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Enhancing scattering strength improvement and color uniformity in white light-emitting diodes using high concentration of cobalt(II) oxide

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ABSTRACT

The study herein investigates the structural development of cobalt(II) oxide (CoO) thin films grown on Ag (0 0 1) substrates and evaluates their impact on optical performance in white light-emitting diodes (WLEDs). The structural and chemical properties of CoO films were characterized using grazing-incidence X-ray diffraction (GIXD), Xray photoelectronic spectroscopic (XPS), as well as low-power electronic diffracting (LEED). The outcomes reveal that CoO films initially grow pseudomorphically up to 3-4 monolayers, followed by gradual relaxation toward the bulk lattice parameter. A periodic mismatch dislocation network forms at approximately 8 monolayers, leading to lattice tilting and the formation of ordered nanoscale domains. In addition, the incorporation of CoO as a scattering material in WLEDs significantly improves light scattering and color uniformity, while maintaining stable luminous performance. Compared with conventional scattering materials, CoO demonstrates lower scattering loss and reduced chromatic deviation, making it a promising candidate for high-precision optoelectronic applications.

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1. INTRODUCTION

Magnetic nano-forms with organized distributions offer intriguing capabilities for preservation, read/write heads, and randomized memories [1], [2]. Currently, lithography has been used mostly to manufacture elements for electrical gadgets, but the continual downsizing of these elements makes manufacturing more costly. Bottom-up methods provide a novel perspective on this issue. The core concept is to use atoms' self-organization into an aggregation of a specified geometric form to achieve the required formations [3]. Thin sheets have been used to create controlled dispersion of nanostructures by generating thin deposits over nano-structured platforms. The most common instance is self-assembled transition metal nanostripes and nanowires formed on the vicinal outermost layers of noble metals [4]-[6]. In recent years, a novel approach for controlling overlayer nucleation has been identified. Throughout heteroepitaxial development, the upper sheet emits stress, resulting in 'defects' with an organized spatial dispersion. The uneven foundation influences the nucleus formation of each subsequent deposit over the nano-structured floors, leading to a structured system of nano-aggregates. Therefore, mismatch lattice defect systems [7] and Moiré structures [8]-[11] of an upper sheet have been effectively used to create the sequential development process for organized systems of nanoparticles. In this paper, we conduct a thorough examination of cobalt(II) oxide (CoO) thin sheets' formation on the (0 0 1) outermost layer of Ag. The CoO/Ag(0 0 1) setting's structural, morphological, and chemical characteristics were determined using grazing-incidence X-ray diffraction (GIXD), X-ray photoelectron spectroscopy (XPS), and low-energy electron diffraction (LEED) [12], [13]. In addition to structural characterization, this study investigates the optical performance of CoO as a scattering material in white light-emitting diode (WLED) systems. Compared with conventional materials such as SiO2, TiO2, and ZnO, CoO exhibits lower scattering coefficients and improved angular color uniformity. This work provides a combined analysis of nanoscale structural evolution and optical performance, which has not been extensively reported in previous studies. The findings demonstrate that CoO is a promising candidate for enhancing color uniformity and luminous efficiency in advanced optoelectronic devices [14]-[16].

2. EXPERIMENTAL

The GIXD test was conducted at the European Synchrotron Radiation Facility's BM 32 beamline, whereas the XPS and LEED characterization experiments took place at the SESAMO Laboratory [17]. The BM 32 beamline's "multi-method" diffractometer [18] measures X-ray diffraction structures in situ using a 360° opening beryllium window. The setting for the experiment is designed to quantify X-ray diffraction during overlayer development and the specimen anneal process. The SESAMO Laboratory [19], [20] has a research platform designed for the investigation of outermost layers and thin sheets. UHV transfer equipment connects one MBE room featuring 5 Knudsen cells to STM equipment and the main laboratory, where we do structure research using LEED, XPD, and PDMEE, as well as chemical investigation with UPS, XPS, and Auger. The specimen was one Ag(0 0 1) crystalline granule that had been cleansed with repeated Ar+ blasting and an annealing process at 700 K. CoO sheets were created by an evaporation process of Co onto an uncontaminated Ag outermost layer under oxygen pressure reaching 1×10-7 Torr. The vaporizing process under this pressure proves paramount, as it ensures the stability of CoO particles. A quartz crystal oscillator measured the evaporating speed, while XPS and reflectance studies confirmed the ultimate CoO thickness. The base heat was maintained at 460 K throughout the CoO development process. Following CoO development, the specimen underwent annealing for 20 minutes at 670 K. Each of the specimens were produced and analyzed under UHV conditions [21], [22].

3. RESULTS AND DISCUSSION

3.1. Formational assessment for CoO sheets

Tests using graze-incidental Xray diffraction (GIXD) were conducted to investigate the structural evolution in CoO thin films grown on Ag(001). The in-plane lattice parameter was used as a key indicator to evaluate the strain state of the film as a function of thickness. The results reveal that CoO initially grows pseudomorphically up to approximately 3–4 monolayers (ML), indicating that the film adopts the lattice structure of the Ag substrate in the early growth stage. As the thickness increases, the CoO film gradually relaxes toward its bulk lattice parameter, reaching approximately 2.98 Å at 23 ML. This transition from pseudomorphic growth to relaxed structure reflects the progressive release of strain accumulated at the interface. The deviation from linear lattice evolution suggests that the relaxation process is not abrupt but occurs through intermediate structural rearrangements.

Further evidence of strain relaxation is observed through the appearance of satellite peaks in GIXD scans. These features indicate the formation of a periodic mismatch dislocation network at the CoO/Ag interface. The average spacing between dislocations is estimated to be approximately 9.2 nm, which is consistent with previously reported values for similar heteroepitaxial systems [23]. The presence of such a periodic dislocation network proves crucial for accommodating lattice mismatch as well as fixating the film structure. X-ray photoelectron spectroscopy (XPS) tests verify the creation of stoichiometric CoO. The Co $2p_{3/2}$ peak observed at approximately 780 eV, together with its characteristic satellite features, agrees well with previously reported spectra for CoO thin films [24]. This confirms that the growth conditions employed in this study are suitable for producing chemically stable CoO layers.

Additionally, low-energy electron diffraction (LEED) patterns show the emergence of satellite spots at film thicknesses greater than 8 ML. These features indicate the development of periodic structural modulation associated with lattice relaxation. The observed diffraction patterns suggest the formation of mosaic-like domains with slight lattice tilting, which are distributed in an ordered manner across the film surface. The formation of these nanoscale domains is particularly important, as it directly influences the optical behavior of the material. The periodic arrangement of tilted domains can enhance light scattering and contribute to improved optical uniformity. Therefore, the structural evolution of CoO films is not only relevant from a fundamental perspective but also proves crucial when it comes to determining their proficiency in optoelectronic settings.

3.2. Thermal stability of CoO

CoO has strong thermic consistency, featuring a liquifying threshold reaching approximately 1933 °C, making it suitable for high-temperature optoelectronic applications. This property is particularly important in white light-emitting diode (WLED) systems, where prolonged operation can lead to thermal degradation of optical materials and reduced device performance. The strong electron–phonon interactions in CoO contribute to stable thermal behavior and efficient heat dissipation. These interactions help maintain the structural integrity of CoO under elevated temperatures, preventing significant changes in optical properties during operation. As a result, CoO-based phosphor layers can sustain consistent luminous output and spectral characteristics over extended periods. In addition, the thermal robustness of CoO plays a crucial role in preserving color stability in WLED systems. Temperature-induced variations in emission spectra are minimized, leading to more stable correlated color temperature (CCT) and reduced chromatic deviation. This stability is essential for applications requiring long-term reliability and consistent lighting quality. Overall, the high thermal stability of CoO enhances device durability and ensures reliable optical performance under practical operating conditions. This characteristic further supports its suitability as a functional material in advanced WLED applications [25].

3.3. Emission characteristics of CoO

CoO exhibits characteristic optical absorption and emission properties that are highly relevant to optoelectronic applications. The emission behavior of CoO originates from electronic transitions within Co^{2+} ions, particularly d–d transitions altered via the crystalline field surrounding them within the oxide lattice. These transitions are sensitive to local coordination and bonding conditions, which directly affect the optical response of the material. In nanostructured or thin-film forms, these optical properties can be further modified by defect states, surface effects, and structural disorder. Defect-related states introduce additional energy levels within the band structure, contributing to broadband emission and influencing the spectral distribution of emitted light. Such effects are especially important in WLED systems, where spectral balance directly determines correlated color temperature (CCT) as well as color rendering index (CRI).

Furthermore, structural features such as nanoscale domains and lattice distortions can alter the local electronic environment and enhance emission variability. This interaction between structural and electronic properties highlights the importance of controlling film growth conditions to optimize optical performance. X-ray photoelectron spectroscopy (XPS) analysis reveals complex multiplet splitting in the Co 2p region, indicating the presence of multiple electronic states and oxidation environments. These features provide insight into the local electronic structure and confirm the role of CoO in modifying optical behavior. Variations in oxygen coordination and defect density further contribute to emission tuning. Overall, the emission characteristics of CoO are governed by both intrinsic electronic transitions and extrinsic structural effects. This dual contribution enables CoO to function not only as a scattering material but also as a spectral-modifying component, making it highly suitable for improving optical performance in WLED systems. These emission-related properties provide a strong foundation for the optical performance enhancements discussed in the following section.

3.4. Optical performance in WLED applications

When incorporated into white light-emitting diode (WLED) systems, CoO can influence various optical properties of the device. In particular, CoO can enhance optical performance when used in phosphor layers or encapsulation materials, especially under appropriate LED driving conditions. Nanostructured CoO improves light scattering due to its relatively high refractive index and tunable morphology. This enhanced scattering leads to better angular color uniformity and improved luminous efficiency, which are essential for WLED systems requiring homogeneous color mixing. The optical behavior of CoO can also be influenced by defect states and d–d electronic transitions within the visible range, which affect the CCT as well as CRI. Previous studies have reported that an optimal CoO concentration of approximately 10 wt.% can improve both brightness and color uniformity, which matches the outcomes from the research herein. In addition, CoO exhibits high thermal stability, allowing it to maintain optical performance under prolonged operating conditions. This property is important for WLED systems, where thermal effects can degrade emission quality over time. As a result, CoO-based phosphor layers contribute to improved durability and more stable optical output. Previous studies using synchrotron radiation and X-ray diffraction techniques have also demonstrated that CoO nanostructures enhance light scattering and spectral tuning in LED encapsulation systems. Furthermore, CoO-integrated materials exhibit enhanced optical absorption and photoluminescence, indicating their potential for advanced LED applications.

Figure 1 shows the connection among illumination scattering and CoO granule size (6–10 μm). Increasing CoO concentration improves light transmission and wavelength conversion efficiency. In addition, forward emission can be enhanced by reducing backscattering and reabsorption effects. Figure 2 reveals the variation in YAG: Ce phosphor dosage as a function of CoO content, where a slight reduction is observed as CoO concentration increases from 6 to 10 wt.%.

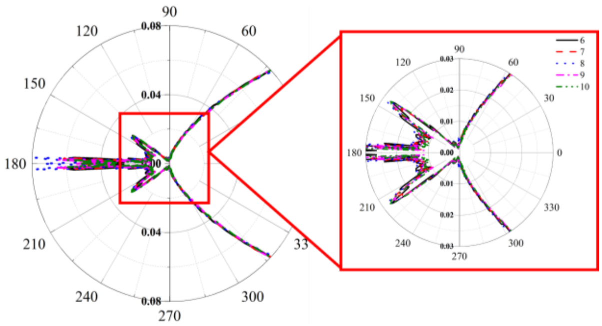

Figure 1. Scattering coefficients subject to disparate wavelength levels

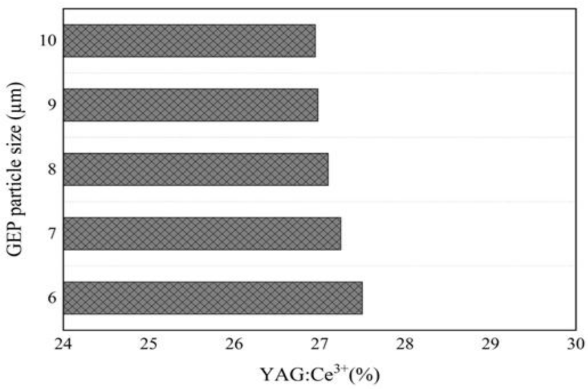

Figure 2. YGA:Ce presence under different CoO levels

According to Figures 3 and 4, the CCT value does not rely on dosage. Figure 3 illustrates how a phosphor's CCT variance is reduced by higher doping. CCT assessment exhibits a low under around 2975 K with a CoO concentration reaching 6 wt.% and a high at approximately 3050 K with a CoO level reaching 9 wt.%. Judging by Figure 4, the D-CCT ultimately drops to the nadir level at about 47 K with 7 wt.% CoO, being about 42 K below the highest level of about 89 K at 9 wt.% CoO.

According to Figure 5, CoO does not significantly increase the brightness for white illumination emissions. A CoO concentration of 10 wt.% produced the greatest result (~73.90 lm), whereas a concentration of 6 wt.% produced the lowest result (~71.49 lm). Lessened blue discharge as well as an irregular color allocation result from increased backscattering and reabsorption. As the concentration of CoO increases, the phosphor turns from blue into yellow or orange-red if exposed to additional backscattered blue illumination. Only up to a certain concentration of CoO may the phosphor coating be prolonged. A shorter emission spectrum would arise from the many reflections caused by the changing light from different objects. Put another way, a high dosage of phosphor may cause a higher percentage of converted light to be reflected back, increasing CCT while lowering luminous strength. Figure 5 shows how brightness and color uniformity are improved by adding 10 wt.% CoO into a recreated WLED featuring a lumen energy of about 73 lm. Figures 6 and 7 exhibit the effects of varying CoO concentrations on white LED brightness as well as hue rendering. Use the CRI and CQS to experiment with color rendition proportions between 6 and 10 wt.%. CoO concentration increased somewhat (from 55.95% to 56.16% under CRI level) as well as slightly (roughly 40.74-42.70% under CQS level). The erratic nature of blue and green, along with yellow-orange, might result in CRI and CQS decreases. Increased dispersion, the leaning towards the yellow-orange spectrum, as well as irregular light emission are all results of high CoO levels. We will modify this phosphor's CRI and CQS as we assess the outcomes, accounting for other elements such as particle size.

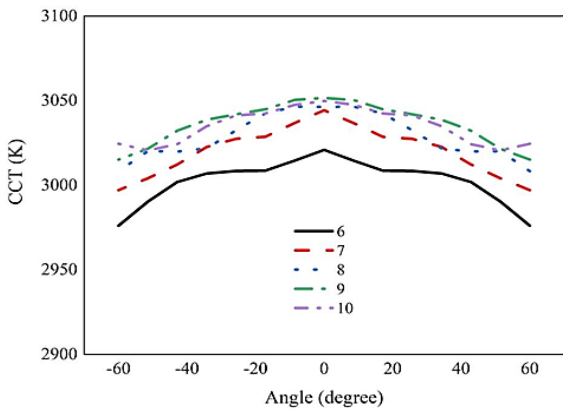

Figure 3. CCT under different CoO levels

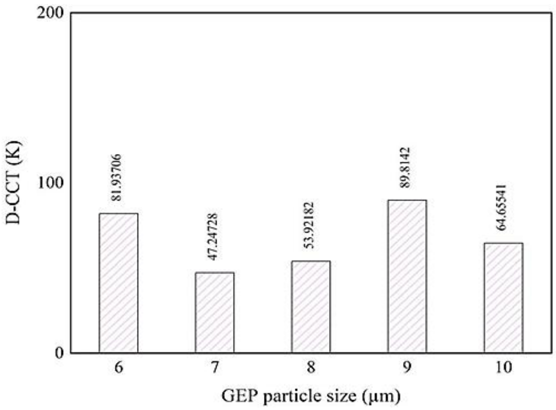

Figure 4. Chroma disparity under various CoO levels

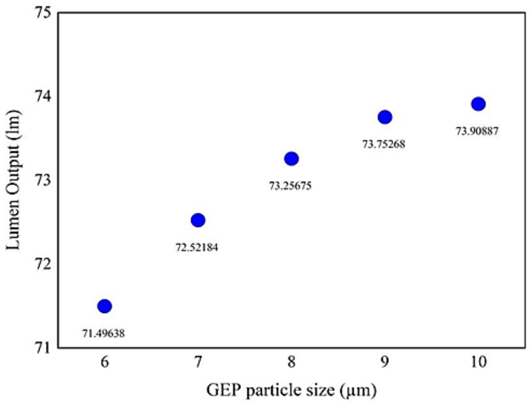

Figure 5. Luminescence strength under different CoO levels

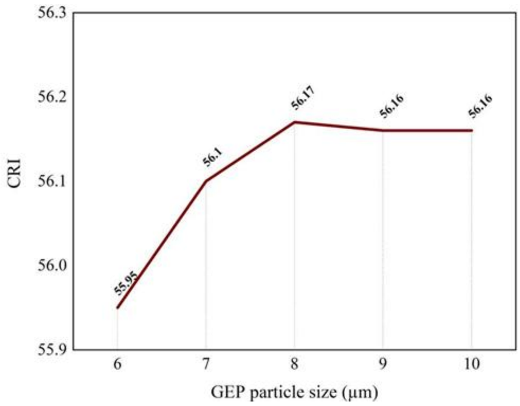

Figure 6. CRI under different CoO levels

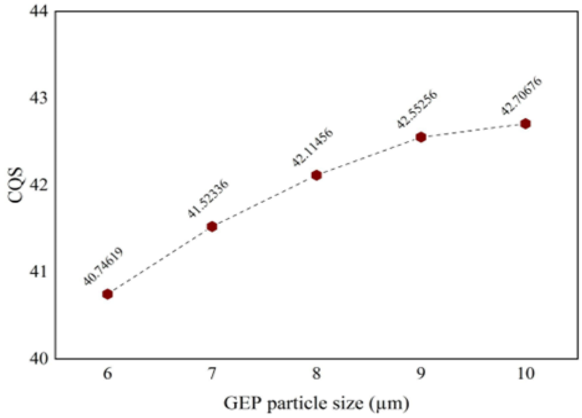

Figure 7. CQS under different CoO levels

Based on the results above, CoO complies with the ICE 62717 standard in terms of LED performance. CoO is capable of augmenting illumination dispersion as well as lumen efficiency when employed within phosphor sheets. The capacity of CoO to adjust emission spectra assists in attaining greater CRI, particularly within white LED apparatuses. Nanoscopic CoO augments angular color homogeneity via dispersing illumination more uniformly. The significant thermal stability of CoO facilitates prolonged optical performance when subject to higher heat levels. CoO's low susceptibility to optical degradation assists in sustaining brightness as time passes.

Regarding the IES TM-30 standard, CoO assists in adjusting emission spectra to be more consistent with reference chromas, boosting fidelity. Through augmenting dispersion as well as spectrum balance, CoO can boost saturation while avoiding distortion. CoO nanoscopic formations encourage homogeneous illumination blending, lessening chroma shifts across angles. CoO sustains spectral performance when subject to heat, facilitating prolonged adherence to IES TM-30.

Regarding the ANSI C78.377 standard, CoO is able to attune emission spectra within phosphor-transmuted LED apparatuses to be more consistent with CCT bins. Nanoscopic CoO augmented illumination dispersion, boosting angular chroma homogeneity. CoO sustains spectrum output when subject to heat, facilitating prolonged chroma stability. Its d-d shifts as well as fault statuses enable spectrum formation for fitting ANSI quadrangles.

Additionally, the optical attributes of the research herein are compared to those of previous works, and the comparison is shown via Tables 1 and 2, between CoO and four other dispersion-augmenting substances (SiO_2, TiO_2, ZnO, $CaCO_3$, and MgO). The research herein is one of the few works that address the applicability of CoO to LED apparatuses when it comes to dispersion capability. Compared to its predecessors, CoO generates noticeably lower scattering coefficients. By generating comparatively less hue aberration than some of its rivals, it also improves color accuracy. One of CoO's own disadvantages is that its CRI and CQS are lower than those of its rivals, suggesting a lower level of color rendition. Solar panels, optical fibers, lenses, and lasers are examples of high-precision optoelectronic devices that can employ CoO despite the aforementioned disadvantages [21], [22].

Table 1. Scattering coefficient outcomes influenced by granule sizes for scattering substances

Scattering Substances	Scattering coefficients (mm^{-1})	Reduced scattering coefficients (mm^{-1})	References
CoO	0.837	0.137	The study herein
KBr	42.5	13.5	[12]
SiO_2	9.16	0.78	[21]

Table 2. Comparison of outcomes from the study herein to earlier studies

Scattering Substances	YAG:Ce^{3+} (%)	CCT (K)	D-CCT (K)	CRI	CQS	Lumen (lm)	References
CoO	27.5	3000	47.25	56.17	55.95	55.95	The study herein
KBr	27.4	3000	35.4	56.2	42.4	42.4	[12]
SiO_2	27.4	3000	30	56.3	42.5	73.7	[21]

4. CONCLUSION

This study investigated the structural evolution of CoO thin films grown on Ag(0 0 1) and their application as scattering materials in white light-emitting diode (WLED) systems. The results show that CoO films initially grow pseudomorphically, followed by strain relaxation through the formation of a periodic mismatch dislocation network. This structural evolution results in ordered nanoscale domains, playing a crucial role in modifying optical behavior. When applied to WLED systems, CoO significantly enhances light scattering and improves angular color uniformity while maintaining stable luminous performance. An optimal concentration range was identified in which chromatic deviation is minimized, and luminous efficiency is improved without introducing significant optical losses. Compared with conventional scattering materials, CoO demonstrates lower chromatic deviation and more stable optical characteristics. These findings emphasize the ability of CoO as a proficient material capable of augmenting color uniformity as well as performance in advanced optoelectronic and lighting applications.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

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Phan Xuan Le	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	✓
Nguyen Doan Quoc Anh	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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