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Structure Optimization Strategies for Infrared CQD Photodetectors

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Abstract. Colloidal quantum dots (CQDs) have a great potential to be used in the production of inexpensive infrared photodetectors. Their performance is however crippled by a few critical problems such as low carrier mobility, high defect density, high energetic disorder and high dark current. The paper critically examines three mainstream optimization strategies, including ligand engineering, design of the device structure, and building of the low-dimensional heterostructures. The basic processes mentioned in pertinent literatures are described and restructured. A study of the literature shows that surface passivation and structural engineering are useful to enhance responsiveness of the device, reduce dark current, and extend the spectral response range. The common heterostructures have exceptional strengths in regards to the detection sensitivity, stability, and scalable fabrication. It is implied that such rational structural optimization is able to address the major bottlenecks of CQD-based photodetectors. According to the existing research advancement, this review also speculates the future development trends of CQD photodetectors in the aspects of the large-scale preparation, CMOS compatibility, and expanded applications in broadband integrated applications.

Keywords: Colloidal quantum dots, Infrared photodetectors, Ligand engineering, Heterostructures, Device performance optimization

1. Introduction

The applications of the colloidal quantum dot (CQD) photodetectors are significant in optical communication, imaging sensing, and smart monitoring. Colloidal quantum dots have been widely of interest because of their low cost, the ability to be processed as solutions, tunable bandgap, and good light absorption properties. These characteristics render them very applicable in high performance infrared detection devices.

Nevertheless, there are still several major limitations to the traditional colloidal quantum dot photodetectors. These consist of low carrier mobility, high surface defect density, gross energy level disorder, inadequate interface coupling and high dark current. These issues directly limit the overall performance of the detectors in real-life applications.

To overcome these problems, scientists have conducted numerous studies on optimization of materials and structure. Currently the primary enhancement plans are the engineering of ligands, design of device structures, and the formation of heterostructures. The primary use of ligand

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engineering is to optimize surface states and charge transport. The design of device architecture assists in the suppression of dark current, and enhancing response speed. Charge separation can be further improved and spectral response extended by incorporating heterostructures.

This research paper gathers, tabulates, summarizes and evaluates the available research results. It methodically analyzes three significant optimization strategies and common heterostructure systems according to the great quantity of reported works. It also sums up the working mechanisms and performance improvement rules of various structures. This paper will attempt to explain the state of the research of high-performance colloidal quantum dot infrared photodetectors, draw a conclusion on effective optimization strategies and offer some reasonable future directions of the research. This source is a very clear and organized source of information in reference to the structural design and performance-enhancement of such photodetectors.

2. Synergistic optimization of materials and structures

2.1. Ligand engineering in colloidal quantum dot photodetectors

Ligand engineering is crucial for CQD photodetectors, as typical quantum dots consist of a crystalline core and a surface ligand shell. Ligands are essential components that maintain quantum dot stability and protect their surfaces. However, common long-chain ligands such as oleic acid are non-conductive, which hinders charge transport between quantum dots and degrades device performance. Researchers are committed to replacing the original ligands with poor conductivity to enhance carrier mobility and film conductivity.

As a typical precursor used in the high-temperature synthesis of quantum dots (120–300 °C), oleic acid ensures colloidal stability and achieves surface passivation. Nevertheless, its insulating property severely limits carrier transport, resulting in low film conductivity and photovoltaic performance. Therefore, ligand exchange is necessary. The replacement ligands are usually divided into two categories: inorganic ligands and short-chain organic ligands.

Common inorganic ligands include indium triiodide and lead halides [1]. Peng et al. [2] reported certain method. The lead halide/ammonium acetate (PbX_2/AA) process efficiently replaces long-chain oleic acid. Briefly, PbX_2 and ammonium acetate were dissolved in DMF, while oleic acid-capped PbS quantum dots (QDs) were dispersed in octane. 5 mL of 10 mg/mL PbS QD/octane solution was vigorously mixed with 5 mL of PbX_2/AA DMF precursor for 1–2 min to achieve complete phase transfer to DMF. The DMF phase was washed three times with octane to remove residual oleic acid. Ammonium protons facilitated the substitution of bulky oleate ligands with $[PbX_3]^-$ anions. Subsequent washing removed excess salts, yielding clean $[PbX_3]^-$/$[PbX]^+$-capped QDs free of organic residues. NH_4^+ and $[PbX]^+$ synergistically stabilized the QDs in polar solvents.

Short-chain organic ligands such as ethanethiol similarly enhance conductivity. Ligand exchange typically involves adding ethanethiol to toluene-dispersed QDs, incubating, precipitating with hexane, centrifuging, and redispersing [3]. Sukhovatkin et al. [4] reported a related solution method. Commercially available PbS QDs were treated with methanol under N_2 twice. Butylamine was then drop-cast onto the device, reacting with PbS and evaporating completely to bind the QDs and redistribute them on the substrate. Excess butylamine was removed by immersing the device in methanol for 2 h, exposing the nanocrystal surface. Notably, this work employed a mixed-ligand strategy rather than conventional liquid- or solid-phase exchange: oleic acid was first removed in solution, followed by in situ butylamine binding on the substrate.

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2.2. Device architectures

CQD photodetectors rely on layered vertical device architectures. Architectures spatially decouple light absorption, charge separation, transport, and collection, enabling independent optimization of responsivity, dark current, response speed, and spectral coverage. A typical device stack is similar to a sandwich. A typical device stack includes electrodes, charge transport layers, the CQD absorption layer, passivation layers, and a substrate. This vertical structure can solve obstacles in pure CQD films. It improves carrier mobility and overcomes defect recombination. It also suppresses current leakage and makes energy levels more ordered.

Prior to the description of advanced vertical architectures, the conventional planar photoconductive structure with interdigitated electrodes stands out for its simple manufacturing process and high photoconductive gain. Gao et al. [5] demonstrated a SnS_2 nanosheet/PbS CQD photodetector using this architecture. Its PbS CQDs act as a near-infrared sensitizer and SnS_2 provides a high-mobility transport channel Upon near-infrared illumination, optical absorption takes place solely in the PbS CQDs. This modulates the Schottky barrier at the SnS_2 interface and results in negative photoconductivity. This device exhibits responsivity exceeding 10^5 A/W and detectivity over 10^{12} Jones, validating that planar structures enable spectral-distinctive, polarity-switchable photodetection unachievable in single-component devices. However, conventional planar architectures suffer from high dark current and slow response due to uncontrolled carrier hopping and trap states.

Vertical depleted heterojunction and p–i–n architectures are used to address these constraints by taking advantage of the inherent field electric fields which are used to accelerate carrier separation and reduce dark current. Based on the high-performance HgTe CQD mid-infrared detectors, Xue et al. [6] introduced a gradient-doped homojunction architecture based on stacked n+, n, intrinsic, p+, and p+ CQD layers. The graded built-in field increases carrier depletion width, decreases trap-assisted recombination and decreases thermal generation, giving detectivities of 10^{-11} Jones at 200 K and 7.6×10^{-9} Jones at room temperature. This vertical layer engineering determines that gradient doping and built-in field design is an important way to boost high-operating-temperature mid-infrared detection. Alternatively, in SnS_2 -based vertical heterostructures, carriers photogenerated at the interface are separated by type-II band alignment, resulting in more than 40 percent reduction in the response time compared to planar devices [5].

Another optimized architecture incorporates interface ligand engineering, compact packing to remove the energetic disorder and enhance charge injection. Liu et al. [1] used lead halide/ammonium acetate ligands to develop solution-phase ligand-exchanged CQD inks to substitute oleic acid. This creates tightly packed films having a flat energy landscape and reduced bandtail states. Such an architecture minimizes Urbach energy to 29 meV and increases the carrier mobility, allowing effective injection of charges into ZnO electron-transport layers. This architecture enhances the external quantum efficiency (EQE) and stability of the PbS CQD photodetectors, and devices retain more than 90 per cent of their original performance during 1000 hours of air exposure [5]. In isolation, Jeong et al. [7] created graphene/PbS heterostructures with optimized interfaces, which increased photocurrent by 5-fold, reduced rise time by 22 percent and decay time by 47 percent.

Taken together, these investigations coalesce around the same set of design principles to high-performance CQD devices: (1) vertical stacking to decouple absorption and transport; (2) built-in/gradient electric fields to inhibit recombination and dark current; (3) interface/ligand engineering to flatten energy landscapes and reduce traps; and (4) type-II heterojunction or graded homoj

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Combined, the architectural approaches address the major tradeoffs between gain, speed, noise, and stability. They pave the way to scalable infrared photodetectors with high performance.

3. Cooperative optimization of heterojunctions and composite structures

3.1. Quantum dot/2D material heterojunctions

Heterojunctions between QDs and 2D materials combine the intensive, tunable broadband absorption of colloidal QDs, with the ultrahigh mobility, rapid charge transport, and low noise of 2D semiconductors. The staggered band positioning at the heterointerface allows efficient exciton dissociation, inhibits charge recombination, and allows directional interfacial charge transfer, which greatly improves responsivity, detectivity, and spectral coverage to high-performance photodetection.

The graphene/PbS CQD heterojunction is a high-performance design of the broadband, tunable at the gate photodetection in the visible to short-wave infrared range. Here, PbS CQDs serve as a highly efficient light-absorbing layer with tunable bandgaps and graphene serves as an ultrahigh-mobility transport channel and enables efficient separation of charges at the van der Waals heterojunction interface. This synergistic design delivers outstanding responsivity up to 10^5–10^6 V/W over a wide spectral range of 400–1800 nm and allows electrical modulation of the photoresponse via gate voltage. the related people made research that wafer-scale fabricated graphene-QD photodetectors have been successfully integrated with CMOS readout circuits to demonstrate image sensor arrays and proof-of-concept imaging systems. Such CQD/2D heterojunction devices show great practical potential in infrared imaging, surveillance, automotive sensing, and low-cost industrial optical detection applications.

The broadband QD materials and optimized optical coupling structures can be used to further expand spectral coverage and communication performance. PbS QDs have good absorption in the visible to near-infrared area, which allows the response of visible to near-infrared broadband. Tankimanova et al. [8] made advances in the experiment. The use of silica-based optical fibers and luminescent concentrators increases the efficiency of light usage. In addition, there is reduced trade-off between responsiveness and speed, which facilitates high-speed optical Internet of things (IoT) connections up to 0.27 Mbit/s.

3.2. Quantum dot/quantum dot heterojunctions

QD/QD heterojunctions are core-shell, gradient-doped and lateral p-n structures. They maximize band alignment and passivation of surfaces to reduce nonradiative recombination and dark current. These architectures take advantage of fixed band offsets and interfacial potential gradients to control carrier dynamics, addressing the major limitations of bare QD systems, based on the fundamental physics of semiconductor heterostructure physics.

The model of surface and bandgap engineering is the InSb/InP core-shell CQDs. InP lattice-matched shell passivates the surface dangling bonds and inhibits the oxidation of Sb. It increases the wavelength of infrared detection cutoff to over 1500 nm. Peng et al. [2] create design which increases the external quantum efficiency (EQE) to 22 and 19 percent at 1500 and 1580 nm, respectively. It shows the effectiveness of core-shell heterojunction in the high-performance near-infrared photodetection. Xue et al. [6] make mid-infrared HgTe CQD detectors with gradient-doped homojunctions. They are stacked n+, n, intrinsic, p and p+ layers. These crossings generate a built-in electric field which is spatially graded. The field hastens the differentiation of photo-generated

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charge carriers. It inhibits thermally generated dark current. This enables mid-infrared detection at high operating temperature without cryogenic cooling.

Lateral planar pn junctions HgTe CQD films are supplementary to vertical heterostructures. These cross-roads are produced by in situ doping of electric-fields. Positive bias causes n-type conductivity in the films that can be controlled. Controllable p-type conductivity is the consequence of negative bias. In a study of Qin et al. [9], the structure enables zero-bias photovoltaic working. It lowers the noise levels of devices by a factor of ten. It helps to produce 640×512 CMOS-integrated Focal Plane Arrays (FPAs). The FPAs have a cutoff of 2.5um. This architecture opens up the way to large-format mid-infrared imaging systems. Li et al. [10] use Wafer-scale graphene/PbS CQD photodetectors to use two-bandgap PbS CQD stacks. These stacks have a bottom absorption layer with narrow-bandgap and a wide-bandgap capping layer. They are employed to construct a p-i-n like heterostructure. This design also expands the spectral response range. It is also useful in increasing the film stability and uniformity which is advantageous to scalable manufacturing.

The overall designs of these QD/QD heterojunction allow surface chemistry and band structure to be accurately tailored on nanoscale. They are based on the physics of semiconductors, and provide a solid foundation in the development of high-performance infrared photodetectors and imaging arrays.

3.3. Quantum dot/metal oxide heterojunctions

QD/metal oxide heterojunctions are a paradigm architecture to high-performance optoelectronic devices, which combines the outstanding light-harvesting capability, bandgap control, and solution processability of colloidal QDs with the high electron mobility, thermal stability, and low leakage current of metal oxide semiconductors. The built-in electric field between the heterointerface created by staggered band alignment provides efficient separation and extraction of photogenerated excitons, inhibits non-radiative recombination and reduces dark current, which significantly increases responsivity, specific detectivity, and response speed. Such heterostructures have inherent advantages that place them at the center of solution to the strict performance needs of the next-generation near-infrared photodetectors, optical communication systems and integrated optoelectronic circuits.

A paradigmatic implementation is the PbS QD/InGaZnO (IGZO) heterojunction phototransistor demonstrated by Zhan et al. [11]. In this configuration, dithiol ligand-functionalized PbS QDs serve as a high-absorption near-infrared photosensitive layer, while IGZO acts as a high-mobility electron-transport channel. The heterojunction mitigates lateral carrier trapping and leakage, and augments vertical charge injection from the QD layer to the IGZO channel, enabling an ultrahigh responsivity exceeding 2×10^4 A/W and a specific detectivity surpassing 10^{14} Jones. This device architecture has been successfully deployed in low-dose near-infrared imaging and optical communication systems, validating the practical viability of QD/metal oxide heterojunctions for high-sensitivity optoelectronic applications.

Furthermore, QD/metal oxide heterojunctions have been instrumental in enabling scalable, wafer-scale integrated photodetector arrays. Li et al. [10] reported a large-area graphene-PbS QD hybrid photodetector, wherein metal oxide dielectric and passivation layers were integrated to enhance carrier transport and device stability. The triple heterostructure of QDs, graphene, and metal oxides achieves broadband photodetection spanning 400–1800 nm, with outstanding responsivity and linear dynamic range. Leveraging the excellent process compatibility of metal oxides, the device demonstrated a fabrication yield of 96% on 200 mm wafers, establishing a scalable pathway for industrial-scale infrared image sensor production.

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In addition, QD/metal oxide heterojunctions have been exploited to optimize charge transfer dynamics in low-dimensional optoelectronic systems. Jeong et al. [7] fabricated a high-performance near-infrared photodetector supported on a SiO_2/Si substrate. It is based on a graphene/PbS QD heterostructure. As a robust metal oxide platform, SiO_2 provides electrical insulation and mechanical stability. However, the QD/oxide interface promotes efficient photogenerated carrier separation and collection. Compared to pristine PbS QD devices, the heterojunction architecture yielded a 5-fold enhancement in photocurrent, alongside a 22% reduction in rise time. It also makes a 47% reduction in decay time under 980 nm illumination. Moreover, it substantiates the efficacy of QD/metal oxide heterojunctions in boosting both sensitivity and dynamic response for practical photodetection systems [8].

Figure 1 illustrates three typical architectures of colloidal quantum dot (CQD)-based photodetectors: the CQD/2D material heterojunction (with a PbS CQD absorber and graphene layer), the CQD/CQD homojunction (with bandgap-graded CQD layers), and the CQD/metal oxide heterojunction (integrating PbS CQDs with an iGZO layer), each representing a distinct strategy to optimize charge separation and transport. Similarly, they have the structure, which is like a sandwich.

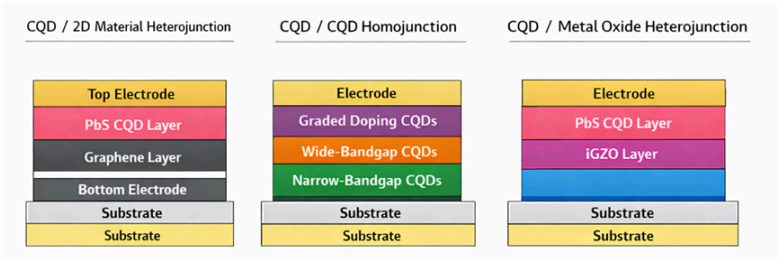


Figure 1. Structural schematics of three typical CQD-based photodetector architectures

4. Comparison and prospect

Table 1 is performance and structural comparison of CQD photodetectors with various heterojunction structures. They demonstrate trade-offs of responsivity, speed, dark current, and stability. Lately, the development of ligand engineering, heterostructure design and integration of devices with various (CQD) photodetectors.

Table 1. Performance and structural comparison of CQD photodetectors with various heterojunction structures

Category	Pure CQD Photodetector	CQD/2D Material Heterojunction	CQD/Metal Oxide Heterojunction
Typical Structure	Single-component CQD thin film	CQD/2D stacked heterojunction	CQD/oxide vertical transport structure
Carrier Transport	Limited, trap-sensitive	Fast, high-mobility transport	Efficient vertical extraction
Dark Current	Medium-High	Low	Ultra-low
Responsivity	High	High	High
Response Speed	Moderate	Fast	Ultra-fast
Stability	Moderate	Good	Excellent

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Table 1. (continued)

Process Compatibility	Simple solution-processing	Complex transfer/integration	CMOS-compatible, fully scalable
Scalability	Medium	Medium	High
Core Advantage	Simple structure, low cost	Broadband, high photoconductive gain	Low noise, long life time, mass-production

Traditional CQD photodetectors are photoconductive based which have the advantage of easy solution processing and high photoconductive gain. These devices are, however, plagued with intense energetic disorder, high dark current and slow response times through random carrier hopping and trap-assisted recombination [4]. Ligand engineering has been used to flatten the energy landscape to alleviate these problems. The introduction of lead halide ligands is successful in substituting long-chain organic insulators, increase interdot coupling, reduce Urbach energy to 29 meV, and make the films more compact and stable [1]. This type of surface engineering provides a generalized mechanism to inhibit nonradiative recombination and enhance a charge carrier.

Heterojunction architectures also push the performance of individual CQD devices beyond its limits. The hybrid structures of CQDs/2D materials combine the high broadband absorption of CQDs and the ultrahigh mobility of 2D crystals. In graphene/PbS QD, the photoinduced charge transfer results in a fivefold increase of photocurrent, a 22% reduction in rise time and 47% reduction in decay time and a high-sensitivity near-infrared detector [7]. In the meantime, CVD-prepared low-dimensional Te nanosheets show excellent room-temperature blackbody sensitivity, high responsivity (6650 AW^{-1} at 1550 nm), high polarization anisotropy and high air stability, which offer a competitive platform to infrared imaging [2].

The built-in electric fields and interface passivation are further optimized by vertical p–i–n and core-shell heterojunctions. InSb/InP core–shell CQDs remove the dangling bonds on the surface, suppress oxidation, and scale the detection cutoff to over 1500 nm with EQE values of 22 and 19% at 1500 and 1580 nm, respectively [2]. In addition to single-band detection, X-ray-to-near-infrared response with detectivity of more than 10^{12} Jones and desirable mechanical stability is demonstrated by flexible broadband photodiode arrays of PbS CQDs, which can be used to perform image fusion across multiple spectral bands without mismatches at the pixel level [12]. In optical communication, PbS CQDs can be used as effective visible-near-infrared color-conversion media, which can be used in optical IoT connections with data rates up to 0.27 Mbit/s through the use of OFDM modulation [8].

In summary, the performance of CQD photodetectors can be enhanced through ligand passivation, heterostructure design, built-in field engineering and heterogeneous integration, which are complementary. Three directions are used to describe the future directions, i.e. the continuous optimization of interface quality and energetic order to reduce noise further and to increase response speed, scalable and CMOS-compatible fabrication to form large-format focal plane arrays, and broadband and multispectral integration between X-ray and infrared to form compact and low-power imaging systems. With the ongoing advancement in technology CQD photodetectors will be facilitating technologies in infrared imaging, optical communication, wearable electronics, and intelligent sensing.

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5. Conclusion

Overall, this paper provides a systematic review and summary of the major optimization methods of high-performance infrared photodetectors, using CQDs, such as ligand engineering, device architecture design, and low-dimensional heterostructure construction. This paper is a literature-based review that aims to thoroughly analyse, compare the performance, and induce progress of representative studies in the literature.

Ligand engineering has proven useful in passivating surface defects, increasing inter-dot electronic coupling, decreasing energetic disorder and inhibiting nonradiative recombination, providing the material basis to enable efficient charge transport. The trade-offs between responsivity, dark current, and response speed can be efficiently achieved through rational design of the device configurations as planar photoconductive structures, vertical depleted heterojunctions, p–i–n structures, and gradient-doped homojunctions. Moreover, combining CQDs with 2D materials and metal oxides results in high-performance heterojunctions. These heterojunctions enhance charge separation, inhibit dark current and enhance photodetection bands.

This paper describes the features of the typical colloidal quantum dot heterostructure systems, the advantages of the respective systems in carrier transport, noise level, stability, and scalable fabrication, and explicitly notes that wafer-scale processing and CMOS compatibility have emerged as key trends to their practical use. The purpose of the work is to present a clear and detailed reference on the structure performance relationship of colloidal quantum dot photodetectors and how this relationship will evolve in the future. As interface quality continues to improve, as do large scale manufacturing processes and integration technologies of broadband, colloidal quantum dot infrared photodetectors should find broader applications in infrared imaging, optical communication, machine vision and others.

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