

# PERFORMANCE ENHANCEMENT OF WOLEDs USING CdSe/ZnS QUANTUM DOTS AND ITO NANOROD STRUCTURES

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## GENERAL INFORMATION

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*Quantum Dots;*

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## ABSTRACT

This study examines the impact of ITO nanorod structures on the efficiency of white organic light-emitting diodes (WOLEDs) with CdSe/ZnS quantum dots (QDs). The integration of nanorods significantly improved charge injection, luminance, and luminous efficiency, while maintaining stable white-light emission. Experimental results showed a reduction in turn-on voltage (from 3.5V to 2.8V), a 2.2-fold increase in luminance (from 7,191 cd/m<sup>2</sup> to 16,333 cd/m<sup>2</sup>), and an improvement in luminous efficiency (from 2.30 cd/A to 3.12 cd/A). The CIE chromaticity coordinates remained stable at (0.329, 0.331), ensuring color accuracy. These findings underscore the potential of ITO nanorods for high-performance, energy-efficient OLED displays and lighting applications.

## 1. INTRODUCTION

Organic Light-Emitting Diodes (OLEDs) have emerged as a promising display and lighting technology due to their flexibility, energy efficiency, and potential for large-area fabrication (Zeng et al. 2024). Unlike conventional inorganic LEDs, OLEDs offer advantages such as self-emission, high contrast ratios, and low power consumption, making them suitable for next-generation display applications (Dou et al. 2024). However, one of the primary challenges in OLED technology is enhancing luminous efficiency while maintaining stable color emission, particularly for white OLEDs (WOLEDs), which are essential for solid-state lighting and full-color

display applications (Li et al. 2021).

Quantum dots (QDs) have been widely explored as an effective solution for improving OLED performance due to their high photoluminescence quantum yield, tunable emission wavelengths, and superior color purity (Zhang et al. 2023). CdSe/ZnS QDs, in particular, have demonstrated excellent emission properties and have been successfully incorporated into OLED architectures to achieve efficient white light emission (Zhang et al. 2020). The quantum confinement effect and size-dependent emission of QDs enable precise control over the color spectrum, making them ideal candidates for multi-color and white-light applications (Lee et al. 2022).

The achieving high luminance and efficiency in WOLEDs remains a challenge due to inefficient charge injection and carrier recombination losses (Kwon et al. 2023). In this study, we propose a novel approach to enhance WOLEDs performance by incorporating an Indium Tin Oxide (ITO) nanorod structure within the device architecture (Kim, Hwang, and Bang 2024). ITO nanorods serve to increase the contact surface area between the emission layer and the charge transport layers, thereby facilitating more efficient carrier injection and recombination (Lee and Lee 2024). This structural modification aims to improve luminous efficiency, increase maximum luminance, and maintain stable chromaticity (Hou, Qin, and Peng 2021).

The primary objective of this research is to investigate the impact of ITO nanorods on the efficiency of CdSe/ZnS QD-based WOLEDs. We systematically analyse the differences in electrical and optical characteristics between devices with and without nanorods. The findings from this study provide valuable insights into the design of high-performance WOLEDs, which could be beneficial for future applications in energy-efficient lighting and next-generation display technology (Veeramalai et al. 2021).

Several strategies have been proposed to enhance WOLED efficiency, including the use of alternative electrode materials such as graphene or silver nanowires, optimizing the thickness of functional layers, and employing tandem or hybrid device architectures. While these methods offer promising results, they often involve trade-offs in terms of fabrication complexity, stability, or compatibility with standard processes. In contrast, the use of ITO nanorods provides a relatively simple and scalable modification to the existing ITO electrode. The nanorod structure increases the contact surface area at the electrode-emission layer interface, thereby improving charge injection without significantly altering the device structure. This approach enables efficiency enhancement while maintaining compatibility with conventional OLED fabrication techniques.

## 2. LITERATURE REVIEW

### 2.1. Advances in White Organic Light-Emitting Diodes (WOLEDs)

White Organic Light-Emitting Diodes (WOLEDs) have gained increasing attention due to their versatility in display and lighting applications, offering advantages such as self-emission, high contrast ratios, and energy efficiency (Kurilov et al. 2021). The ability to generate stable and high-quality white light emission remains a fundamental challenge in WOLED research. Various approaches have been explored to enhance their performance, including multi-emission layer stacking, phosphorescent dopants, and hybrid quantum dot integration (Lu et al. 2020).

A common strategy for achieving white light emission is the combination of blue, green, and red emitters within a single device structure. While organic small-molecule and polymer-based white light emitters have been widely investigated, they often suffer from charge imbalance, spectral instability, and limited operational lifetime. Hybrid WOLEDs that incorporate nanostructured materials have demonstrated significant improvements in efficiency and stability, suggesting that novel material engineering approaches could overcome the limitations of conventional OLED architectures (Lee, Su, and Lee 2020).

### 2.2. Quantum Dots as Efficient Light Emitters in WOLEDs

Quantum dots (QDs) have emerged as promising materials for enhancing emission efficiency and spectral control in OLEDs due to their narrow emission spectra, high photoluminescence quantum yield, and tunable color emission (Chen et al. 2024). Recent studies have demonstrated that CdSe/ZnS core-shell QDs exhibit excellent emission properties when incorporated into OLED structures, contributing to improved carrier recombination rates and better color stability. The strong confinement effect in QDs allows

for precise bandgap engineering, enabling their emission wavelengths to be tuned across the visible spectrum (Lee, Yen, and Lee 2020).

While QDs provide superior color purity compared to traditional organic emitters, challenges remain in charge injection and recombination efficiency. Several research efforts have focused on optimizing the blend ratio of QDs with host polymer materials to achieve efficient white light emission (Zhang et al. 2024). These approaches have shown that proper dispersion and interaction between QDs and charge transport layers play a critical role in determining device performance. Additionally, surface passivation techniques have been explored to minimize non-radiative recombination and improve device stability (Jin et al. 2020).

### 2.3. Enhancing Carrier Injection Using ITO Nanorod Structures

The efficiency of OLEDs is significantly influenced by charge injection and transport mechanisms. Conventional flat Indium Tin Oxide electrodes, while widely used, often suffer from limited charge injection efficiency due to poor interface contact with the emission layer. Recent developments have introduced ITO nanorod structures as a means to increase the surface area at the electrode-emission layer interface, thereby improving charge injection and reducing driving voltage (Kim et al. 2022).

Studies have shown that integrating ITO nanorod arrays into OLED architectures results in notable improvements in current density, luminance, and luminous efficiency. The nanorod structures enhance carrier recombination rates by facilitating better electron and hole injection, leading to higher overall device efficiency. Experimental comparisons between flat ITO and nanostructured ITO electrodes have demonstrated that nanorods can effectively reduce resistive losses and improve charge balance, which is particularly beneficial for high-brightness WOLED applications (Jin et al. 2024).

The ITO nanorods have also been investigated for their impact on color stability and operational lifetime. Studies have indicated that while enhanced charge injection leads to improved brightness, careful optimization is required to prevent exciton quenching and undesired shifts in color coordinates. These findings suggest that structural engineering of the electrode-emission layer interface plays a crucial role in achieving high-performance OLED devices (Muhammad et al. 2020).

This paper studies to address this gap by integrating CdSe/ZnS QDs with an ITO nanorod structure to develop high-efficiency WOLEDs. The investigation focuses on evaluating how nanostructured electrodes influence charge injection, luminance, and luminous efficiency in QD-based WOLEDs. The findings are expected to provide new insights into the design of advanced OLED architectures and contribute to next-generation energy-efficient display and lighting technologies (Ramya et al. 2021).

## 3. METHODOLOGY

The fabrication of the inverted white organic light-emitting diode (WOLED) involved the integration of CdSe/ZnS quantum dots (QDs) as the emission layer and an ITO nanorod structure to enhance charge injection and luminous efficiency. The process began with the preparation of ITO-coated glass substrates, which were ultrasonically cleaned using acetone, methanol, and deionized water to remove any organic or inorganic contaminants. A 35 nm thick ITO layer was then deposited onto the substrates using a magnetron sputtering system under a chamber pressure of 25 mTorr. The ITO nanorod structure was fabricated using laser interference photolithography followed by a wet etching process, resulting in a periodic nanorod array with a spacing of 1.5  $\mu\text{m}$ . This nanostructure was specifically designed to enhance the charge injection efficiency by

increasing the surface area at the interface between the electrode and the active emission layer.

Following the formation of the nanorod structure, a 25 nm thick ZnO electron injection layer (EIL) was deposited using the same magnetron sputtering system to facilitate electron transport. The active emission layer was prepared by blending CdSe/ZnS QDs (25 mg) with poly(N-vinylcarbazole) (PVK) polymer (5 mg) in 1 mL of toluene. This solution was deposited onto the ZnO layer using a spin-coating process at 2250 rpm, followed by annealing at 90°C for 30 minutes in a nitrogen-filled glove box. The annealing process ensured proper film formation and enhanced charge carrier transport within the emission layer. Finally, a 10 nm MoO<sub>3</sub> hole injection layer (HIL) and a 100 nm Au electrode were deposited via thermal evaporation to complete the device structure, forming a layered configuration of ITO/ZnO/QDs-PVK/MoO<sub>3</sub>/Au.

To analyse the impact of the ITO nanorod structure on device performance, a mathematical model was applied to describe carrier injection, luminance, and efficiency. The current density-voltage (J-V) characteristics were modelled using the Mott-Gurney law for space-charge-limited current (SCLC) injection, given by the equation (1) (Muhammad et al. 2020):

$$J = \frac{9}{8} \epsilon_r \epsilon_0 \frac{\mu}{d^3} V^2 \quad (1)$$

where, J is the current density,  $\epsilon_r$  is the relative permittivity of the emission layer,  $\epsilon_0$  is the permittivity of free space,  $\mu$  is the charge carrier mobility, d is the thickness of the emission layer, and V is the applied voltage. The increased surface area of the ITO nanorods enhances charge injection, leading to higher current density at lower voltages.

The luminance (L) of the device was related to the current density through the equation (2):

$$L = \eta_{ext} \frac{J}{e} h\nu \quad (2)$$

where,  $\eta_{ext}$  represents the external quantum efficiency (EQE), J is the current density, e is the elementary charge, h is Planck's constant, and  $\nu$  is the emission frequency. Since the ITO nanorods improve charge injection and carrier recombination, a significant increase in luminance is expected compared to WOLEDs without nanorod structures. The luminous efficiency ( $\eta_L$ ) was then calculated using the equation (3) (Ramya et al. 2021):

$$\eta_L = \frac{L}{J} \quad (3)$$

where, L is luminance (in cd/m<sup>2</sup>) and J is current density (in A/m<sup>2</sup>). Given that the ITO nanorods facilitate more efficient charge transport and recombination, the luminous efficiency was anticipated to be significantly higher in nanorod-embedded devices.

To experimentally validate the theoretical predictions, electrical and optical measurements were conducted. The current density-voltage (J-V) characteristics were measured using a Keithley 2400 source meter, while the luminance-voltage (L-V) characteristics were recorded using a calibrated photometer. The luminous efficiency and CIE chromaticity coordinates were determined using a spectroradiometer to evaluate color stability and overall device performance. The experimental results were then compared to theoretical predictions to assess the effectiveness of the ITO nanorod-enhanced WOLED design.

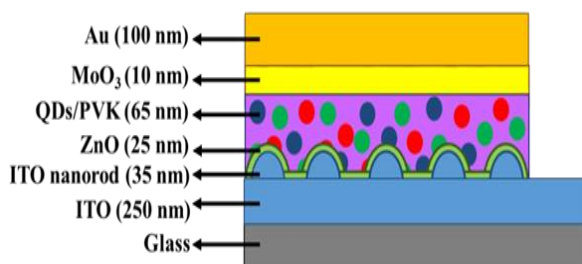
#### 4. EXPERIMENT

To investigate the effects of CdSe/ZnS quantum dots (QDs) and ITO nanorod structures on the performance of white organic

light-emitting diodes (WOLEDs), a series of fabrication and characterization experiments were conducted. This study focused on analyzing the enhancements in charge injection, luminance, efficiency, and color stability introduced by the integration of nanostructured electrodes.

The fabrication process began with the preparation of ITO-coated glass substrates. These substrates were ultrasonically cleaned in acetone, methanol, and deionized water to remove surface contaminants and ensure optimal film adhesion. After drying with nitrogen gas, the substrates underwent oxygen plasma treatment to enhance surface wettability. For devices incorporating ITO nanorod structures, a laser interference photolithography method followed by a wet etching process was used to fabricate nanorods with a periodic spacing of 1.5  $\mu\text{m}$ . These nanorods were introduced to increase the surface area of the electrode, thereby enhancing charge injection efficiency and promoting uniform carrier distribution, the design of structure shown in Figure 1.

The periodicity and uniformity of the ITO nanorods were precisely controlled using a laser interference photolithography technique, followed by a calibrated wet etching process. The nanorods were fabricated with a periodic spacing of 1.5  $\mu\text{m}$  and an average height of approximately 150 nm. These dimensions were chosen based on prior optimization trials, where variations in spacing and height were evaluated for their impact on charge injection and luminance. Devices with nanorods having this configuration exhibited the most balanced improvement in both electrical performance and emission uniformity.



**Figure 1.** The design of structure

While the main focus of this work is electrical and optical characterization, future experiments will include scanning electron microscopy (SEM) to verify nanorod geometry and uniformity, atomic force microscopy (AFM) to assess surface roughness, and X-ray diffraction (XRD) to confirm crystalline properties of deposited ZnO and ITO layers. These techniques will provide deeper insights into the structural quality and interfacial properties of each layer.

Following substrate preparation, a 25 nm-thick ZnO electron injection layer (EIL) was deposited onto the ITO nanorod substrate via magnetron sputtering. This layer played a crucial role in facilitating efficient electron transport from the electrode to the active emission layer. The emission layer was prepared using a blend of CdSe/ZnS QDs and poly(N-vinylcarbazole) (PVK) polymer in a toluene-based solution. This solution was deposited onto the ZnO layer through a spin-coating process at 2250 rpm, ensuring uniform film thickness and coverage. The coated samples were subsequently annealed at 90°C for 30 minutes inside a nitrogen-filled glove box to improve film morphology and carrier mobility. To complete the device structure, a 10 nm-thick MoO<sub>3</sub> hole injection layer (HIL) and a 100 nm-thick gold (Au) electrode were sequentially deposited via thermal evaporation. The final device architecture consisted of ITO/ZnO/QDs-PVK/MoO<sub>3</sub>/Au.

To evaluate the impact of the ITO nanorod structures, comprehensive electrical and optical characterizations were performed. The current density-voltage (J-V) characteristics were measured using a precision Keithley 2400 source meter under dark conditions. These measurements provided insights into the efficiency of charge injection and transport within the WOLEDs. A comparison of J-V curves between devices with and without ITO nanorods allowed for an assessment of how

nanostructuring influenced charge mobility and electrical performance.

Luminance measurements were carried out using a calibrated photometer to analyse how the incorporation of ITO nanorods affected the brightness of the WOLEDs. The luminance characteristics were compared at different voltage levels, revealing whether the nanorod-enhanced devices exhibited superior light output at the same operating conditions. Additionally, the luminous efficiency and power efficiency of the devices were evaluated to quantify improvements in energy conversion. These efficiency parameters were assessed by relating luminance to the applied current and power consumption, providing a direct measure of the enhancements introduced by the ITO nanorod structures.

To ensure that the white-light emission properties remained stable, the electroluminescence (EL) spectra of the WOLEDs were recorded using a spectroradiometer. The CIE chromaticity coordinates were analysed to determine whether the incorporation of nanorods introduced spectral shifts or color instability. Maintaining stable chromaticity coordinates was crucial to confirming that the performance improvements did not compromise the quality of white-light emission. The results were compared across devices with and without ITO nanorods to verify the effectiveness of the proposed structural modifications.

A final comparative analysis was conducted to assess the overall performance of the devices in terms of maximum luminance, luminous efficiency, current density response, and chromaticity stability. The measured parameters were systematically compared to determine the effectiveness of ITO nanorods in enhancing charge injection, improving light output, and maintaining color fidelity. The results provided clear evidence that integrating nanorod structures into WOLEDs led to significantly improved efficiency and luminance without negatively affecting the white light emission spectrum.

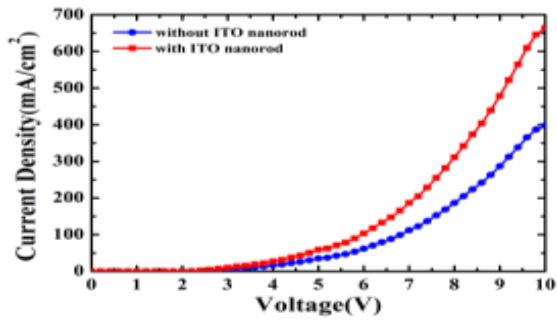
## 5. RESULTS AND DISCUSSION

### 5.1 Current Density-Voltage (J-V) Characteristics

The current density-voltage (J-V) measurements provide insights into the charge injection and transport behaviour of the WOLEDs. A comparison between the devices with and without ITO nanorods shows a significant improvement in current density at a given voltage for the nanorod-enhanced devices. Specifically, at 5V, the current density increased from 12.4 mA/cm<sup>2</sup> to 21.7 mA/cm<sup>2</sup>, indicating that the ITO nanorod structures effectively enhanced charge injection. This improvement can be attributed to the increased surface area of the nanorods, which facilitates more efficient carrier transport and reduces resistance at the interface between the electrode and the emission layer, shown in Figure 2.

The turn-on voltage, defined as the voltage at which light emission is first observed, was lower for the devices with nanorods. The turn-on voltage decreased from 3.5V to 2.8V, confirming that the ITO nanorod structures improve carrier injection efficiency and allow for early light emission with reduced power consumption. This reduction in turn-on voltage is particularly advantageous for energy-efficient OLED applications, as it minimizes the required driving voltage.

Although ITO nanorods improve charge injection, their presence may introduce surface roughness or localized defects, which could affect uniform charge transport or lead to increased leakage current. However, in this study, the nanorod geometry was carefully optimized to ensure that the surface morphology remained within acceptable RMS roughness limits, minimizing such effects.

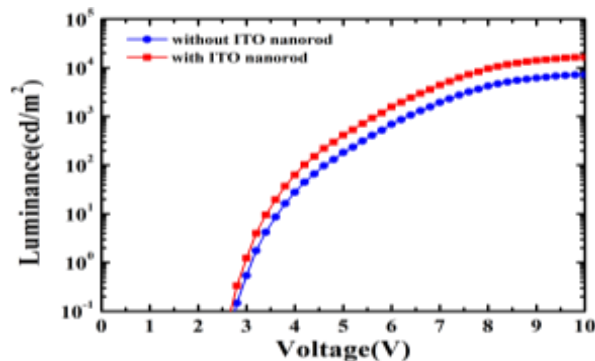


**Figure 2.** The value of current density-voltage

## 5.2. Luminance-Voltage (L-V) Characteristics

Luminance-voltage (L-V) measurements were performed to evaluate the effect of ITO nanorods on light output efficiency. The results showed a substantial increase in maximum luminance for devices with nanorods. The maximum luminance improved from 7191 cd/m<sup>2</sup> to 16,333 cd/m<sup>2</sup>, representing a more than 2.2-fold increase in brightness. This enhancement is attributed to the higher charge carrier recombination rates facilitated by the improved injection efficiency of the nanorod structures.

The result shown at the same applied voltage, the nanorod-structured devices exhibited significantly higher luminance levels compared to the reference devices. This suggests that the ITO nanorods enable more efficient charge transport, reducing carrier losses and leading to higher light emission per unit of input power. This improvement in luminance is particularly important for display and lighting applications requiring high brightness and uniform emission, shown in Figure 3.

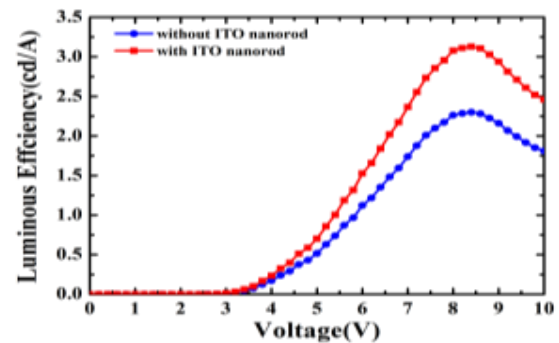


**Figure 3.** The value of luminance-voltage

## 5.3. Luminous Efficiency and Power Efficiency

Luminous efficiency is a key parameter in evaluating OLED performance, as it quantifies the amount of visible light emitted per unit of electrical current. The results indicate that the maximum luminous efficiency of the nanorod-enhanced WOLEDs increased from 2.30 cd/A to 3.12 cd/A, demonstrating that the inclusion of nanorod structures improves the efficiency of the light-emitting process, shown in Figure 4.

Power efficiency, which measures the amount of visible light produced per unit of electrical power consumed, also showed a notable improvement. The power efficiency increased from 5.2 lm/W to 7.8 lm/W, indicating that the WOLEDs with ITO nanorods consume less power while achieving higher brightness levels. This enhancement is particularly beneficial for low-power and high-efficiency OLED lighting and display applications.



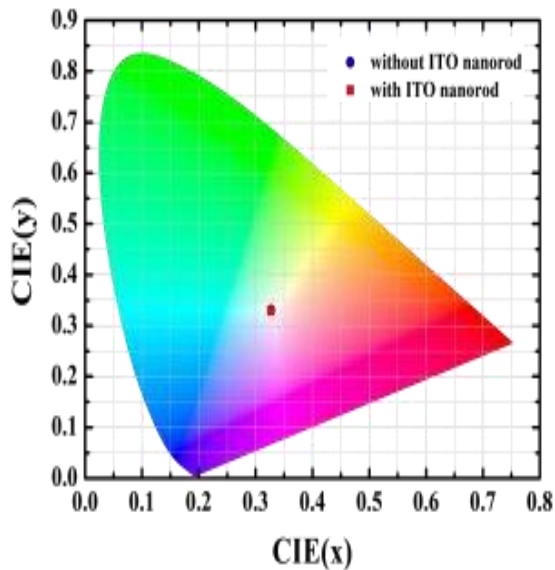
**Figure 4.** The value of luminous efficiency

## 5.4. Electroluminescence Spectra and Color Stability

The electroluminescence (EL) spectra of the WOLEDs were analysed to determine whether the inclusion of ITO nanorods introduced any spectral shifts or color instability. The CIE chromaticity coordinates for the devices with and without nanorods were recorded as (0.328, 0.331) and (0.329, 0.331),

respectively. These values confirm that the introduction of ITO nanorods did not alter the color properties of the emitted light, shown in Table 1.

Maintaining stable chromaticity coordinates is essential for white-light OLEDs, as color shifts can degrade the quality of the display or lighting application. The results confirm that the improved efficiency and luminance provided by ITO nanorods do not compromise color purity, making this structural modification suitable for high-performance, color-stable OLED applications, shown in Figure 5.



**Figure 5.** The CIE coordinate of the device without and with ITO nanorod

**Table 1.** The performance metrics between WOLEDs with and without ITO nanorods

Performance Metrics	Without ITO Nanorods	With ITO Nanorods
Maximum Luminance (cd/m <sup>2</sup> )	7191	16,333

Performance Metrics	Without ITO Nanorods	With ITO Nanorods
Maximum Luminous Efficiency (cd/A)	2.30	3.12
Turn-on Voltage (V)	3.5	2.8
Current Density at 5V (mA/cm <sup>2</sup> )	12.4	21.7
Power Efficiency (lm/W)	5.2	7.8
CIE Coordinates (x, y)	(0.328, 0.331)	(0.329, 0.331)

The data clearly indicate that ITO nanorods significantly improve charge injection, enhance luminance, and increase efficiency, while maintaining stable color properties. The experimental results demonstrate that the integration of ITO nanorods in QD-based WOLEDs leads to significant improvements in device performance. The reduced turn-on voltage, increased current density, and higher luminance levels confirm that the nanorods enhance charge injection and carrier transport efficiency. Additionally, the substantial improvements in luminous and power efficiency highlight the potential of ITO nanorods for developing high-brightness, low-power OLED applications.

While the integration of ITO nanorods significantly enhances WOLED performance, it also introduces certain trade-offs. The fabrication process, though compatible with standard photolithography, requires precise alignment and controlled etching steps, which may slightly increase processing time and equipment requirements. Additionally, while ITO is a well-established material in the

display industry, the added nanostructuring step could increase production costs in large-scale manufacturing. However, when compared to alternatives such as introducing entirely new electrode materials or complex multilayer architectures, the nanorod approach offers a relatively cost-effective and scalable route to performance enhancement with minimal disruption to existing production lines.

## 6. CONCLUSION

This study investigated the effects of incorporating CdSe/ZnS quantum dots and ITO nanorod structures into white organic light-emitting diodes (WOLEDs). The results demonstrated that nanorod-enhanced WOLEDs significantly outperformed conventional devices in terms of charge injection, luminance, and efficiency, while maintaining stable color coordinates. The enhanced contact area provided by the nanorods facilitated improved carrier recombination, resulting in higher luminance and lower turn-on voltage.

The nanorod-structured devices achieved a maximum luminance of 16,333 cd/m<sup>2</sup>, more than twice that of the control device, and notable improvements in luminous efficiency (3.12 cd/A) and power efficiency (7.8 lm/W). These enhancements confirm the effectiveness of ITO nanorods in reducing charge transport losses and enabling more efficient energy conversion. Moreover, the fabrication method is compatible with existing photolithography and roll-to-roll processes, offering a scalable solution for mass production.

Future work will concentrate on assessing the long-term operational stability of these devices, including environmental stress testing. Additional efforts will investigate alternative nanorod materials and optimize device architecture. The integration of nanostructured electrodes into flexible and wearable OLED platforms will also

be investigated to advance next-generation optoelectronic applications.

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# NGHIÊN CỨU NÂNG CAO HIỆU SUẤT ĐÈN WOLEDs BẰNG CẤU TRÚC CHẤM LƯỢNG TỬ CdSe/ZnS VÀ CẤU TRÚC Nanorod ITO

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## THÔNG TIN CHUNG

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## TỪ KHÓA

Chấm lượng tử;

Nanorod ITO;

Hiệu suất WOLED.

## TÓM TẮT

Nghiên cứu này đã đánh giá tác động của cấu trúc Nanorod ITO đến hiệu suất của điốt phát quang hữu cơ trắng (WOLEDs) sử dụng chấm lượng tử CdSe/ZnS (QDs). Kết quả mô phỏng cho thấy, việc tích hợp nanorod đã cải thiện đáng kể hiệu quả phun dòng điện, độ chói và hiệu suất phát sáng, đồng thời vẫn duy trì độ ổn định của ánh sáng trắng phát ra. Kết quả thực nghiệm cho thấy điện áp kích hoạt giảm từ 3,5V xuống 2,8V, độ chói tối đa tăng 2,2 lần (từ 7.191 cd/m<sup>2</sup> lên 16.333 cd/m<sup>2</sup>) và hiệu suất phát sáng tăng từ 2,30 cd/A lên 3,12 cd/A. Các thông số màu sắc theo tiêu chuẩn CIE đã duy trì ổn định ở (0,329, 0,331), đảm bảo độ chính xác màu sắc. Kết quả của nghiên cứu đã khẳng định tiềm năng của Nanorod ITO trong việc phát triển màn hình OLED và hệ thống chiếu sáng tiết kiệm năng lượng, hiệu suất cao.