High efficiency green InP quantum dot light-emitting diodes by balancing electron and hole mobility

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The industrialization of quantum dot light-emitting diodes (QLEDs) requires the use of less hazardous cadmium-free quantum dots, among which ZnSe-based blue and InP-based green and red quantum dots have received considerable attention. In comparison, the development of InP-based green QLEDs is lagging behind. Here, we prepare green InP/ZnSe/ZnS quantum dots with a diameter of 8.6 nm. We then modify the InP quantum dot emitting layer by passivation with various alkyl diamines and zinc halides, which decreases electron mobility and enhances hole transport. This, together with optimizing the electron transport layer, leads to green 545 nm InP QLEDs with a maximum quantum efficiency (EQE) of 16.3% and a current efficiency 57.5 cd/A. EQE approaches the theoretical limit of InP quantum dots, with an emission quantum yield of 86%.
Colloidal quantum dots (QDs) are considered as the next-generation emissive materials for quantum light-emitting diodes (QLEDs) owing to their size controllable bandgaps, excellent photoelectric properties and high color purity. The first QLED reported in 1994 suffered an extremely low external quantum efficiency (EQE) of less than 0.01%. It was not until 2011, a milestone for the breakthrough was made, where QLED was emerged with the introduction of n-type ZnO nanoparticles into the hybrid QLEDs as the electron transport layer (ETL), demonstrating then a high luminance (68,000 cd m⁻²) for green CdSe-ZnS QDs. Ever since, progress has been continuously evolved for the CdSe relevant QLEDs, where EQE reaches the theoretical limit of 20% and luminance that attains 3.6 × 10⁹, 1.7 × 10⁹, and 6.3 × 10⁶ cd m⁻² for red, green, and blue devices, respectively. Despite excellent performance for CdSe relevant QLEDs, however, the use of Cd has been banned in numerous consumer electronics because of its environment and health hazard. In the quest of an alternative, the development of Cd-free QLEDs is thus demanding for their broad and practical implementation. In this regard, QLEDs incorporating a number of other QDs, such as InP, ZnSe, CuInS₂, and lead halide perovskites, etc., have also been widely studied, among which indium phosphide (InP)-based and zinc selenide (ZnSe)-based QDs are considered as promising benign alternatives, which are also capable of covering nearly the full range of natural colors.

Up to this stage, Cd-free QLEDs still show inferior performance to those with Cd-based QLEDs. Nevertheless, having spent intense efforts in recent years, blue ZnSeTe and red InP QLEDs have a leapfrog advance. The optimized blue ZnSeTe QLED with double emitting layers showed an EQE of 20.2% close to the theoretical limit with a brightness of 88,900 cd m⁻². In yet another approach, the red InP QLED has achieved an EQE of 21.4% with a high brightness of 1.0 × 10⁴ cd m⁻². In comparison, the progress of InP-based green QLEDs still lags far behind. Under a conventional device structure that incorporates green InP/ZnSe/ZnS core/shell QDs, a champion EQE of 13.6% was reported with a maximum luminance of 13,900 (cd m⁻²). As for a more practical inverted structure, the record high EQE for green InP QLEDs was even lower, which was reported to be 10.0% with a maximum luminance of 4000 (cd m⁻²). The inferior performance of green InP-based QLEDs mainly lies in the mismatched mobility between electron and hole. In the state-of-the-art organic/inorganic hybrid QLEDs, ZnO is commonly applied as an effective electron injection layer, rendering fast electron mobility. Conversely, the hole injection is usually impeded due to the energy-level offset between emissive InP QDs and hole transporting layers. This leads to unbalanced electrons and holes in the recombining zone and hence low device efficiency. Moreover, during the device operation, the excessive carriers accumulated at the barrier interface not only act as the non-radiative centers but also increase the driving voltage, limiting the device lifetime. Theoretically, finding hole transport materials (HTMs) to match the energy levels of InP QDs is likely to improve hole injections, which unfortunately, is a great challenge because of the deep valance band of InP QDs. Especially, theoretical approach on the energy-level alignments of a green InP/ZnSe/ZnS core/multi-shell structure indicates that the green InP QDs have a smaller e/h wave function overlap, leading to further difficulty in adjusting the balance between electron and hole.

To circumvent the obstacle of electron/hole mismatch in green InP QLEDs, considerable efforts have been made to improve the energy-level alignment between the highest occupied molecular orbital (HOMO) of HTL and valence band of the InP QDs by tailoring the shell structure of QDs. These methods are, however, nontrivial, which must undergo modification by the synthesis of QDs multilayer structure. Alternatively, it may be more facile and effective to post-modify the structures of QDs, which may simultaneously minimize several impeding factors such as energy transfer, Auger recombination and/or charge accumulation at the interfaces, promoting the charge balance. In light of this, ligand exchange plays one of the keys, which is able to influence the carrier mobility by altering the inter-QD dielectric environment as well as the tunneling distance. It has been reported that the mobility can increase exponentially upon decreasing ligand length in the absence of any other modification. Moreover, appropriate ligands can passivate electronic trap sites on the QD surface arising from the structural aperiodicity and/or off-stoichiometry of the QD core. This result may increase carrier and exciton lifetimes as well as provide a degree of control over the doping level and type of the coupled QD film. Similar to the modification of the shell structure, altering the identity of the chemical binding group and dipole moment of the ligand should change the strength of the QD-ligand surface dipole, shifting the vacuum energy hence the valence band maximum (VBM) and conduction band minimum (CBM) of QDs. The influence of surface chemistry on the QD energy levels has been reported in a number of studies.

The above modification, in theory, depends on the properties of the as-prepared InP QDs in terms of core/shell structure, original ligand passivation and importantly the emission quantum yield. The latter should be sufficiently high for the QLEDs performance, which is commonly inferior for InP QDs (cf. CdSe QDs). In this work, based on the green QDs (GQDs) of InP, that consistently exhibit high emission yield of 86 ± 2% at 535 nm, we then performed post-modification of the QDs surface as well as interlayer modification of the energy levels. The key lies in the checks and balance of electron and hole mobility synergistically by post-passivation of the as-prepared InP GQDs. The systematic tuning brings closer the electron and hole mobility, resulting in a record high green InP QLED under an inverted device structure. Based on 30 devices being examined, an average EQE of 15.3% can be obtained, among which the champion EQE reaches 16.3% with the brightness of 1.26 × 10⁴ cd m⁻² at 545 nm. Detail of results and discussion is elaborated in the following sections.

**Results and discussion**

**Ligand-dependent properties.** For clarity, Fig. 1 depicts the progressive pathways to passivate the InP-based QDs. The as-prepared green InP/ZnSe/ZnS core/shell QDs containing oleic acid ligands were measured to have an average diameter of ~8.6 ± 1.2 nm. These QDs, denoted as InP GQDs, consistently maintain their photoluminescence quantum yield (PLQY) of 86 ± 2% (see Supplementary Fig. 1 for the detail of characterization). The resulted InP GQDs were further modified by the passivation of various alkyl diamines consisting of two amino groups, respectively, at two terminals bridged by various lengths of the alkyl chain. Note that one of the alkyl diamines, 1,2-ethylendiamine, used as a ligand, has been reported to boost the emission properties of CdTe/ZnS QDs by reducing the trapping site. In addition to accommodate perhaps the trapping sites, the interaction of alkyl diamines with ZnS also has been reported to affect the ZnS structure, changing from cubic to hexagonal packing and hence altering the size of the particle to fine-tune the energy gap. Similar alkyl diamines modification approach has not been explored in InP QDs. Due to the different lattice sizes and atom adduct properties, the exploitation of 1,2-
ethylenediamine passivation in boosting CdTe/ZnS QDs may not work in InP QDs. In addition, as for various lengths of the alkyl chain, their insulation property may also largely affect the charge tunneling effect and hence the mobility. In this study, various alkyl diamines were selected and optimized via the performance of InP QLEDs where InP GQDs were modified by different alkyl diamines. As elaborated in the section of device fabrication it turned out that 1,4-butanediamine (BDA) rendered the top performance. Therefore, the results and discussion of the properties of post-modification are based on the BDA treated InP GQDs. The rest related data of the other alkyl diamines such as (1,2-ethylenediamine, EDA) and (1,6-hexanediamine, HDA) are listed and elaborated in the Supplementary Fig. 2.

Followed by the alkyl diamine (BDA) modification, further modification of InP GQDs were carried out by incorporating the halogen anions (Fig. 1). Addition of the halide salts to improve band (CB) and valance band (VB). This is plausibly caused by CdSe/ZnS QDs47. Theoretical calculations have shown that the QDs optoelectronic performance has been reported in the case of InP QDs. Therefore, the results and discussion of the properties of post-modification are based on the BDA treated InP GQDs. The rest related data of the other alkyl diamines such as (1,2-ethylenediamine, EDA) and (1,6-hexanediamine, HDA) are listed and elaborated in the Supplementary Fig. 2.

Optical measurements. Figure 2a reveals the absorption spectra of the InP GQDs before and after passivation by BDA. Upon BDA passivation, non-negligibly, the absorption onset has been extended from 550 nm (2.25 eV) to 560 nm (2.21 eV). The decrease of bandgap after modification infers a number of possible combinations of the energy alignment between conduction band (CB) and valance band (VB). This is plausibly caused by different degrees of CB and VB shift induced by the surface dipoles49, which, in theory, is an opportunity to block the electron injection but facilitate the hole injection. Further evidence of the bandgap change is given by the emission red shift from 535 to 540 nm in toluene upon BDA modification (see Fig. 2b). This BDA-modification-dependent luminescent peak wavelength in solution seems to be a disadvantage for later QLEDs application. However, upon fabrication into the device, it is interesting to know that the electroluminescence spectrum has negligible shift (<1 nm) between those with and without BDA-modified QDs devices (see Fig. 2c). This perhaps is due to the dominant dielectric interlayer environment that offsets the spectral changes in the device (vide infra). Further addition of metal halogen ions such as ZnCl2, ZnBr2, and ZnI2 do not change the absorption and emission properties QDs (see Fig. 2a and b for the addition of ZnCl2, ZnBr2, and ZnI2). This implies that only rather small portion of trap sites remained after BDA modification. Nevertheless, due to the capping of the remaining trap sites at a large, the emission properties in terms of lifetime increase, as elaborated below.

The comparative studies were then made in the photoluminescence lifetime before and after the BDA modification; the corresponding data are listed in Table 1 (modification by other diamine and zinc halides, as shown in Supplementary Table 1). The time-resolved emission for the as-prepared and BDA-modified InP GQDs in toluene can be sufficiently fitted by two single exponential decay kinetics \((\tau_1, \tau_2)\) of \((19.5 \text{ ns}, 68.6 \text{ ns})\) and \((23.2 \text{ ns}, 84.5 \text{ ns})\), respectively (see Fig. 2d and Table 1). Apparently, both \(\tau_1\) and \(\tau_2\) components increase with BDA post-modification. In general, the shorter \(\tau_1\) is related to a high rate of transition of interparticle charge and energy transfer, while the second exponent \(\tau_2\) is attributed to charge carrier recombination50-53. The longer \(\tau_1\) and \(\tau_2\) observed in BDA-modified InP GQDs simply indicate less surface unfiled and oxidative defects, which is attributed to the uniform crystalline orientation on the QD surface54,55. The BDA modifying oxidation state of Zn in the InP GQDs is supported by XPS (see Supplementary Fig. 4), where the oxidation state of Zn is
reduced, rendering the evidence of less surface unfilled and oxidative defects. Upon adding ZnI2 to the BDA-modified InP GQDs, despite the unchanging of the absorption and emission spectral profile, \( \tau_1 \) and \( \tau_2 \) increase to 25.8, 85.5 ns, respectively, supporting the further suppression of the trapping sites.

Device performance. Prior to the device fabrication and performance, we firstly examined if the charge balancing has been improved by post-modification. This has been done by dividing the device structure into two parts, the electron-only and hole-only sections (Fig. 3a and b), and measured the current density for each site to correlate with the electron and hole mobility, respectively. Each part is mimicking half of the real device and the integration of these two parts exactly reproduces the whole device architecture elaborated later.

Figure 3a shows the current density versus voltage of the electron-only device (EOD). Apparently, in comparison to that of the as-prepared InP GQDs, the BDA post-modification effectively suppress the ability of electron injection. All other single post-modification processes are listed in the Supplementary Figs. 5 and 6 for comparison. The UPS data (see detailed description in Supplementary Fig. 7) suggests that the decrease of the electron mobility is due to the shift of vacuum level induced by the surface dipoles, resulting in the mismatch between the conduction band with the electron transport layer. Conversely, as mentioned early, the BDA post-modification decreases the hole trapping sites. As a result, the current density versus voltage of the hole-only device (HOD) reveals slight enhancement of the hole injection ability for the BDA-modified InP GQDs (see Fig. 3b). Evidently, after BDA modification, the decrease of the electron mobility as opposed to the increase of the hole mobility makes more balance between electron and hole injection. Further improvement can be made by the BDA modification followed by the addition of zinc halides using ZnI2 as the additive. The results shown in Fig. 3b reveal further increase of the hole injection mobility whereas the change of electron mobility is not as significant. This may be rationalized, on the one hand, by the additional filling of vacancies by the zinc iodide salt, further reducing the hole traps\(^5\). On the other hand, the weak surface interaction as well as relatively small amount of the passivated iodide does not change the surface dipole and hence the band levels remain relatively unchanged (cf. the BDA modification only). We also noticed that the film morphology of InP GQDs has been improved accordingly via sequence of passivation. Figure 3c–e shows the atomic force microscope (AFM) height

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**Table 1 The photoluminescence decay dynamics**\(^a\) of the as-prepared and post-modified InP GQDs\(^b\).

| Post-modification | \( a_1 \) | \( \tau_1 \) (ns) | \( a_2 \) | \( \tau_2 \) (ns) | \( \chi^2 \) |
|-------------------|-------|----------|-------|----------|-------|
| As prepared       | 0.86  | 19.5     | 0.14  | 68.6     | 1.18  |
| BDA               | 0.89  | 23.2     | 0.11  | 84.5     | 1.33  |
| BDA/ZnI\(_2\)     | 0.90  | 25.8     | 0.10  | 85.5     | 1.07  |

\(^{a}\)Lifetime fitting by dual single exponential decay function: \( D(t) = a_1 \exp(-t/\tau_1) + a_2 \exp(-t/\tau_2) \) where \( a_1 \) and \( a_2 \) are the pre-exponential factors.

\(^{b}\)The concentration for BDA and ZnI\(_2\) was 0.4 and 0.125 mg ml\(^{-1}\), respectively.

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**Fig. 2 Optical properties of InP GQDs.** a Absorption spectrum, b Photoluminescence spectrum, c Electroluminescence spectra at the same measuring condition (5 V), and d Photoluminance decay of the InP GQDs in toluene. The instrument response is shown by a solid gray line. The colors shown in the figure represent InP GQDs before (black), after post-modification by BDA (red), and BDA followed by adding ZnI\(_2\) (blue). The excitation wavelength for b, c, and d is at 400 nm.
image of the same scanned area for the as-prepared InP GQDs film (RMS roughness 1.63 nm), BDA-modified film (RMS roughness 1.39 nm), and BDA followed by ZnI2 passivated film (RMS roughness 1.17 nm). Because BDA with double end NH2 can both anchor Zn on the InP GQD surface, it provides an opportunity to bridge the nearby QDs, stabilizing the film formation. Accordingly, we speculate that the decrease in RMS is related to some BDA bound to the proximal QDs on the surface. The decrease of RMS roughness along the sequence of BDA and then ZnI2 modification manifests the improvement of the surface smoothness and hence suppression of the leakage current.

Figure 4a shows the schematic diagram of the InP GQDs device structure applied in this study. Also depicted in Fig. 4a are the cross-sectional SEM images of the interlayer configuration. Note that the electron transport layer consists of ZnxMg1-xO where Mg has been fined-tuned to 12.5% for the optimized performance. Table 2 systematically lists the device performance data for the as prepared, BDA and other alkyl diamines modified as well as the combination of BDA and zinc halides modified InP GQDs QLEDs. For each condition, data shown in Table 2 are the average value of a number of devices fabricated. Comprehensive data of all measured devices are listed in Supplementary Table 2. From Table 2, EDA-modified InP GQDs devices, the ethylene 1,2-diamine (EDA)-modified InP GQDs devices have already shown better performance than that of the unmodified InP GQDs device. For example, typical device performance indices such as maximum external quantum efficiency (EQEmax) and maximum current efficiency (CEmax) for EDA-modified InP GQDs, measured to be 7.9% and 35.9 cd A⁻¹, respectively, are higher than that (5.7% and 27.9 cd A⁻¹) of the unmodified InP GQDs device. Upon increasing the alkyl lengths of diamines from none, EDA, BDA to HDA, both CEmax and external EQEmax exhibit a volcano shape-like plot, reaching the pinnacle at BDA-modified InP QLED with CEmax and EQEmax of 44.3 cd A⁻¹ and 8.5%, respectively (see Table 2). Therefore, BDA with four carbon bridging lengths seems to be optimum for filling the trap sites as well as for tuning the electron/hole balance, consistent with the results of charge mobility measured in the electron and hole-only section of the device (vide supra). Upon further increasing the ligand length to six carbon atoms, i.e., the HDA, the long spatial distance between two terminal amines increases the structure variance, which is unfavorable for the diamino-chelation onto the surface of QDs. This, together with the increase of the hydrophobic/insulation to suppress the charge injection, leads to the inferiority in device performance, being dropping to only 14.4 cd A⁻¹ and 1.8% for CEmax and EQEmax, respectively.

Supplementary Table 2 lists other performance data such as CE, PE, and EQE at 1000 cd m⁻². Based on the BDA-modified InP GQDs, we then move one step further by additionally passivating zinc halides to examine if the BDA/zinc halides modified InP GQDs can further improve the QLED properties. Note that more balanced electron/hole mobility has been proved by the current density versus voltage of the electron and hole-only device individually (see Fig. 3). Even though the devices show similar performance by passivation of different zinc halides (see Supplementary Table 2), ZnI2 shown better solubility and hence better device efficiency upon combining BDA, which is supposed to be a synergistic effect. For a fair comparison, the best device performance for BDA/ZnI2 passivated InP GQDs are depicted in Fig. 4b and c with corresponding data listed in Table 2. Apparently, the BDA/ZnI2 passivated InP GQDs make leap advance in either the current density and luminescence versus the applied voltage or the
current efficiency and EQE versus current density. Having fabricated 30 devices where InP GQDs are passivated by BDA, followed by ZnI₂ addition (0.125 mg, see Supplementary Fig. 8 for detail), the average CE max and EQE max are as high as 45.5 ± 5.5 cd A⁻¹ and 15.3 ± 1.0%. The champion one gives CE max and EQE max of 57.5 cd A⁻¹ and 16.3%, respectively.

We also examined the device performance of adding other zinc halides additives such as ZnCl₂ and ZnBr₂ to the BDA-modified InP GQDs. The resulted data listed in Table 2 and Supplementary Table 2 all show better performance than that of the BDA modified only InP QLED. Nevertheless, champion performance still belongs to that of BDA/ZnI₂ passivated green InP QLED. It is also noteworthy that emission quantum yield of InP QLED is within 86%. Taking the internal quantum efficiency of 100% and 1/5 of all solid angles covered, a theoretically limited EQE of 17.2% can reach. The champion device of EQE 16.3% is thus close to the theoretical limit. The device also achieves a brightness of 1.26 × 10⁴ cd m⁻² under a bias of 8.8 V. Figure 5 highlights the systematic improvement in each stage, where the performance of devices treated by BDA/ZnI₂ modification process is clearly better than those of the BDA modified only and the as-prepared ones.

As the modification process progresses, the EQE is increasing with the current density of HOD, and decreasing with current density of EOD. Other devices performances shown in Fig. 5, including L max, C E max, and P E max, also reveal superiority to those of the as-prepared one.

Comparison of green QD-LEDs. We then fairly compare the above results with those of the reported green InP QLEDs up to this stage. The corresponding data listed in Table 3 clearly manifest the breakthrough of the device performance in this work. Under the same inverted device structure, this work shows leapfrog enhancement, in which CE max, PE max, and EQE are more than 12 folds, 13 folds, and 1.6 times better than those of the previous best data reported for each single parameter. Further extension to all InP QDs relevant devices, including those of the conventional structures, the current device renders the same level of PE max and luminance, but apparently is superior in terms of the lowest turn-on voltage of 2.2 V, the highest EQE of 16.3% and highest CE max of 57.5 cd A⁻¹.

Last but not the least, in this study we also carried out the device lifetime measurements to gain further insight into the relationship between electroluminescence efficiency and stability. To our knowledge, there is no practical and meaningful report in regards to the lifetime of the green-emitting InP-based QD-LEDs.
shows the evolution of electroluminescence intensities and other parameters for the InP GQD devices operating over a period of 4 h at an initial luminance of 2000 cd m$^{-2}$. Also, the $T_{50}$ value at 100 cd m$^{-2}$ was estimated by fitting the data with an empirical equation $L^n \times T_{50} = \text{constant}$, where $L$ is the initial luminance and $n$ is the acceleration factor that was determined by fitting the data shown in Supplementary Fig. 9. As a result, $T_{50}$ at 100 cd m$^{-2}$ increases from 373.9 to 545.8 h upon BDA modification. After BDA/ZnI$_2$ modification, $T_{50}$ at 100 cd m$^{-2}$ lifts significantly to 1033.4 h. We must admit that the relatively crude packaging system currently existing in the lab cannot satisfy the rigorous lifetime test. Nevertheless, the trend of systematic increase of the device lifespan makes promising the superiority of BDA/ZnI$_2$ modification in addition to the record high performance in device efficiency.

**Conclusion**

In summary, we have carried out extensive post-modification of the colloidal green InP QDs by a sequence of ligand exchanges with various alkyl diamines and zinc halides. Our goal is to balance the electron and hole mobility and hence to promote the corresponding QLED performance. The alkyl diamines ligation provides bifunctionality, where upon surface passivation both energy level of CB and VB of InP GQDs lift due to the interface dipole interaction, facilitating the hole mobility, whereas the electron injection is retarded. In addition, the passivation fills the hole trapping sites as well as smoothens the surface of the film. Accommodation of the hole trapping site can be further suppressed by adding zinc halides, such that the InP GQDs and the corresponding QLEDs can be shaped up to the optimal condition. The comprehensive test of alkyl diamines and zinc halides turns out that BDA and ZnI$_2$ are shaped up to the optimal condition. The comprehensive test of alkyl diamines and zinc halides turns out that BDA and ZnI$_2$ are the optimized combination to balance the electron/hole mobility and hence to promote the corresponding QLED performance.

The EQE (red circle) increases in HOD (black square) and decreases in EOD (black triangle) upon increasing the current density. The error bars show standard deviation of as prepared for $n = 5$, BDA modified for $n = 10$, and BDA/ZnI$_2$ modified for $n = 30$, respectively. b The relative multiples with respect to the as-prepared device for $I_{\text{max}}$, $C_{\text{max}}$, $P_{\text{max}}$, and $E_{\text{max}}$.

**Device fabrication.** The ITO/glass substrates were ultrasonically cleaned with deionized water, acetone, and IPA for 20 min, respectively. The ZnMgO nanoparticle solution was then spin-coated onto the ITO/glass substrates at 2500 r.p.m. for 50 s and baked at 185 °C for 30 min. Post-modified QDs as mentioned above were spin-coated onto the ZnMgO layer at 3000 rpm for 50 s and then baked at 150 °C for 20 min. TCTA, MoO$_3$ and Al electrodes were evaporated using a thermal evaporation system through shadow masks under a high vacuum ($<10^{-5}$ Pa). The active device areas were 10 mm$^2$ and measured with encapsulation. The final surface ligands exchange percentages were identified and quantified by FTIR, TGA, and XPS experiments shown in Supplementary Figs. 10–12 and Supplementary Table 3, see Supplementary Note 1.

**Characterization.** Absorption and PL spectra of QDs were recorded by Hitachi U-3310 spectrophotometer and Edinburgh FS980 fluorimeter, respectively. The emission quantum yield of InP QDs was measured by a diluted InP QDs in the toluene where the absorbance at the excitation wavelength (e.g., 450 nm) no more than 0.1 to avoid reabsorption. The integrated emission intensity was then compared with the standard Rhodamine 6 G in EtOH where the quantum yield of the 552 nm emission band was reported to be 95%. The PLQY is then calculated by following equation.

$$Q_e = \frac{1}{Q_0} \frac{I_A}{I_B} \left( \frac{A_e}{A_B} \right) \left( \frac{n_e^2}{n_B^2} \right)$$
Table 3 Major progress of the InP green QDs-based QLEDs.

| Device Structure | Inverted | Normal |
|------------------|----------|--------|
| QD structure     | lnP/ZnS6s/ | lnP/GaP/ |
| PL (nm)          | 535      | 535    |
| PL FWHM (nm)     | 1.5      | 1.5    |
| EL (nm)          | 525      | 525    |
| EQEmax (%)       | 86       | 86     |
| PEmax (lm/W)     | 12,646   | 2938   |
| CEmax (cd/A)     | 57.5     | 13.7   |
| J (mA/cm²)       | 2.2      | 2.2    |
| V (V)            | 4.44     | 4.44   |
| L (cd/m²)        | 10,490   | 10,490 |
| PLQY (%)         | 56.4     | 56.4   |

Where Qφ is the quantum yield of an unknown fluorescent sample and Qφ is the quantum yield of the reference standard. Here, Iₘ and Iₘ are the integrated fluorescence intensities for the unknown and reference samples, respectively, while Aₛ and Aₛ are the respective absorbance values of the unknown and reference samples; rₖ and rₖ are the refractive indices of the unknown and reference samples.

Cross-sectional scanning transmission electron microscopy (SEM) images were performed using a Hitachi S-4800 field emission scanning electron microscope. Atomic force microscopy (AFM) measurements were conducted on a Utek Material Nanoview 1000 with tapping mode at ambient temperature. The current density − voltage − luminance (J−V−L) and current efficiency−luminance (CE−EQE−L) characteristics were characterized by a CR-280 spectrometer equipped with a source meter (Keithley 2400).

Data availability
Main data supporting the findings of this study are contained within the paper and its associated Supplementary Information. All relevant data of this study are available from the corresponding authors upon reasonable request.

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Author contributions
W.C.C. conceived the work. T.H.C. manufactured the samples. Y.C.L. performed SEM characterization. W.C.C. performed the analysis and discussion. T.H.C. and W.C.C. wrote the paper. Y.C.L. and T.H.C. contributed equally.

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The authors declare no competing interests.

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