivity in ZnO layers is strongly dependent on microstructural characteristics, crystallographic orientation, and defect distribution within the material.

Another important aspect of the study is the technological advantage of ion-plasma deposition compared with conventional thin-film fabrication methods. The technique provides precise control over film growth parameters, high adhesion to dielectric substrates, and formation of structurally homogeneous semiconductor coatings.

The investigated ZnO thin films demonstrate promising potential for application in optoelectronic devices, transparent conductive coatings, gas sensors, and photovoltaic systems. Their stable electrophysical behavior and structural uniformity make them suitable for integration into modern semiconductor technologies.

Despite the favorable experimental results, several limitations should be considered. Further investigations involving optical characterization, Hall-effect measurements, and temperature-dependent conductivity analysis are necessary for more detailed understanding of charge transport mechanisms in ion-plasma-grown ZnO films.

In conclusion, the present study demonstrates that ion-plasma deposition is an effective method for fabrication of ZnO thin films with controlled structural and electrophysical characteristics. Optimization of deposition conditions may further improve material performance and expand practical applications of ZnO semiconductor thin films in advanced electronic and photonic technologies.

Conclusion

The present study demonstrated that ZnO thin films deposited on dielectric substrates by the ion-plasma method possess stable crystal structure and favorable electrophysical characteristics. Structural analysis confirmed formation of a polycrystalline hexagonal wurtzite phase with preferential orientation along the (002) crystallographic plane.

It was established that deposition parameters significantly influence crystallinity, grain growth, defect concentration, and electrical behavior of the films. Improved structural ordering contributed to lower electrical resistivity and enhanced charge transport properties.

The obtained results indicate that ion-plasma deposition technology provides effective control over structural and electrophysical properties of ZnO semiconductor thin films. Optimization of oxygen concentration, plasma discharge conditions, and substrate temperature allows formation of homogeneous films with stable electrical characteristics.

The investigated ZnO thin films demonstrate promising potential for application in optoelectronic systems, photovoltaic technologies, transparent conductive coatings, and semiconductor sensor devices. Their structural stability and favorable conductivity properties make them suitable for modern electronic and photonic applications.

Further investigations involving optical characterization, carrier mobility analysis, and defect engineering may contribute to deeper understanding of physical processes occurring in ion-plasma-grown ZnO thin films and expand their technological applications.

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