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Material Advantages and Device Challenges of Ag_2Se Quantum Dots for Near-Infrared QLED Applications

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Abstract. Near-infrared quantum-dot light-emitting diodes (NIR QLEDs) are being investigated for applications such as optical communication, sensing, imaging, and emerging display technologies. However, many established near-infrared quantum dots, such as CdSe- and PbS-based materials, or other heavy-metal-containing materials. Their toxicity presents an important obstacle to large-scale manufacturing, disposal, and commercial use. Ag_2Se quantum dots offer a possible alternative. They have several attractive features for near-infrared optoelectronic devices, including a narrow bandgap, near-infrared emission, and compatibility with solution-based processing. However, these material advantages have not yet been fully translated into high-performance NIR QLEDs. At present, the development of Ag_2Se-based NIR QLEDs is still at an early stage, mainly because device performance is affected by several issues, such as surface defects, non-radiative recombination, insulating long-chain ligands, imbalanced charge injection, poor film quality, and limited operational stability. This work reviews the principal material advantages of Ag_2Se quantum dots and discusses the major challenges associated with their integration into NIR QLEDs. Potential improvement strategies, including surface passivation, ligand exchange, carrier-transport-layer optimization, interface engineering, and device encapsulation, are also evaluated. Overall, Ag_2Se QDs have considerable promise for lower-toxicity NIR light-emitting devices. However, further progress in synthesis reproducibility, film formation, and operational stability is still needed.

Keywords: Ag_2Se quantum dots, near-infrared quantum-dot light-emitting diodes, surface passivation, ligand engineering

1. Introduction

In recent years, colloidal quantum dots have attracted considerable attention in optoelectronic devices because their optical properties can be tuned by controlling particle size. When the size of quantum dots changes, their bandgap also changes, which leads to a shift in the emission wavelength. As a result, quantum dots can emit light across a wide spectral range, from the visible region to the infrared region. Besides this size-dependent tunability, quantum dots usually show strong light absorption and relatively narrow emission bands. These features make them useful for full-color displays, optical communication, bioimaging, and other related applications [1]. In quantum-dot light-emitting diodes (QLEDs), quantum dots serve as the emissive layer, where

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injected electrons and holes recombine to generate light. Nevertheless, achieving high-performance QLEDs remains challenging, since device efficiency and stability can still be affected by field-induced quenching, non-radiative recombination, unwanted energy transfer, and operational degradation.

Conventional near-infrared quantum dots, including CdSe, PbS, PbSe, and Hg-based materials, have been widely investigated because they possess tunable narrow bandgaps and relatively mature synthesis routes. However, their practical use is still restricted by the presence of toxic heavy metals such as Cd, Pb, and Hg, which may cause concerns related to human health, environmental safety, and large-scale commercialization. For example, the European RoHS Directive limits the use of hazardous substances, including lead and cadmium, in electrical and electronic equipment. This regulatory background has encouraged the development of quantum dots with lower toxicity or without regulated heavy-metal elements. As shown in Table 1, although conventional near-infrared quantum dots usually show favorable optical properties, their heavy-metal composition remains a major limitation.

Table 1. Comparison of conventional near-infrared quantum dots and lower-toxicity alternatives

Quantum-dot material	Main elements	Optical advantage	Main concern	Remarks
CdSe QDs	Cd, Se	Mature synthesis and excellent optical properties with tunable bandgap	Cd-related toxicity and environmental concerns	Restricted by RoHS directive due to Cd content
PbS QDs	Pb, S	Narrow bandgap and strong NIR absorption/emission	Pb-related toxicity and regulatory restrictions	Restricted by RoHS directive due to Pb content
PbSe QDs	Pb, Se	Suitable bandgap for NIR optoelectronic applications	Pb-related toxicity and environmental concerns	Restricted by RoHS directive due to Pb content
Hg-based QDs	Hg-containing compounds	Narrow bandgap and NIR response	High toxicity of Hg-based materials	Environmental and health risks limit commercialization
Ag_2Se QDs	Ag, Se	NIR emission and relatively lower toxicity	Further improvement in stability, PLQY, and device performance is still needed	Promising less-toxic alternative for NIR optoelectronic applications

Ag_2Se quantum dots have been explored as alternative materials for near-infrared optoelectronic devices. As a silver chalcogenide, Ag_2Se generally raises fewer toxicity concerns than infrared quantum dots containing lead or mercury. It also shows intrinsic near-infrared emission, while its optical response can be adjusted to some extent through the control of particle size and composition. Experimental studies have confirmed that colloidal Ag_2Se QDs are optically active in both the near-infrared and short-wave-infrared regions. Zhu et al., for example, prepared Ag_2Se QDs with tunable emission in the second near-infrared window [2]. Shi et al. reported Ag_2Se QDs with absorption peaks ranging from 830 to 954 nm and fluorescence quantum yields reaching 23.4% [3]. These results suggest that Ag_2Se QDs may be useful for infrared light-emitting and sensing applications. However, their material development is still less advanced than that of conventional infrared QDs. Difficulties remain in controlling particle size, improving photoluminescence quantum yield, reducing surface defects, and maintaining colloidal stability. In addition, their optical properties are

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strongly affected by crystal phase, surface composition, and ligand structure, making reproducible synthesis and device optimization more difficult.

Accordingly, this review focuses on the use of Ag_2Se QDs in near-infrared QLEDs. The following sections first introduce the main material advantages of Ag_2Se QDs, and then discuss the key problems that still limit their device performance. Possible strategies for improving emission efficiency, device stability, and environmental compatibility in NIR electroluminescent applications are also considered.

2. The material advantages of Ag_2Se quantum dots

2.1. Low-toxicity advantage

A key advantage of Ag_2Se quantum dots is the absence of cadmium, lead, and mercury, which are commonly found in many conventional infrared quantum dots. Cd-, Pb-, and Hg-based QDs can offer excellent optical properties, but their potential toxicity and environmental impact remain major barriers to wider practical use. From this perspective, Ag_2Se QDs are usually regarded as a lower-toxicity option for near-infrared devices and bio-related applications. Still, this advantage needs to be understood carefully. As with many nanomaterials, the biological effects of Ag_2Se QDs can be influenced by particle size, surface ligands, dose, exposure duration, and surface chemistry. For example, Tang et al. studied the in vivo behavior and chemical transformation of Ag_2Se QDs and found that their surface properties affected biodistribution, degradation, excretion, and biological response [4]. Therefore, Ag_2Se QDs are more appropriately described as lower-toxicity alternatives to Cd-, Pb-, and Hg-containing QDs, rather than as completely non-toxic materials.

2.2. Near-infrared emission advantage

Ag_2Se quantum dots are also valued for their emission in the near-infrared region. This wavelength range is useful in a number of practical areas, such as sensing, bioimaging, optical communication, and infrared light-emitting devices. As shown in Fig. 1, these applications suggest that Ag_2Se QDs could play a role in future optoelectronic and imaging technologies.

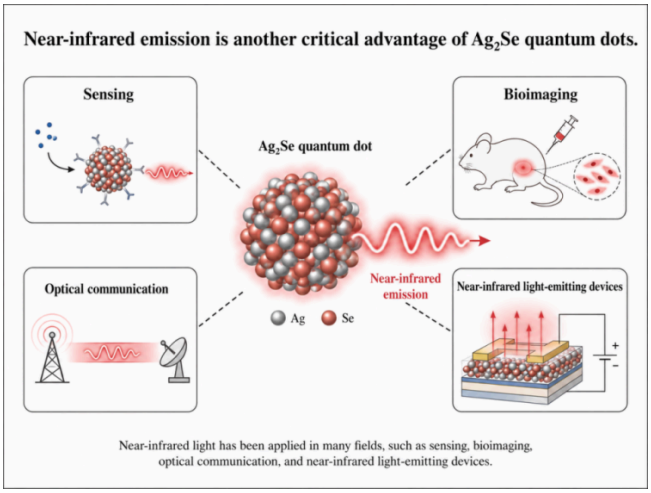


Figure 1. Representative applications of near-infrared emission from Ag_2Se quantum dots in sensing, bioimaging, optical communication, and near-infrared light-emitting devices

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For QLED applications, the emissive material should possess a suitable bandgap and be able to emit at the desired wavelength. Ag_2Se is a narrow-bandgap semiconductor, which allows Ag_2Se QDs to respond optically in the near-infrared region. Recent studies further indicate that their potential is not limited to fluorescence imaging. For example, low-toxicity Ag_2Se QDs have been reported to exhibit near-infrared optical gain, suggesting their possible use in more environmentally friendly NIR optoelectronic devices [5]. These near-infrared emission and optical-gain characteristics indicate that Ag_2Se QDs can function as active light-emitting materials. Therefore, their NIR optical activity is one of the main reasons why they are considered promising candidates for NIR QLED applications.

2.3. Size-tunable optical properties

Size-tunable optical properties represent another key attribute of Ag_2Se quantum dots. The radii of ultrasmall Ag_2Se QDs increase from approximately 0.75 ± 0.20 to 1.20 ± 0.25 nm, remaining substantially smaller than the exciton Bohr radius of bulk Ag_2Se (approximately 2.9 nm). This size relationship supports quantum confinement. Therefore, Different from bulk semiconductors, quantum dots can show changes in electronic structure and effective bandgap when their size varies. As a result, their absorption and emission wavelengths can be tuned by controlling the nanocrystal size. This size-dependent optical behavior is shown schematically in Fig. 2.

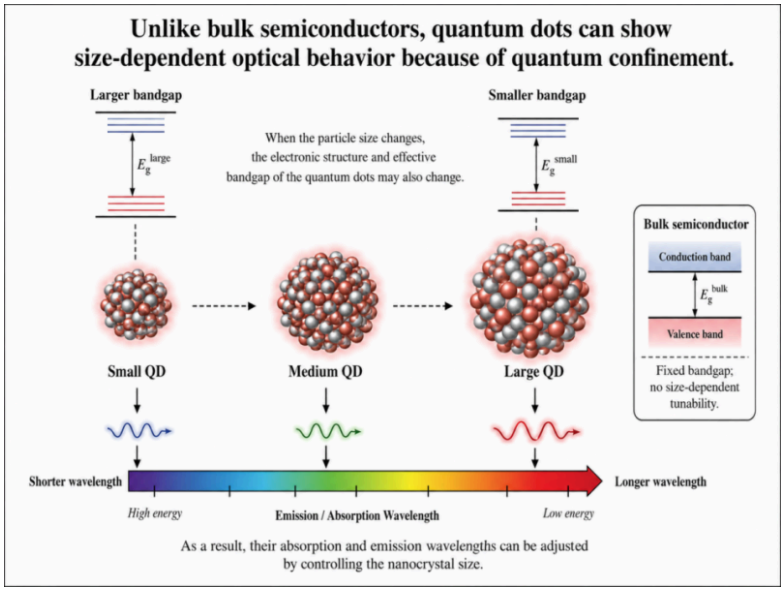


Figure 2. Schematic illustration of the size-dependent optical behavior of quantum dots caused by quantum confinement. The bandgap and emission wavelength can be tuned by controlling nanocrystal size

For near-infrared QLEDs, this tunability is particularly useful because it gives the device more flexibility in wavelength selection. By controlling the size of Ag_2Se QDs, the emission wavelength can be shifted toward different NIR spectral windows, depending on the intended application. For example, monodisperse Ag_2Se QDs with tunable size, efficient NIR-II emission and high PLQY have been successfully prepared, showing that careful control of the synthesis process is important for improving their optical properties [6]. In this way, the size-dependent emission of Ag_2Se QDs gives more flexibility in designing NIR emissive materials, although this advantage still relies on well-controlled synthesis conditions.

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2.4. Solution processability

Colloidal quantum dots can generally be dispersed in solvents, making them suitable for solution-based thin-film fabrication methods such as spin coating, spraying, and printing. Compared with high-vacuum deposition, solution processing may provide a lower-cost and more flexible route for preparing large-area optoelectronic devices. As shown in Fig. 3, the solution processability of colloidal QDs enables a practical progression from QD dispersion to thin-film formation and device fabrication.

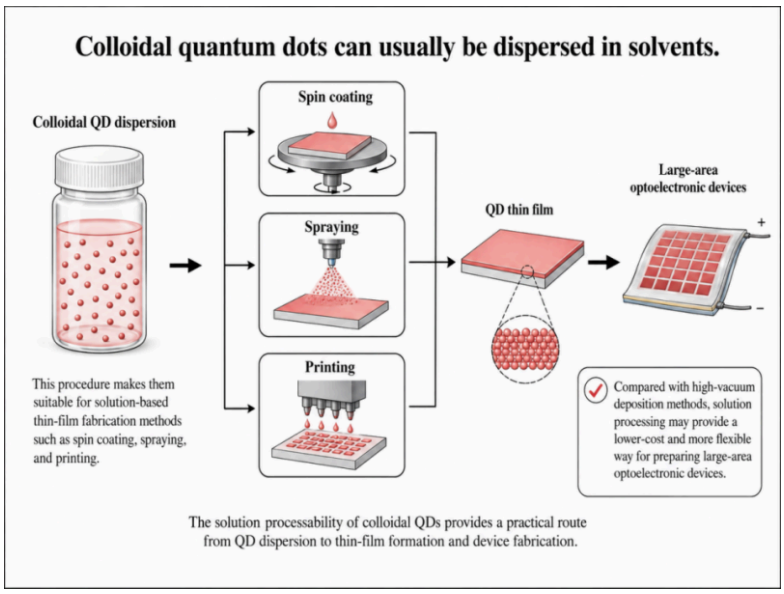


Figure 3. Schematic illustration of solution-based thin-film fabrication using colloidal quantum dots

For QLED applications, this property is critical because the quantum-dot emissive layer needs to be deposited as a uniform thin film. Previous studies have reported colloidal silver chalcogenide nanocrystals, such as Ag_2Se, Ag_2Te and Ag_2S, with infrared emission and photoconductive behavior [7]. This suggests that the colloidal and solution-processable character of Ag_2Se QDs could be helpful for future thin-film preparation and NIR QLED fabrication. However, being solution-processable does not automatically lead to high device performance. Other factors, including film uniformity, ligand length, charge transport and interfacial defects, still need to be well controlled.

3. Ag_2Se-based near-infrared quantum-dot light-emitting diodes

Ag_2Se-based near-infrared QLEDs usually adopt a multilayer structure, which is similar to that used in conventional colloidal quantum-dot LEDs. A common device structure includes a transparent anode, hole injection layer, hole transport layer, Ag_2Se quantum-dot emissive layer, electron transport layer and metal cathode. In this device, Ag_2Se QDs work as the active emitting material. Electrons and holes are injected from opposite sides and then recombine in the quantum-dot layer to produce near-infrared light.Although this structure is relatively standard, Ag_2Se QLEDs are still much less developed than CdSe- or PbS-based QLEDs. This is partly related to the intrinsic properties of Ag_2Se. Bulk Ag_2Se has a narrow band gap of about 0.15 eV, while Ag_2Se QDs can show optical transition energies around 1.1 eV because of their nanoscale size. In addition, their surface chemistry is different from that of many conventional quantum dots. These features make device design more demanding, especially in terms of energy-level matching and interface stability.

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As shown in Fig. 4, the transparent anode, commonly indium tin oxide (ITO), allows light extraction and provides hole injection from the bottom side of the device. Hole injection and hole transport layers, such as PEDOT: PSS and polymeric HTLs, are commonly introduced to reduce the hole-injection barrier and transport holes toward the QD emissive layer. On the opposite side, inorganic electron transport layers such as ZnO or ZnMgO nanoparticles are used to facilitate electron injection from the cathode and to transport electrons toward the emissive layer.

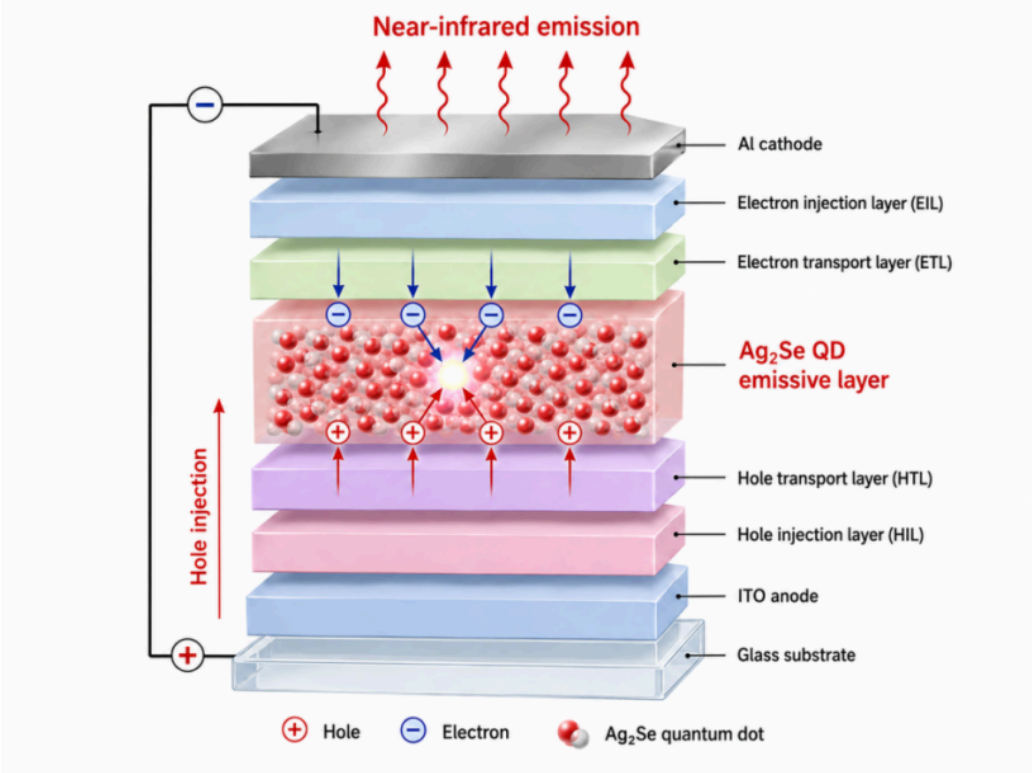


Figure 4. Schematic device structure of a representative Ag_2Se-based near-infrared QLED

The Ag_2Se QD emissive layer is the key functional layer for near-infrared electroluminescence. When Ag_2Se QDs are incorporated into a QLED structure, their film quality, surface ligands, defect density, and energy-level alignment with adjacent transport layers can strongly influence radiative recombination and device efficiency. This is mainly because Ag_2Se QDs are susceptible to surface oxidation, which may alter their surface stoichiometry and introduce additional carrier-trapping states. In contrast to well-passivated CdSe QD emissive layers, which can often be processed under ambient conditions, Ag_2Se QD films are preferably fabricated under an inert atmosphere to minimize oxidation-induced surface defects and preserve surface integrity.

The working process of an Ag_2Se-based NIR QLED can be described by charge injection, charge transport, carrier recombination, and photon emission. Under an applied voltage, holes are injected from the anode side and transported through the HIL/HTL. Electrons are injected from the cathode side and transported through the ETL simultaneously. When electrons and holes meet in the Ag_2Se QD layer, they can recombine radiatively and emit near-infrared photons. This multi-step carrier dynamics highlights that efficient operation requires not only high intrinsic photoluminescence of the Ag_2Se QDs but also balanced carrier injection, suitable energy-level alignment, good interfacial contact, and suppressed non-radiative recombination [8].

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4. Device challenges of Ag_2Se-based near-infrared QLEDs

Although Ag_2Se QDs offer attractive advantages for near-infrared emission, their integration into QLEDs still presents several challenges. In multilayer QLED architectures, electroluminescence performance is governed by the morphological quality of the QD film, the chemical state of the QD surface, and the energetic alignment at each heterojunction. Among these issues, surface defects, charge-transport barriers caused by surface ligands, and unbalanced carrier injection are the main limitations in Ag_2Se-based devices [9]. These problems are summarized schematically in Fig. 5.

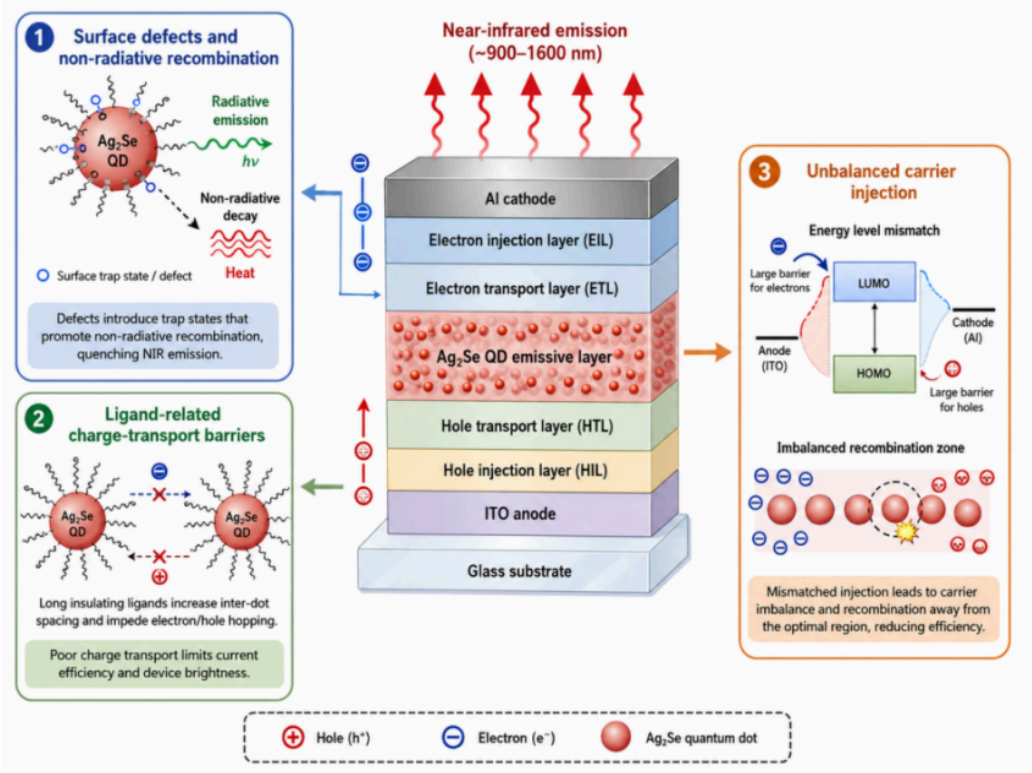


Figure 5. Schematic illustration of the major device challenges in Ag_2Se-based near-infrared QLEDs

4.1. Surface defects and non-radiative recombination

Surface defects are one of the main factors limiting the performance of Ag_2Se-based QLEDs. Because quantum dots have a high surface-to-volume ratio, a large proportion of their atoms are located at or near the surface. Some of these surface atoms may be undercoordinated or not fully passivated, leading to the formation of trap states within the bandgap. These traps can capture excited carriers and promote non-radiative recombination, where the energy is lost as heat rather than emitted as light. As a result, both the photoluminescence efficiency of the quantum dots and the electroluminescent efficiency of the device are reduced. In Ag_2Se QDs, this issue becomes especially important when surface passivation is insufficient, since poorly passivated surfaces can cause strong emission quenching and weaken overall device performance.

The defect chemistry of Ag_2Se QDs is relatively complex compared with many conventional II–VI semiconductor QDs. In typical II–VI quantum dots, surface defects are often related to chalcogen vacancies. For Ag_2Se QDs, however, both Ag vacancies and Se vacancies may exist, and they can introduce trap states at different energy levels. More recent studies suggest that these defect-related states are not always purely detrimental. Under certain conditions, they may also participate in

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radiative recombination, making it difficult to distinguish clearly between trap-assisted emission and band-edge emission. As a result, surface defects in Ag_2Se QDs may influence device performance in two ways: they can enhance non-radiative recombination, but they may also modify the intrinsic emission behavior of the material [10].

4.2. Ligand-related barriers

Another major challenge comes from the surface ligands on colloidal Ag_2Se QDs. In colloidal synthesis, organic ligands are needed to stabilize the nanocrystals, guide their growth and stop them from aggregating in solution. However, after the QDs are deposited into a film, long-chain insulating ligands can weaken the electronic coupling between neighboring particles. This makes charge transport across the Ag_2Se QD emissive layer more difficult, which may increase the driving voltage and reduce the efficiency of carrier recombination.

Ligands play a central role in balancing surface passivation and charge transport in Ag_2Se quantum-dot films. Long-chain organic ligands, such as oleic acid and oleylamine, are often used during the synthesis of Ag_2Se QDs because they help stabilize the colloids and passivate surface defects. This passivation can improve photoluminescence by reducing trap-related losses. However, these ligands can also become a problem in devices. If the ligand chains are too long or poorly conductive, they increase the distance between adjacent quantum dots and act as tunneling barriers for injected carriers. In many quantum-dot films, long-chain ligands can lead to interdot separations of more than 2 nm, which strongly limits carrier-hopping transport. For Ag_2Se-related QDs, previous studies have shown that ligand chain length can affect photoluminescence intensity through surface-defect passivation, suggesting a close connection between ligand design and optical performance [10]. For this reason, ligand engineering, especially partial or complete ligand exchange, is an important step when Ag_2Se QDs are used as the emissive layer in QLEDs.

4.3. Unbalanced carrier injection

Efficient QLED operation requires balanced injection and transport of electrons and holes into the QD emissive layer. If electron and hole transport rates are mismatched, one type of carrier can accumulate at an interface or within the QD layer. Such accumulation can cause non-radiative recombination, interfacial exciton quenching, and device degradation. Previous QLED studies have shown that device performance is closely related to the charge-transport kinetics of the electron- and hole-transport layers and that balanced carrier arrival at the active layer is important for improving emission efficiency. achieving balanced carrier injection remains difficult, partly because the commonly used charge-transport layers do not transport electrons and holes at comparable rates. ZnO electron-transport layers usually have electron mobilities of about 10^{-3}–10^{-2} $cm^2\ V^{-1}\ s^{-1}$, whereas most polymer hole-transport layers show much lower hole mobilities, typically around 10^{-5}–10^{-4} $cm^2\ V^{-1}\ s^{-1}$. Because of this large mobility difference, electrons are injected more efficiently than holes, leading to electron-rich conditions in the quantum-dot emissive layer and a shortage of holes for radiative recombination.

Carrier imbalance can also cause quantum-dot charging and Auger recombination, particularly under high current density. During Auger recombination, the energy released from exciton recombination is transferred to another carrier instead of being emitted as a photon. This process reduces light-emission efficiency and is one of the reasons for efficiency roll-off in QLEDs. Therefore, Ag_2Se-based NIR QLEDs need careful control of energy-level alignment, transport-layer

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thickness, and interfacial charge transfer, so that electron–hole recombination can occur more efficiently within the Ag_2Se QD emissive layer.

Overall, the main difficulties in Ag_2Se-based NIR QLEDs are closely related to surface chemistry, ligand design and charge balance. These issues show that the material advantages of Ag_2Se QDs do not directly translate into high device performance. Therefore, the next section discusses possible strategies to address these limitations and improve device efficiency.

5. Performance improvement strategies

The limited performance of Ag_2Se-based NIR QLEDs is mainly related to surface defects, insulating surface ligands and poor carrier balance. To address these problems, several strategies can be considered, including surface passivation, ligand exchange and interface engineering. Since direct studies on Ag_2Se QLEDs are still limited, the following discussion also draws on evidence from Ag_2Se materials, related AgAuSe QLEDs and more established QLED systems.

5.1. Surface passivation

Ag_2Se quantum dots have a high surface-to-volume ratio, making their optical behavior is easily affected by undercoordinated atoms and surface-related states. As shown in Fig. 6, these uncoordinated surface atoms can form trap states, which may capture injected carriers and increase non-radiative recombination. Time-resolved and temperature-dependent photoluminescence measurements have shown that Ag_2Se emission dynamics vary with particle size and temperature, emphasizing the need to control non-radiative decay channels [11]. Surface modification has also produced bright, water-soluble Ag_2Se QDs with improved colloidal stability and photostability. These results show that complete and stable surface coordination is important for efficient Ag_2Se emitters.

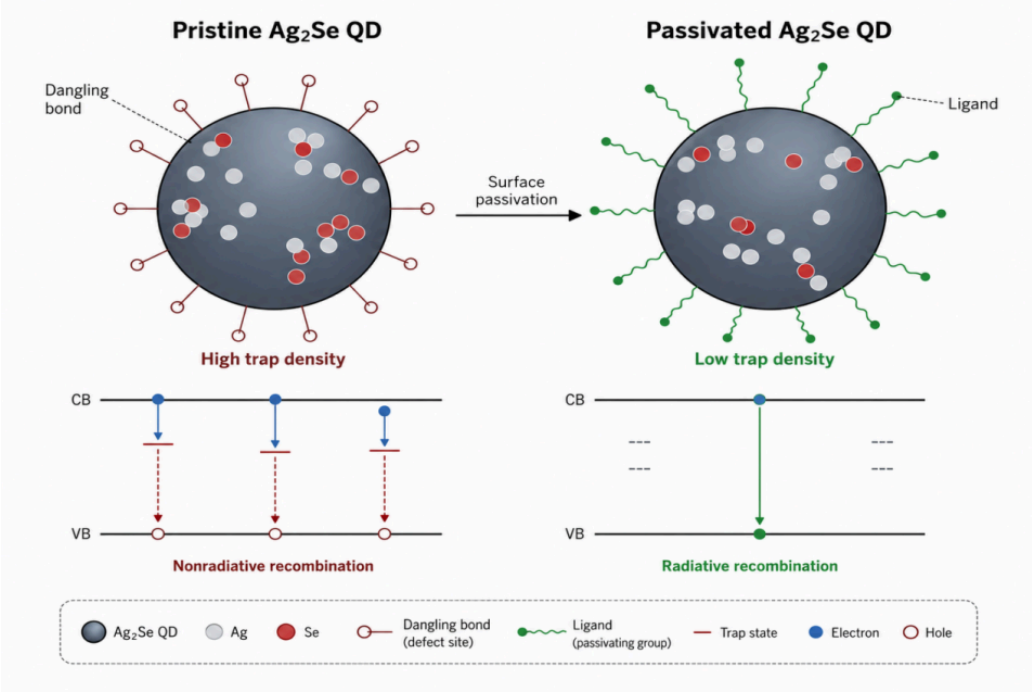


Figure 6. Schematic illustration of surface passivation in Ag_2Se quantum dots

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Possible approaches include strongly binding thiol- or amine-containing ligands, compact inorganic passivants, and wider-bandgap surface layers. These treatments should reduce carrier trapping while preserving radiative recombination. However, an excessively thick or insulating passivation layer may impede charge injection. Passivation should therefore be assessed using both optical measurements, such as PLQY and time-resolved PL, and device measurements, including turn-on voltage and EQE.

5.2. Ligand exchange and charge-transport optimization

Long-chain ligands regulate quantum-dot growth and prevent aggregation, but in a solid film they increase the distance between neighboring QDs and act as tunneling barriers. Replacing them with shorter organic molecules or compact inorganic species may improve electronic coupling and carrier transport. As shown in Fig. 7, shorter organic or inorganic ligands decrease interparticle spacing, strengthen electronic coupling, and facilitate carrier transport through the Ag_2Se quantum-dot film. Ag_2Se surface ligands can also affect energy levels. Luo et al. showed that changing the coordination state of nitrogen-containing groups altered the bandgap of Ag_2Se QDs by up to 140 meV and reversibly shifted the PL peak by up to 75 nm [12]. Ligand engineering can therefore influence passivation, energy-level alignment, and emission simultaneously.

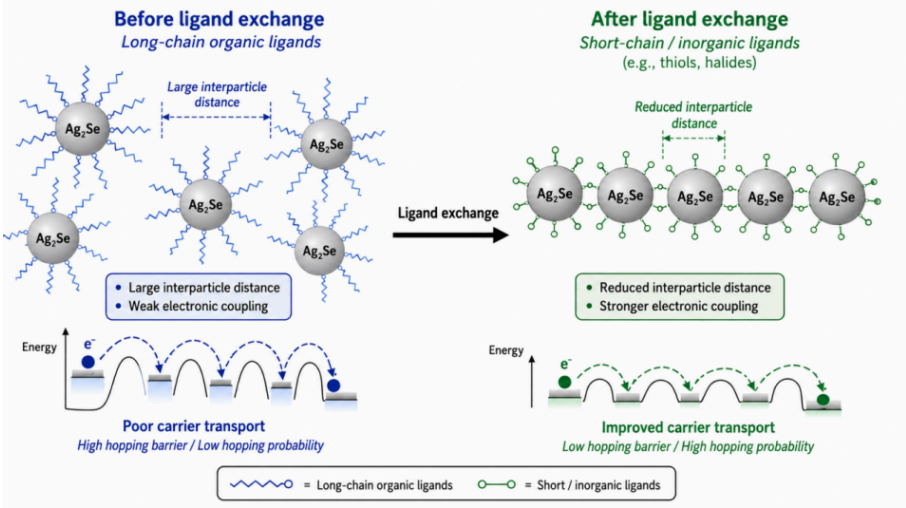


Figure 7. Schematic illustration of the effect of ligand exchange on charge transport in an Ag_2Se quantum-dot film

Solution-phase ligand exchange has been used to prepare transport-active Ag_2Se QD inks for infrared photodetectors [13]. Although this is not direct QLED evidence, it demonstrates the feasibility of forming electronically functional Ag_2Se QD solids. In QLEDs more generally, electrochemically stable ligands have helped bridge the gap between photoluminescence and electroluminescence performance. For Ag_2Se QLEDs, controlled or partial exchange may be preferable to complete ligand removal, because the film must retain adequate surface coverage, processability, and smooth morphology while reducing electrical resistance.

5.3. Interface engineering

QLED performance requires electrons and holes to reach the emitting layer at comparable rates. When one carrier is injected more rapidly, charge can accumulate in the QD layer or at an interface.

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Conventional QLED studies show that charge imbalance changes the internal field distribution and contributes to degradation [14]. Direct electron-transport measurements further reveal that excess electrons can leak into the hole-transport layer or recombine non-radiatively at the HTL/QD interface [15].

Interface engineering should therefore regulate both energy-level alignment and contact defects. Possible methods include ZnO surface modification, insertion of an ultrathin dipolar layer, suppression of excessive electron injection, and use of a better-matched hole-transport material. In the related AgAuSe QLED system, cysteamine-mediated contact treatment removed contact defects, blocked excess electrons, and enhanced hole injection; the device reached an EQE of 15.8% at 1046 nm. This is not direct evidence for Ag_2Se QLEDs, but it demonstrates the value of interface dipoles and contact passivation in a related silver-selenide emitter. Other QLED work has also shown that suppressing electron leakage can improve efficiency and stability. Future Ag_2Se devices should verify these effects using electron-only and hole-only devices, energy-level measurements, impedance spectroscopy, and electroluminescence characterization.

6. Conclusion

Ag_2Se quantum dots are promising emitters for near-infrared QLEDs because of their relatively low toxicity, narrow bandgap, size-tunable optical properties, and compatibility with solution processing. Nevertheless, their electroluminescent application is restricted by surface-related non-radiative losses, electrically resistive ligand shells, and unbalanced electron and hole injection. Surface passivation may reduce trap-assisted recombination, while controlled ligand exchange can improve interparticle coupling and charge transport. Interface engineering is also required to regulate carrier-injection rates, suppress leakage, and confine recombination within the quantum-dot layer. These strategies are strongly interdependent: improved transport should not be achieved at the expense of surface passivation, and enhanced carrier injection should not generate excessive charge accumulation. Direct studies of Ag_2Se QLEDs are still limited, and several proposed approaches are derived from Ag_2Se material studies, related AgAuSe devices, or other QLED systems. Future work should therefore focus on device-level verification, reproducible film formation, carrier-dynamics analysis, operational lifetime, and environmental stability. With coordinated optimization of surface chemistry, ligand structure, and device interfaces, Ag_2Se QDs may become a feasible lower-toxicity platform for near-infrared electroluminescent devices in the future.

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