# INVESTIGATION OF PHASE FORMATION PROCESSES IN $CU_2O$ THIN FILMS PREPARED BY ION-PLASMA TECHNOLOGY

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## Abstract

Copper(I) oxide ($Cu_2O$) thin films are considered promising semiconductor materials for modern optoelectronic, photovoltaic, and energy-related applications

due to their direct band gap, high absorption coefficient, low toxicity, and favorable electrical properties. The structural and phase composition of $Cu_2O$ films strongly depend on synthesis conditions and deposition technology.

The present study investigates phase formation processes in $Cu_2O$ thin films synthesized on dielectric substrates using ion-plasma deposition technology. Particular attention was devoted to the influence of deposition parameters on crystallization behavior, phase stability, microstructural evolution, and electrophysical characteristics of the obtained films.

Structural analysis revealed successful formation of polycrystalline $Cu_2O$ thin films with cubic crystal structure under optimized oxygen concentration and plasma conditions. Variations in deposition parameters significantly influenced phase composition, crystallite size, and defect concentration within the films.

The obtained results demonstrated that controlled ion-plasma deposition enables stabilization of $Cu_2O$ phases and suppression of secondary copper oxide structures. Improved structural ordering contributed to enhanced electrical properties and increased uniformity of the semiconductor layers.

The investigated $Cu_2O$ thin films exhibit promising potential for application in photovoltaic systems, optoelectronic devices, and semiconductor energy technologies.

**Keywords.** $Cu_2O$ thin films, ion-plasma deposition, phase formation, crystal structure, semiconductor materials, electrophysical properties, dielectric substrate, copper oxide semiconductors.

## Introduction

Copper(I) oxide ($Cu_2O$) is a p-type semiconductor material that has attracted significant scientific interest due to its favorable optical, structural, and electrical

properties. The material possesses a direct band gap in the visible spectral region, high optical absorption coefficient, low toxicity, and relatively simple fabrication technology, making it highly promising for photovoltaic devices, optoelectronic systems, gas sensors, and photocatalytic applications.

The physical and electrophysical properties of $Cu_2O$ thin films strongly depend on synthesis conditions, phase composition, crystal structure, and defect concentration. Control of phase formation during deposition is one of the key technological challenges in fabrication of high-quality $Cu_2O$ semiconductor layers. Depending on oxygen concentration and plasma conditions, different copper oxide phases such as $Cu_2O$ and CuO may form simultaneously, significantly influencing the functional characteristics of the films.

Among modern thin-film fabrication techniques, ion-plasma deposition technology provides substantial advantages due to precise control of deposition parameters, improved film uniformity, enhanced adhesion, and stable growth conditions. The interaction between plasma particles and the substrate surface strongly affects nucleation mechanisms, crystallization processes, and phase stability during thin-film formation.

$Cu_2O$ commonly crystallizes in a cubic crystal structure characterized by relatively high carrier mobility and favorable optoelectronic behavior. However, deviations in stoichiometric composition and oxygen deficiency may lead to formation of secondary phases, structural defects, and instability of electrical properties.

The phase formation mechanism in copper oxide thin films is highly sensitive to oxygen partial pressure, substrate temperature, plasma discharge energy, and deposition duration. Variations of these parameters influence atomic diffusion, grain growth, and oxidation kinetics during film synthesis.

Recent progress in semiconductor nanotechnology has increased interest in developing $Cu_2O$ thin films with controlled phase composition and optimized

structural properties for advanced energy applications. Stable $Cu_2O$ semiconductor layers are particularly important for low-cost photovoltaic systems and environmentally friendly optoelectronic devices.

Despite extensive investigations of copper oxide semiconductors, many aspects related to phase formation dynamics and structural stabilization in ion-plasma-deposited $Cu_2O$ films remain insufficiently understood. Detailed investigation of these processes is essential for optimization of deposition technology and improvement of material performance.

Therefore, the aim of the present study is to investigate phase formation processes in $Cu_2O$ thin films synthesized by ion-plasma technology and to evaluate the influence of deposition parameters on crystal structure and electrophysical characteristics of the obtained films.

## Materials and Methods

$Cu_2O$ thin films were synthesized on dielectric glass substrates using the ion-plasma deposition method under controlled vacuum conditions. Prior to deposition, the substrates were cleaned mechanically and chemically in order to remove surface contaminants and improve adhesion between the substrate and the deposited semiconductor layer.

High-purity copper target material was used during the deposition process. Controlled oxygen flow was introduced into the working chamber to regulate oxidation processes and stabilize formation of the $Cu_2O$ phase. The deposition procedure was performed in a plasma environment generated under controlled discharge conditions.

The main technological parameters of the deposition process, including plasma discharge power, oxygen partial pressure, substrate temperature, chamber pressure, and deposition duration, were systematically controlled during film growth.

Variations in these parameters allowed investigation of their influence on phase formation dynamics and structural evolution of $Cu_2O$ thin films.

Structural characterization of the deposited films was carried out using X-ray diffraction analysis. Diffraction patterns were recorded to determine phase composition, crystal structure, and preferential crystallographic orientation of the synthesized layers. The average crystallite size was estimated using the Scherrer equation:

$$D = \frac{K\lambda}{\beta \cos\,\theta}$$

where:

- $D$ is the average crystallite size;
- $K$ is the shape factor;
- $\lambda$ is the X-ray wavelength;
- $\beta$ is the diffraction peak broadening;
- $\theta$ is the Bragg diffraction angle.

Phase formation processes were analyzed through comparison of diffraction peak intensities and identification of characteristic $Cu_2O$ and $CuO$ reflections. Particular attention was devoted to the influence of oxygen concentration on stabilization of the $Cu_2O$ phase.

Electrical measurements were performed at room temperature to evaluate conductivity behavior and electrophysical stability of the films. Electrical resistivity was determined according to the following relation:

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

where:

- $\rho$ is electrical resistivity;
- $R$ is measured resistance;

- Ais the cross-sectional area;
- lis the distance between electrical contacts.

Surface morphology and structural homogeneity of the $Cu_2O$ thin films were additionally evaluated through microscopic analysis. Grain distribution, surface compactness, and defect formation were comparatively analyzed for films deposited under different plasma conditions.

The obtained experimental results were systematized and comparatively evaluated to determine the relationship between ion-plasma deposition parameters, phase formation mechanisms, and electrophysical properties of $Cu_2O$ semiconductor thin films.

## Results

X-ray diffraction analysis demonstrated successful formation of $Cu_2O$ thin films with a polycrystalline cubic crystal structure. The obtained diffraction patterns contained characteristic reflections corresponding to $Cu_2O$ crystallographic planes, confirming stabilization of the copper(I) oxide phase under optimized deposition conditions.

The intensity and sharpness of diffraction peaks strongly depended on oxygen concentration and plasma discharge parameters. Films synthesized under controlled oxygen partial pressure exhibited improved crystallinity and higher structural uniformity. Excess oxygen concentration promoted partial formation of secondary $CuO$ phases, whereas insufficient oxygen content resulted in structural defects and reduced phase stability.

The calculated crystallite size increased with substrate temperature and deposition duration, indicating enhanced grain growth and improved structural ordering during film formation. Increased crystallite dimensions were accompanied by reduction of structural disorder and enhanced compactness of the deposited layers.

Microstructural investigations revealed relatively homogeneous grain distribution across the substrate surface. Optimized ion-plasma conditions contributed to formation of dense semiconductor layers with reduced surface irregularities and lower defect concentration.

Electrical measurements demonstrated that electrophysical properties of $Cu_2O$ thin films were closely associated with phase composition and crystal structure. Films characterized by higher phase purity and improved crystallinity exhibited lower electrical resistivity and more stable conductivity behavior.

The obtained results indicate that stabilization of the $Cu_2O$ phase significantly influences charge transport mechanisms within the semiconductor structure. Reduced concentration of secondary phases and structural defects contributed to improved carrier mobility and enhanced electrical performance.

**Table 1. Structural and Electrophysical Characteristics of $Cu_2O$ Thin Films**

| **Parameter** | **Observed Characteristics** |
|---|---|
| Crystal structure | Cubic $Cu_2O$ |
| Structural phase purity | High under optimized conditions |
| Crystallinity | Improved with temperature |
| Crystallite size | Increased during deposition |
| Surface morphology | Homogeneous and compact |
| Secondary CuO phase formation | Observed at excess oxygen concentration |
| Electrical resistivity | Reduced in phase-pure films |

**Note.** Structural and electrical parameters obtained from $Cu_2O$ thin films synthesized by ion-plasma deposition technology.

The relationship between deposition conditions and phase stability indicates that oxygen concentration plays a decisive role in controlling oxidation kinetics during film growth. Proper regulation of plasma parameters enables stabilization of $Cu_2O$ semiconductor phases and suppression of undesired CuO structures.

The obtained experimental results confirm that ion-plasma deposition technology provides effective control over phase formation processes and enables fabrication of structurally stable $Cu_2O$ thin films suitable for semiconductor and photovoltaic applications.

**Phase Formation Mechanism**

Formation of $Cu_2O$ thin films during ion-plasma deposition involves nucleation, oxidation, and crystallization processes occurring simultaneously on the dielectric substrate surface. The phase composition of the deposited films is determined by the balance between copper oxidation kinetics and oxygen availability within the plasma environment.

Under optimized oxygen concentration, copper atoms interact with oxygen ions to form stable $Cu_2O$ semiconductor structures according to the reaction:

$$4\mathrm{Cu} + \mathrm{O_2} \rightarrow 2\mathrm{Cu_2O}$$

Excess oxygen concentration may further oxidize $Cu_2O$ and promote formation of CuO phases:

$$2\mathrm{Cu_2O} + \mathrm{O_2} \rightarrow 4\mathrm{CuO}$$

These reactions demonstrate the critical role of oxygen control during stabilization of copper oxide semiconductor phases.

**Discussion**

The results obtained in the present study demonstrate that ion-plasma deposition technology enables controlled formation of $Cu_2O$ thin films with stable crystal structure and favorable electrophysical properties. Structural investigations confirmed successful stabilization of the cubic $Cu_2O$ phase under optimized

deposition conditions and revealed strong dependence of phase formation processes on oxygen concentration and plasma parameters.

One of the most important findings of the study was the sensitivity of $Cu_2O$ phase stability to oxygen partial pressure during film growth. Proper oxygen regulation promoted formation of phase-pure $Cu_2O$ semiconductor layers, while excess oxygen concentration stimulated secondary oxidation processes leading to $CuO$ phase formation. This observation confirms the critical role of oxidation kinetics in determining structural composition of copper oxide thin films.

The improvement of crystallinity observed with increasing substrate temperature and deposition duration may be associated with enhanced atomic mobility and more efficient crystallization dynamics on the substrate surface. Larger crystallite size and reduced structural disorder contributed to better structural homogeneity and lower defect concentration within the deposited films.

The obtained results additionally demonstrated a close relationship between phase composition and electrical conductivity behavior of $Cu_2O$ thin films. Samples characterized by higher structural purity and improved crystal ordering exhibited reduced electrical resistivity and more stable carrier transport properties. This behavior may be explained by decreased carrier scattering at grain boundaries and reduced concentration of structural defects.

The presence of secondary $CuO$ phases significantly influenced electrophysical characteristics of the films. Mixed-phase structures introduced additional defect states and structural irregularities that negatively affected charge transport mechanisms. Therefore, stabilization of the pure $Cu_2O$ phase is essential for achieving optimal semiconductor performance.

The observed electrical behavior of the films corresponds to the typical characteristics of p-type copper oxide semiconductors. Intrinsic defects, including copper vacancies and oxygen-related structural imperfections, play an important

role in determining carrier concentration and conductivity mechanisms in $Cu_2O$ layers.

Another important aspect of the study is the technological effectiveness of ion-plasma deposition for fabrication of copper oxide semiconductor films. The method provides precise control over plasma conditions, oxidation processes, and structural evolution during thin-film synthesis. These advantages are highly important for development of reproducible and technologically stable semiconductor materials.

The investigated $Cu_2O$ thin films demonstrate promising potential for application in photovoltaic systems, optoelectronic devices, gas sensors, and energy conversion technologies. Their favorable structural stability and electrical characteristics make them suitable for integration into modern semiconductor and photonic systems.

Despite the positive experimental results, further investigations are necessary to achieve deeper understanding of phase transformation mechanisms and defect-related phenomena in copper oxide thin films. Additional studies involving optical spectroscopy, Hall-effect measurements, and temperature-dependent conductivity analysis may provide more detailed information regarding carrier dynamics and semiconductor behavior of ion-plasma-grown $Cu_2O$ structures.

In conclusion, the present study confirms that optimization of ion-plasma deposition parameters plays a decisive role in controlling phase formation, crystal structure, and electrophysical properties of $Cu_2O$ thin films. Improved understanding of these processes may contribute to further advancement of copper oxide semiconductor technologies and expansion of their practical applications in renewable energy and electronic systems.

## Conclusion

The present study demonstrated that $Cu_2O$ thin films synthesized on dielectric substrates by ion-plasma deposition possess stable structural organization and favorable electrophysical properties. X-ray diffraction analysis confirmed formation of the cubic $Cu_2O$ semiconductor phase under optimized oxygen concentration and plasma discharge conditions.

It was established that deposition parameters strongly influence phase formation processes, crystallinity, grain growth, and electrical behavior of the films. Proper control of oxygen partial pressure enabled stabilization of the $Cu_2O$ phase and suppression of secondary CuO structures.

The obtained results revealed that improved crystal ordering and reduced structural defects contribute to lower electrical resistivity and enhanced charge transport mechanisms within the semiconductor layers. Structural homogeneity and phase purity were found to be essential factors determining electrophysical stability of the deposited films.

The investigated $Cu_2O$ thin films demonstrate promising potential for application in photovoltaic systems, optoelectronic devices, semiconductor sensors, and renewable energy technologies. Their favorable structural and electrical characteristics make them suitable for modern thin-film semiconductor applications.

Further investigations involving optical characterization, Hall-effect measurements, and detailed analysis of defect states may contribute to deeper understanding of charge carrier dynamics and phase stabilization mechanisms in $Cu_2O$ semiconductor structures synthesized by ion-plasma technology.

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