QUANTUM DOTS-BASED INFRARED LIGHT-EMITTING DIODES: A STRATEGIC APPROACH TO ACHIEVE BETTER DEVICE PERFORMANCE

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Abstract. Quantum dots (QDs) are chemically synthesized nanomaterials with tunable optical properties, making them attractive for applications such as light-emitting diodes, sensors, and related optoelectronic devices. While visible-emitting QDs have been successfully commercialized in display technologies, infrared (IR)-emitting QDs are equally important for applications including IR light-emitting diodes, photovoltaics, and photosensors. Conventional IR devices rely on energy-intensive solid-state fabrication processes, whereas solution-based chemical processing offers a low-cost alternative. However, this approach faces challenges related to material quality and process-induced defects. This review addresses these issues and outlines strategies to achieve high-efficiency infrared devices through optimized chemical processing.

Keywords. Quantum dot, quantum dot light-emitting diodes, infrared light source.

1 INTRODUCTION

Quantum dots (QDs), recognized as advanced zero-dimensional semiconductor materials, have attracted extensive research over the past three decades due to their unique optical and electronic properties.[1] These characteristics include size- and composition-dependent emission tunability, narrow spectral bandwidth, and high quantum yield (QY). Such features enable precise control of emission wavelength across a wide spectral range, making QDs highly attractive for optoelectronic applications. QDs emitting in the visible region have already been commercialized in display technology, primarily through photoluminescence-based architectures, while electroluminescence quantum dot light-emitting diodes (QLEDs) have also achieved rapid progress and advanced prototype stages in recent years. [2, 3]

In contrast to visible QLEDs, the development of infrared quantum-dot-based light-emitting diodes (QD-IRLEDs) remains significantly more challenges. These include intrinsically lower radiative recombination rates, stronger non-radiative losses, inefficient charge balance, and severe optical out-coupling limitations. As a result, achieving high-performance IR electroluminescence requires simultaneous optimization of materials characteristic, interfaces stability, and device architecture. Currently, QDs designed for near-infrared (NIR) and middle of shortwave infrared (SWIR) emissions remain under intense research and development to meet the demands of industrial applications.

Infrared light sources are essential components in a wide range of applications, including the internet of things, security systems, and electrical vehicles, where the integration of light-emitting diodes with sensors is critically important. [4, 5] These application areas have significantly driven research interest toward IR-emitting QDs, and QD-based IR optoelectronic devices.

Currently, IR devices are predominantly fabricated using conventional solid state-semiconductor technologies. Although these approaches deliver high performance and reliability, they are typically energy-intensive and impose stringent manufacturing requirements, including ultra-clean environments, precise control of temperature and humidity, and equipment with massive energy consumption.[6] Such constraints impede low-cost production and limit integration with diverse substrates.

However, QDs offer a promising alternative for IR device fabrication due to their advantages in materials synthesis, compatibility with ambient processing conditions on wide range of substrates. Nevertheless, several challenges remain in applying QDs to IR devices, following both the materials properties and the complexities of fabrication, which can adversely affect device performance.

To enhance the IR device performance, particularly quantum dot based infrared light-emitting diodes (QD-IRLEDs), various approaches have been required, including optimization of materials synthesis, device

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structure, and fabrication techniques. Several review articles have summarized the development of infrared quantum dots and their optoelectronic applications. However, most of these studies primarily focus on either material development or device performance individually. In contrast, this review aims to provide a broader perspective by integrating discussion on quantum dot materials, ligand engineering, charge transport layers, device architectures, and optical enhancement strategies within a unified framework. By examining the interplay among these factors, this review highlights the key challenges limiting quantum dot–based infrared light-emitting diodes (QD-IRLED) performance and outlines potential approaches for achieving efficient and stable infrared electroluminescence.

2 REVIEW METHODOLOGY

The literature discussed in this review was selected based on its relevance to the development of QD-IRLEDs. Particular attention was given to studies addressing performance optimization through materials design, device architecture, preparation and ligand exchange processes, charge transport layers, and optical management. Both foundational and recent publications were considered to provide a balanced overview of the current progress, challenges, and future directions of infrared quantum-dot light-emitting devices.

3 DISCUSSION

3.1 An overview of materials

Quantum dots (QDs) are inorganic semiconductor nanocrystals with emission characteristics that can be finely tuned through compositional control and size modulation, primarily governed by confinement effects. Chemical synthesis enables precise control over QD morphology and dimensions by selecting appropriate elemental composition, allowing emission across the entire electromagnetic spectrum – from visible to infrared wavelength, as presented in Figure 1.[7] Lead chalcogenide QDs, including lead sulfide (PbS, PbCdS), selenide (PbSe) and telluride (PbTe), are among the most widely utilized materials for NIR and IR applications. However, lead chalcogenide QDs exhibit several intrinsic material limitation, such as spare energy band level, large exciton Bohr radius, and low amount of surface atom, which can lead to reduced optical performance.[8] To address these issues, core/shell structures are commonly employed.[9] In such architectures, a wider-band gap inorganic semiconductor shell is epitaxially grown around the emissive core, which effectively suppresses surface trap states and enhance exciton recombination efficiency. Despite their excellent optoelectronic properties, concerns regarding the use of heavy-metal elements have motivated the development of heavy-metal-free IR QDs, with Indium Arsenide (InAs) QDs emerging as a promising candidate. However, InAs QDs require multiple shell layers – often more than two – to ensure high material quality, which substantially increase the complexity of QDs synthesis process and can hinder charge transport. [10, 11]

In addition to core and shell engineering, long-chain organic ligands are commonly introduced on the surface of both core or core/shell QDs to ensure solubility in non-polar solvent, improve surface passivation and enhance QDs colloidal stability.[12] While these ligands are essential for solution processing, the long-chain carbon ligand also acts as insulating barriers, thereby limiting charge transport and reducing the electrical conductivity of QDs based optoelectronic devices.

Beyond QDs, metal-halide perovskite and organic semiconductors have also been explored as active materials for NIR LEDs applications. [13, 14] Although devices based on these materials often exhibit high radiance and external quantum efficiency (EQE), their fabrication processes are generally more complex than those of QD-IRLEDs. For instance, organic LEDs often rely on thermal evaporation, while perovskite-based devices require cleanroom processing. In contrast, QDs offer more straightforward solution-processing approach, and their ligand chemistry additionally provides flexibility for device customization. Importantly, the luminescence spectra of perovskite and semiconductor organic materials generally peak below 900 nm, limiting their applicability for broader infrared application. By comparison, QDs can be engineered to emit across a wider spectral range through careful control of composition and size, making them highly suitable for variety applications such as medical imagining, environmental sensing and night vision technologies. Although heavy-metal-free alternatives such as InAs QDs are increasingly attractive for commercialization, lead chalcogenide QDs (PbS, PbSe) continue to dominate QD-IRLED research due

to their simpler surface chemistry, stronger electronic coupling, and higher achievable electroluminescence efficiency. The advantages and limitations of different QDs materials is summarized in Table 1.

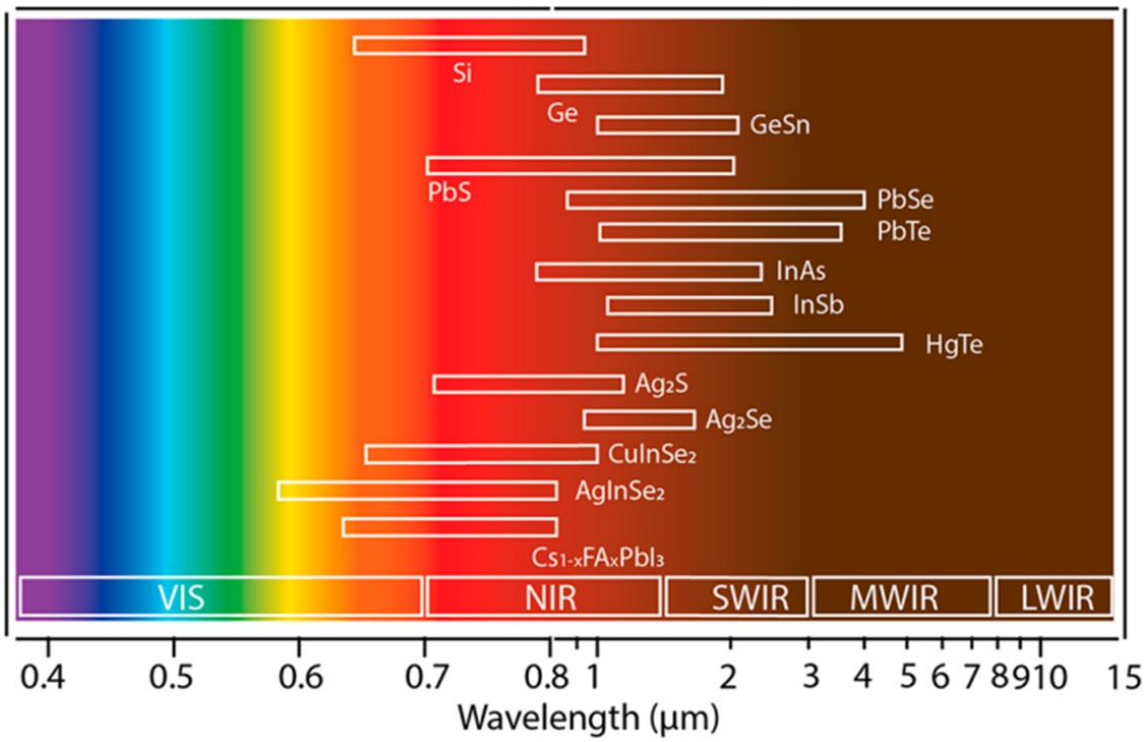


Figure 1. Quantum dots composed of various chemical elements exhibit distinct emission wavelengths. Reproduced from Reference [7] with permission. Copyright 2019, American Chemical Society.

Table 1. Comparison of different types of Infrared-based Quantum Dot materials

QD system	Emission range	Advantages	Key limitations
PbS/PbSe (lead chalcogenide)	NIR-SWIR	High quantum yield Relatively simple synthesis Compatible with device fabrication under ambient conditions	Contains heavy-metal elements (e.g., Pb)
InAs	NIR-SWIR	Heavy metal-free composition (e.g.,indium-based materials	Requires complex shell engineering, often involving multiple shell layers such as ZnSe and ZnS Device fabrication typically requires specialized processing environments, including cleanroom facilities
Perovskites	NIR	Quantum yield exceeding 90%	Limited stability under ambient conditions Emission wavelength generally limited to below 900 nm Requires stringent fabrication conditions and specialized equipment.

3.2 Light-emitting diodes device structure

Light-emitting diodes (LEDs) are semiconductor-based optoelectronic devices that emit light when an external voltage bias is applied. Their operation relies on the injection of charge carriers into the emissive layers, where radiative recombination occurs, resulting in light emissions. A typical LED structure consists of a fluorescent semiconducting emissive layer positioned between two (or more) charge transport layers (CTLs), as shown in Figure 2. These CTLs facilitate efficient injection and transport of electrons and holes into the emissive region while preventing charge recombination at the electrode interfaces. By aligning the energy levels appropriately, CTLs confine carriers within emissive zones, promoting efficient recombination and light generation corresponding to the bandgap of the emissive materials.

LEDs are generally fabricated in either conventional or inverted structural configurations. In conventional structure, the hole transport layer is directly deposited onto the substrate, followed by the emissive layer and then the electron transport layer (ETL). Conversely, inverted structure begins with the ETL on the substrates, followed by the emissive layer and the hole transport layer. Both configurations have been widely investigated for QD-IRLED, and comparable device performance has been reported, with no definitive preference on a better structure.

In addition to these two common architectures, tandem LED architecture has been developed, particularly for organic semiconductor-based devices. Tandem LEDs consist of multiple electroluminescent units vertically stacked and interconnected through charge-transport layer, offering a potential pathway to increased luminance and operation lifetime under low current densities.[15, 16] However, for NIR and IR LED, achieving constructive optical interference and efficiency remains challenging. Moreover, optical losses caused by waveguided modes, surface plasmon polaritons, inaccurate positioning of recombination zone, and the increased complexity associated with multilayer thin-film fabrication often negate the potential advantage of tandem stacking.[16, 17] Despite the difference in device the structure, several structural factors critically affect LED operation, including charge imbalance, recombination zone location and optical losses in different layers. The charge imbalance between electron-current and hole-current can shift the recombination zone toward interface or charge transport layers, resulting in increased non-radiative recombination and degraded device performance.[18] Besides, the photon generated within recombination zone may lose its characteristic due to absorption, scattering, or reflection as they propagated through multilayer structure.[19] Therefore, optimizing the CTLs of devices is also necessary to achieve high-performance LED operation.

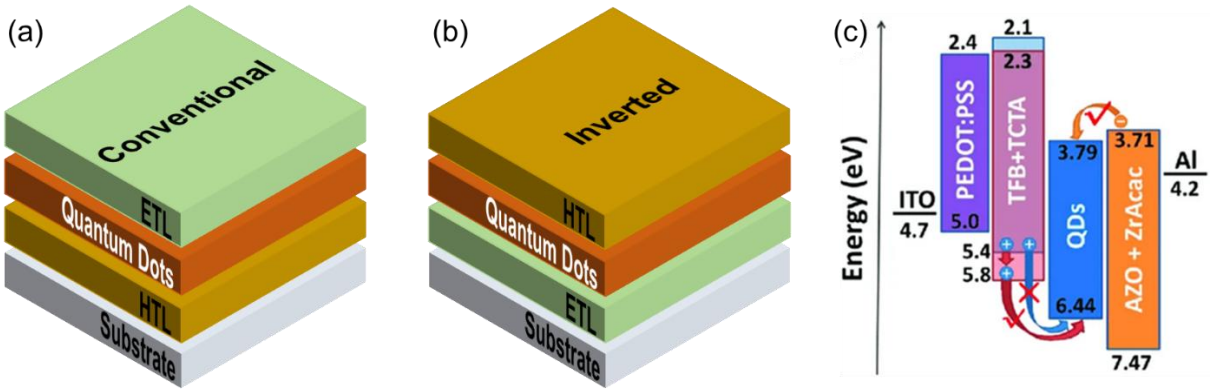


Figure 2 Schematic representations of two distinct light-emitting diode (LED) device architectures. (a) In the conventional structure, the hole transport layer (HTL) is deposited directly onto the substrate as the first layer, whereas (b) in the inverted configuration, the electron transport layer (ETL) serves as the initial layer on the substrate. (c) Differences in the energy-band levels between the charge transport layers (CTLs) and the emissive layer (EML) influence charge transport and, consequently, device performance. Reproduced from Reference [18] with permission. Copyright 2019, American Chemical Society.

3.3 Materials Preparation for Device Fabrication

Colloidal infrared quantum dots are typically synthesized with long-chain organic ligands to ensure colloidal stability, effective surface passivation, and solubility in non-polar solvents. Although these ligands

are essential during synthesis, their insulating characteristic severely impedes charge transport in solid-state optoelectronic devices. As a result, ligand exchange is a critical step in QD-IRLED fabrication,[20] with the main objective of enhancing charge carrier injections and transport within the device. Ligand exchange strategies can generally be categorized into solution-phase and solid-states processes. In the solution-phase approach, QDs capped with long-chain ligands are dispersed in a solution containing short ligands for a defined period to enable ligand replacement (Figure 3a). The resulting short-ligand-capped QDs are then redispersed in suitable solvent (most commonly butylamine – BTA, dimethylformamide - DMF, or mixture of both in different ratio) for further film deposition. This approach can produce relatively smooth QD films; however, it option compromises QDs stability and photoluminescence due to the strong surface-solvent interactions.[21, 22] Moreover, polar solvents such as BTA and DMF are chemically aggressive and poor compatible with multilayer device fabrication, which significantly limits the utilize of solution-phase ligand exchange in light-emitting diodes.

In contrast, solid-state ligand exchange remains the most compatible method for multilayer IRLED fabrication, because QDs are largely exposed to solvents only after film deposition. In this process, a QD film is first deposited on the substrate, followed by the dropping of short-ligand solution. During the ligand exchange, long ligands are replaced by short ones, accompanied by the re-arrangement of QD particles within the film. This rearrangement can induce film contraction and crack formation.[23] To mitigate cracking, additional QD layers are often deposited sequentially, with ligand exchange performed after each deposition. While this approach helps reduce macroscopic cracks, it typically results in increased surface roughness. Furthermore, repeated solid-state ligand exchange and solvent-rising steps may reduce overall ligand coverage, leading to degraded surface passivation and device performance. Despite these limitations, solid-state ligand exchange has become the dominant strategy for QD-IRLED fabrication due to its better compatibility with multilayer device structure. The advantages and disadvantages of two ligand exchange processes are summarized in Table 2.

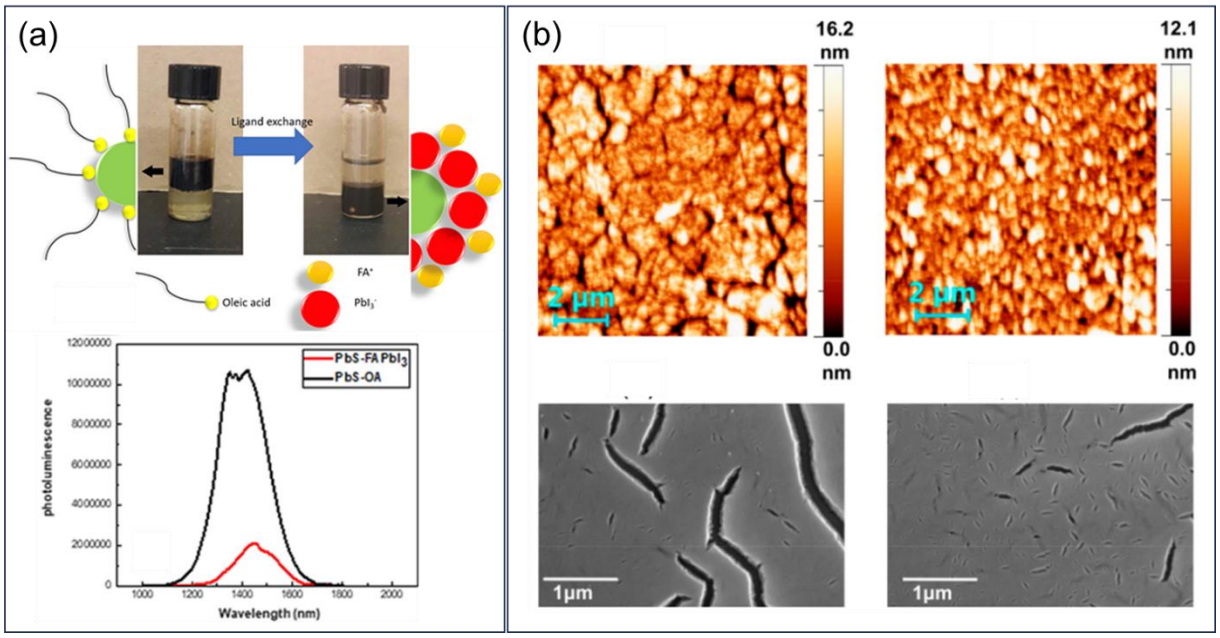


Figure 3 (a) Solution-phase ligand exchange: Quantum dots (QDs) initially dispersed in a non-polar solvent remain above the polar phase containing short-chain ligands. After exchange, QDs functionalized with short ligands migrate to the bottom, accompanied by a notable reduction in photoluminescence intensity. (b) Solid-state ligand exchange: The QD film exhibits pronounced cracking due to particle rearrangement during ligand replacement, affecting film uniformity. Reproduced from Reference [22] and [23] with permission. Copyright 2020 and 2021, respectively, American Chemical Society.

To overcome these drawbacks with ligand exchange, various optimization strategies have been explored to improve film morphology and quality. One common approach involves post-synthetic treatments to remove the residue precursors, thereby enhancing interparticle connectivity. Moreover, the selection of solvents

used to deliver short ligands is essential to allow sufficient exchange time and controlled the QDs rearrangement, resulting in a dense and uniform film.[24] These refinements directly contribute to improved device efficiency.

Beyond the film morphology, surface passivation plays a vital role in determining QD-IRLED performance. Replacing the long ligand with short ones significantly enhances electrical conductivity, with ligand chain length strongly influencing device behavior.[4] The shortest ligand, such as two-carbons chain, often yield low efficiencies due to insufficient surface passivation, whereas intermediate chain lengths (around six to eight carbons) tent to provide better performance. In particular, QDs capped with seven-carbon ligands have been reported to exhibit the highest efficiencies, possibly attributed to improved surface passivation, stronger electronic coupling between adjacent QDs, and more balanced charge-carrier dynamics within the EML. Additional passivation strategies include coating QDs with conductive polymers or perovskite materials, [25, 26] which can further enhance charge transport and device efficiency. Another promising approach involves mixing small and large QDs within the emissive layer.[27] In this configuration, smaller QDs passivate larger ones and act as donor states, transferring carrier to acceptor state of larger QDs. From an energy-band perspective, smaller QD introduces higher energy barrier that confines carriers within the lower-energy barrier larger QDs, thereby enhancing recombination efficiency. Related strategies include incorporating ZnO nanoparticles or using multiple sized QDs to tailor charge transport and broaden the EL spectra for specific applications.[28]

Given the extensive use of solvents during ligand exchange, the selection of CTL is critically important for stable QD-IRLED operation. Polar solvents and alcohols commonly used during ligand exchange – such as methanol, ethanol, DMF, or BTA – can partially dissolve polymer-based CTLs.[29] Common hole-transport layers including PEDOT, PVK and TFB are particularly vulnerable, often leading to interfacial degradation, poor charge balance, and extremely weak electroluminescence. Early QD-IRLEDs employing polymer-based architectures exhibited very low emission intensities due to damage to underlying polymer layers during solid-state ligand exchange.[30] These observations highlight the importance of solvent-resistant and well-aligned CTLs. Inorganic CTLs, including smaller lead chalcogenide nanoparticles, such as PbS, offer a promising alternative due to their superior chemical and thermal stability.[6] Smaller QDs possess larger bandgaps, enabling flexible energy-level alignment across device layers. Furthermore, ligand selection directly influences the valanced band position of QD layers, making ligand engineering critical for optimal device performance. Overall, inorganic CTLs - particularly metal-oxide-based electron transport layers such as ZnO – are widely adopted due to their facile synthesis, tunable properties, and quantum dot-like behavior, in which smaller particle size corresponds to larger energy bandgaps, facilitating device configuration. A comparison of device performance achieved using different approaches is presented in Table 3.

Table 2. Comparison of two ligand exchange process – solution-phase ligand and solid-state ligand exchange

Method	Pros	Cons	Device impact
Solution-phase	Smooth films	Toxic solvents Instability	Rarely use
Solid-state	Device - compatible	Cracks High roughness	Needs optimization

Table 3. Comparison of device performance based on different optimization approaches.

Device structure	Materials (Emission layer)	Emission wavelength (nm)	EQE (%)	Stability	Ref
Conventional: TPD/EML/MZO	Perovskite - FAPbI3	850	9.5	600 h	[35]
Conventional: TAPC/mCP/EML/B_3PyMPM	Organic materials – Py-TPA	726	22.2	N/A	[36]
Inverted: ZnO/PMMA/EM-L/TPD/MoO_x	InAs@ZnSe 7ML shell	900	13.3	24 h	[37]

Inverted: ZnO/EML/NPB/MoO_3	PbS (Solution ligand exchange with TBAI)	~1400	4.12	N/A	[38]
Conventional: PEDOT/TFB/EM-L/ZnO	PbS (Solid state ligand exchange with EDT)	~1530	0.35	N/A	[39]
Inverted: ZnO/EML/EDT-PbS	PbS (Solid state ligand exchange with MPA)	~1000	4.12	532 h (@7 W sr^{-1} m^{-2})	[40]

3.4 Metasurface application

Even with optimized QDs materials and electrical device architecture, the external efficiency of QD-IRLEDs remains fundamentally limited by optical losses. These losses originate from waveguiding within device layer, absorption by substrate, and free-carrier absorption at long wavelengths.[31] Such intrinsic optical limitations cannot be completely addressed through materials and electrical optimization alone, thereby motivating the development of photonic strategies aimed at enhancing infrared light extraction.

In this context, metasurface-assisted optical engineering has recently emerged as a promising approach to improve infrared light transmission and emission efficiency. Specifically, metasurfaces are integrated onto the substrates, the substrate surface is patterned with engineered micro-nano structure designed to manipulate the propagation of light and enhance the optical output. In contrast to conventional transparent electrodes such as indium tin oxide (ITO), which exhibit progressively reduced transmittance in the infrared region - with losses reaching about 20% - carefully designed metasurface can manipulate resonant light-matter interactions.[32] These structures enable suppression of reflection, enhancement of resonant scattering, and preferential redirection of infrared emission toward the forward direction.

Previous studies have shown that patterning metasurface on both sides of a silicon (Si) substrate can increase optical transmittance by up to 40% in the 7 – 14 μm wavelength range compared to an unmodified Si substrate.[33] These meta-surfaces are typically based on Mie-resonant nanophotonic structure, which enhance constructive resonance to achieve anti-reflection behavior and forward-directed light scattering. Such structural designs offer a cost-effective alternative to conventional window optics in long-wave infrared (LWIR) application.

Another metasurface strategy involves circular patterning of dielectric silicon nitride (Si_3N_4)-gold (Au) stacks deposited on dual-layered Si_3N_4/Au structure fabricated on a silicon substrate.[34] This configuration has demonstrated an experimental emissivity of ~80% across 8 – 14 μm wavelength range. The observed broadband high emissivity is attributed to the combined effect of surface plasmon resonance (SPR) and multiple gap plasmon resonance (GPR). In this design, SPR is primarily governed by the periodicity of metasurface, while the GPR arises from metal-dielectric metal (MDM) cavity structures with varying dielectric thicknesses. Within the stacked nanocavity meta-emitter design, the Au cylinder and Au bottom reflector act as reflective mirrors, whereas Si_3N_4 cylinder and Si_3N_4 dielectric layer function as optical spacers that control resonance conditions.

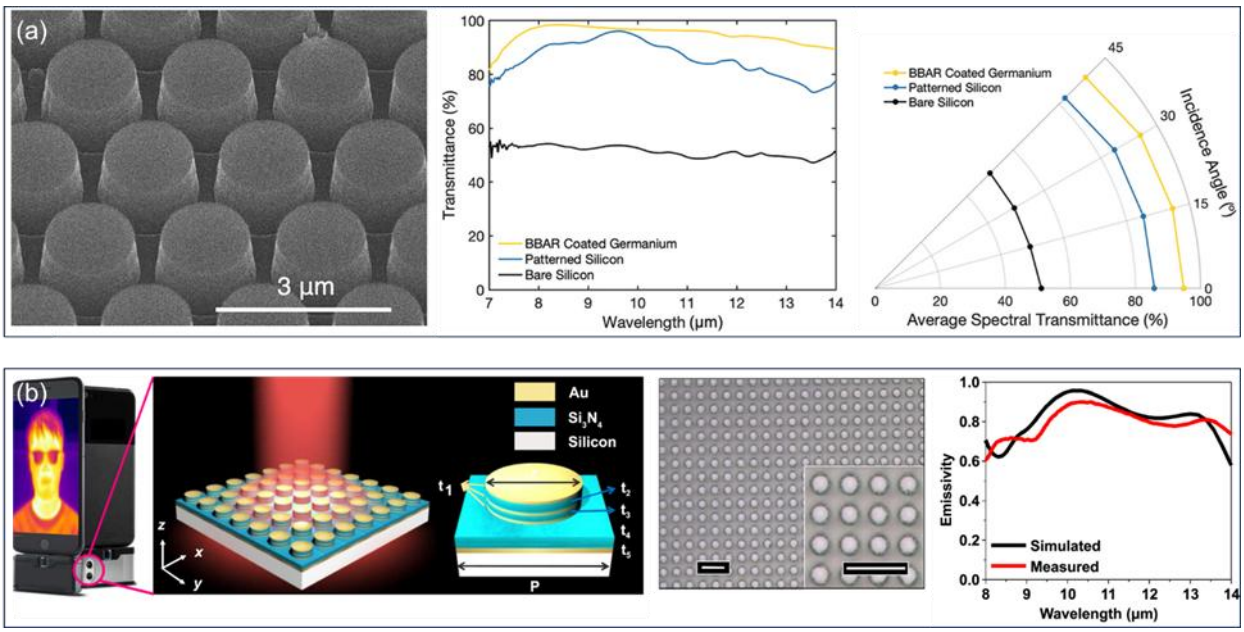


Figure 4 (a) Meta-surface patterned on the top surface of a silicon (Si) substrate, achieving ~80% transmittance in the 7–14 µm range—significantly higher than that of bare Si. Reproduced from Reference [33] with permission. Copyright 2023, American Chemical Society. (b) Meta-surface structure integrated atop a dual-layered Si_3N_4/Au stack on a Si substrate. The SEM image (scale bar: 10 µm) shows the fabricated structure, which exhibits an emissivity of approximately 85%, closely matching simulated values. Reproduced from Reference [34] with permission. Copyright 2022, IOP Publishing.

4 OUTLOOK AND CONCLUSION

Infrared quantum-dot light-emitting diodes (QD-IRLEDs) represent a promising class of solution-processed optoelectronic devices, offering potential advantages in terms of cost, material versatility, and compatibility with large-area and flexible substrates. Compared with conventional solid-state infrared emitters, QD-IRLEDs enable wavelength tunability through materials design and can be fabricated under relatively mild processing conditions. Nevertheless, achieving high efficiency and long-term stability in IR electroluminescence remains significantly more challenging than in visible QLEDs.

The performance limitations of QD-IRLEDs arise from several interconnected factors, including intrinsically lower radiative recombination rates in infrared emitters, enhanced non-radiative losses, inefficient charge balance, and severe optical out-coupling losses at long wavelengths. As discussed in this work, these challenges cannot be addressed through material optimization alone. Instead, they require a holistic strategy that integrates quantum dot synthesis, surface and ligand engineering, device architecture design, and optical management.

Ligand chemistry plays a central role in determining both film morphology and charge transport within the emissive layer. Although solid-state ligand exchange has emerged as the most practical approach for multilayer IRLED fabrication, it often introduces film cracking, surface roughness, and partial loss of surface ligands. Future progress in this area will depend on the development of ligand systems and exchange protocols that simultaneously provide strong electronic coupling, effective surface passivation, solvent compatibility, and mechanical film stability.

Interfacial engineering and charge transport layer selection are equally critical for stable IRLED operation. The chemical vulnerability of polymer-based transport layers to polar solvents commonly used in ligand exchange highlights the importance of solvent-resistant inorganic transport layers and well-aligned energy-levels across the device interfaces. Achieving balanced carrier injection is particularly important for suppressing non-radiative recombination processes, which are especially detrimental in infrared devices.

Beyond electrical optimization, optical losses associated with substrate absorption, waveguiding effect, and limited electrode transparency fundamentally constrain the external efficiency of IRLEDs. Emerging photonic strategies, such as metasurface-assisted light extraction and photon-management techniques, provide promising pathways to address these optical bottlenecks and complement materials-level

improvements. Although integration of these approaches into QD-IRLED architectures is still at an early stage, their importance is expected to grow as internal quantum efficiency continues to improve.

No single strategy can fully address the performance limitations of QD-IRLEDs. While material optimization, ligand engineering, charge transport layer design, and optical management can each improve specific aspects of device performance, the highest efficiencies are typically achieved through their combined optimization. Therefore, future progress is expected to rely on the synergistic integration of these approaches to simultaneously enhance device efficiency, stability, and manufacturability.

In summary, further advancement of QD-IRLEDs will require coordinated innovation across materials chemistry, interfacial engineering, device physics, and optical design. By systematically addressing challenge related to charge transport, surface passivation, solvent compatibility, and light-extraction efficiency, the performance of quantum-dot-based infrared light-emitting diodes can be further improved. However, additional progress in device stability, operational lifetime, reproducibility, and scalable fabrication processes will be necessary before QD-IRLEDs can be considered for extensive practical deployment in applications such as sensing, imaging, communications, and infrared illumination.

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