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ARTICLE

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QUANTUM DOTS: BRIDGING THE GAP BETWEEN NANOSCIENCE AND REAL-WORLD APPLICATIONS

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Quantum dots (QDs) have emerged as a transformative technology, seamlessly connecting the realms of nanoscience to practical applications across various industries. These nanoscale semiconductor particles exhibit unique optical and electronic properties due to quantum confinement effects, making them highly attractive for a plethora of applications including optoelectronics, biomedicine, energy and environmental monitoring. This paper explores the fundamental aspects of QDs, encompassing their synthesis, characterization and manipulation at the nanoscale. Additionally, it delves into the diverse array of real-world applications where QDs have demonstrated remarkable potential, such as light-emitting diodes (LEDs), solar cells, bioimaging agents and quantum computing. Furthermore, challenges associated with QD-based technologies, such as toxicity concerns and scalability issues, are discussed alongside ongoing research efforts aimed at addressing these obstacles. Through a comprehensive examination of the current state-of-the-art and future prospects, this paper underscores the pivotal role of QDs in bridging the gap between nanoscience and tangible technological advancements with profound societal implications.

Introduction

QDs represent a fascinating intersection between nanoscience and practical applications, offering a myriad of possibilities in fields ranging from electronics and medicine to energy and environmental science[1]. QDs are semiconductor nanoparticles typically composed of elements from groups II-VI (e.g., CdSe, CdTe) or III-V (e.g., InP, GaAs) of the periodic table[2]. These tiny semiconductor particles, typically ranging from 1 to 10 nanometers in size, exhibit unique quantum mechanical properties due to their confined dimensions, making them highly attractive for various technological advancements. The ability to precisely engineer their size, shape and composition grants researchers unparalleled control over their optical, electronic and chemical properties, paving the way for innovative solutions to longstanding challenges[3].

Professor Moungi G. Bawendi of Massachusetts Institute of Technology, Cambridge, MA, USA: Professor Louis E. Brus of Columbia University, New York, NY, USA and Alexei I. Ekimov (or, Aleksey I. Yekimov) of Nanocrystals Technology, Inc., New York, NY, USA, jointly were awarded the Nobel Prize in Chemistry in 2023 "for the discovery and synthesis of quantum dots"[4]. QDs are nanoparticles and their properties are dependent on quantum phenomena, hence they are named as QDs. The properties of an element are dependent on the electrons around the nucleus. In case of QDs, as the size decreases, the quantum energy levels of the electrons change. Attaining the nanoscale size, the electrons are confined by the size of their surroundings i.e. the natural volume. By changing the energy levels, the electrons respond, when the size of the electrons becomes smaller than the natural volume. Thus, changes are observed in case of the interaction between the systems with light. Hence, QDs show size dependent colours.

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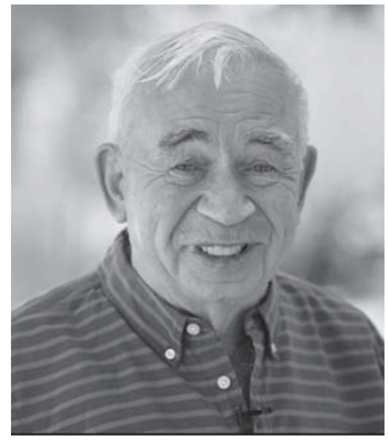

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The journey of QDs from fundamental research to real-world applications has been marked by significant breakthroughs and ongoing exploration. Initially discovered in the 1980s, QDs garnered attention for their size-dependent optical properties, including tunable fluorescence and narrow emission spectra, which found immediate use in biological imaging and sensing applications[5,6]. However, it is in recent years that QDs have truly emerged as versatile building blocks for cutting-edge technologies, propelling nanoscience into the realm of practical utility. In the context of QDs, the term "zero dimension" refers to the confinement of charge carriers (electrons and holes) in all three spatial dimensions, resulting in discrete energy levels. This confinement leads to quantum confinement effects, where the electronic properties of the material are significantly influenced by its nanoscale dimensions[7].

In electronics, QDs hold promise for revolutionizing computing, communication and display technologies. Their ability to confine charge carriers in three dimensions offers advantages in miniaturization and energy efficiency, leading to the development of QD-based transistors, quantum computing architectures and high-resolution displays with vibrant colour and low power consumption[8]. Moreover, QDs have demonstrated potential in next-generation solar cells, where their unique electronic properties enable efficient light absorption and charge transport, enhancing the performance and scalability of photovoltaic devices[9].

Besides electronics, QDs are driving innovations in biomedicine and environmental science[10]. Functionalized with biomolecules or targeting ligands, QDs serve as sensitive probes for molecular imaging, drug delivery and therapeutic applications, offering unprecedented insights into biological processes at the nanoscale[11]. Furthermore, their use in environmental monitoring and remediation holds promise for detecting pollutants, catalyzing chemical reactions and purifying water resources with enhanced efficiency and selectivity.

Despite their tremendous potential, the widespread adoption of QDs faces challenges related to scalability, toxicity and cost-effectiveness. Addressing these concerns requires interdisciplinary collaborations among physicists, chemists, engineers and biologists to develop scalable synthesis methods, biocompatible coatings and sustainable manufacturing processes. Moreover, regulatory frameworks must ensure the safe handling and disposal of QD-based products while fostering innovation and commercialization.

Fabrication Methods of QDs: The synthesis of QDs plays a critical role in determining their properties and suitability for various applications[2]. Following are the few synthesis methods which are used to fabricate QDs along with the mechanisms.

- Colloidal Synthesis: Colloidal synthesis is one of the most common methods for producing QDs with precise control over size, composition and surface properties. In this method, semiconductor precursors are dissolved in a coordinating solvent and a reducing agent is added to initiate the nucleation and growth of nanocrystals[12]. The size and shape of the QDs can be controlled by adjusting reaction parameters such as temperature, precursor concentration and reaction time. Surface ligands or coatings are often used to stabilize the QDs and impart specific functionalities.
- Epitaxial Growth: Epitaxial growth involves the deposition of semiconductor materials onto a crystalline substrate using techniques such as

molecular beam epitaxy (MBE) or metalorganic chemical vapor deposition (MOCVD). QDs are formed through the self-assembly of atomic layers on the substrate surface, leading to the formation of nanoscale islands with quantum confinement effects. Epitaxial growth allows for precise control over the size, composition and crystallinity of the QDs, making it suitable for industrial-scale production and integration into semiconductor devices.

- Chemical Vapor Deposition (CVD): Chemical vapor deposition is another technique used to synthesize QDs by introducing precursor gases into a reactor chamber at elevated temperatures. The precursors decompose and react on the substrate surface, leading to the nucleation and growth of semiconductor nanocrystals. CVD offers advantages such as scalability, uniformity and compatibility with various substrates, making it suitable for large-area deposition and thin-film fabrication. However, controlling the size distribution and morphology of QDs in CVD remains challenging and requires precise control over reaction conditions.
- Microfluidic Synthesis: Microfluidic synthesis involves the controlled mixing of precursor solutions in microscale channels or reactors to produce QDs with narrow size distributions and high reproducibility. Microfluidic devices offer advantages such as rapid mixing, precise control over reaction kinetics and the ability to perform multiplexed synthesis of QDs with different properties. This method enables the synthesis of QDs with enhanced optical and electronic properties for specific applications in sensing, imaging and catalysis[13].
- Laser Ablation: Laser ablation involves the use of high-energy laser pulses to vaporize a target material, which then condenses to form nanoparticles, including QDs, in a surrounding inert gas atmosphere[14]. This method offers advantages such as rapid synthesis, narrow size distributions and minimal chemical contamination[15]. Laser ablation can be used to fabricate QDs from a wide range of materials, including metals, semiconductors and insulators.
- Electrochemical Deposition: Electrochemical deposition involves the electrodeposition of semiconductor materials onto conductive substrates from a solution containing precursor ions. By applying an electrical potential, ions in the solution are reduced at the electrode surface, leading to the formation of QDs[16]. This method offers advantages such as simplicity, scalability and control over QD size and density. It is particularly suitable for fabricating QD thin films and heterostructures[17].

To improve scalability, reproducibility and sustainability of production methods of QDs, novel approaches such as microwave-assisted synthesis, continuous-flow reactors and green synthesis using bio-inspired templates or biogenic precursors have been developed to overcome limitations associated with traditional synthesis techniques. Furthermore, efforts have been made to engineer QDs with enhanced stability, biocompatibility and functionality for applications in areas such as energy storage, quantum computing and photonics.

Characteristics of QDs: QDs are fascinating nanoscale semiconductor structures with unique characteristics that arise due to quantum confinement effects.

- Size-Tunable Optical Properties: QDs exhibit size-dependent optical properties, including their absorption and emission spectra[11]. As the size of a quantum dot decreases, its energy levels become more closely spaced, leading to a blue shift in both absorption and emission wavelengths. This tunability makes quantum dots ideal candidates for applications such as light-emitting diodes (LEDs), displays and biological imaging.
- Discrete Energy Levels: QDs are zero-dimensional structures, meaning charge carriers (electrons and holes) are confined in all three spatial dimensions[18]. This confinement leads to quantized energy levels, resulting in a discrete density of states (DOS). The discrete energy levels give rise to unique electronic and optical properties, such as sharp absorption and emission peaks, as observed in spectroscopic measurements.
- High Quantum Yield: QDs can exhibit high quantum yield, which refers to the efficiency of light emission upon excitation. This property makes them attractive for applications requiring bright and stable fluorescence, such as bioimaging and sensing. Surface passivation and careful control of synthesis conditions are crucial for maximizing quantum yield and preventing non-radiative recombination processes.

- Broad Absorption Spectrum: Unlike traditional fluorescent dyes, quantum dots typically have broad absorption spectra, spanning a wide range of wavelengths. This broad absorption allows for excitation using a single light source, simplifying multiplexed imaging and sensing applications where multiple colours are required simultaneously.
- Size-Dependent Electronic Structure: The electronic structure of quantum dots is highly sensitive to their size, shape, and composition[15]. Quantum confinement effects lead to discrete energy levels, with larger dots exhibiting behaviour closer to bulk semiconductors and smaller dots displaying more pronounced quantum effects. The ability to engineer the electronic structure of QDs enables fine control over their optoelectronic properties for various applications[19].

In the context of density of states (DOS), QDs represent a fascinating system due to their nanoscale dimensions, which lead to discrete energy levels. The DOS describes the distribution of available electronic states within a material as a function of energy. In QDs, the discrete energy levels arise from quantum confinement effects, where the confinement of charge carriers in all three spatial dimensions leads to quantized energy levels.

- Quantum Confinement Effects and Density of States: In bulk materials, the DOS typically shows continuous bands of allowed energy states[20]. However, when the size of a material becomes comparable to or smaller than the characteristic length scales associated with the electron wavelength (the de Broglie wavelength), quantum confinement effects become prominent. In QDs, which are essentially zero-dimensional structures, the discrete energy levels emerge due to the confinement of charge carriers within a small volume[19]. As the size of the quantum dot decreases, the energy levels become more closely spaced, leading to a pronounced quantization of the electronic states. This quantization results in a discrete DOS, with distinct peaks corresponding to the available energy levels within the QDs.
- Experimental Observations and Theoretical Models: Experimental techniques such as scanning tunneling microscopy (STM), transmission electron microscopy (TEM) and optical spectroscopy have provided valuable insights into the DOS of QDs[7]. These techniques allow researchers to probe the electronic structure of individual QDs and observe the discrete energy levels directly. Theoretical models, including effective mass approximation, tight-binding models and density functional theory (DFT), have been employed to understand and predict the DOS of QDs. These models take into account factors such as the size, shape and composition of the QDs, as well as the effects of electron-electron interactions and confinement potentials.

Characterization Techniques of QDs: Characterization of QDs is essential for understanding their structural, optical and electronic properties, which ultimately determine their performance in various applications. A wide range of characterization techniques have been developed to probe QDs at different wave length scales under different conditions, which are discussed below:

- Transmission Electron Microscopy (TEM): TEM is a powerful technique for imaging the morphology, size and crystallinity of QDs with nanometer resolution[12]. High-resolution TEM (HRTEM) provides detailed information about the lattice structure and defects within the QDs. Additionally, energy-dispersive X-ray spectroscopy (EDS) coupled with TEM enables elemental analysis and mapping of the chemical composition of QDs.
- Scanning Electron Microscopy (SEM): SEM allows for imaging of QDs with higher depth of field and larger field of view compared to TEM. SEM is often used in conjunction with energy-dispersive X-ray spectroscopy (EDS) or wavelength-dispersive X-ray spectroscopy (WDS) to obtain elemental information and chemical mapping of QDs.
- Atomic Force Microscopy (AFM): AFM is a surface imaging technique that provides topographical and mechanical information about QDs at the nanoscale. AFM can be used to measure the size, shape and surface roughness of QDs deposited on solid substrates. Additionally, AFM-based techniques such as Kelvin probe force microscopy (KPFM) and conductive AFM (c-AFM) can probe the electrical properties of QDs.
- X-ray Diffraction (XRD): XRD is used to characterize the crystal structure, lattice parameters and phase purity of QDs. By analyzing the

diffraction patterns generated by X-rays interacting with the crystalline lattice of QDs, XRD provides valuable information about their structural properties, including crystal orientation, grain size and strain.

- Photoluminescence Spectroscopy (PL): PL spectroscopy is a powerful technique for probing the optical properties of QDs, including their absorption, emission and quantum efficiency[21]. PL measurements provide information about the energy levels, band gap and radiative recombination processes within the QDs. Time-resolved PL (TRPL) and temperature-dependent PL measurements can reveal insights into carrier dynamics and excitonic behaviour in QDs.
- Raman Spectroscopy: Raman spectroscopy is used to study the vibrational and phonon modes of QDs, providing information about their chemical composition, surface functionalization and lattice structure[22]. Raman spectra of QDs exhibit characteristic peaks corresponding to specific vibrational modes, which can be used for chemical identification and structural analysis.

Recent advancements in characterization techniques for QDs have focused on enhancing spatial resolution, sensitivity and versatility. For example, advancements in electron microscopy techniques, such as aberration-corrected TEM and scanning transmission electron microscopy (STEM), enable atomic-scale imaging and spectroscopy of QDs. Additionally, advancements in spectroscopic techniques, such as single-molecule spectroscopy and super-resolution imaging, allow for the study of individual QDs with unprecedented sensitivity and spatial resolution.

Applications of QDs: Synthesized QDs using above mentioned various techniques find applications in diverse fields, including, Optoelectronics, Biomedicine, Environmental Monitoring, Energy Storage and many more.

Applications of QDs in Optoelectronics: QDs have emerged as key players in the field of optoelectronics, offering unique optical and electronic properties that can be finely tuned by controlling their size, shape and composition[23]. These semiconductor nanocrystals exhibit quantum confinement effects, resulting in discrete energy levels and size-dependent optical properties.

- Light-Emitting Diodes (LEDs): QD-based LEDs offer advantages such as narrow emission line widths, high colour purity and tunable emission spectra. By precisely controlling the size and composition of QDs, researchers can achieve emission across the visible spectrum, enabling the development of full-colour displays with enhanced brightness and energy efficiency[8]. QD LEDs also exhibit improved stability and longevity compared to traditional phosphor-based LEDs.
- Solar Cells: QDs have garnered significant interest for use in next-generation solar cells due to their high absorption coefficients, tunable band gaps and solution-processability. QD-based solar cells can be engineered to absorb a broad spectrum of sunlight, including near-infrared wavelengths, leading to increased power conversion efficiencies[24]. Additionally, QDs can be integrated into tandem or multi junction solar cell architectures to further enhance performance and scalability.
- Photodetectors: QD-based photodetectors exhibit high sensitivity, fast response times, and low noise levels, making them suitable for applications such as imaging, sensing and communication[3]. By leveraging the size-dependent absorption and photoluminescence properties of QDs, photodetectors can be tailored to specific wavelengths of electromagnetic spectrum. QD photodetectors also offer potential advantages in terms of low-cost fabrication and compatibility with flexible substrates.

Applications of QDs in Biomedicine: Due to the unique optical and electronic properties QDs have gained significant attention in the field of Biomedicine.

- Bioimaging: QDs are widely used in bioimaging applications due to their high brightness, photostability and tunable emission spectra. They offer advantages over traditional organic fluorophores. Narrow emission peaks and resistance to photobleaching, make them ideal candidates for long-term cellular and molecular imaging[11].
- Drug Delivery: QDs can be functionalized with targeting ligands and therapeutic agents to enable targeted drug delivery and controlled release[25]. Their small size and large surface area allow for efficient encapsulation of drugs, while surface modifications facilitate specific targeting of diseased tissues or cells[26].

- Biosensing: QDs serve as highly sensitive and selective probes for the detection of biomolecules, pathogens and environmental pollutants[27]. They offer advantages such as high signal-to-noise ratio, rapid detection and multiplexed analysis.

- Theranostics: QDs are integrated into theranostic platforms for simultaneous diagnosis and therapy of diseases[28]. They enable real-time imaging of biological processes and targeted delivery of therapeutic agents, leading to personalized medicine approaches[29].

- Photodynamic Therapy (PDT): QDs can serve as photosensitizers for PDT, a minimally invasive treatment modality for cancer and other diseases[30]. Upon irradiation with light, QDs generate reactive oxygen species that induce localized cell death, making them promising candidates for cancer therapy.

Applications of QDs in Energy Storage and Conversion: QDs have shown promising potential in energy storage and conversion applications which are discussed in the following section.

- Solar Cells: QDs can be used in solar cells to enhance light absorption and improve photovoltaic performance[31]. They can be incorporated into the active layer of solar cells to extend the spectral range of absorption and increase the efficiency of energy conversion.

- Photocatalysis: QDs are employed as photocatalysts for various energy conversion reactions, including water splitting and carbon dioxide reduction. Their size-tunable band gap and efficient charge separation properties make them effective catalysts for driving these reactions under sunlight.

- Light-Emitting Diodes (LEDs): QDs are used as phosphors in LED lighting applications to produce high-quality white light with tunable colour and improved efficiency[32]. They can be tailored to emit specific wavelengths of light by controlling their size and composition, making them suitable for a wide range of lighting applications.

- Batteries and Supercapacitors: QDs are investigated for use in next-generation batteries and supercapacitors due to their high surface area, tunable band gap and fast charge/discharge kinetics[33]. QD-based energy storage devices offer advantages such as high energy density, long cycle life and rapid charging.

- Lithium-Ion Batteries: QDs are investigated for use in lithium-ion batteries as electrode materials or additives to improve battery performance. They can provide high capacity, cycling stability and rate capability, which make them potential candidates for next-generation energy storage devices[34].

- Fuel Cells: QDs serve as catalysts and electrocatalysts in fuel cells for the conversion of chemical energy into electrical energy. QD-based fuel cells offer advantages such as high catalytic activity, improved durability and reduced cost.

Applications of QDs in Environmental Monitoring: These semiconductor nanocrystals exhibit size-tunable fluorescence, high photostability and surface modifiability, which make them well-suited candidates for applications in water quality assessment, air pollution monitoring and detection of hazardous substances, which is discussed in the following section.

- Water Quality Assessment: QDs are utilized for the detection and quantification of various water pollutants, including heavy metals, organic contaminants and microbial pathogens[35]. Functionalized QDs can selectively bind to target analytes in water samples, enabling rapid and sensitive detection using fluorescence-based assays. QD-based sensors offer advantages such as high sensitivity, low detection limits and real-time monitoring capabilities, which make them valuable tools for ensuring water quality and safety.

- Air Pollution Monitoring: QDs are employed in sensors for monitoring air quality and detecting airborne pollutants such as volatile organic compounds (VOCs), particulate matter and gases[36]. QD-based sensors can be integrated into portable devices or deployed in fixed monitoring stations to provide real-time data on air pollution levels[37]. By leveraging the high sensitivity and selectivity of QDs, these sensors enable early detection of pollutant emissions, identification of pollution sources and assessment of air quality in urban and industrial areas.

- Hazardous Substance Detection: QDs are used for the detection of hazardous substances in environmental samples, including chemical warfare agents, pesticides and explosives[8]. Functionalized QDs can selectively bind to target molecules or ions, leading to changes in their fluorescence properties that can be detected and quantified. QD-based sensors offer rapid response times, high specificity and low detection limits, making them suitable for applications in homeland security, environmental remediation and emergency response[38].

Toxicity of QDs: QDs have shown immense promise in various fields due to their unique optical and electronic properties. However, concerns regarding their potential toxicity have raised questions about their safe use in biomedical applications and consumer products.

- Heavy Metal Toxicity: QDs are typically composed of heavy metal elements such as cadmium, lead and selenium, which can pose toxicity risks[39]. The release of heavy metal ions from QDs due to degradation or surface oxidation can lead to oxidative stress, DNA damage and disruption of cellular processes.
- Reactive Oxygen Species (ROS) Generation: QDs can generate reactive oxygen species (ROS) such as superoxide radicals, hydrogen peroxide and hydroxyl radicals through photochemical reactions or interactions with cellular components. ROS production can cause oxidative damage to biomolecules, including lipids, proteins and DNA, leading to cellular dysfunction and apoptosis.
- Surface Chemistry Effects: Surface coatings and ligands used to stabilize QDs can influence their toxicity profile. Hydrophobic coatings may enhance cellular uptake and accumulation of QDs, while hydrophilic coatings can reduce interactions with cellular membranes and mitigate toxicity.
- Size-Dependent Effects: The size of QDs can impact their toxicity, with smaller particles exhibiting increased cellular uptake and cytotoxicity compared to larger particles[40]. Size-dependent effects may be attributed to differences in surface area, surface charge and interactions with cellular components.

Methods for Toxicity Assessment of QDs: Some common methods used for toxicity assessment of QDs are following:

- Cell Viability Assays: Cell viability assays such as MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) or Alamar Blue assays are commonly used to assess the cytotoxicity of QDs[41]. These assays measure the metabolic activity of cells and can indicate whether QDs affect cell viability or not.
- Cell Membrane Integrity Assays: Techniques such as lactate dehydrogenase (LDH) release assays assess cell membrane integrity by quantifying the leakage of LDH enzyme from damaged cells. Increased LDH levels indicate cell membrane damage caused by QDs.
- Reactive Oxygen Species (ROS) Assays: QDs can induce oxidative stress by generating reactive oxygen species. Assays such as dichlorodihydrofluorescein diacetate (DCFH-DA) staining or measurement of superoxide dismutase (SOD) activity can be used to detect ROS production in cells exposed to QDs.
- Apoptosis and Necrosis Assays: Flow cytometry-based assays using Annexin V/propidium iodide staining can distinguish between apoptotic and necrotic cells following QD exposure. Changes in cell morphology and DNA fragmentation can also be assessed using fluorescence microscopy and TUNEL (terminal deoxynucleotidyl transferase dUTP nick end labeling) assays.
- Inflammatory Response Assays: QDs may induce inflammation in biological systems. Enzyme-linked immunosorbent assays (ELISAs) can be used to quantify the secretion of pro-inflammatory cytokines such as interleukin-6 (IL-6) and tumor necrosis factor-alpha (TNF-á) by cells exposed to QDs.
- Genotoxicity Assays: Assessment of genotoxicity involves evaluating DNA damage induced by QDs. Techniques such as the comet assay (single-cell gel electrophoresis) and micronucleus assay can detect DNA strand breaks and chromosomal aberrations in cells treated with QDs.
- *In Vivo* Studies: Animal models, such as mice or zebrafish, can be used to evaluate the systemic toxicity of QDs. *In vivo* studies assess parameters such as organ toxicity, biodistribution, immune response and long-term effects following QD exposure via different routes of administration (e.g., intravenous, intraperitoneal or oral). Techniques such as histopathological analysis,

bioimaging and blood chemistry assays help assess the physiological and toxicological effects of QDs following administration.

- *In Vitro* Studies: Cell-based assays are commonly used to assess the cytotoxicity, genotoxicity and oxidative stress induced by QDs. Techniques such as cell viability assays, reactive oxygen species assays and DNA damage assays provide insights into the mechanisms of QD toxicity in cultured cells.
- Bioaccumulation and Biodistribution Studies: Techniques such as fluorescence imaging and inductively coupled plasma mass spectrometry (ICP-MS) are used to track the distribution and accumulation of QDs in various tissues and organs over time.
- Long-Term Exposure Studies: Assessing the effects of prolonged QD exposure is essential for understanding their chronic toxicity. Long-term studies involve repeated exposure of cells or organisms to QDs over extended periods to monitor cumulative toxicity and potential adverse effects.
- Computational Modeling: Computational approaches such as molecular dynamics simulations and quantitative structure-activity relationship (QSAR) modeling can predict the interactions of QDs with biological molecules and infer their potential toxicity based on structural properties.

Mitigation Strategies: Mitigating the potential toxicity of QDs is essential for their safe and effective utilization in various applications.

- Surface Coating and Functionalization: Modifying the surface of QDs with biocompatible coatings or functional groups can enhance their stability, biocompatibility and reduce their interaction with biological molecules. Coatings such as polyethylene glycol (PEG), silica or amphiphilic polymers can help shield the QD core and minimize cytotoxicity.
- Encapsulation: Encapsulating QDs within protective shells or matrices can prevent direct exposure of the core material to biological environments, reducing potential toxicity. Lipid-based, polymer-based or silica-based encapsulation techniques provide a barrier between the QD surface and surrounding biological components.
- Core Material Selection: Developing QDs using less toxic or non-toxic core materials is a fundamental approach to mitigate toxicity. Cadmium-free QDs based on materials such as indium phosphide (InP), silicon (Si) or graphene QDs offer lower toxicity profiles compared to cadmium-based QDs.
- Size Control: Controlling the size of QDs is crucial as smaller QDs tend to exhibit greater toxicity due to increased cellular uptake and interaction[42]. Precise size control can be achieved through synthesis techniques to produce QDs within a biologically compatible size range.
- Surface Engineering for Targeting and Clearance: Functionalizing QD surfaces with targeting ligands or biomolecules can facilitate specific interactions with cellular receptors or tissues, improving targeted delivery and reducing off-target effects. Additionally, surface modifications that enhance QD clearance mechanisms, such as renal clearance or enzymatic degradation, can minimize their retention in biological systems.
- Biocompatibility Testing: Comprehensive evaluation of QD biocompatibility using *in vitro* and *in vivo* models is essential for assessing their safety profile and identifying potential adverse effects. Biocompatibility testing involves assessing parameters such as cell viability, inflammatory response, genotoxicity and long-term systemic effects.
- Regulatory Compliance and Standards: Adhering to regulatory guidelines and standards for nanomaterials and biomedical devices is critical to ensure the safe development and use of QDs.

Mechanisms Influencing Scalability of QDs: Scalability refers to the ability to manufacture QDs in large quantities while maintaining uniformity, quality and cost-effectiveness. Scalability of QDs depends on several factors:

- Synthesis Methods: The choice of synthesis method significantly affects the scalability of QDs. Colloidal synthesis techniques, such as hot-injection and microwave-assisted methods are scalable and allow for the production of QDs in large batches. However, challenges such as reproducibility and batch-to-batch variation may arise, impacting scalability.

- Precursor Materials: The availability and cost of precursor materials, such as cadmium, selenium and lead, can influence the scalability of QD production[43]. Developing efficient recycling and purification processes for precursors can improve scalability and reduce production costs.
- Size Control: Ensuring precise control over the size and uniformity of QDs is essential for scalability. Techniques like ligand-assisted self-assembly or template-directed growth can aid in achieving this control consistently on a large scale.
- Manufacturing Infrastructure: Establishing robust manufacturing infrastructure tailored to QD production is necessary for scalability[44]. This includes equipment for synthesis, purification and characterization, as well as quality control processes to ensure uniformity and reproducibility.
- Encapsulation and Stability: Developing strategies to encapsulate QDs to enhance stability and prevent degradation is vital for scalability. Encapsulation can also facilitate integration into various applications while maintaining their optical and electronic properties.
- Environmental and Health Considerations: Addressing environmental and health concerns associated with QDs, such as toxicity and disposal issues, is critical for scalability. Developing eco-friendly synthesis methods and recycling processes can enhance the scalability of QDs.
- Application-Specific Requirements: Tailoring QD properties to specific application requirements can drive scalability. For instance, optimizing QD size, composition and surface chemistry for applications like displays, lighting, solar cells or biomedical imaging can facilitate large-scale production.
- Surface Passivation: Proper surface passivation of QDs is essential for their stability and performance. Scalable passivation methods, such as ligand exchange reactions and *in situ* surface modification, ensure uniform coverage and stability of QDs during synthesis.

Assessment of Scalability: Assessing the scalability of QDs involves evaluating various factors related to their production, application and market demand, which are following:

- Production Yield: The production yield, defined as the percentage of desired QDs obtained from a synthesis process, is a critical parameter for assessing scalability[45]. High production yields indicate efficient synthesis methods suitable for large-scale production.
- Batch-to-Batch Variation: Consistency in product quality across multiple batches is essential for scalability. Assessing batch-to-batch variation in size distribution, optical properties and stability provides insights into the reproducibility of QD synthesis methods.
- Production Rate: The production rate, measured as the rate of QD synthesis per unit time, determines the scalability of synthesis processes. Increasing production rates while maintaining product quality is essential for meeting demand in large-scale applications.

Mitigation Strategies for Scalability Challenges: Scalability is a critical factor in the commercialization and widespread adoption of QDs in various applications. Understanding the mechanisms influencing scalability, assessing scalability parameters and implementing mitigation strategies are essential for overcoming scalability challenges and realizing the full potential of QD technology.

- Process Optimization: Optimizing synthesis parameters such as temperature, reaction time and precursor concentrations can improve scalability and production yields. Process optimization using high-throughput screening methods accelerates the discovery of scalable synthesis conditions[46].
- Automation and Robotics: Implementing automation and robotics in synthesis processes enables precise control over reaction conditions, reduces human error and increases production throughput. Automated platforms facilitate scalability by standardizing synthesis protocols and minimizing variability.
- Continuous Flow Synthesis: Continuous flow synthesis systems offer advantages such as rapid reaction kinetics, precise control over reaction parameters and scalability. Continuous flow reactors enable continuous production of QDs, eliminating batch-to-batch variation and improving scalability.

Principles of Quantum Computing with QDs: QDs have shown promise as potential components for quantum computing due to their unique electronic and optical properties.

- Qubit Implementation: QDs can serve as qubits in quantum computing systems[47]. The spin states of individual electrons or the charge states of QDs can be used as qubits, with the spin-up and spin-down states corresponding to the quantum states respectively.
- Coherent Control: Coherent control techniques, such as pulsed microwave and radiofrequency fields, allow for precise manipulation of the quantum states of electron spins in QDs[48]. By applying carefully designed control pulses, quantum gates can be implemented to perform quantum operations, such as single-qubit rotations and two-qubit entangling gates.
- Decoherence Mitigation: Decoherence, resulting from interactions with the environment, poses a significant challenge to quantum computing with QDs. Techniques such as dynamical decoupling, spin echo sequences and error correction codes are employed to mitigate decoherence and preserve the coherence of quantum states over extended time scales, enabling fault-tolerant quantum computation.

Recent Progress in Quantum Computing with QDs: Being a promising avenue for advancing quantum computing, some of the recent progressions are discussed in the following section:

- Demonstration of Quantum Gates: Researchers have demonstrated various quantum gates, including single-qubit rotations and two-qubit entangling gates, using electron spins in semiconductor QDs[49]. These experiments validate the feasibility of implementing quantum algorithms and error correction protocols using QDs as qubits.
- Scalability and Integration: Progress has been made towards achieving scalability and integration of QD qubits into larger quantum computing architectures. Techniques such as lithographic patterning, self-assembly and hybrid integration with superconducting qubits enable the fabrication of multi-qubit QD arrays and QD–superconductor hybrid devices.
- QD Hybrid Systems: QDs are integrated with other quantum systems, such as superconducting circuits, photonic cavities and topological materials to exploit complementary strengths and capabilities for quantum information processing. Hybrid QD systems offer advantages such as enhanced coherence times, tunable coupling strengths and novel functionalities for quantum computing[50].

Challenges and Future Directions in Quantum Computing with QDs: While QDs hold significant promise for quantum computing, several challenges must be addressed to fully realize their potential.

- Decoherence and Error Correction: Overcoming decoherence and implementing error correction codes remain major challenges in quantum computing with QDs[51]. Developing robust error correction schemes and improving coherence times are essential for scaling up QD-based quantum computers.
- Scalability and Fabrication Complexity: Fabricating large-scale QD arrays with high fidelity and uniformity presents technical challenges related to lithography, material growth and control electronics. Developing scalable fabrication techniques and integration strategies is critical for realizing practical QD-based quantum computers.
- Hardware and Software Development: QD-based quantum computers require advances in both hardware and software components, including qubit connectivity, control electronics and quantum algorithms. Collaborative efforts between experimentalists, theorists and engineers are needed to address these challenges and accelerate progress towards practical quantum computing applications.

Conclusion

The emergence of QDs represents a significant milestone in the convergence of nanoscience and real-world applications, promising transformative advancements across diverse fields. In the realm of electronics, QDs serve as building blocks for next-generation devices, enabling unprecedented levels of miniaturization, efficiency and functionality. Their size-tunable band gap and exceptional charge transport properties make them ideal candidates for transistors, sensors and optoelectronic devices, paving the way for faster, smaller and more energy-efficient electronics. Moreover, QDs have revolutionized the field of photonics by unlocking new possibilities in light manipulation and emission. Their ability to emit light with precise wavelengths and narrow spectral linewidths has led to breakthroughs in displays, lighting and telecommunications. QD-based light-emitting diodes (LEDs) and QD displays offer superior colour reproduction, energy efficiency and durability compared to conventional technologies, driving the transition towards more immersive and sustainable visual experiences. In energy applications, QDs hold immense promise for revolutionizing solar cells, photocatalysis and energy storage devices. QD-based photocatalysts are facilitating sustainable energy production through water splitting and carbon dioxide reduction, while QD-modified electrodes are enhancing the performance of batteries and supercapacitors, thus addressing the pressing need for clean and renewable energy sources. Furthermore, QDs are making significant contributions to the fields of biomedicine and environmental sensing, offering innovative solutions for disease diagnosis, drug delivery and pollutant detection. QDs represent a paradigm shift in the translation of nanoscience from theoretical concepts to practical applications. ❐

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