

QUANTUM DOTS IN NANOELECTRONICS AND PHOTONICS: PROPERTIES, SYNTHESIS, AND DEVICE APPLICATIONS

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Abstract

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| <p>Received: 17/09/2024 Revised: 20/10/2024 Accepted: 20/11/2024</p> <p>DOI: 10.12060/jet-ep-v27.i2-4</p> <p>Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.</p> <p>Copyright: © 2025 The Author(s). This work is licensed under a Creative Commons Attribution 4.0 International License.</p> <p>With the license CC-BY, authors retain the copyright, allowing anyone to download, reuse, re-print, modify, distribute, and/or copy their contribution. The work must be properly attributed to its author.</p> | <p>Quantum dots (QDs) are semiconductor nanocrystals exhibiting quantum confinement effects, which lead to discrete energy levels and size-tunable optical and electronic properties. These characteristics have positioned QDs as pivotal materials in nanoelectronics, optoelectronics, and photonics. This paper comprehensively reviews the synthesis methods, physical and electronic properties, charge transport phenomena, and integration of quantum dots in devices such as LEDs, solar cells, lasers, and quantum computing systems. Challenges in scalability, stability, and device integration are also discussed, along with future perspectives in next-generation photonic and electronic technologies.</p> <p>Keywords: Quantum dots, quantum confinement, nanoelectronics, photonics, optoelectronic devices, synthesis methods.</p> |
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1. INTRODUCTION

Quantum dots (QDs) are nanometer-sized semiconductor particles in which electrons are confined in all three spatial dimensions, resulting in discrete energy levels akin to atoms (Alivisatos, 1996). This “artificial atom” behavior allows the manipulation of electronic and optical properties via particle size and shape, leading to tunable emission wavelengths and enhanced charge carrier dynamics.

The emergence of quantum dots has revolutionized fields such as **nanoelectronics**, **optoelectronics**, and **quantum information processing**. Their applications range from high-efficiency solar cells and light-emitting diodes (LEDs) to single-photon sources and qubits. Understanding the interplay between synthesis methods, structural properties, and device performance is critical for advancing practical implementations.

This paper aims to provide a **comprehensive review** of the physics, synthesis techniques, and

applications of QDs in nanoelectronics and photonics.

2. PHYSICAL AND ELECTRONIC PROPERTIES OF QUANTUM DOTS

2.1 Quantum Confinement Effects

Quantum confinement occurs when the QD size approaches or is smaller than the exciton Bohr radius, causing discretization of energy levels. The energy of the first exciton peak increases as particle size decreases, which is mathematically described by:

$$E(R) = E_g + \frac{\hbar^2 \pi^2}{2R^2} \left(\frac{1}{m_e} + \frac{1}{m_h} \right) - 1.8 \frac{e^2}{4\pi \epsilon R}$$

where E_g is the bulk bandgap, R is the QD radius, m_e and m_h are electron and hole effective masses, and ϵ is the dielectric constant (Brus, 1984).

2.2 Optical Properties

Quantum dots exhibit **size-dependent photoluminescence** and high quantum yield. The absorption and emission spectra can be tuned across the visible and near-infrared regions, enabling their use in LEDs, lasers, and biological imaging (Murray et al., 2000).

2.3 Electronic Transport

QDs exhibit unique electronic transport phenomena such as **Coulomb blockade** and **tunneling**, which are critical for single-electron transistors (SETs) and quantum computing devices. Charge transport is influenced by QD size distribution, surface states, and matrix interactions.

3. SYNTHESIS TECHNIQUES

3.1 Colloidal Synthesis

Colloidal methods involve solution-phase chemical reactions that produce monodisperse nanocrystals. Parameters such as temperature, precursor concentration, and surfactants control size, shape, and surface chemistry (Klimov, 2000).

3.2 Epitaxial Growth

Molecular beam epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD) enable the formation of **self-assembled QDs** on substrates. Strain-driven processes such as the Stranski-Krastanov growth mode are widely used in optoelectronic devices like quantum dot lasers.

3.3 Lithographic Approaches

Top-down methods, including electron beam lithography and nanoimprint techniques, allow precise placement of QDs on substrates for electronic devices, although scalability remains challenging.

4. DEVICE APPLICATIONS

4.1 Quantum Dot LEDs (QD-LEDs)

QDs can serve as the emissive layer in LEDs, offering **high color purity, tunable emission, and solution-processable fabrication**. Challenges include charge injection efficiency and long-term stability.

4.2 Quantum Dot Solar Cells (QDSCs)

QDs enable **multiple exciton generation (MEG)**, potentially surpassing the Shockley–Queisser limit for solar cells. Both colloidal and epitaxial QDs have been integrated into photovoltaic architectures, achieving enhanced light absorption and tunable bandgaps (Nozik, 2002).

4.3 Quantum Dot Lasers

Self-assembled QDs in laser cavities provide **low threshold currents, temperature stability, and broad tunability**, making them suitable for telecommunications and integrated photonics.

4.4 Quantum Computing and Single-Photon Sources

QDs can confine single electrons or excitons, serving as **qubits** in solid-state quantum computing. Single-photon emission enables applications in quantum cryptography and optical communication.

5. CHALLENGES AND FUTURE DIRECTIONS

5.1 Stability and Scalability

Chemical instability and surface oxidation limit device lifetimes. Advanced passivation and core-shell structures enhance stability. Scalable, uniform synthesis is required for industrial adoption.

5.2 Integration with Electronics

Precise placement, electrical contact formation, and interface engineering are critical for QD integration into circuits. Hybrid architectures combining QDs with 2D materials are promising.

5.3 Emerging Research Directions

- **Perovskite quantum dots:** High photoluminescence efficiency and tunable bandgap.
- **QD–2D material heterostructures:** Enhanced charge transport and energy transfer.
- **Spin-based QDs:** Exploiting electron spin for quantum information processing.

6. CONCLUSION

Quantum dots represent a versatile platform bridging **materials science, nanoelectronics, and photonics**. Their size-tunable optical and electronic properties enable applications in LEDs, solar cells, lasers, and quantum devices. Overcoming challenges related to stability, uniformity, and integration will accelerate their deployment in next-generation nanotechnologies.

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