Progress and Challenges of QD-EL Technology

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Abstract

Quantum-dot light-emitting diodes (QLEDs) have emerged as revolutionary candidates for advanced display systems, demonstrating exceptional electroluminescent performance across the visible spectrum. While current developments have achieved near-industrialization benchmarks in efficiency and operational stability for RGB emissive devices, critical commercialization prerequisites—particularly batch-to-batch consistency and long-term reliability metrics—remain critically underinvestigated. This work systematically decouples the fundamental origins of performance variability in QLED architectures through interfacial engineering analysis. We demonstrate that controlled surface passivation of zinc oxide electron transport layers (ZnO ETLs) effectively suppresses both temporal and spatial performance fluctuations. These interfacial stabilization strategies establish a universal framework for resolving the principal consistency-reliability trade-off that currently impedes QLED technology transition from laboratory-scale achievements to industrial manufacturability.

Author Keywords

Quantum dots; Quantum dot light emitting diode (QLED); Inkjet printing; Positive aging; Device consistency; Device reliability

1. Introduction

Quantum dot light-emitting diodes (QLEDs) have emerged as a leading candidate for next-generation display technology, garnering widespread recognition for their exceptional attributes. These attributes include a wide color gamut (reaching 100% Rec. 2020), remarkable luminescence efficiency, and the potential for cost-effective mass production. Consequently, substantial research efforts have been devoted to enhancing device efficiency, with recent advancements enabling quantum efficiencies exceeding 20% across all three primary colors (red, green, and blue) (1, 2, 3). However, despite these achievements, the limited operational lifetime of QLEDs, particularly blue QLEDs, remains a significant barrier to commercialization. Blue QLEDs are particularly susceptible to degradation, with their lifetime (T95@1000 nits) typically confined to approximately 10 hours. Moreover, the commercial viability of QLEDs is further challenged by other critical issues, such as the performance disparity between spin-coated and inkjet-printed (IJP) devices, as well as the adverse side effects associated with the positive aging phenomenon. While positive aging is often employed to enhance device performance, it concurrently introduces severe complications that hinder the large-scale production of QLED displays.

To address these challenges, the TCL QLED team has made significant progress in the development of high-performance QLED devices through a comprehensive and synergistic approach. This strategy encompasses the redesign of quantum dot energy structures, optimization of charge transport layers to achieve balanced charge injection, and elucidation of degradation mechanisms using various in-situ characterization techniques. As a result, the lifetime performance of QLED devices has been significantly improved, reaching a level comparable to that of organic light-emitting diodes (OLEDs). Additionally, we have successfully implemented a top-emission device architecture, which not only meets the requirements for panel mass production but also enhances current efficiency and color gamut.

Furthermore, the performance gap between spin-coated and IJP devices has been substantially narrowed. This achievement is attributed to concerted efforts in optimizing inks, improving film quality, and refining the IJP fabrication process. Table 1 presents the encouraging results in terms of efficiency and lifetime for red, green, and blue devices achieved through the application of top-emission spin-coating and IJP techniques. Notably, the blue spin-coated device has demonstrated a remarkable lifetime exceeding 200 hours, thereby meeting the stringent industry standards.

Table 1. Device performance of TCL's state of the art QLEDs based on Cd-containing QDs with acrylic acid-free encapsulation. Current Efficiency was recorded at 1000 nits and T95 was recorded at 1000 nits

Color	TCL T/E QLEDs			
	Spin-coating		Inkjet printing	
	CE_{max}(cd/A)	T95@1knit(h)	CE_{max}(cd/A)	T95@1knit(h)
Red	~75	~21000	~67	~15500
Green	~210	~21000	~185	~15500
Blue	~13	~200 （CIEy<0.06）	~10	~110 （CIEy<0.06）

The long lifetime of QLEDs is closely associated with a phenomenon known as positive aging, which refers to the increase in device efficiency over storage or electrical stressing time. This phenomenon has garnered significant attention in recent years and has been investigated by several research groups. Studies have revealed that positive aging is induced by the interaction between acidic gases released by the acrylic resin used for encapsulation and zinc oxide electron-transporting materials, resulting in reduced interfacial charge injection barriers and defect passivation (4, 5, 6, 7, 8). More recently, further investigations have been conducted to elucidate the mechanisms underlying the continuous variation in device performance. The role of moisture in zinc oxide nanoparticles has been identified as a critical factor. Jin's group reported that the presence of trace amounts of moisture enhances electron transport and eliminates intragap trap states in zinc oxide materials, thereby improving device performance(9). Additionally, Peng et al. demonstrated that the reaction between water and metal contacts generates reductive species that remove deep traps in the zinc oxide layer and alter the hole-blocking properties(10).

While the positive aging effect significantly enhances device performance, it also introduces critical issues related to device consistency and reliability, posing challenges for commercialization. To address these challenges and facilitate the

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mass production of QLEDs, we propose two methods to modify the properties of zinc oxide nanoparticles. Detailed device characterizations have been conducted to verify the improvements in device consistency and reliability.

2. Results and Discussion

Device consistency and reliability are two pivotal factors that determine the commercial viability of quantum dot light-emitting diode (QLED) technology. Consistency pertains to the reproducibility of device performance across different batches, which can be assessed by comparing the current-voltage (J-V) or current efficiency-current density (CE-J) curves. Reliability, on the other hand, is characterized by the stability of device performance under sequential multiple electrical scans and the absolute value of performance metrics during storage in an elevated temperature environment (e.g., 80°C). Currently, the research community primarily focuses on the efficiency and lifespan of QLEDs, while the behaviors related to device consistency and reliability have received relatively less attention.

QLEDs devices with architecture of glass/ITO/Poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate)(PEDOT:PSS)/Poly(9,9-dioctylfluorene-alt-N-(4-sec-butylphenyl)-diphenylamine)(TFB)/QDs/Zinc Oxide (ZnO)/Silver (Ag) were fabricated to evaluate the consistency and reliability properties for red, green and blue QLEDs. In this study, UV-curable resin was employed as an encapsulant, replacing the commonly used acrylic resin, to prevent the undesirable reaction between the acidic gases released from the resin and the zinc oxide layer. As observed in Figure 1, QLEDs for all three primary colors possessed poor device consistency in terms of CE and conductivity, with red device showing the least discreteness, followed by green and blue devices. In terms of the reliability test, RGB devices once again showed severe variation in the device performance during storage. This result suggested that poor device consistency and reliability properties are common issue in the QLEDs regardless of the emission colors.

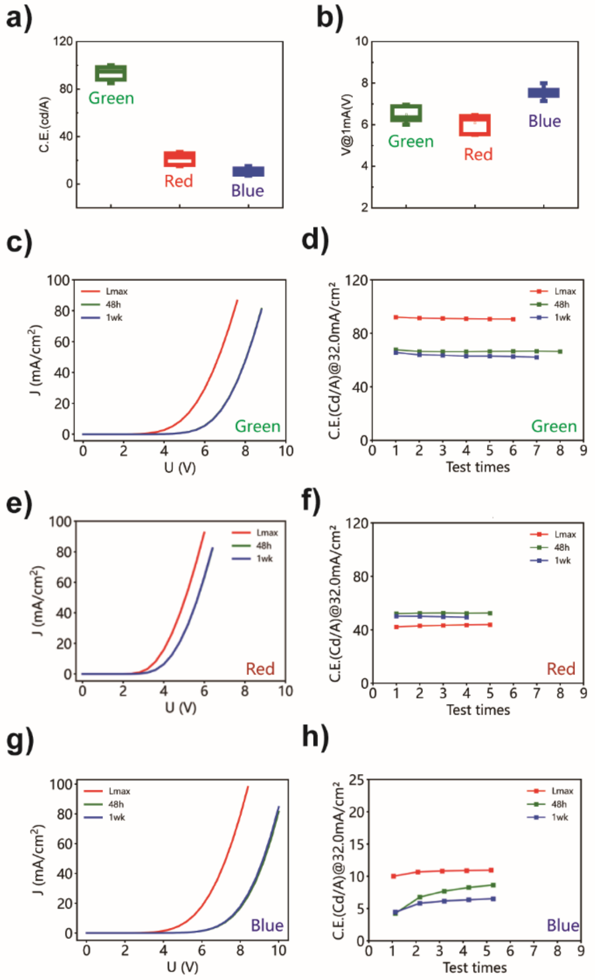

Figure 1. QLED device consistency and reliability. a) Comparison of device consistency in current efficiency (CE) between red, green and blue devices. b) Comparison of device consistency in conductivity between red, green and blue devices. c-d) Variation in device JV and CE during storage for green QLEDs. e-f) Variation in device JV and CE during storage for red QLEDs. g-h) Variation in device JV and CE during storage for blue QLEDs.

Proper understanding of the underlying mechanism for device discreteness in consistency and reliability is essential in order to push QLEDs towards commercialization. Hence, three types of zinc oxide nanoparticles (pristine as ZnO, Mg-doped as ZMO and core-shell structure as ZnO@M) were utilized to assess the impact of surface defects on device consistency and reliability. The results are presented in Figure 2.

Statistical analysis revealed that conventional QLED devices fabricated with all type of electron-transporting material exhibited significant variability in performance, as evidenced by the inconsistent J-V and CE-J characteristics across different samples. In the reliability assessment, devices incorporating pristine ZnO showed increasing divergence in their CE versus scan cycle profiles with extended storage time. Conversely, devices with ZMO and ZnO@M demonstrated convergent CE behavior over multiple scan cycles. However, the trend was reversed when examining the J-V characteristics during storage. The enhanced passivation of ZnO surfaces achieved through Mg doping and core-shell structure effectively reduced the intrinsic reactivity of ZnO (11, 12). The observed convergence in CE was attributed to the minimized interfacial quenching between QDs and ZMO.

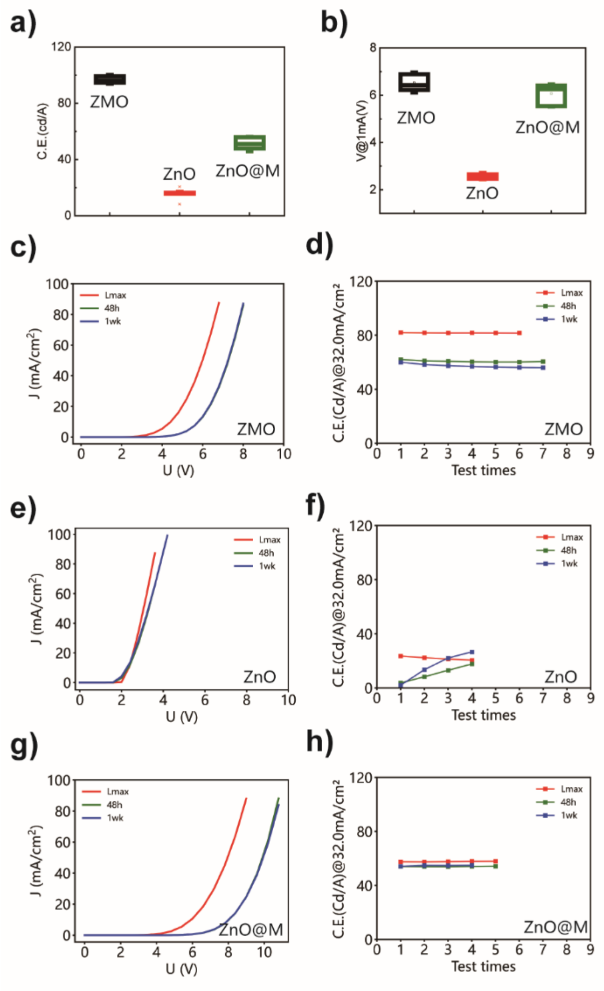

Figure 2. QLED device consistency and reliability. a) Comparison of device current efficiency (CE) between ZMO and ZnO. b) Comparison of device conductivity between ZMO and ZnO. c-d) Variation in device JV and CE during storage for ZMO based QLED. e-f) Variation in device JV and CE during storage for ZnO based QLED. g-h) Variation in device JV and CE during storage for ZnO@M based QLED.

To validate the hypothesis regarding ZnO surface passivation effects on CE variance during reliability assessments, we engineered a comparative device architecture incorporating a widely used insulating PMMA interfacial layer between QD and ZnO layers. Figure 3c-d reveals that PMMA-modified devices demonstrated enhanced CE convergence throughout electrical cycling tests. Notably, the modified configuration simultaneously achieved higher peak CE values compared to baseline devices - a performance enhancement consistent with established charge balance optimization mechanisms enabled by polymer interlayers (13). To further confirm the hypothesis, an alternative polymeric electron transporting material (denoted as Organic-ETL) was also utilized as interfacial layer. As can be observed in Figure 3e-f, device with organic ETL as interfacial layer also demonstrated significant improvement in the convergence of device CE during cycling test. This provided conclusive evidence that interfacial characteristics at the QD/ZnO junction fundamentally govern CE discreteness phenomena.

Intriguingly, J-V characteristic discreteness remained unaffected by the insertion of interlayer at the QD/ZnO interface, suggesting that bulk ZnO properties or ZnO/metal electrode interfacial dynamics might predominantly dictate J-V variability and requires further investigation.

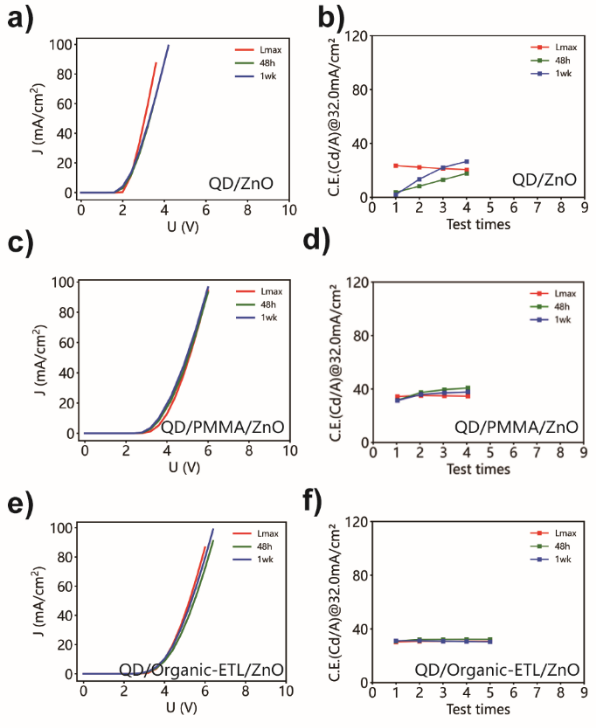

Figure 3. The effect of interfacial passivation on reliability properties of QLED. a-b) Variation in JV and CE for QLED without interfacial passivation. c-d) Variation in JV and CE for QLED with PMMA interfacial passivation. e-f) Variation in JV and CE for QLED with organic ETL interfacial passivation.

3. Conclusion

In summary, this study establishes two critical insights for QLED commercialization: 1) The fundamental importance of operational consistency and reliability metrics in device engineering. 2) The decisive role of electron transport layers in governing these stability parameters.

Results revealed that the discreteness in device consistency and reliability is a universal issue in QLEDs regardless of the emission wavelength of QDs. Systematic characterization demonstrates that inherent defects in ZnO/ZMO architectures mediate interfacial quenching dynamics at QD/ETL junctions, thereby directly influencing current efficiency stability during operational cycling. These findings provide a methodological framework for addressing the principal stability challenges impeding QLED technology translation.

Crucially, this work redirects research priorities beyond conventional efficiency optimization toward holistic reliability engineering—a paradigm shift essential for successful quantum dot display commercialization.

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