Advancements in Doped ZnO as an Efficient Electron Transport Layer for QLEDs

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Abstract

Quantum Dot Light-Emitting Diodes (QLEDs) have attracted significant attention as next-generation display technologies due to their high color purity, tunable emission wavelengths, and compatibility with solution-based fabrication. Among various electron transport materials, zinc oxide (ZnO) nanoparticles are widely used as electron transport layers (ETLs) because of their high electron mobility, favorable energy level alignment with quantum dots, and excellent optical transparency. However, pristine ZnO often suffers from excessive electron injection, abundant surface defects, and spontaneous interfacial charge transfer with the quantum dot emissive layer (QD-EML), which lead to charge imbalance, exciton quenching, and device instability. To overcome these limitations, extensive efforts have been devoted to modifying ZnO through various doping strategies. This review briefly summarizes recent advances in doped ZnO ETLs for QLED applications, including metal cation doping, halogen anion passivation, and organic-inorganic hybrid modification. The roles of these dopants in regulating energy band alignment, suppressing defect states, and optimizing carrier transport are discussed. Finally, the remaining challenges and future research directions for doped ZnO ETLs are outlined, providing insights for the development of high-efficiency and long-lifetime QLED devices.

Keywords

Quantum Dot Light-Emitting Diodes, Electron transport layers, Metal cation, Emissive layer

Introduction

Quantum Dot Light-Emitting Diodes (QLEDs) have redefined the landscape of optoelectronic display technology, with their unmatched color performance and solution-processable fabrication driving global research efforts toward commercialization. The electron transport layer (ETL) is a pivotal component dictating QLED charge balance and operational longevity, and zinc oxide (ZnO) has become the material of choice for this critical layer.

Quantum Dot Light-emitting Diodes

QLEDs have emerged as one of the most promising next-generation technologies for flat-panel displays and solid-state lighting [1,2]. Over the past three decades, rapid progress in quantum dot synthesis and device engineering has enabled QLEDs to achieve remarkable improvements in efficiency, color purity, and operational stability [3]. Compared with conventional display technologies such as liquid crystal displays (LCDs) and Organic Light-Emitting Diodes (OLEDs), QLEDs possess several inherent advantages derived from the unique optical properties of semiconductor quantum dots (QDs) [4].

Quantum dots are nanoscale semiconductor crystals that exhibit size-dependent quantum confinement effects. By precisely controlling the particle size, the emission wavelength of QDs can be continuously tuned across the visible spectrum [5]. This tunability allows QLEDs to achieve extremely high color purity and wide color gamut coverage, meeting or even exceeding advanced display standards such as Rec. 2020. In addition, QDs typically exhibit a high photoluminescence quantum yield (PLQY), which can approach nearly 100% in well-passivated core–shell structures. Their emission spectra are also characterized by a narrow full width at half maximum (FWHM), which further enhances color saturation and display quality [6,7].

Another important advantage of QLED technology is its compatibility with solution-based fabrication processes. Unlike OLED devices, which often require expensive vacuum deposition, QLED layers can be fabricated using low-cost solution methods such as spin coating, inkjet printing, or roll-to-roll processing. These scalable fabrication techniques provide significant potential for large-area flexible displays and low-cost mass production [8].

In addition to their excellent optical properties, quantum dots also exhibit superior chemical and photothermal stability compared with organic emitters. The inorganic crystal lattice of QDs makes them less susceptible to degradation caused by oxygen, moisture, or thermal stress. Consequently, QLEDs are widely considered strong candidates for next-generation display technologies that may eventually replace conventional OLED and LCD systems [9].

Despite these advantages, the performance of QLED devices is still limited by several key challenges, particularly those associated with charge transport and interfacial recombination. Among these factors, the design and optimization of charge transport layers play a decisive role in determining device efficiency and operational stability.

Role of electron transport layers

A typical QLED device adopts a multilayer “sandwich” architecture consisting of an anode, a hole injection layer (HIL), a hole transport layer (HTL), a quantum dot - emissive layer (QD-EML), an ETL, and a cathode. Within this multilayer structure, the charge transport layers are responsible for regulating carrier injection, transport, and recombination within the device [10].

The ETL plays a particularly critical role in determining device performance. Its primary function is to efficiently transport electrons from the cathode to the emissive layer while simultaneously blocking holes to ensure that radiative recombination occurs within the QD-EML. Ideally, the ETL should possess high electron mobility, appropriate energy level alignment with the quantum dots, good optical transparency, and excellent film uniformity.

However, achieving balanced carrier injection in QLED devices remains a major challenge. In most device architectures, commonly used electron transport materials exhibit significantly higher electron mobility than the hole mobility of typical hole transport materials such as Poly-(N,N’-bis(4-butylphenyl)-N,N’-bis(phenyl)-benzidine) (TPD), Poly(9-vinylcarbazole) (PVK), and Poly [(9,9-dioctylfluorenyl-2,7-diyl)-alt-(4,4’-(N-(4-butylphenyl))diphenylamine)] (TFB). Furthermore, the valence band energy level of quantum dots is relatively deep, resulting in a large hole injection barrier at the HTL/QD interface. In contrast, the electron injection barrier at the ETL/QD interface is generally much smaller [11].

This asymmetry in energy level alignment leads to an imbalance in carrier injection, where electrons are injected into the emissive layer more efficiently than holes. As a consequence, excessive electrons accumulate within the QD-EML, giving rise to severe non-radiative Auger recombination and exciton quenching processes. These parasitic recombination pathways significantly reduce the external quantum efficiency (EQE) of the device and accelerate degradation during long-term operation.

Therefore, optimizing the electron transport layer to achieve balanced charge injection has become a central research topic in QLED device engineering.

ZnO as a promising ETL material

Among the various materials explored for electron transport layers, zinc oxide (ZnO) nanoparticles have emerged as one of the most widely used ETL materials in QLED devices. ZnO is a wide-bandgap semiconductor that exhibits excellent electronic and optical properties, making it particularly suitable for charge transport applications [12].

One of the most significant advantages of ZnO nanoparticles is their high electron mobility, which is several orders of magnitude higher than that of typical organic electron transport materials. This high mobility enables efficient electron transport across the device and helps reduce the turn-on voltage. In addition, ZnO exhibits high optical transparency in the visible region, ensuring that the emitted light from the QD-EML can be efficiently extracted without significant absorption losses.

Another key advantage of ZnO is its favorable energy band structure. The conduction band minimum (CBM) of ZnO is well aligned with the conduction band of many commonly used quantum dots, particularly CdSe-based QDs. This alignment facilitates efficient electron injection from the ETL into the emissive layer.

Furthermore, ZnO nanoparticles can be synthesized through low-temperature solution processes such as the sol-gel method. These solution-processable characteristics make ZnO highly compatible with scalable manufacturing techniques for large-area display applications.

Despite these advantages, ZnO ETLs also suffer from several intrinsic limitations. First, the excessively high electron mobility of ZnO can exacerbate carrier imbalance within the device, leading to excessive electron injection into the QD-EML. This unbalanced charge injection further shortens device operational lifetime and compromises overall device stability. Second, the surface of ZnO nanoparticles typically contains a large number of intrinsic defect states, including oxygen vacancies and hydroxyl groups. These defects act as charge traps and exciton quenching centers at the ZnO/QD interface, which significantly reduces the radiative recombination efficiency [13].

Another critical issue associated with ZnO is the spontaneous interfacial charge transfer that occurs when ZnO comes into contact with the quantum dot emissive layer. This phenomenon can lead to charge accumulation within the QDs and results in the so-called "positive aging" effect, where device performance changes during the early stages of operation. Although positive aging may temporarily enhance device efficiency, it introduces significant instability and makes it difficult to maintain consistent brightness and color uniformity in practical display applications [14].

Doping strategies for ZnO

To overcome these limitations, extensive research efforts have been devoted to modifying the electronic and surface properties of ZnO through doping strategies. Doping involves the intentional introduction of foreign atoms or molecules into the ZnO lattice or surface in order to tailor its electrical conductivity, energy band structure, and defect chemistry.

In general, doping can improve QLED performance through two primary mechanisms. The first mechanism involves energy level engineering. By introducing appropriate dopant elements, the conduction band minimum of ZnO can be shifted upward, thereby increasing the electron injection barrier between the ETL and the QD-EML. This modification helps suppress excessive electron injection and improves charge balance within the device [15].

The second mechanism involves defect passivation. Many dopants can effectively passivate surface defects such as oxygen vacancies and hydroxyl groups on ZnO nanoparticles. By reducing the density of defect states at the ZnO/QD interface, non-radiative recombination processes can be suppressed, leading to improved exciton recombination efficiency and longer device lifetime.

A wide range of doping approaches have been investigated in recent years. These include single-element doping using metal cations such as Mg, Al, Ga, Y, Ni, Li, and Sn; anion doping using halogens such as F, Cl, and I; multi-element co-doping strategies such as Li-Mg or Ga-Mg; and hybrid organic-inorganic modification methods involving polymers or small molecules [16].

Figure 1 Schematic illustration of QLED devices employing various metal-cation-doped ZnO electron transport layers (ETLs), including Mg-, Al-, Ga-, Y-, Li-, Sn-, Ni-, and In-doped ZnO, alongside corresponding energy level diagrams and device stack architectures. This visual overview highlights the diversity of doping elements explored to optimize charge injection and interface properties in QLEDs.

For example, Mg doping can effectively widen the bandgap of ZnO and shift its conduction band upward, thereby reducing excessive electron injection. Al or Ga doping can modify the Fermi level and enhance electrical conductivity [17]. Meanwhile, halogen doping can passivate oxygen vacancies and suppress trap-assisted recombination, which significantly improves device stability.

Scope of this review

This review summarizes recent progress in the development of doped ZnO electron transport layers for high-performance QLED devices. Particular emphasis is placed on understanding how different dopants influence the electronic structure, carrier transport properties, and surface chemistry of ZnO nanoparticles. Key design principles and future research directions toward efficient and stable QLEDs are also highlighted.

First, the fundamental properties of ZnO ETLs and their interactions with quantum dot emissive layers are discussed. Next, various doping strategies, including metal cation doping, anion doping, co-doping, and organic-inorganic hybrid modification, are systematically reviewed. The mechanisms by which these modifications improve device efficiency and operational stability are analyzed in detail. Finally, the remaining challenges and future research directions for doped ZnO ETLs are discussed, with particular focus on large-scale manufacturing, Cd-free QLED technologies, and advanced characterization techniques.

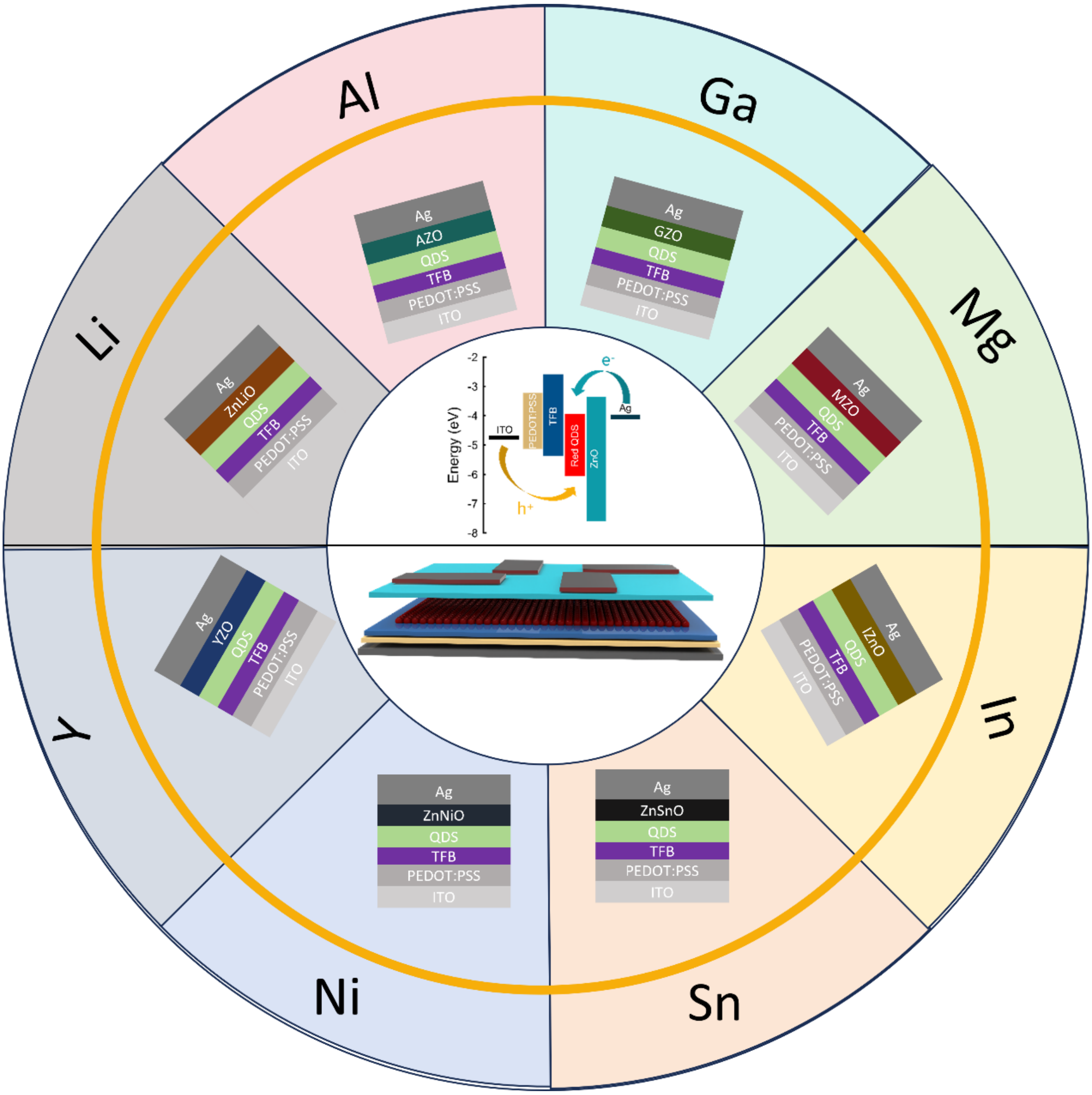

Figure 1. QLED device structure, band alignment of QLED, mechanism of ZnO doping.

Fundamentals of ZnO ETLs in QLEDs

Electronic properties of ZnO

ZnO nanoparticles are widely used as electron transport layers in QLED devices due to their outstanding electronic properties as n-type semiconductors. The high electron mobility of ZnO enables efficient charge transport from the cathode to the emissive layer, which helps reduce resistive losses within the device.

In addition to high mobility, ZnO nanoparticles exhibit excellent optical transparency in the visible region, ensuring minimal optical absorption of emitted photons. Their chemical stability and compatibility with low-temperature solution processing further contribute to their suitability for QLED fabrication.

Energy band alignment with quantum dots

The conduction band minimum of ZnO nanoparticles is typically located at approximately −4.4 eV relative to the vacuum level. This energy level aligns well with the conduction band of many commonly used CdSe-based quantum dots. As a result, electrons can be efficiently injected from the ETL into the QD-EML.

Once electrons are injected into the quantum dots, negatively charged intermediate states can be formed. These negatively charged states can facilitate hole injection through Coulombic interactions, thereby promoting exciton formation within the emissive layer.

Interfacial challenges

Despite the favorable electronic properties of ZnO, several interfacial issues arise at the ZnO/QD interface.

The first issue is charge injection imbalance. Due to the deep valence band of quantum dots, hole injection into the QD-EML is relatively inefficient compared with electron injection. This imbalance results in electron accumulation within the emissive layer, which promotes non-radiative Auger recombination.

The second issue is interfacial exciton quenching. The surface of ZnO nanoparticles contains numerous intrinsic defects, including oxygen vacancies and hydroxyl groups. These defects serve as charge trapping sites and can induce spontaneous charge transfer between ZnO and the quantum dots. Such processes lead to exciton dissociation and reduce the radiative recombination efficiency.

Advantages of doping strategies

Doping has proven to be one of the most effective strategies for improving the performance of ZnO ETLs in QLED devices. The benefits of doping can be summarized in three major aspects.

First, doping enables energy level engineering. By adjusting the conduction band position or Fermi level of ZnO, the electron injection barrier can be optimized to achieve better carrier balance.

Second, dopants can passivate surface defects, thereby reducing non-radiative recombination centers at the ZnO/QD interface.

Third, doping can modulate the electrical conductivity and electron mobility of ZnO, allowing better matching with the relatively low hole mobility of organic HTLs.

Doped ZnO ETLs

To overcome the intrinsic limitations of pristine ZnO nanoparticles, including excessive electron mobility, abundant surface defects, and interfacial instability, extensive efforts have been devoted to developing various doping strategies. These strategies aim to modify the electronic structure, defect chemistry, and transport properties of ZnO. Through appropriate dopant selection and concentration control, the conduction band position, carrier mobility, and surface states of ZnO can be effectively tuned. As a result, the charge injection balance in QLED devices can be significantly improved while suppressing exciton quenching at the ZnO/QD interface.

In general, doping strategies for ZnO ETLs can be broadly categorized into metal cation doping, anion doping, alkali metal compound blending, and organic-inorganic hybrid modification.

Metal cation doping

Metal cation doping represents the most widely adopted strategy for modifying the electronic and structural properties of ZnO. The influence of dopants depends largely on their valence state, ionic radius, and chemical bonding characteristics relative to Zn atoms in the ZnO lattice.

(1) Magnesium (Mg) doping

Magnesium doping is currently one of the most commonly employed strategies for improving QLED efficiency. Because Mg^{2+} and Zn^{2+} possess similar ionic radii (0.57 Å and 0.60 Å, respectively), Mg atoms can readily substitute for Zn atoms in the ZnO crystal lattice without causing significant structural distortion [18].

The most notable effect of Mg incorporation is the widening of the ZnO bandgap and the upward shift of the conduction band minimum (CBM). As the Mg content increases, the CBM of ZnMgO can shift from approximately −4.4 eV to around −3.4 eV. This upward shift increases the electron injection barrier between the ETL and the QD-EML, thereby suppressing excessive electron injection into the emissive layer.

In addition, the Mg-O bond possesses a higher bond dissociation energy (393.7 kJ/mol) than the Zn-O bond (284.1 kJ/mol). Consequently, the incorporation of Mg can reduce the formation of oxygen vacancies and lower the intrinsic electron density of ZnO. This reduction in defect density contributes to improved interfacial stability and reduced exciton quenching.

In high-efficiency green QLED devices, ZnO co-doped with Li and Mg (MLZO) has demonstrated remarkable performance improvements. For example, devices employing 10% MLZO as the ETL have achieved an external quantum efficiency (EQE) of 18.4%, which is more than twice that of devices using undoped ZnO. Notably, $Zn_{0.85}Mg_{0.15}O$-based interfacial modification layers have also been reported to enhance QLED efficiency by optimizing energy level alignment [19,20].

(2) Group III element doping

Group III elements such as aluminum (Al), gallium (Ga), and indium (In) are commonly used as n-type dopants to enhance the electrical conductivity of ZnO [21].

Aluminum-doped ZnO (AZO) is one of the most widely studied systems. Al^{3+} doping can increase the carrier concentration in ZnO through substitutional incorporation at Zn sites. In addition, Al doping can modify the optical band structure through the Burstein-Moss effect. AZO films often exhibit improved electrical conductivity and smoother surface morphology, which contributes to better film uniformity and reduced interfacial roughness [22].

In certain non-inverted QLED structures, AZO-based ETLs have demonstrated higher luminance compared with ZnMgO layers, mainly due to their higher current density and improved charge transport properties.

Gallium-doped ZnO (GZO) represents another important doping system. Because Ga and Zn have similar electronegativities and covalent bond lengths, Ga can be incorporated into the ZnO lattice with high solubility. Ga doping effectively reduces the work function of ZnO and suppresses spontaneous charge transfer at the ZnO/QD interface. As a result, red QLED devices employing GZO ETLs have achieved current efficiencies of up to 15 cd/A.

Indium-doped ZnO (IZO) has also been investigated in environmentally friendly InP-based QLEDs. In these systems, in doping helps reduce electron over-injection and passivate interfacial defect states. As a result, device efficiency can increase by approximately three times compared with devices using undoped ZnO [23].

(3) Lithium (Li) doping

Lithium doping is particularly effective in inverted QLED structures. Although Li is known to induce p-type characteristics in certain oxide semiconductors, its primary function in ZnO ETLs is surface defect passivation.

In solution-processed ZnO films, a large number of hydroxyl groups are typically present on the nanoparticle surface. These hydroxyl groups act as exciton quenching centers. Li doping can effectively passivate these surface hydroxyl groups, thereby reducing non-radiative recombination at the interface.

Experimental studies have shown that Li doping at concentrations of approximately 3 wt.% significantly reduces exciton quenching sites while slightly shifting the conduction band position upward. This dual effect of defect passivation and energy level tuning not only suppresses non-radiative recombination but also fine-tunes charge injection balance, a critical factor for maximizing electroluminescence yield. As a result, inverted red QLED devices employing Li-doped ZnO ETLs have achieved EQE values as high as 16.40%, representing one of the highest efficiencies reported for sol-gel processed ZnO ETLs.

(4) Other metal dopants (Y, Ni, Sn)

In addition to Mg and Group III elements, several other metal dopants have been investigated for ZnO modification.

Yttrium-doped ZnO (YZO) has been shown to effectively suppress excessive electron injection by significantly reducing electron mobility. Even a small doping concentration of approximately 2.00% Y can decrease electron mobility by several orders of magnitude (see Figure 2). As a result, the operational lifetime of QLED devices can be extended by up to eight times, while quantum dot charging effects are effectively suppressed.

Nickel-doped ZnO also exhibits promising performance improvements. The high bond dissociation energy of the Ni-O bond allows Ni doping to act as an effective carrier transport inhibitor. By reducing charge accumulation at the ZnO/QD interface, Ni-doped ZnO ETLs can extend the predicted lifetime of InP-based QLED devices to over 160,000 hours.

Beyond lifetime extension, Ni doping also mitigates interface exciton quenching, further boosting the external quantum efficiency (EQE) of InP-based devices without compromising charge balance. Tin-doped ZnO (ZnSnO) provides improved chemical stability and smaller nanoparticle sizes. These characteristics reduce the density of surface oxygen defects and enhance the long-term shelf-life and colloidal stability of ZnO nanoparticle inks, which is particularly beneficial for solution processing techniques [24].

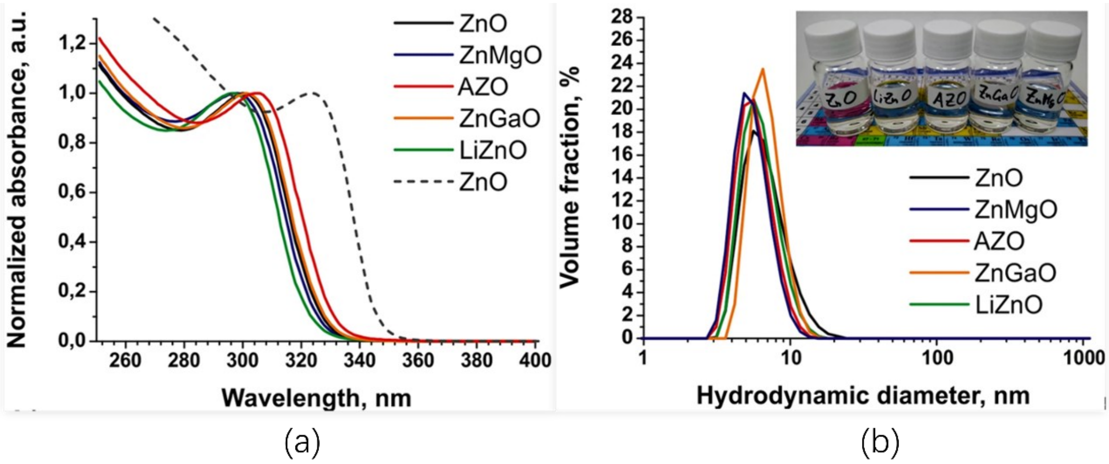

Figure 2. Optical absorbance spectra and size distribution by volume of the as-prepared doped and undoped ZnO nanoparticles. Optical absorbance spectra (a) and size distribution by volume (b) of ZnO (black line), ZnMgO (blue), AZO (red), ZnGaO (orange), LiZnO (green), ZnO (dashed) nanoparticles obtained with ethanol as the solvent for TMAH. The inset shows the photograph of the NP solutions used for the QLED fabrication.

Halogen and anion doping

Halogen doping is widely recognized as an effective approach for surface defect passivation and interfacial charge regulation in ZnO ETLs.

Fluorine doping is one of the most effective strategies. Because fluorine possesses extremely high electronegativity, it can occupy oxygen vacancy sites in the ZnO lattice. Plasma-treated fluorine-doped ZnO nanoparticles (FZnO) exhibit significantly reduced defect densities and suppressed interfacial charge accumulation.

Devices employing FZnO ETLs have demonstrated remarkable stability improvements. For example, at a luminance of 100 cd m^{-2}, QLED devices using FZnO have achieved LT_{50} lifetimes exceeding 2.37 million hours, which is dramatically longer than that of devices using pristine ZnO [25,26].

Chlorine and iodine doping also provide significant benefits. These halogen ions can act as hole scavengers that neutralize the positive surface charges formed during interfacial charge transfer. This mechanism suppresses non-radiative recombination losses during device operation.

Additionally, chlorine ions can replace insulating organic ligands on the surface of quantum dots. This ligand exchange process improves carrier injection efficiency while maintaining charge balance within the device [27].

Alkali metal carbonate blending

To further improve device stability under high current density conditions, alkali metal carbonates have been incorporated into Mg-doped ZnO ETLs.

The incorporation of alkali metal ions can increase the glass transition temperature (Tg) of the ETL layer, thereby improving thermal stability during device operation. Among various alkali metal salts, rubidium carbonate (Rb_2CO_3) has shown particularly promising results.

When Rb_2CO_3 is incorporated into Mg-doped ZnO (MZO), efficiency roll-off at high brightness is significantly suppressed. Furthermore, the operational stability of QLED devices is dramatically improved, with the LT_{95} lifetime increasing from approximately 0.06 hours to over 620 hours [28].

Organic-inorganic hybrid modification

Another effective strategy for modifying ZnO ETLs involves incorporating organic electron transport materials into the ZnO nanoparticle matrix.

Small-molecule materials such as LiQ, TPBi, and BPhen possess relatively shallow Lowest Unoccupied Molecular Orbital (LUMO) levels and lower electron mobility compared with ZnO. When these molecules are physically blended with ZnO nanoparticles, they form a composite electron transport layer that introduces an additional energy barrier for electron injection.

For example, incorporating 7 wt.% LiQ into ZnO ETLs has been shown to double the EQE of QLED devices from 3.98% to 7.74%. This improvement arises from both energy level modulation and physical separation between ZnO nanoparticles.

Polymer additives such as polyvinylpyrrolidone (PVP) and polyethylenimine ethoxylated (PEIE) have also been widely used. The long-chain molecular structure of these polymers can coat the surface of ZnO nanoparticles and increase the spacing between particles. This steric hindrance effect reduces electron hopping probability and effectively lowers electron mobility. As summarized in Table 1, PVP doping also contributes to precise and efficient charge balance control by matching carrier transport speeds between the ETL and hole transport layer (HTL).

Table 1. Comparative analysis of dopants.

Energy level modulation	Mg Y	Suitable for systems with shallow quantum dot conduction bands and severe electron injection excess.
	Al Ga	Optimizing injection by adjusting the position of the Fermi level helps reduce the turn-on voltage.
Defect and passivation	Li F	It demonstrates the best performance in eliminating surface hydroxyl groups and filling oxygen vacancies, which directly results in a longer exciton radiative decay time.
	Sn	Shortening the chain length enhances the colloidal stability and film-forming properties of the particles.
Charge balance control	Y Ni PVP	By significantly reducing the electron mobility, the carrier transport speeds of the ETL and the organic HTL have been matched.
Long-term stability	F Rb_2CO_3	It offers a decisive advantage in extending device lifespan, and is particularly effective in mitigating forward aging effects.

Interface engineering and device performance

In QLED devices, the interface between the electron transport layer and the quantum dot emissive layer is the primary region where exciton recombination occurs. Therefore, the physical and chemical properties of this interface play a crucial role in determining device efficiency and operational stability.

Because ZnO nanoparticles contain numerous surface defects such as dangling bonds, oxygen vacancies, and hydroxyl groups, the ZnO/QD interface often becomes a major source of exciton quenching and charge leakage. Consequently, interface engineering strategies are essential for improving device performance.

Atomic force microscopy (AFM) images (Figure 3) reveal that different dopants significantly alter the surface morphology and roughness of ZnO films, which directly impacts interface contact and defect passivation at the ZnO/QD junction.

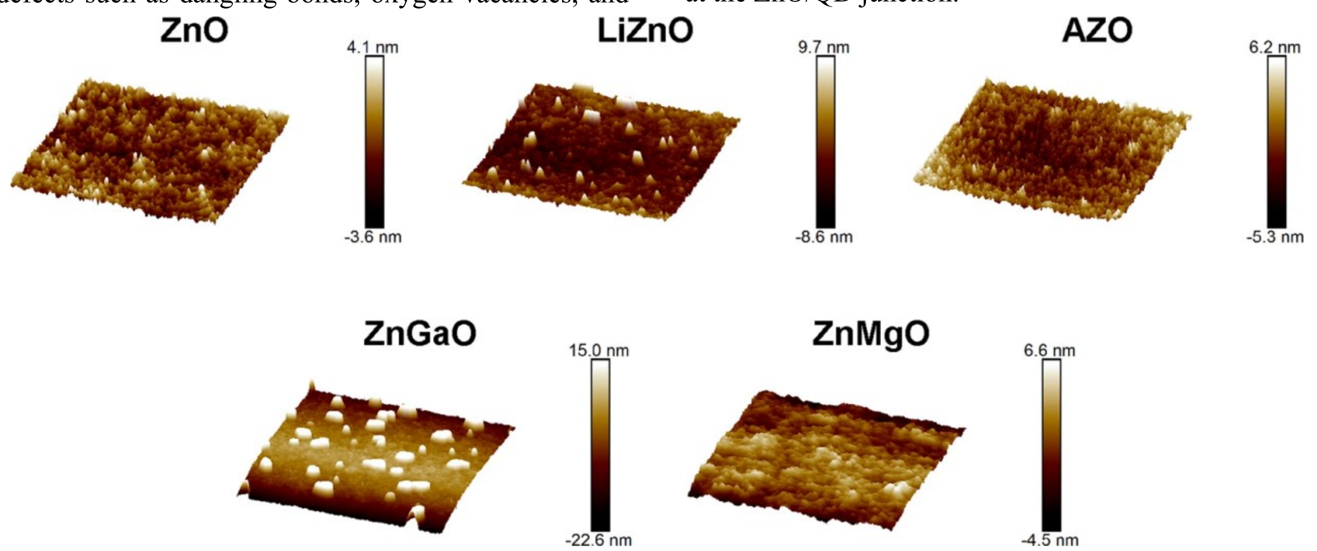

Figure 3. Topographic atomic force microscopy images of the top ZnO/doped ZnO nanoparticle layers of the fabricated QLEDs.

Interface modification strategies

Several interface modification approaches have been developed, including doping-induced modification, surface passivation, and the introduction of interfacial intermediate layers.

Doping-induced modification adjusts the electronic properties of ZnO by incorporating metal ions such as Mg, Y, Li, Ni, Sn, Al, or Ga. These dopants modify the energy band structure and reduce defect density, thereby improving charge injection balance. Performance radar plots (Figure 4) further validate these effects, demonstrating that doped ZnO variants (e.g., AZO, ZnGaO, LiZnO) outperform pristine ZnO in turn-on voltage, current efficiency, and brightness, directly correlating with the dopant-specific mechanisms outlined in Table 1.

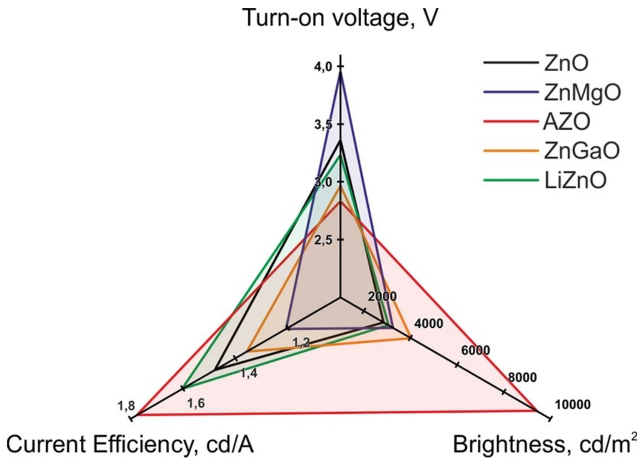

Figure 4. Brightness, current efficiency, and turn-on voltage of the fabricated QLEDs with different electron transport layer materials: ZnO (black line), ZnMgO (blue), AZO (red), ZnGaO (orange), LiZnO (green).

Surface passivation strategies involve treating the ZnO surface with halogen ions or organic molecules. For example, fluorination treatments can effectively eliminate hydroxyl groups and reduce electron trap density. Organic ligands such as ethanolamine or mercapto-based molecules can also modify the ZnO surface through dipole interactions, thereby adjusting the work function and improving interfacial compatibility.

Another effective approach involves inserting an ultrathin interfacial intermediate layer between the ZnO ETL and the QD-EML. Materials such as polymethyl methacrylate (PMMA) or wide-bandgap oxides like ZnMgO can serve as insulating barriers that physically separate the ZnO nanoparticles from the quantum dots. This spatial isolation suppresses spontaneous charge transfer and reduces exciton quenching [29].

Impact on charge balance

One of the most important benefits of interface engineering is the improvement of carrier injection balance.

By introducing dopants such as Mg or Y, or by incorporating organic molecules with shallow LUMO levels, the effective conduction band of the ETL can be shifted upward. This shift increases the electron injection barrier and prevents excessive electron injection into the emissive layer.

Meanwhile, polymer additives such as PVP reduce electron mobility by increasing the spacing between ZnO nanoparticles. This effect slows down electron transport and allows it to better match the hole transport rate of the HTL.

Additionally, defect passivation reduces charge trapping at the interface, thereby suppressing leakage currents and promoting efficient exciton recombination within the QD-EML.

Improvements in device performance

Interface engineering has led to substantial improvements in multiple performance metrics of QLED devices.

In terms of efficiency, Mg/PVP co-doping has been shown to increase the efficiency of red QLED devices by approximately 2.5 times. Li-doped ZnO ETLs enable inverted red QLEDs to achieve EQE values of up to 16.4%.

In cadmium-free InP-based QLEDs, indium-doped ZnO ETLs have demonstrated approximately threefold improvements in device efficiency [30].

Significant improvements have also been observed in luminance and turn-on voltage. Aluminum-doped ZnO ETLs increase device luminance from approximately 6,380 cd m^{-2} to over 26,700 cd m^{-2} due to their excellent conductivity and smooth film morphology.

Operational stability has also been dramatically enhanced accordingly. Fluorine-passivated ZnO ETLs have achieved LT_{50} lifetimes exceeding 2.37 million hours at 100 cd m^{-2}. Furthermore, alkali metal carbonates significantly improve thermal stability and suppress efficiency roll-off at high brightness [31,32].

Influence of solution processing and spin-coating conditions

In addition to material design through doping strategies, the solution-processing conditions of ZnO nanoparticle (ZnO NP) films play a crucial role in determining the interfacial quality and overall device performance of QLEDs. Among these parameters, spin-coating conditions - such as rotation speed, precursor concentration, and solvent composition - directly influence the film thickness, surface morphology, and defect distribution of the electron transport layer (ETL).

As a representative example, Figure 5 illustrates the influence of spin-coating conditions on the optical and electrical properties of ZnO-based QLED devices. The photoluminescence (PL) spectra exhibit a sharp and symmetric emission peak, indicating that the intrinsic optical properties of the quantum dots remain largely unaffected by the spin-coating process. This suggests that variations in device performance are primarily governed by interfacial and transport effects rather than changes in the emissive layer itself.

In contrast, the current density-voltage (J-V) characteristics show a clear dependence on processing conditions. Devices fabricated under optimized spin-coating parameters exhibit moderated current injection behavior, indicating improved control over electron transport and reduced leakage. This is consistent with a more uniform and defect-suppressed ZnO film that enables balanced carrier injection.

Furthermore, the external quantum efficiency (EQE) curves demonstrate that optimized spin-coating conditions can significantly enhance device efficiency while suppressing efficiency roll-off at higher current densities. This improvement can be attributed to the combined effects of reduced interfacial trap density, improved film uniformity, and better matching between electron and hole injection rates.

Overall, these results highlight that spin-coating is not merely a fabrication step but a critical parameter for tuning the structure-property-performance relationship of ZnO ETLs. Precise control of processing conditions enables the optimization of film morphology and interfacial quality, which in turn plays a key role in achieving high-efficiency and stable QLED devices. Such synergistic design holds great promise for practical applications. Therefore, future studies should integrate material doping strategies with process engineering to fully exploit the potential of ZnO-based electron transport layers [33].

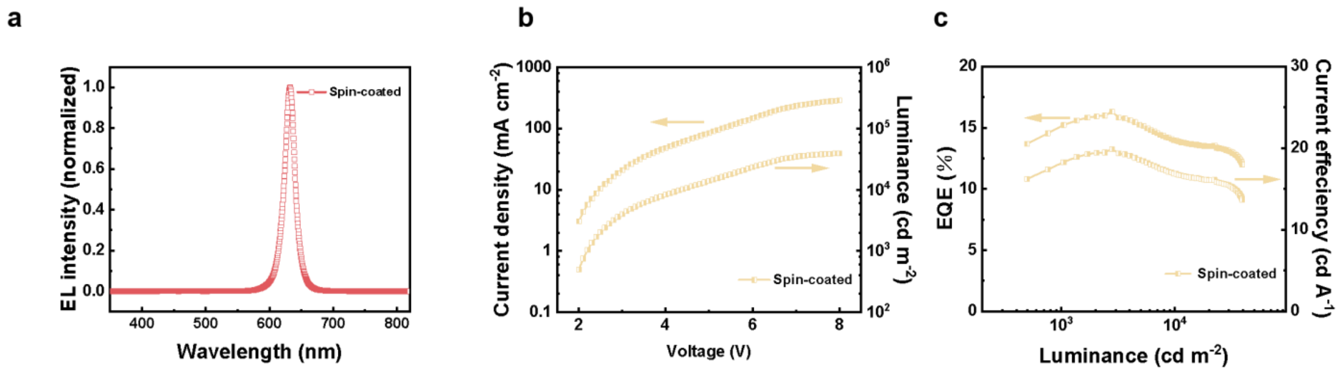

Figure 5. Optoelectronic characteristics of quantum dot light-emitting diodes (QLEDs) with spin-coated ZnO film as the electron barrier layer (EBL). (a) Normalized electroluminescence (EL) spectrum; (b) current density-voltage (J-V) and luminance-voltage (L-V) characteristics; (c) external quantum efficiency (EQE) and current efficiency as a function of luminance.

Challenges and future perspectives

Despite the significant progress achieved through ZnO doping strategies, several critical challenges remain before QLED technology can be fully commercialized.

Remaining challenges

One major challenge is the positive aging effect, which is commonly observed in QLED devices. During the early stages of operation, device performance often improves over time due to gradual stabilization of interfacial states. Although this phenomenon can temporarily enhance carrier balance, it introduces significant instability in large-area displays, where millions of pixels must operate consistently [34,35].

Another challenge involves colloidal stability and fabrication scalability. ZnO nanoparticles are prone to aggregation during solution processing, which complicates large-scale manufacturing techniques such as inkjet printing. Additionally, dopants may alter surface chemistry and reduce ink storage stability.

A further issue arises in cadmium-free QLED systems, particularly those based on InP quantum dots. Because InP QDs possess different energy band structures and surface defect characteristics compared with CdSe QDs, doping strategies optimized for CdSe devices may not perform effectively in InP systems [36,37].

Future research directions

Future research efforts should focus on developing multi-component co-doping systems that combine multiple functions within a single ETL material [38-40]. For example, co-doping strategies such as Li-Mg or Ga-Mg may simultaneously achieve energy level engineering, defect passivation, and mobility tuning.

Another promising direction involves the development of environmentally friendly synthesis methods and green solvents [41]. As environmental regulations become increasingly stringent, the use of toxic ligands and solvents must be minimized [42,43].

Finally, advanced in situ characterization techniques such as in situ X-ray photoelectron spectroscopy (XPS) and photoluminescence spectroscopy will be essential for understanding interfacial charge dynamics and degradation mechanisms during device operation.

Conclusions

In summary, ZnO nanoparticles represent one of the most promising electron transport layer materials for QLED devices due to their high electron mobility, favorable energy band alignment, and compatibility with solution processing. However, pristine ZnO suffers from several intrinsic limitations, including excessive electron injection, abundant surface defects, and interfacial instability.

Doping strategies have proven to be highly effective in addressing these issues. Metal cation doping, such as Mg, Y, Li, Al, and Ga, enables precise tuning of the conduction band position and carrier transport properties. Halogen anion doping, including F, Cl, and I, effectively passivates oxygen vacancies and surface trap states, thereby improving device stability. Meanwhile, organic-inorganic hybrid modification offers additional advantages in reducing electron mobility and achieving better carrier balance.

Although challenges such as the positive aging effect and large-scale fabrication consistency remain, continued advances in doping design and interface engineering are expected to further enhance the performance of ZnO ETLs. With ongoing progress in material synthesis, device architecture, and characterization techniques, doped ZnO electron transport layers will play a crucial role in enabling high-efficiency, long-lifetime, and fully commercialized quantum dot display technologies.

Funding

This work was supported by the Tianjin Undergraduate Innovation and Entrepreneurship Training Program, undertaken by Tiangong University (Grant No. 202510058054).

Authors' contributions

Siyuan Yang and Zheng Liu contribute equally to the article.

Acknowledgements

The authors would like to show sincere thanks to those techniques who have contributed to this research.

Conflicts of Interest

The authors declare no conflict of interest.

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