Quantum dots: A journey from fundamental discovery to technological impacts

Abeera Hassan,† Jaspreet Kaur,† Ou Chen,* and Moungi G. Bawendi*

This article traces the evolution of quantum dots (QDs) from their initial discovery to growing technological impacts. We highlight the key breakthroughs in the development of colloidal QDs that have enabled precise control over their unique optical and optoelectronic properties. We also discuss a range of QD-based applications and address commercialization efforts. Finally, we examine ongoing challenges and emerging opportunities that are set to shape the future of QD research and technological advancement.

Introduction

In 2023, the Nobel Prize in Chemistry was awarded for "*the discovery and synthesis of quantum dots*."[1] The term of quantum dots (QDs) refers to semiconductor nanocrystals (NCs) typically ranging from a few to tens of nanometers in size. At this scale, quantum confinement effects emerge as the crystallite size approaches and falls within the Bohr diameter of an exciton (a bound electron–hole pair), leading to unique and tunable optical and electronic properties, vastly different from their bulk counterparts.[2,3] As shown in **Figure** 1, the bandgap of QD materials can be tailored in a wide range by changing their size and composition. The remarkable tunability in these properties makes QDs valuable for applications in optoelectronics, displays, bioimaging, solar cells, and more.[4] Following the initial discoveries independently made by Alexei Ekimov and Louis Brus in the early 1980s,[5,6] the field experienced an explosive growth since the 1990s, markedly after the introduction of the "hot-injection" synthesis method,[7] which allowed the synthesis of high-quality colloidal QDs with precisely controlled particle size (Figure 1). This surge is reflected in the cumulative rise of publications, including original research, reviews, and granted patents (**Figure** 2).

Given the numerous comprehensive reviews that cover various aspects of QDs,[8–14] this article aims to provide an integrated overview of their major historical milestones (**Figure** 3), key scientific breakthroughs, significant applications and commercialization efforts, as well as current challenges and future prospects—particularly in light of the recent Nobel recognition.

Historical background

The concept of quantum confinement—where semiconductor materials exhibit size-dependent optical and electronic properties when their size is reduced to the nanoscale—was theoretically anticipated long before it could be experimentally realized.[15] The synthesis of materials at such small dimensions posed significant challenges due to technological limitations. This changed in 1981 when Alexei Ekimov provided the first experimental evidence of quantum size effects in CuCl NCs embedded in a glass matrix.[5] This study was followed up by another study, where the microscopically dispersed CdS and CuCl nanoscale crystals were formed by diffusion-controlled phase decomposition of a supersaturated solid solution. These NCs exhibited a distinct blueshift in exciton absorption as their size decreased—a characteristic behavior of quantum confinement.[16] Initially, this phenomenon was interpreted using the "particle-in-a-box" model. However, a mismatch between theoretical predictions and experimental data prompted a

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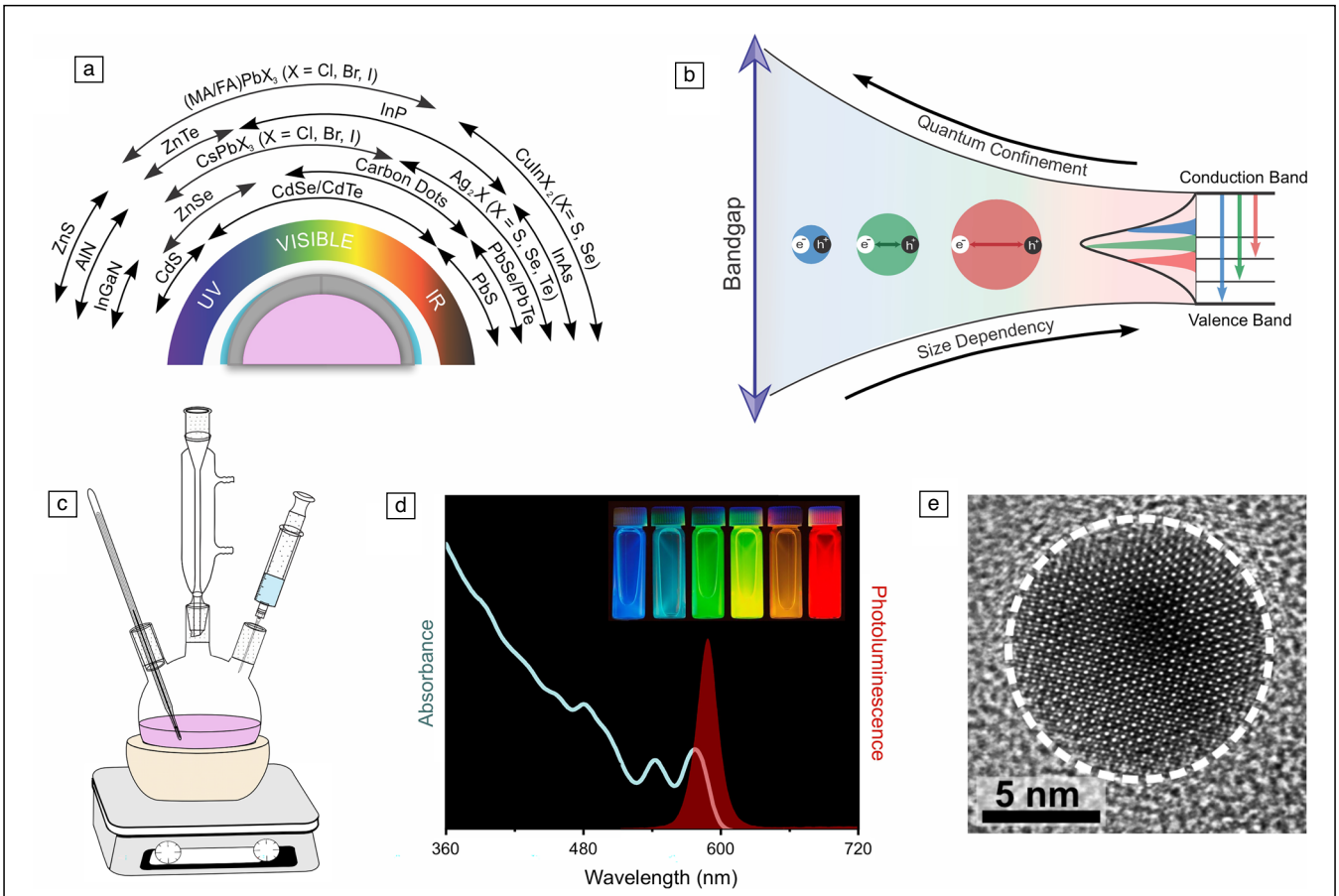


Figure 1. (a) Representative quantum dot (QD) materials positioned according to their emission wavelengths across the electromagnetic spectrum. (b) Illustration of the quantum confinement effect, showing the shift in emission wavelength with QD size. (c) Schematic diagram of the hot-injection method for QD synthesis. (d) Typical absorption and photoluminescence emission spectra of Cd-chalcogenide QDs (Courtesy: Chen group); the inset shows vials of CdSe QDs exhibiting different emission colors due to size variations (Bawendi Lab: Photographer F. Frankel). (e) Representative high-resolution transmission electron microscopy image of a Cd-chalcogenide QD (Courtesy: Chen group).

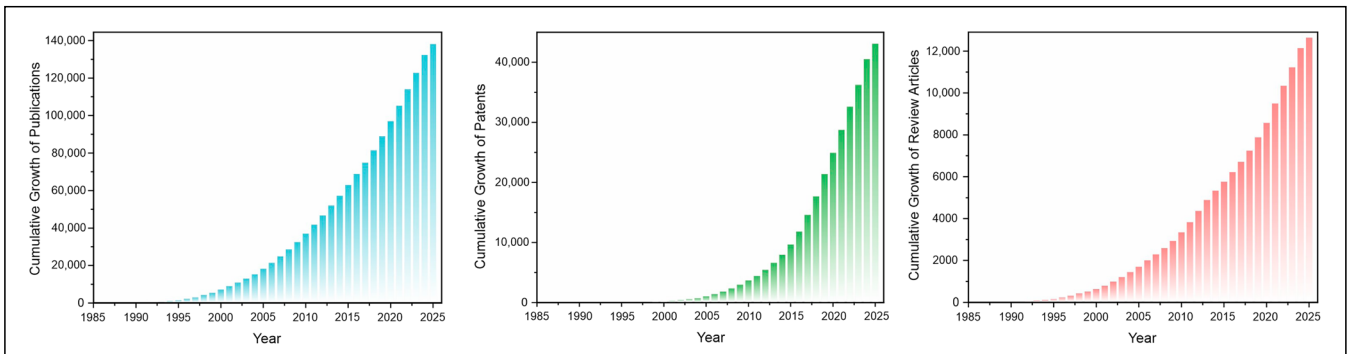


Figure 2. Cumulative number of publications (left), patents (middle), and review articles (right) citing "quantum dot" in SciFinder over time (accessed date 29 July 2025).

collaboration between Ekimov and Alexander Efros, leading to the development of the effective mass approximation (EMA) model.[17] This model successfully accounted for the size dispersity in ensembles of NCs, laying the theoretical foundation for understanding optical transitions in semiconductor QDs.

Around the same time, Louis Brus independently discovered size-dependent optical shifts in colloidal CdS crystallites synthesized in aqueous solution and reported the results in 1983.[6,18] While investigating surface redox chemistry, his group observed redshifts in excitonic absorption while aging

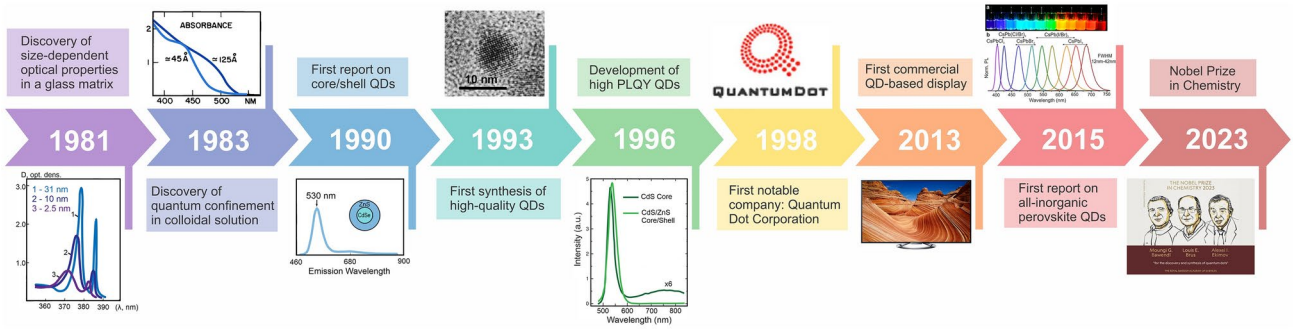


Figure 3. Historical timeline of major milestones in quantum dots (QDs) research and commercialization. PLQY, photoluminescence quantum yield. Reproduced with permission from References 5–7, 37, 39, 102.

the colloidal CdS crystallites under acidic conditions. They attributed this optical property change to the particle size growth via Ostwald ripening. Brus independently applied the EMA framework to rationalize these findings to validate the quantum size effect in solution-processed QDs. Although this colloidal synthesis approach was a significant step forward, it lacked precise control over QD particle size, monodispersity, and surface passivation. Around the time, Efros and colleagues worked on developing the k·p model for CdSe spectra in glasses, providing a foundational framework for subsequent evaluations of spectral properties of colloidal QDs.[19] A major leap occurred in 1993 with the introduction of a hot-injection method.[7] This organometallic synthesis involved rapid injection of "cold" precursors into "hot" coordinating solvents, initiating a burst of nucleation followed by diffusion-controlled particle growth. The underlying growth mechanism was explained by the LaMer theory of nucleation, originally developed to explain the synthesis of monodispersed hydrosols.[20] The synthesis resulted in uniform, highly crystalline II–VI Cd-chalcogenide QDs (i.e., CdS, CdSe, and CdTe) with tunable optical properties.[21] This method not only improved synthetic control, but also provided a general strategy for high-quality QD production, which had later been applied for the synthesis of nearly all types of QD materials. Over the following decade, this synthetic platform has been continuously refined by researchers. Notably, Alivisatos and his group extended the hot-injection method to show deliberate shape-controlled QD syntheses, yielding rods, tetrapods, arrows, etc., through anisotropic growth strategies by selective crystalline facet passivation using surfactants.[22–26] Later, in the early 2000s, Peng and co-workers replaced hazardous precursors like dimethylcadmium with safer alternatives such as cadmium oxide (CdO)[27] and cadmium acetate ($(CH_3COO)_2Cd$).[28] In 2001, during his time at IBM, Murray further extended the hot-injection approach to synthesize high-quality PbSe QDs, successfully tuning their emission beyond the visible spectrum into the infrared (IR) range of 700–1150 nm.[29]

Despite these advances, surface-related defects remained a challenge, often resulting in broad photoluminescence (PL) features and reduced quantum efficiency at room temperatures. To address this, researchers began exploring passivation strategies.[30–35] The earliest work by the Weller group on colloidal CdS particles activated with $Cd(OH)_2$ showed that inorganic capping could significantly enhance PL quantum yield (PLQY), reaching up to 20% at room temperature.[36] This was followed by the first report of growing a ZnS shell on CdSe QDs surface in inverse micelle solutions in 1990.[37] In 1996, two independent studies reported the controlled surface passivation of CdSe QDs with different shell materials of ZnSe and ZnS at elevated temperatures.[38,39] In particular, the CdSe/ZnS core/shell QDs showed significantly enhanced PLQY of up to 50% for the first time, marking a major breakthrough in the development of stable and highly luminescent QDs.[39] A subsequent study further confirmed the effectiveness of ZnS passivation, presenting a size series of CdSe/ZnS core/shell QDs with excellent optical stability.[40] In 1997, Peng and Alivisatos successfully transferred the two-dimensional solid-state epitaxial growth concept to colloidal NCs, achieving precise control of CdS shell thickness on CdSe core QDs with high PLQYs.[41] This report provided the first experimental evidence of hole confinement within the core and electron delocalization across the core/shell structure, indicating that these QDs were highly luminescent and electronically accessible for optoelectronic applications. These breakthroughs confirmed the importance of controlling surface chemistry and inorganic shell thickness in optimizing QD performance. Building on these insights, Peng and colleagues introduced the SILAR (successive ion layer adsorption and reaction) technique in 2003,[42] which allowed for precise, layer-by-layer shell growth using stable and cost-effective precursors. In 2013, Chen and Bawendi further refined the synthesis of CdSe/CdS core/shell QDs, achieving exceptional particle uniformity, near-unity PLQY, narrow and symmetric emission peaks, and significantly suppressed single-dot blinking by slowing down the shell growth kinetics at elevated temperatures.[43] These early successes with the inorganic shell passivation on core QDs spurred research into broadening the scope of core/shell and related architectures across nearly all QD systems. This momentum led to a wave

of exciting discoveries, including advanced shape-, composition-, and surface-controlled QDs,[24,44–50] optimized optical and electronic properties at both ensemble and single-particle levels,[43,51–58] and integration into more complex heterostructures and assembled superstructures.[29,59–75]

Safety concerns surrounding toxic heavy metals such as cadmium and lead prompted the search for alternative, environmentally benign QD materials. As early as 1994, researchers explored Cd-free QDs, notably InP-based NCs, achieving narrower size distributions by using trioctylphosphine-based ligands.[76] Around the same time, other III–V QDs such as indium arsenide (InAs) were also explored for their near-infrared (NIR) emission properties.[77] Another breakthrough came with the development of I–III–VI_2 QDs, especially copper indium selenide ($CuInSe_2$), which was first synthesized in 1999 using a modified trioctylphosphine oxide-based synthesis, commonly used for II–VI QDs, to study their unusual optical properties.[78] Later in 2003, a single-source molecular precursor with a suitable ligand was used to synthesize $CuInS_2$ (CIS) and $CuInSe_2$ (CISe) with the PLQY of ~5 percent.[79] Other promising early candidates for nontoxic QDs included silver-based materials, such as Ag_2S, $AgInS_2$, and Ag_2Se QDs, which demonstrated potential for NIR-emitting applications with relatively low toxicity.[80–86] In 2004, carbon QDs (CQDs) were accidentally discovered during the purification of single-walled carbon nanotubes.[87] These CQDs showed excellent water-solubility, tunable fluorescence, and chemical stability, quickly translating to bio-related applications such as biosensing, bioimaging, and drug delivery.[88–92] This discovery paved the way for an emerging class of group-IV-based metal-free QD, including graphene, silicon, and carbon nitride QDs—materials developed mainly to address concerns around toxicity and long-term environmental sustainability.[93–99]

More recently, a new class of materials has rapidly gained prominence within the QD family—perovskite QDs—beginning with the synthesis of hybrid organic–inorganic methylammonium lead bromide ($MAPbBr_3$) NCs in 2014.[100] Later in 2015, Zhong and co-workers introduced the ligand-assisted reprecipitation (LARP) method, a simple and low-temperature solution-based approach that enabled the rapid production of these perovskite QDs.[101] The field accelerated explosively after Kovalenko's group applied the hot-injection method to synthesize high-quality all-inorganic $CsPbX_3$ (X = Cl, Br, I) QDs in 2015.[102] These materials, characterized by ionic bonding, high defect tolerance, fully tunable emission across the visible spectrum with near-unity PLQY, make them potentially attractive for next-generation displays, light-emitting diodes, and other optical and optoelectronic applications.[103–107] However, the inclusion of lead raises environmental concerns, motivating ongoing research into an array of lead-free perovskite and perovskite-analog QD materials.[108–111]

QDs in applications

With decades of synthetic refinement and growing materials diversity, producing QDs with high PLQYs, tunable emission, and robust stability has become routine—transforming them from laboratory curiosities into versatile platforms for real-world technologies. Their functionality hinges on how excitons—bound electron–hole pairs generated upon excitation—are manipulated. Depending on the application, exciton recombination can yield light emission, while charge separation enables current generation or chemical reactions. This section highlights major scientific breakthroughs for QD applications by examining these two key mechanisms (**Figure** 4). For a detailed discussion on exciton dynamics, readers are referred to sources elsewhere.[112–119]

Exciton recombination-based applications

Displays and lighting

With bright, solution-processable QDs in hand, researchers moved quickly to demonstrate electroluminescent

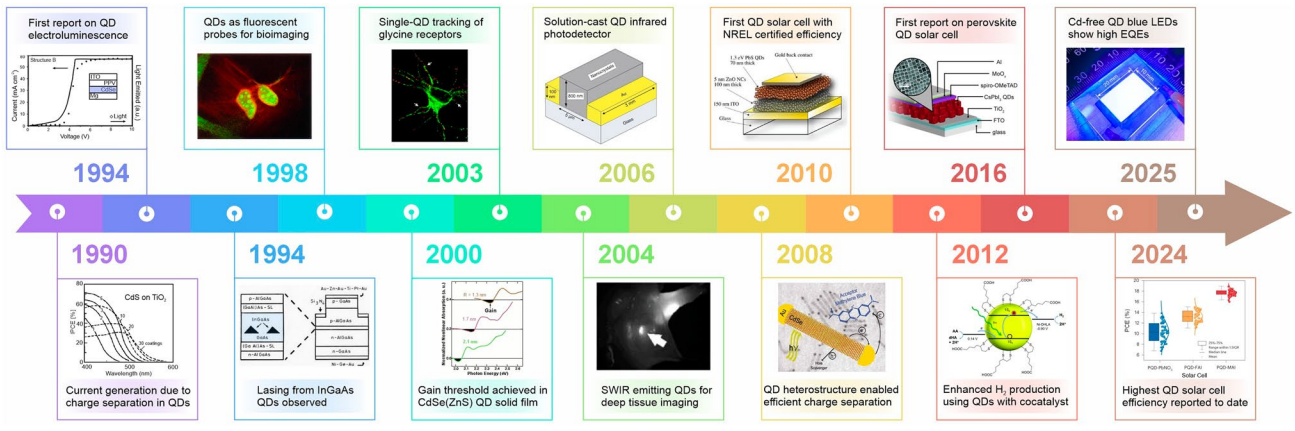


Figure 4. Timeline of major scientific breakthrough publications illustrating the integration of quantum dots (QDs) into diverse technological applications. NREL, National Renewable Energy Laboratory; NCs, nanocrystals; EQEs, external quantum efficiencies; SWIR, shortwave infrared; LEDs, light-emitting diodes; IPCE, incident photon-to-current efficiency; PCE, power-conversion efficiency; PQD, perovskite quantum dot; FAI, formamidinium iodide; MAI, methylammonium iodide. Reproduced with permission from References 120, 139, 141, 143, 149, 152, 165, 171, 192, 197, 198, 222, 250, 253.

devices. The first QD light-emitting diode (QD-LED) was reported in 1994 by Colvin, Schlamp, and Alivisatos, who incorporated CdSe QDs into a polymer LED structure.[120] This prototype device showed electroluminescence peaking at the QD emission wavelength, proving that injected charges could recombine in QDs to produce light. However, the initial QD-LEDs had very low external quantum efficiency (~0.001–0.01%) due to poor charge balance and incomplete QD surface passivation. A major breakthrough was reported in 2002 by Bulović, showing that using monolayer thickness of QDs could significantly enhance luminescence efficiency.[121] Although this work demonstrated a significant improvement in electroluminescent efficiency in comparison to earlier QD-LEDs, device performance was still far from its fundamental limits, with challenges remaining in quantum efficiency and color purity. Over the next decade, research tackled these challenges: improved core/shell QDs raised internal efficiency, and better device architectures were designed for balanced electron and hole injection into the QD layer. By the 2010s, hybrid QD-LEDs achieved modest efficiencies and any color across the visible spectrum by size-tuning of CdSe-based QDs.[121–126] An important advance for high flux devices came with engineering of multilayer QD shells and alloyed compositions to suppress Auger recombination (a nonradiative process where one exciton recombination energy re-excites another charge).[127–129] However, the subsequent progress in the QD-LEDs was largely driven by converging understandings of device architectures, charge-transport mechanisms, and materials design. By around 2015, the best colloidal core/shell QD-LEDs reached external quantum efficiencies (EQEs) exceeding 10% and exhibited luminance suitable for display technologies.[130–133] Over the last decade, numerous studies have reported a substantial improvement in EQEs of Cd-based QD-LEDs with values commonly exceeding 20% across red, green, and blue emission colors.[134–136] For non-cadmium-based QD-LEDs, heavy metal-free InP/ZnSeS core/shell QDs were developed as efficient green and red emitters, culminating in 2019 with InP-based QDs achieving near parity with CdSe in electroluminescence performance.[137] The EQEs of state-of-the-art Cd-free red, green, and blue QD-LEDs have achieved 21.4%,[137] 26.68%,[138] and 24.7%,[139] respectively. Although device stability remains a challenge, particularly for blue QD-LED, these milestone studies have demonstrated that colloidal QDs could serve as high-quality emitters, offering full visible spectrum coverage with high color purity (narrow emission bandwidth), and solution-processable fabrication.[140] This progress has directly informed both modern QD-LED research and commercial display and lighting technologies.

Lasers and stimulated emission

QD lasers utilize the discrete energy levels of QDs to achieve size-tunable, low-threshold stimulated emission, offering advantages in coherence, efficiency, and spectral control of photonic applications. Early efforts in the mid-1990s focused on epitaxial QD lasers: in 1994, researchers in Berlin demonstrated the first diode laser with self-assembled InAs/GaAs QDs as the active layer.[141] These QD diode lasers showed lower threshold currents and temperature insensitivity relative to quantum well lasers, confirming the advantages of zero-dimensional carrier confinement.[142] In colloidal systems, achieving stimulated emission required overcoming losses from Auger recombination and exciton ionization. A landmark result was reported in 2000: by close-packing CdSe/ZnS QDs into a solid film and optically pumping it, the authors observed narrow-band stimulated emission with a clear gain threshold, tunable by QD size.[143] This experiment demonstrated the feasibility of colloidal QD lasers, even though sustaining optical gain required a high excitation flux due to fast multiexciton Auger decay. Subsequent research introduced innovations such as "charged" QDs (to favor single-exciton lasing),[144] and thick-shell "giant" QDs to mitigate Auger losses.[51,145–147] By the 2010s, optically pumped colloidal QD lasers operated at room temperature with increasingly low thresholds, and integration with optical cavities was explored for eventual electrical pumping.[147,148] Heterostructure engineering played a key role here: Type I core/shell QDs with more than 10 layers of CdS shells were shown to support amplified spontaneous emission without rapid Auger quenching, enabling sustained optical gain.[128] While a true electrically driven colloidal QD laser is still a goal, these milestone studies in QD photonics firmly established that exciton recombination in QDs can produce stimulated emission for lasers.

Biological imaging and tracking

The mid-1990s advances in QD brightness and stability soon led to breakthroughs in biotechnology. In 1998, two independent reports (Bruchez et al. and Chan and Nie) demonstrated that water-dispersible core–shell QDs can be used as fluorescent biomarkers in cells.[149,150] In particular, Bruchez et al. employed CdSe/CdS QDs,[149] while Chan and Nie used CdSe/ZnS QDs provided by Hines and Guyot-Sionnest.[150] These QDs were functionalized with biomolecules and coated with hydrophilic ligands or silica to ensure biocompatibility and target-specific labeling. Compared to organic dyes, QDs offered several advantages: broad absorption spectra allowed single-source excitation of multiple QDs, each emitting narrow, tunable peaks. Their exceptional photostability enabled long-term imaging of biological processes without photobleaching.[151] By the early 2000s, QDs allowed dynamic single-particle tracking—most notably in a study by Dahan et al., where neurotransmitter receptors on live neurons were imaged and tracked for extended periods.[152] Subsequent efforts focused on optimizing QD surface chemistry. Strategies such as PEGylation, micelle encapsulation, and polymer coatings improved aqueous dispersibility, reduced nonspecific interactions, and enhanced circulation time.[153–156] To address the toxicity of cadmium-based QDs, researchers developed heavy-metal-free alternatives including InP/ZnS, $CuInS_2$/ZnS, carbon, silicon,

graphene, and silver chalcogenide QDs.[108,157–164] These materials offer tunable emission and improved biocompatibility, making them suitable for both *in vitro* and *in vivo* applications.

A significant advancement was extending QD emission into the NIR and short-wave infrared (SWIR) ranges, enabling deeper tissue imaging. In 2004, NIR QDs (~800 nm) enabled sentinel lymph node imaging ~1 cm beneath the skin with minute doses.[165] Later, Ag_2S QDs (~1200 nm) demonstrated bright, biocompatible emission in the NIR-II window.[166] Recently, InAs-based core/shell QDs with size-tuned SWIR emission (>1000 nm) have shown high PLQYs, narrow emission peaks, and excellent stability.[167] These QDs have been used for targeted, real-time imaging of vascular and metabolic processes *in vivo* with remarkable depth and clarity.[167–170]

Together, these advances have cemented QDs as powerful tools in bioimaging, from single-cell resolution to deep-tissue tracking, while addressing long-standing challenges of toxicity and biological compatibility.

Exciton separation-based applications

Solar-energy harvesting and conversion

Soon after QDs were discovered, researchers recognized their potential in photovoltaics: quantum confinement allows tuning of bandgaps and even the prospect of generating multiple charge carriers from a single high-energy photon. Early work in the 1990s explored QD-sensitized solar cells, analogous to dye-sensitized ones, by adsorbing semiconductor QDs onto wide-bandgap oxide electrodes.[171] For example, TiO_2 films sensitized with CdS or CdSe QDs showed photocurrents under illumination, demonstrating that QD excitons could be separated at an interface to produce electrical power.[172,173] These proof-of-concept solar conversion devices had low efficiencies, but by the mid-2000s incremental progress was made.[174,175] Researchers also proposed that hot carriers or multiple exciton generation (MEG) in QDs could be harnessed to surpass the Shockley–Queisser efficiency limit.[176,177] Experimental reports of MEG in PbSe and PbS QDs quickly followed, although the early reports were contaminated with artifacts from photo-induced charging of QDs.[178–183] These studies showed that QDs could convert excess photon energy into additional charge carriers rather than waste it as heat, a process with potentially important implications for next-generation solar cells. To translate QDs into actual photovoltaic devices, improved QD solids and junction architectures were needed. A solid-state ligand exchange strategy introduced by the Guyot-Sionnest group was a breakthrough discovery that made CdSe QD films electrochemically active and conductive.[184,185] Building on this foundation, around 2004–2010, Sargent and other groups developed methods to create conductive films of QDs by cross-linking them with short ligands (replacing long insulating surfactants).[186–191] This enabled the first all-inorganic solar cells, where QD layers acted as the light absorber in a *p-n* or Schottky junction.[192] By 2010, such cells (often using PbS or PbSe QDs for broad IR absorption) reached power-conversion efficiencies of a few percent, climbing to over 10% by the late 2010s as surface passivation and QD packing improved.[193–196] By 2016, engineering advances extended to perovskite QDs in solar cells: Luther et al. reported the first all-perovskite-QD solar cell, leveraging the facile bandgap tunability and defect tolerance of $CsPbX_3$ perovskite QDs.[197] The current state-of-the-art QD-based solar cell was reported by Sung-Yeon Jang and co-workers, who employed methylammonium iodide in isopropanol to achieve ligand exchange and replace long-chain organic ligands (oleic acid and oleylamine) on formamidinium lead triiodide ($FAPbI_3$) perovskite QDs, achieving a record power-conversion efficiency of 18.1 percent.[198] (Note: An unpublished new record of 19.1% has been updated on the National Renewable Energy Laboratory [NREL] best research-cell efficiency chart.)[199]

Beyond traditional QD solar cells, QD-based luminescent solar concentrators (QD-LSCs) have emerged as a complementary strategy for solar-energy harvesting.[200–204] QD-LSCs use QDs embedded in transparent matrices to absorb sunlight and reemit it at longer wavelengths, guiding the light to photovoltaic cells placed at the edges of the devices total internal reflection. This approach reduces the need for large-area photovoltaic materials and enables integration into (semi-) transparent windows and building facades.[205,206] Over time, improvements in QD stability, Stokes shift, spectral coverage, and PLQYs have significantly enhanced LSC efficiency.[207–216] The use of heavy-metal-free conventional and perovskite-based QDs and tandem structures has further addressed environmental and spectral mismatch challenges, making QD-LSCs a promising route for building-integrated photovoltaics and urban energy harvesting.[217,218]

These milestones underscore how materials design addressed technical hurdles in QD solar cells and solar-energy harvesting, leading to steady improvements in efficiencies. While QD solar light harvesting technologies are still maturing, the past two decades of research, from MEG physics and novel QD compositions to innovative device architecture strategies, have solidified QDs as a promising platform for solar-energy harvesting and conversion.

Photodetectors

QD-based photodetectors are another class of exciton separation devices, where incident light creates excitons that are split into electrons and holes to generate a photocurrent. QDs offer the unique advantage of spectral tunability into the IR, which is attractive for detecting wavelengths beyond what bulk semiconductors such as silicon can sense. Early attempts in the 1990s demonstrated QD photoconductors (e.g., QDs spin-coated on electrodes yielding an IR photoresponse), but these suffered from high dark current and slow response.[219–221] The field leapt forward in 2006 when Konstantatos and Sargent reported IR photodetectors using PbS colloidal QDs.[222] By using a Schottky diode structure and a film of densely packed, ligand-exchanged QDs, they achieved comparable

normalized detectivities to commercial InGaAs photodiodes in the SWIR.[223] Around the same time, a study led by Sargent's group also highlighted the importance of surface chemistry: treatments that passivated QD surfaces and reduced trap-assisted recombination were critical to obtaining high sensitivity.[222] Following this, QD photodetector research expanded rapidly. By 2010, hybrid structures combining QDs with thin-film transistors or optical cavities improved gain and noise characteristics.[224] Electrical coupling strategies (e.g., compact halide ligands and controlled necking between QDs) were developed to increase carrier mobility in QD films, similar to the solar cell efforts.[225–228] As a result, QD photodiodes and photoconductors achieved fast response times and multispectral detection capabilities. For instance, photodiodes based on solution-processed Pb and Hg chalcogenide QDs were engineered to cover short-, mid-, and even long-wave IR ranges (up to ~10 μm) by tuning QD size and utilizing both inter- and intraband transitions.[229–240] A notable achievement is that modern QD IR detectors can operate at room temperature, whereas many traditional IR sensors require cooling. By 2016, a comprehensive review by Saran and Curry surveyed a full "toolbox" of Pb-chalcogenide QD photodetector technologies, indicating a maturation of this research area.[229] Compared to traditional QDs, which often suffer from limited charge mobility, perovskite QDs exhibit significantly higher mobility along with excellent optical properties. When implemented in photodetectors, they have also demonstrated remarkable performance improvements over the past decade, as detailed in prior reviews.[241–243]

The progress in QD photodetectors exemplifies how addressing inter-dot charge transport (via ligand engineering) and passivation challenges led to functional devices with competitive performance.[244,245] These milestones have established colloidal QDs as a viable materials platform for photodetection across visible and IR bands.

Photocatalysis

QDs have emerged as promising photocatalysts due to their tunable bandgaps, unique catalyst-substrate interface, high surface area, and strong light absorption.[246,247] Early studies in the 2000s demonstrated that QDs, such as CdS, could harvest visible light for hydrogen generation when coupled with supports such as TiO_2.[248,249] However, a central challenge was minimizing charge recombination while promoting efficient transfer of photoexcited electrons and holes to perform redox reactions. To address this, researchers have introduced various co-catalysts and/or modified surface and compositions of QD catalysts. For example, Krauss and his group reported that by adding Ni^{2+}-based co-catalysts to CdSe QDs, hydrogen generation rates can be significantly enhanced while maintaining the superior catalytic performance over the course of 360 h.[250] In addition, coating CdS QDs with a ZnS shell or coupling them with metal (Au, Pt, and Pd) nanoparticles can improve charge separation and catalytic turnover.[251–256] Recently, Type I CdS/ZnS QDs decorated with Au domains were shown to enhance hydrogen evolution by forming local heterojunctions that facilitate charge transfer and mobility.[257] Moreover, Type II core/shell QDs, such as $CuInS_2$/CdS, offer another effective strategy. Their staggered band alignment spatially separates electrons and holes into different regions, extending carrier lifetimes and improving photocatalytic efficiency.[258,259] In such systems, electrons in the CdS shell drive proton reduction while holes in the $CuInS_2$ core oxidize sacrificial donors.

In addition, QDs have also been employed for photocatalytic organic transformations.[260,261] Some of the earliest demonstrations of photo-reductive transformations were reported in 1985 when ZnS NCs were used to reduce cyclic ethers to alcohol and primary amines to secondary amines.[262,263] Since then, QDs have later been applied to a range of photocatalytic organic transformations, including C–C bond formation,[264–266] C–X (X = N, O, B, halogen, etc.) bond formation,[267,268] reductive transformations,[269–271] oxidative transformations,[272–274] photoinitiated polymerization reactions,[275,276] and stereoselective reactions.[264,277,278] One of the unique advantages of QDs for organic reactions is their tunability of redox potential through size and composition modifications, which enable selective activation of diverse organic substrates.[279] In addition, their long-lived excited states facilitate electron and energy-transfer mechanisms critical for initiating bond-forming or bond-breaking steps.[280] Moreover, the tunable QD–substrate interface can be modulated with ligand exchange or heterostructure design, providing additional control over substrate binding, spatial preorganization, and reaction selectivity.[281]

Perovskite QDs have recently entered the photocatalysis space due to their strong optical properties. They have been successfully utilized in a wide range of photocatalytic organic reactions and CO_2 reduction reaction.[282–286] However, their instability in aqueous environments limits their use to non-aqueous systems, and their long-term durability remains a concern.[287–289] Carbon-based QDs, particularly nitrogen-doped variants, have also been explored for photocatalysis under visible light. These materials utilize surface functional groups to engage in redox chemistry, offering a metal-free, eco-friendly alternative—though their efficiencies remain modest.[290–292]

Overall, the development of QD-based photocatalysts has been shaped by advances in heterostructure design, surface engineering, and band alignment strategies. These innovations have enabled QDs to serve as efficient light harvesters and charge mediators in a range of photocatalytic reactions, from simple hydrogen evolution to complex organic transformations.[264,265,286,293–297]

Commercialization path of QDs

Toward the end of the 20th century, as maturing QD synthesis—producing materials with high luminescence, tunable properties, and improved stability, the momentum led to the transition from laboratory-scale innovation to practical applications with the emergence of startups and industrial collaborations focused on translating QD technologies into commercially viable products (**Table** I).

Table I. A partial list of companies focusing on QDs as products.

Company Name	Year Founded	Current Status	Major Products	Applications
Quantum Dot Corporation	1998	Acquired by Invitrogen	QD-based fluorescent probes	Biological imaging and labeling
NNCrystal US Corporation	2001	Active	Cd-based and Cd-free QDs	Biomedicine and optoelectronic devices
Nanosys	2001	Acquired by Shoei Chemical, Inc.	QDs for LEDs	Display technology
Nanoco Technologies	2001	Active	PbS, InP, InAs, InSb-based QDs	Displays and IR sensing
QD Vision	2004	Acquired by Samsung	CdSe-based QDs	Display and Lighting
Ocean Nanotech	2004	Active	Cd-based chalcogenides QDs	Various applications, i.e., sensing, drug delivery, cell imaging, and labeling of biomolecules
Mesolight	2005	Active	PbS, ZnSe, CdSe, and InP-based QDs	Display, image sensing, and biological applications
QD Laser, Inc.	2006	Active	InAs, InGaAs-based QDs	Semiconductor lasers
InVisage Technologies	2006	Acquired by Apple	PbS QDs	Image sensors
CD Bioparticles	2007	Active	Perovskite QDs, Cd-, Pb-, In-based QDs, Graphene QDs	Biotechnology
Avantama	2008	Active	Perovskite QDs	Display, Photovoltaics, and sensors
Ossila	2009	Active	Perovskite QDs, CQDs, Graphene QDs	Various applications
Qlight Nanotech	2009	Acquired by Merck	CdSe and Zn-chalcogenides QDs	Lighting and displays
Core Quantum Technologies	2012	Active	Various types of QDs	Spectral flow cytometry, fluorescence microscopy, and imaging
UbiQD	2014	Active	$CuInS_2$ QDs	Agriculture, Solar Cells, Security inks
QD Solar	2014	Active	Perovskite and QDs	Photovoltaic cells
Glass to Power	2016	Active	$CuInS_2$/ZnS QDs Perovskite QDs	Building integrated photovoltaics
Quantum Science	2008	Acquired by AIML-Innovations	InGaAs, SiGe, PbS, Ag_2S, Ag_2Se QDS	Infrared imaging and sensing
Quandela	2017	Active	QD-based single-photon source	Quantum information system
Quantum solutions	2017	Active	PbS, InAs, Perovskite QDs	Image Sensors
QDI Systems	2019	Active	PbS QDs	Medical imaging devices (x-ray and SWIR range)
NanoPattern Technologies	2019	Active	Photopatternable QD inks	Next-generation displays
QustomDot	2020	Active	InP-based core/shell QDs	Custom solutions for various applications

One of the earliest and most notable ventures was the founding of Quantum Dot Corporation (QDC) in 1998, which aimed to develop QD-based fluorescent labels for biomolecular detection and bioimaging. This marked a critical turning point, signaling growing industrial interest in the biomedical potential of QDs. QDC's products, such as the Qdot® nanocrystal probes, offered superior brightness and photostability compared to conventional dyes. The company was acquired by Invitrogen in 2005, later becoming part of Thermo Fisher Scientific, and its QD technologies remain used in biological research and diagnostics today. In the display technologies, QDs found their first major consumer-facing application in 2010, when QD Vision, a startup spun out of MIT, collaborated with Nexxus Lighting to release the first QD-enabled LED lamp, using its proprietary Quantum Light™ optic.[298] While this was a milestone for solid-state lighting, it was the display industry that truly catapulted QDs into the mainstream. The first commercial use of QDs in displays came in 2013, when Sony incorporated QDs into the TRILUMINOS™ TV line using QD Vision's technology to significantly enhance color gamut and image quality. This breakthrough demonstrated the power of QDs as photoluminescent color converters for LCD backlights. Building on this momentum, in 2015, Samsung launched a TV product line with Cd-free QD-enhanced displays for the first time, in compliance with environmental regulations such as RoHS.[299] The success of Samsung QLED™ displays helped solidify QDs as a core component in next-generation display technologies, offering vivid color reproduction, energy efficiency, and improved durability over traditional display materials. Since then, major electronics companies including Samsung, Sony, LG, TCL, and Vizio have integrated QD-based display technologies into their product lines.

Beyond display technologies, a growing group of companies is actively advancing QDs for emerging applications in solar-energy harvesting, imaging and sensing, agriculture, and quantum computing. In solar energy, companies such as QD Solar and Glass to Power are developing perovskite-QD hybrid solar cells and LSCs, respectively, to enhance spectral harvesting and enable transparent photovoltaics—key technologies for meeting near zero energy building (NZEB) standards.[300] For sensing and imaging, companies such as

InVisage Technologies (acquired by Apple Inc. in 2017), Quantum Solutions, Quantum Science, and QDI Systems are commercializing QD-based SWIR sensors for IR cameras, autonomous vehicles, and medical imaging applications. In agriculture, UbiQD is engineering QD films that modify light spectra to improve greenhouse crop productivity and energy efficiency. Very recently, UbiQD announced its official collaboration with First Solar to develop bifacial solar cells. Meanwhile, in quantum technology, Quandela has been developing deterministic single-photon sources using InAs QDs to scale photonic quantum computing.

Over the past decade, the commercialization of QDs has been shaped by a convergence of scientific discovery and engineering innovation. Key challenges such as material toxicity, device integration, and manufacturing scalability have been gradually overcome. Today, QDs are commercially used not only in displays and lighting, but also in bioimaging tools, sensors, and are actively being used for other applications as mentioned above. The commercialization journey of QDs exemplifies the trajectory of modern nanotechnology, where sustained research, collaborative innovation, and strategic investments have transformed a nanomaterial from a fundamental scientific curiosity into a versatile platform with broad technological impact.

Conclusion and outlooks

The story of QDs is a remarkable testament to how deep scientific curiosity, precise synthetic chemistry, and interdisciplinary innovation can converge to transform a fundamental concept into a widely impactful technology. Since their first experimental discovery in the early 1980s, QDs have progressed from obscure NCs with unusual size-dependent behavior to versatile materials central to modern optoelectronics, energy, and biomedical science. The awarding of the 2023 Nobel Prize in Chemistry to QDs not only recognizes the pioneering origins of the field but also highlights the extraordinary journey of QDs—from discovery to deployment.

Looking ahead, the next few decades promise to be equally transformative for QD research. As new material classes (such as perovskite and metal-free QDs) emerge and fabrication technologies mature, QDs are poised to enable novel functionalities across diverse fields. Yet, to fully realize this potential, several challenges must be addressed across synthetic, environmental, and device engineering landscapes (**Figure** 5).

Scalability and manufacturing innovation

Despite tremendous advances in colloidal synthesis, achieving consistent large-scale production of high-quality QDs remains a hurdle for many emerging applications. Efforts to transition from batch synthesis to continuous flow reactors and on-site production have shown great promise,[301–304] not only in improving reproducibility but also in reducing cost and environmental impact. The integration of autonomous optimization platforms—combining machine learning with real-time feedback—could drastically accelerate the discovery of new QD materials and scalable processes tailored for specific optoelectronic properties.[304–310]

Environmental safety and materials substitution

The presence of heavy metals such as cadmium and lead in the most thoroughly studied QDs continues to pose regulatory and sustainability concerns, particularly for consumer electronics and biomedical applications. This challenge has catalyzed a surge in research into alternative QD compositions such as InP, $CuInS_2$, carbon, silicon, and lead-free perovskites.[108,157–163,311] While InP-based QDs are now widely used in commercial displays, carbon and silicon QDs are emerging as more biocompatible alternatives for use in imaging, drug delivery, and sensing.[88,137,312,313] We anticipate a continued push toward high-performance, heavy-metal-free QDs that balance optical quality, stability, and environmental safety.

Stability and device integration

Long-term operational stability remains a key factor limiting broader deployment of QDs, particularly in solar cells, photodetectors, and photocatalysts. QDs are susceptible to photobleaching, surface oxidation, and thermal degradation—processes that are exacerbated under prolonged exposure to light, moisture, or heat.[314] As already discussed, advanced passivation techniques, such as epitaxial shell growth, compact ligand chemistries, and polymer encapsulation, have improved QD robustness significantly.[30–35,40,315–317] However, a deeper understanding of degradation mechanisms—particularly at interfaces and under device-operating conditions—is crucial for building durable QD-enabled technologies.

Emerging frontiers: Quantum and photonic technologies

Beyond displays and photovoltaics, colloidal QDs are rapidly gaining traction in next-generation quantum and photonic applications. Single colloidal QDs have already demonstrated photon antibunching and single-photon coherent emission, making them promising sources of single-photon emission for quantum communication and linear optical quantum computing,[318–320] and assembled QD superstructures have shown coherent superradiant quantum light.[321–323] Spin properties of QDs could also offer routes to scalable quantum computing architectures compatible with existing semiconductor infrastructure. In addition, the formation of polaritons in the QDs coupled with optical cavities has opened new avenues to develop low-threshold polaritonic lasers and quantum photonic devices that harness nonlinear optical effects, both of which have a strong potential to transform photonic computing.[324–328] As fabrication techniques advance, we foresee bottom-up assembly of ordered QD arrays and hybrid superstructures tailored for long coherence times and low-noise operation, which would place QDs as a key component for next-generation quantum computing systems.



Figure 5. Schematic illustration of the current and future landscape of quantum dot technologies. CB, conduction band; VB, valence band. Reproduced with permission from References 304, 309, 310, 311, 314, 317.

Toward a convergent future

The field of QDs is entering a phase of convergence—where foundational chemistry and physics meet real-world imperatives of scale, cost, safety, and integration. The path ahead will require continued collaboration across academia, industry, and regulatory bodies. As new materials and device paradigms emerge, QDs will continue to play a central role in enabling next-generation technologies in energy, health care, computing, and communication.

In conclusion, the journey of QDs is far from over. If the past four decades have demonstrated their scientific richness, the coming decades will define their full technological impact. With continued innovation and thoughtful development, QDs are poised to remain a dynamic and foundational component of the materials science landscape well into the future.

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Author contributions

A.H. and O.C. proposed and designed the conceptual framework of the manuscript; A.H. and J.K. performed the literature research and analyzed the relevant data; J.K. and O.C. worked on the preparation of figures in the project. A.H., J.K., O.C., and M.B. wrote the manuscript. All authors commented on and edited the manuscript. O.C. and M.B. supervised the project.

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Conflict of interest

On behalf of all authors, the corresponding authors state that there is no conflict of interest.

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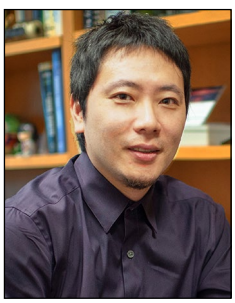
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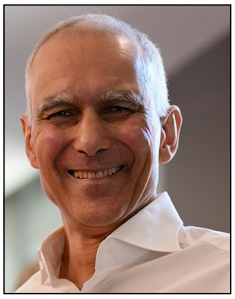
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