Electrically Pumped QD Light Emission from LEDs to Lasers

As part of visible wavelength light-emitting QLEDs’ palpable progress, luminance efficiency and device operation stabilities for both red and green wavelengths are now viable for commercial display applications.

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QUANTUM-CONFINED COLLOIDAL SEMICONDUCTOR nanocrystals (NCs), also known as colloidal quantum dots (CQDs), represent one of the most promising phosphor materials for next-generation display, lighting, and laser applications. CQDs can be excited to emit light via color-conversion or electrical excitation. Especially in electroluminescent (EL) mode, CQD technology may offer extremely competitive advantages, including reduced device structure complexity, enhanced dynamic range, and high-power conversion efficiency.

With this in mind, this article focuses on EL CQD emission technology and discusses current advances and prospects for visible QD light-emitting diodes (QLEDs), covering CQD materials’ development, device structure optimization, and working mechanism studies. Also, we discuss narrowing the CQD band gap to create devices that emit infrared (IR) light. We detail overall progress on this fast-growing QD technology area, IR-emitting QLEDs, aiming at device performance improvement by optimizing CQD film morphologies. Next, we focus on the recent and tremendous progress toward electrically driven CQD lasing technology that is tunable in the visible and IR portion of the spectrum.

CQDs represent a new wave of disruptive innovation in display and lighting applications. The bright and narrow-band emission of CQDs can be tuned across the ultraviolet, visible, and IR regions of the spectrum through compositional and structural changes. The quantized energy states and charge interactions can be manipulated to produce amplified spontaneous emission (ASE) and lasing. CQDs are nanoscale semiconductors with high photoluminescence quantum efficiency (PLQY), narrow full-width-at-half-maximum (FWHM), and great chemical stability. Additionally, their solution-processability enables them to realize cost-effective, large-scale film deposition via methods such as roll-to-roll, spin-coating, blade-coating, and inkjet printing (IJP).

Visible Range QLEDs
CQDs can be optically excited to emit light, so they are photoluminescent (PL), or they can be electrically excited—that is, EL. The former is passive luminescence, where green and red light is generated by excitation via higher-energy blue light illumination and is used in the backlight units of commercial LCDs. The latter is active luminescence used to create QLEDs, where electrons and holes are injected into the QD emissive layer (EML) to form excitons that then radiatively decay to release photons. EL QD display technology has become more appealing in research and industry recently because of its high contrast, fast response, foldability, and ultrathin structure, as compared with the use of PL QDs.

The development roadmap for commercializing QLEDs can be divided into four categories. The first is optimizing the CQD core-shell ligand structure to protect the particle from environmental influences and to facilitate and balance charge injection. The second step is to modify device functional layers and structures to improve external quantum efficiency (EQE) and device operational stability. The third is to switch from R&D lab spin-coating
device fabrication to the IJP approach to enable large-scale production. Finally, the fourth step is mass production, where the main purpose is to fine tune procedures to achieve high product yield while maintaining high performance. During the past decade, significant progress has been made on all four of these steps for red, green, and blue (RGB) QLEDs for displays. Currently, the best QLED research is transitioning from device development to the IJP stage. Here, we focus on optimizing CQD materials and device improvement.

COLLOIDAL QDS FOR QLED DISPLAY APPLICATIONS

II-VI and III-V QDs are the most widely developed for use in QLED display technology. Among group II-VI materials, CdSe is investigated extensively and reported with high device performance.6 By tuning sizes and core-shell structures, CdSe-based QDs can emit light covering the entire visible range with a FWHM below 20 nm (Fig. 1a). At the same time, Cd-based QDs have been shown to have excellent crystallinity because of their more ionic bond character (Fig. 1a). To date, Cd-based QD EL displays are the most well-established technology, with bottom-emission device EQEs higher than 20 percent for all three colors (RGB) now close to reaching the theoretical limit.4 Spin-coated red and green devices now have been demonstrated with lifetime performance fully meeting the industrial requirements for displays. Along with the recent improvement in lifetime for blue QLEDs, Cd-based QLEDs are becoming close to mass production readiness relative to any other CQD materials being researched. TCL, a Chinese display panel manufacturer, is active in promoting the industrialization of Cd-based QLED displays.

Although Cd-based QDs used in QLEDs have been widely studied, cadmium is a toxic heavy metal and can be detrimental to the environment and human health. As a result, for many years, research also has been conducted on more environmentally benign CQDs. Among the heavy-metal-free semiconductor materials, the III-V group InP CQDs have been the most extensively investigated to date. Because of its more covalent nature and stronger quantum confinement, InP CQD batches typically have a larger size dispersion and broader spectral distribution than CdSe CQDs. The EL spectral FWHM of InP-based CQDs is larger than 30 nm, which is much wider than that of group II-VI QDs (Fig. 1b).

Owing to the relatively small bulk band gap of 1.3 electron volts (eV), InP is more commonly used in red and green QLEDs. Developing blue InP EL devices is restricted, because it requires ultra-small QD dimensions that lead to CQD inhomogeneity and poor stability issues.6 Another impediment is that InP CQD cores cannot form alloys with Zn chalcogenide shells, making it difficult to realize smooth energy distributions and gradient energy band adjustments of the core-shell structure. In addition to InP, ZnSeTe is another Cd-free CQD material system that has been explored extensively.7 Such materials can provide a wide range of fluorescent emission wavelengths by adjusting the Se/Te ratio, resulting in prime-color EL RGB. The ZnSeTe QD morphology also can be tuned to generate uniform facet-covered surfaces for better passivation. ZnSeTe, however, suffers from chemical and electrical stability problems because of the existence of reactive Te. Today, ZnSeTe-based CQDs are still early in development. Currently, ZnSeTe CQDs mainly are used to generate blue QLEDs. Companies, including Samsung, Nanosys, and Sharp, have been placing more emphasis on environmentally benign QDs, and in the past five years, Samsung has reported multiple breakthroughs on EL Cd-free QDs.5,7 Even more recently, Sharp has begun to publish their remarkable Cd-free QLED results.6–10 Yet, their performance to date still is not comparable with Cd-based QDs in EL devices, leaving large gaps toward mass production.

THE WORKING PRINCIPLE OF QD-BASED ELECTROLUMINESCENT DEVICES

Similar to that of OLEDs, QLEDs’ device structure contains a hole injection layer (HIL), a hole transport layer (HTL), a QD EML, an electron transport layer (ETL), and electrodes. The EL is generated by exciton formation via electron and hole injections into the QD layer (Fig. 2a).11 Holes and electrons driven by the external electrical field enter the valance band of the HTL and the conduction band of the ETL from the anode and cathode, respectively. These charge carriers progress into the QD EML and create excitons. Energy then is released through radiative decay to emit photons. Based on this luminescent mechanism, there are
three key exciton-quenching elements that can affect QLED performance significantly (Fig. 2b): QD surface defects, QD surface charge, and interfaces between EML and functional layers.\(^{11-13}\)

Consequently, to develop high-performance QLEDs, it is crucial to reduce the non-radiative recombination of charge carriers. This can be resolved by keeping the exciton recombination zone within the QD layer and away from interfaces to reduce exciton quenching. In general, based on our experience with OLED technology development, it is of great importance to achieve balanced electron and hole injections in the QD EML. This can be attained by energy band alignment optimization, as well as modifying the ETL/HTL and EML mobilities. However, based on more in-depth research of the specific QLED working mechanisms, it has been found that, unlike OLEDs, QLEDs show many unique characteristics owing to the use of CQDs and ZnO NCs with special surface chemistry. Different from the idea of balancing the dynamic charge-carrier concentrations, as suggested by the classical OLEDs theory, Prof. Jin has proposed that the carrier balance is insignificant in the fresh state of QLEDs.\(^{14}\) QLEDs exhibit a distinctive ability to "self-adjust" their charge-carrier levels to reach the balanced state under continuous operation (Fig. 2c). Such an inspirational view indicates that OLED technology know-how cannot be applied simplistically to developing high-performance QLEDs. As a result, the device structure of QLEDs must be tailored and optimized for their specific needs and applications.

**QD ELECTROLUMINESCENT DEVICE PROGRESS**

Substantial progress has occurred during the past two decades of QLED technology development in terms of EQE and device operational longevity. These breakthroughs can be summarized into four areas of development.

1. The tailored design and optimization of the core-shell structure and surface ligands of QDs to meet the specific needs of QLED devices. Conventional QD material improvement mainly focused on improving their optical properties, such as PLOY and FHWM. In fact, as seen in research reports,\(^{15-17}\) the enhancement of QLED performance has hit a bottleneck when applying the conventional method. TCL research teams have proposed a novel CQD core-shell optimization route to fit the need of QLED devices. In this work, a pioneering approach has been suggested to use ZnSe as the shell to extensively increase the hole injection efficiency while maintaining the CQD PLOY. In 2015, we reported for the first time on RGB QLED devices, where all three colors achieved an EQE above 10 percent, as well as a spin-coated red QLED device lifetime performance fulfilling all mass-production requirements (Fig. 3a).\(^{18}\) In addition, we reported on the importance of how optimizing the QD surface ligands is indispensable. Prof. Peng has...
suggested the concept of electrochemically stable ligands.\textsuperscript{19} In this model, MX2 ligand types, such as cadmium oleate with low reducing electrochemical potentials, are prone to experience redox reactions under external electric fields, which can lead to exciton quenching and ultimately can cause a dramatic reduction of QLED device performance. Therefore, the solution is to replace the low reducing potential MX2 ligands with high reducing potential redox-inert ligands (Fig. 3b). Moreover, TCL research teams also have reported groundbreaking progress in high-performance IJP red QLED devices via QD surface ligand optimization, specifically to enable the IJP device fabrication approach for mass production.\textsuperscript{20}

2. The optimization of QLED device structures and functional layer materials. Nanosized ZnO has proven to be an excellent ETL material for QLED devices to date. Dr. Qian was the first to report using ZnO NC thin films as an ETL to achieve outstanding QLED device performance.\textsuperscript{21} The enhancement of device efficiency can be attributed to the high electron mobility in ZnO NC thin films, the well-aligned conduction band of ZnO NCs with that of the QDs, as well as the deep valence band to block holes. ZnO NC thin films not only exhibit excellent stability under $\text{H}_2\text{O}/\text{O}_2$, but they also seem to effectively block $\text{H}_2\text{O}/\text{O}_2$ permeation into the QD EML, resulting in significant improvement in device lifetime (Fig. 3c). By inserting an insulating layer between the QD layer and ETL to optimize the charge injection balance state in QLED devices and to suppress the interface exciton quenching, Prof. Peng pushed the EQE of red QLEDs above 20 percent for the first time (Fig. 3d).\textsuperscript{4} Traditionally, a bottom emission device structure is used because of the ease of fabrication. However, the EQE of this thin-film planar device structure is limited to approximately 20 to 25 percent because of the waveguiding of most of the generated light being lost in the horizontal direction. To improve light extraction efficiency and to drive the device with a thin-film transistor (TFT) for a display application, a top emission device structure is necessary. In this device geometry, by tuning the functional layers to the proper thickness and creating a cavity effect, the light hitting the bottom electrode can be reflected back up and out of the planar device, leading to much higher luminance under the same applied bias.\textsuperscript{22} Because QDs inherently have narrow-band emission relative to organic molecules, this cavity effect in a top-emission QLED device can generate more light output than OLED pixels.

3. Resolving the degradation mechanism of QLED devices. Even with the significant increase in QLED R&D activities during the past five years, improving device performance has been slower than expected. A lot of this effort has been placed on resolving the degradation mechanism of QLEDs to overcome the sticking point that has prevented QLEDs from competing with OLED displays in the marketplace. Based on the research on red QLED lifetime in both regular and inverted structures, Prof. Chang and Prof. Jin both have suggested that the degradation of red QLED devices is caused by the physical damage of the organic HTL material from excessive electrons (Fig. 3e).\textsuperscript{23,24} These excess electrons could be creating nonradiative recombination centers within the HTL, leading to severe quenching of excitons and physical degradation of the HTL. As a result, these research groups targeted improving hole injection efficiency in red QLEDs to inhibit the overflowing of electrons into the HTL. With this insight, they recently reached major advancements in red QLED lifetime. As for the study of the degradation mechanism of blue QLEDs, joint research teams at Suchow University and TCL Research have examined the charge accumulation conditions in blue QLEDs under operation.\textsuperscript{25} The lifetime degradation in blue devices primarily was being caused by massive electron accumulation at the QD/ETL interface (Fig. 3e). The primary reason for the heavy charge accumulation was most likely a result of the large energy barrier between the QD and ETL conduction bands. To resolve this problem, the team is focusing on optimizing the QDs and ETL material conduction band barrier. Additionally, further study of the positive aging or burn-in effect in QLEDs could play a large role in getting the performance of blue QLEDs to the next level for commercial displays.

4. Active-matrix QLED display demonstrations. With the dramatic improvement of QLED device performance in recent years, more active-matrix (AM) RGB display panels have been fabricated to demonstrate the feasibility of CQD EL technology for commercial displays. In 2018, TCL introduced an AM RGB 5-inch display demonstration panel using all three colors generated with QLEDs and fabricated using IJP technology. Furthermore, TCL went on to generate a 32-inch hybrid display demo panel using red and green QLEDs combined with blue OLED pixels on the Generation (Gen) 4.5 production line. As blue QLED pixel performance has improved over the past 2–3 years, blue OLED pixels ultimately were replaced with blue QLED pixels to fabricate an all-QLED panel. In 2020, BOE successfully fabricated and introduced the first 55-inch RGB QLED panel using IJP technology fabrication, which is the largest to date.\textsuperscript{26} Sharp also recently reported a 6.2-inch AM-QLED panel fabricated using photolithography instead of IJP, which enables higher resolution displays.\textsuperscript{7,10} The successful fabrication of QLED pixels on TFT driving backplanes to generate AM RGB QLED panels amply demonstrates the commercial potential of RGB QLED technology. Currently, these QLED demonstration panels suffer from short operation stability because of the immature IJP technology combined with underdeveloped device reproducibility. These areas of improvement are the focus of QLED research groups in the display industry that will lead to more advanced RGB QLED display panel demonstrations.

**Infrared QLEDs**

Visible wavelength light-emitting QLED device performance has received significant attention over the past 10 years by research teams around the world in academia and industry, and there has
been tremendous progress made on device performance overall. However, IR EL QLED device development and performance has lagged behind. This is most likely due to the difference in commercial opportunities each technology could capture in the marketplace. Near-IR (NIR) and short-wave IR (SWIR) LEDs find widespread applications in fiber optic telecommunication, biomedical, night vision, and computing. Extensive studies have been performed to obtain OLEDs and perovskite thin-film LEDs (PeLEDs) with high EQEs in the IR. However, both types of materials suffer from fundamental band gap limitations to address the full SWIR spectrum. Organic dyes and polymers especially have a hard time addressing wavelengths beyond 1 µm and currently suffer from stability issues because of their relatively high conduction band energy relative to the vacuum. CQDs synthesized from narrow band gap IV-VI and III-V semiconductors, on the other hand, are ideal candidates for realizing high-performance IR-emitting LEDs, because of advantages such as high PLQY, narrow FWHM, tunable wavelength, high stability, and solution-based processability. PbS CQD materials, for example, can cover a broad spectral range of IR-emission wavelengths spanning from 900 to more than 2,000 nm, from NIR to full SWIR coverage.

To further improve IR-emitting QLED device EQEs, QD solid-state films simultaneously need to achieve high PLQY and highly efficient and balanced charge injection. The low luminescence efficiency of current solid-state IR-emitting CQD films is mainly caused by a CQD surface trap-assisted nonradiative recombination and inter-dot energy transfer. Previous strategies focused on reducing nonradiative decay in the CQD EML of IR-emitting QLEDs included thick epitaxial inorganic shell protection, long chain organic surfactant QD surface passivation, and QD incorporation into a polymer matrix. These strategies, however, inevitably block charge injection and cause a high turn-on voltage. One promising way to break this trade-off is to employ the host-guest concept, which is widely used in OLEDs. The role of the host is to effectively separate the emitting guest from self-quenching and diffuse charges in a balanced manner into the guest. Using this approach, both record-high EQE and maximum radiance have been reported in the literature. Currently, there are two kinds of host-guest EMLs: QDs-in-QDs and QDs-in-perovskite. The first one combines large band gap PbS CQDs and ZnO NCs as the matrix and uniformly embeds small band gap IR-emitting PbS QDs into this nanoparticle guest environment. Ligand exchange with short chain molecules also was performed to improve the charge diffusion length in the EML film, where the ZnO NCs and PbS CQDs in the matrix are responsible for the electron and hole transport, respectively.

Another synergistic role of the ZnO NCs is to remotely passivate electron traps on the PbS CQD IR-emitters. This QD-in-QD emissive CQD EML layer design led to high device performance with high radiance. The QD-in-perovskite approach leverages a perovskite network to form a Type I band structure with the IR-emitting PbS CQDs. Perovskites are known for their defect-free crystalline structure, which allows for a long carrier diffusion length and relatively good mobility. Also, by tuning the halide ratio between Br and I ions, the lattice mismatch between the matrix and the guest PbS CQDs can be minimized, effectively reducing CQD surface traps. By embedding CQDs in quantum-confined 2D perovskites, the charge also can be injected from the host to the CQD guest in the form of excitons, leading to balanced injection. Using this methodology, the EQE and brightness further improved. Also, the use of Cesium-containing triple cation perovskites to replace mono-cation versions improved film uniformity and robustness even further, leading to increased charge-carrier diffusion lengths. When also inserting a porphyrin interlayer between the anode and the EML, strong hole injection and therefore device operational stability are realized. The current
FRONTLINE TECHNOLOGY

November/December 2021 | informationdisplay.org

QD Lasers

COLLOIDAL QD-STIMULATED LIGHT EMISSION

Net-stimulated emission from QCDs was first observed for CdSe-based materials in 2000. This finding initiated a widespread research effort to harness QCD materials for optical gain, which is driven by the promise of forming solution-processed gain materials with tunable optical properties. Not unlike organic laser dyes or lanthanide ions, stimulated emission from QCDs involves an electronic transition between discrete states, typically the QCD LUMO and HOMO or band-edge levels (Fig. 4a). Given the sizeable oscillator strength of this so-called exciton transition, a fully inverted film of densely packed QCDs can attain a material gain exceeding 1,000 cm⁻¹. Given such a figure, QCDs have a clear advantage as a gain material for realizing small footprint microlasers. In QCD materials, the minor exciton-exciton Coulomb interaction minimizes the energy difference between the exciton and biexciton transition, such that biexciton absorption neutralizes exciton-stimulated emission (Fig. 4b). As a result, the exciton state is optically transparent at best, and net stimulated emission only is obtained from biexciton states. For a QCD ensemble, this implies a best-case scenario in which optical gain is only attained when QCDs contain one exciton on average, leading to the often used (N) = 1 benchmark, as outlined in Fig. 4c. More problematic than the increased gain threshold, however, is the rapid loss of biexcitons through Auger processes, a non-radiative recombination mechanism depicted in Fig. 5a that can attain a rate kₐu of 10⁻¹⁰ to 10⁻⁸ s⁻¹ in QCDs. This rapid loss of the inverted state raises the lasing threshold, especially for QCD lasers driven by continuous-wave (CW) optical pumping or DC electrical pumping.

ENGINEERING COLLOIDAL QDS FOR STIMULATED EMISSION

To overcome limitations related to biexciton gain in QCDs, CdSe/CdS core-shell materials have been widely used as a model system. Researchers show that engineering the core-shell structure is a good strategy to tweak the exciton-exciton Coulomb interaction and the Auger recombination rate. In the case of thin CdS shells, for example, the biexciton interaction is attractive, and net-stimulated emission can be attained below the (N) = 1 level. On the other hand, thick CdS shells and alloyed interfaces slow Auger recombination to 10 to 100 fold to levels comparable with the radiative exciton lifetime in core-only QCDs (Fig. 5c). However, as thicker CdS shells dilute the density of emissive CdSe cores in the solid-state QCD film and promote exciton-exciton repulsion, biexciton lifetime is traded against material gain and gain threshold. So, QCD laser development requires careful design of the QCD physical structure and its properties.

Next to adjusting biexciton properties, several directions to bypass the threshold limits inherent to biexciton gain have been explored in literature. Net gain from single excitons was obtained by leveraging the massive biexciton blueshift induced by the staggered band alignment in CdS/ZnSe QCDs, while nearly thresholdless-stimulated light emission was realized through optical transitions involving surface trap states in HgTe QCDs. Both approaches, however, involve low oscillator strength transitions that sacrifice material gain to obtain a long inverted state lifetime and a low gain threshold. More recently, electrochemical doping of CdSe/CdS or chemical doping of PbS QCDs was successfully explored as a method to reduce the gain threshold, yet stimulated emission still involves a multi-exciton state prone to rapid Auger recombination. Finally, theoretical considerations highlighted the possible impact of exciton-phonon coupling, which can yield single exciton gain when combined with biexci-

Fig. 5.

(a) QCD level model highlighting the Auger recombination process of a biexciton. (b) Time delay and wavelength map of material gain recorded on CdSe/CdS QCDs after femtosecond pulsed excitation. The decay of the material gain with increasing pump-probe delay reflects biexciton Auger recombination. (c) Auger lifetime as a function of the CdSe/CdS core-shell dimensions, comparing (markers) actual data with theoretical predictions based on volume scaling. The strong suppression of Auger recombination is assigned to interfacial alloying.
ton repulsion, not unlike organic dyes. Currently, however, no CQD material has fit this bill.

OPTICALLY PUMPED CQD LASERS
Looking at Auger recombination as the rate-determining bielectron loss process, two regimes of optical pumping of CQD lasers can be distinguished. Femtosecond (fs) pumping instantaneously creates an initial exciton population that is determined by the CQD absorption cross section and the pump fluence, but not the Auger recombination rate. Assuming an absorption cross section $\sigma_{\text{pump}} = 5 \times 10^{-15}$ cm$^2$ at a pump wavelength of $\lambda_{\text{pump}} = 400$ nm, the $\langle N \rangle = 1$ threshold is then reached with pulse energies of ~100 $\mu$J/cm$^2$, which are easily attained using amplified fs lasers. Upon CW pumping, on the other hand, the exciton population results from the balance between excitation and biexciton recombination. Here, the estimated pump fluences to sustain a biexciton population vary from 1 MW/cm$^2$ to 10 kW/cm$^2$ when the Auger rate drops from 10 ns$^{-1}$ to 0.1 ns$^{-1}$. Such power levels are regularly reached with nanosecond (ns) lasers but pose considerable challenges for plain CW pumping.

In particular when using CdSe-based CQDs, fs-pumped CQD lasers were demonstrated shortly after the first observation of gain by CQDs. By now, the demonstration of several engineered devices, such as vertical-cavity surface-emitting lasers, distributed feedback lasers, or integrated microdisk lasers, with lasing thresholds within the expected range (30–300 $\mu$J/cm$^2$) attest to the remarkable versatility CQDs have as an optical gain material (Fig. 6). Moreover, similar devices active at IR wavelengths recently were demonstrated using PbS CQDs. Under ns pumping, CdSe-based CQD lasers attain lasing action at equivalent CW pump fluences that can be as low as 39 kW/cm$^2$, and lasers using CsPbBr$_3$ perovskite CQDs recently were demonstrated. Microsecond lasing at similar pump fluences was achieved by replacing the long organic ligands at the CQD surface by short inorganic moieties to enhance thermal conductivity of CQD films and suppress heating during pumping. More recently, strain in the CdSe/CdS core-shell structure was exploited to further reduce gain thresholds and demonstrate actual CW pumping at thresholds slightly smaller than 10 kW/cm$^2$. Interestingly, such thresholds are comparable with the output power of commercial blue laser diodes.

ELECTRICALLY PUMPED CQD LASERS
Following the advent of high-efficiency QLEDs, research into electrically pumped CQD lasers has surged in the past five years. However, as compared to EL, considerably higher current densities are required to attain population inversion in a CQD EML. Indeed, to sustain the inversion of the band-edge transition, electron-hole pairs must be supplied at a rate approximately given by the product $n_{\text{QD}} \times k_{\text{Auger}}$ of the CQD surface density $n_{\text{QD}}$ and the Auger rate. Hence, for $n_{\text{QD}}$ ranging between $10^{12}$ to $10^{13}$ cm$^{-2}$, current densities of 100–1,000 A/cm$^2$ can be expected. Focusing architectures and avoiding current crowding in organic ETL/HTL layers, along with pulsed excitation, now allow CQD device structures to reach these high levels of current densities (Fig. 7a). However, next to such demands on materials, the step from a high brightness QLED to a laser diode also imposes severe constraints on the laser design.
Lasing action requires the combination of net-stimulated emission and feedback in an optical cavity, where the roundtrip gain must overcome the roundtrip loss. A first approach to an electrically pumped laser consists of a CQD film atop a distributed feedback grating (Fig. 6b and Fig. 7b) embedded within a QLED architecture. Here, the CQD film must be sufficiently thick to provide optical gain and ensure in-plane waveguiding. However, while optically pumped lasing could be attained in such architectures, electrical excitation has not been reached yet. Inverting thicker CQD films requires higher current densities, and additional losses can result from charge accumulation at interfaces, unbalanced charge injection, or increased trapping of charges in the CQD layer. Alternatively, as demonstrated recently, a QLED formed on top of a single-mode optical waveguide can be made part of a cavity (Fig. 7c). Such an integrated-photonic approach enables the optical mode to separate better from metallic contacts and to use the best QLEDs, yet population inversion in such a design has not been demonstrated.

**ALTERNATIVE GAIN MATERIALS**

CQD phosphor and LED technology decisively turned to III-V CQDs as a Cd-free alternative. Because epitaxial III-V InAs-based QDs routinely are used as a gain medium in electrically injected lasers, one expects III-V CQDs to be equally relevant for amplified emission, gain, or lasing. Even so, only a few studies in the literature report stimulated emission from III-V CQDs. Opposite from epitaxial III-V QDs, which are invariably embedded by iso-electronic III-V barrier layers, III-V CQDs typically are shelled with a II-VI semiconductor, such as ZnSe or ZnS. Hole-trap states have been linked to the uncontrolled Zn-incorporation in the InP core, while the hetero-electronic InP/ZnSe interface has a facet-dependent electronic structure that can contribute to charge-carrier trapping. Forming iso-electronic III-V/III-V core-shell QDs may open a new path for optical gain using III-V CQDs. Significant headway has been made relative to spherical (3D) CdSe-based CQDs for optical gain by exploring different NC shapes and new material classes. In particular, CdSe 2D nanoplatelets (NPLs) have shown promise. CdSe NPLs have a substantially larger material gain with gain thresholds of a few μJ/cm² when measured under fs optical pumping. Both aspects are correlated with the increased absorption coefficient...
brought about by the 2D NPL shape and the bosonic nature of the exciton, which suppresses gain saturation.\textsuperscript{31,66,68} Auger recombination rates are also comparable to the biaxiont radiation rate.\textsuperscript{66,68} and at present, optical gain under CW pumping has been observed.\textsuperscript{69} A second interesting class is formed by the lead halide perovskite NCs. Being typically larger in dimension than their Bohr radius, they benefit from a reduced Auger recombination rate because of the volume scaling effect,\textsuperscript{41} and likely a stricter enforcement of momentum selection rules that apply to Auger recombination. As a result, gain thresholds comparable to CdSe 2D NPLs have been recorded, as well as gain under ns to CW optical excitation.\textsuperscript{70} Results thus far show that controlling the size, shape, and interface of core-shell QCDs is paramount to obtaining efficient gain in these materials.

**Conclusion**

Impressive progress has been made to date in developing visible wavelength light-emitting QLEDs. Luminance efficiency and device operation stabilities for both red and green wavelengths are viable for commercial display applications. We now see literature reports focused on top-emission device structures that can be driven by TFT backplanes with improved light extraction efficiency and aperture ratio.

The current focus for RGB QLED commercialization mainly lies on further blue QLED device lifetime improvement and UP uniformity and robustness for large-scale manufacturing. Cd-based RGB colloidal QLED devices show the most advanced UP performance over a large area mainly because of the ability to fine-tune both QD conduction and QD valence bands via highly engineerable alloyed core-shell structure composition. In contrast, InP-based CQD synthesis and composition engineering are not mature enough to allow the core with II-VI shells because of the oxidation number difference. Thus, Cd-based QLED devices most likely will be the first type of QLED devices to be used commercially in products such as next-generation middle- to large-sized display screens.

Large displays in particular are well suited to be manufactured using CQD UP technology based on the screen resolution and pixel size being perfectly matched with current high-throughput, mass production UP capabilities. Based on recent industry achievements, our confidence is high that commercial QLED devices based on inkjet printing will be in the marketplace soon. We also expect to see the commercialization of IR-emitting QLEDs; with further development, they significantly lower applied bias compared to visible devices (because of their narrower band gap) will most likely boost device operation stability.

Opposite from QLED technology, the formation of CQD lasers is in an earlier stage of development and strong application cases are needed to direct research efforts. Optically pumped red and green CQD lasers, for example, offer a single technology that can be combined with blue pump lasers for laser projection and displays—applications that will strongly benefit from the future realization of electrically pumped CQD lasers. CQD lasers in the IR, however, probably hold the most promise, where telecommunication, sensing, inspection, or automated vision all need small, low-cost, and versatile laser sources. \(\square\)

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