

QUANTUM DOTS AND NANOSTRUCTURES: ELECTRONIC CONFINEMENT AND DEVICE APPLICATIONS

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Abstract

<p>Received: 12/06/2024 Revised: 17/07/2024 Accepted: 24/08/2024</p> <p>DOI: 10.12060/jet-ep-v27.i2-1</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 and semiconductor nanostructures exhibit discrete energy levels due to quantum confinement, leading to size-dependent electronic and optical properties. These nanoscale systems bridge atomic physics and bulk solid-state physics, offering unique opportunities for both fundamental research and engineering applications. This paper reviews the physical principles underlying quantum confinement, electronic structure, and carrier dynamics in quantum dots, discusses fabrication and characterization techniques, and highlights applications in optoelectronics, biomedical imaging, and quantum information technologies.</p> <p>Keywords: Quantum dots, nanostructures, quantum confinement, optoelectronics, condensed matter physics.</p>
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1. INTRODUCTION

Advances in nanofabrication have enabled the creation of structures with dimensions comparable to the de Broglie wavelength of electrons. In such systems, quantum confinement effects dominate, leading to discrete energy spectra similar to those of atoms. Quantum dots are often referred to as “artificial atoms” due to their quantized electronic states (Bimberg et al., 1999).

Quantum dots and nanostructures play a critical role in modern condensed matter physics and engineering, with applications ranging from light-emitting devices to quantum computing platforms.

2. QUANTUM CONFINEMENT: PHYSICAL PRINCIPLES

2.1. Confinement Regimes

Quantum confinement occurs when charge carriers are restricted in one or more spatial dimensions. Zero-dimensional quantum dots confine carriers in all three dimensions, resulting in fully discrete energy levels.

The confinement energy increases as dot size decreases, allowing precise tuning of electronic and optical properties.

2.2. Density of States

The density of states in quantum dots is discrete, contrasting with the continuous density of states in bulk materials. This discrete nature enhances optical transitions and enables efficient light emission.

3. ELECTRONIC AND OPTICAL PROPERTIES

3.1. Size-Dependent Band Gap

Quantum dots exhibit a tunable band gap that depends on their size and composition. Smaller dots have larger band gaps due to stronger confinement, resulting in blue-shifted emission.

3.2. Excitons and Carrier Dynamics

Excitons—bound electron–hole pairs—play a central role in quantum dot optics. Strong confinement increases exciton binding energy, allowing stable excitons at room temperature.

4. FABRICATION TECHNIQUES

4.1. Epitaxial Growth

Self-assembled quantum dots are commonly fabricated using molecular beam epitaxy and metal–organic chemical vapor deposition. Strain-driven growth enables uniform dot formation.

4.2. Colloidal Synthesis

Colloidal quantum dots are synthesized chemically in solution, offering low-cost, scalable production with precise size control. These dots are widely used in displays and biological applications.

5. CHARACTERIZATION METHODS

Spectroscopic techniques such as photoluminescence and absorption spectroscopy probe electronic transitions, while scanning probe microscopy provides structural and electronic information at the nanoscale.

6. ENGINEERING APPLICATIONS

6.1. Optoelectronic Devices

Quantum dots are used in lasers, light-emitting diodes, and photodetectors due to their high quantum efficiency and wavelength tunability. Quantum dot displays offer enhanced color

purity and energy efficiency.

6.2. Biomedical Imaging and Sensing

Fluorescent quantum dots serve as biomarkers for imaging and diagnostics, offering high brightness and photostability compared to organic dyes.

6.3. Quantum Information Processing

Quantum dots can act as qubits, where electron spin or excitonic states encode quantum information. Their compatibility with semiconductor technology makes them promising for scalable quantum computing.

7. CHALLENGES AND LIMITATIONS

Despite their advantages, quantum dots face challenges such as:

- Surface defects and nonradiative recombination
- Toxicity concerns (e.g., Cd-based dots)
- Integration with conventional electronic platforms

Addressing these issues is essential for wider adoption.

8. FUTURE PERSPECTIVES

Future research aims to develop environmentally friendly quantum dots, hybrid nanostructures, and topological quantum dots. Advances in material design and quantum control will expand their technological impact.

9. CONCLUSION

Quantum dots and nanostructures exemplify the profound effects of quantum confinement in condensed matter systems. Their tunable properties and versatility continue to drive innovation across physics, engineering, and biotechnology.

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