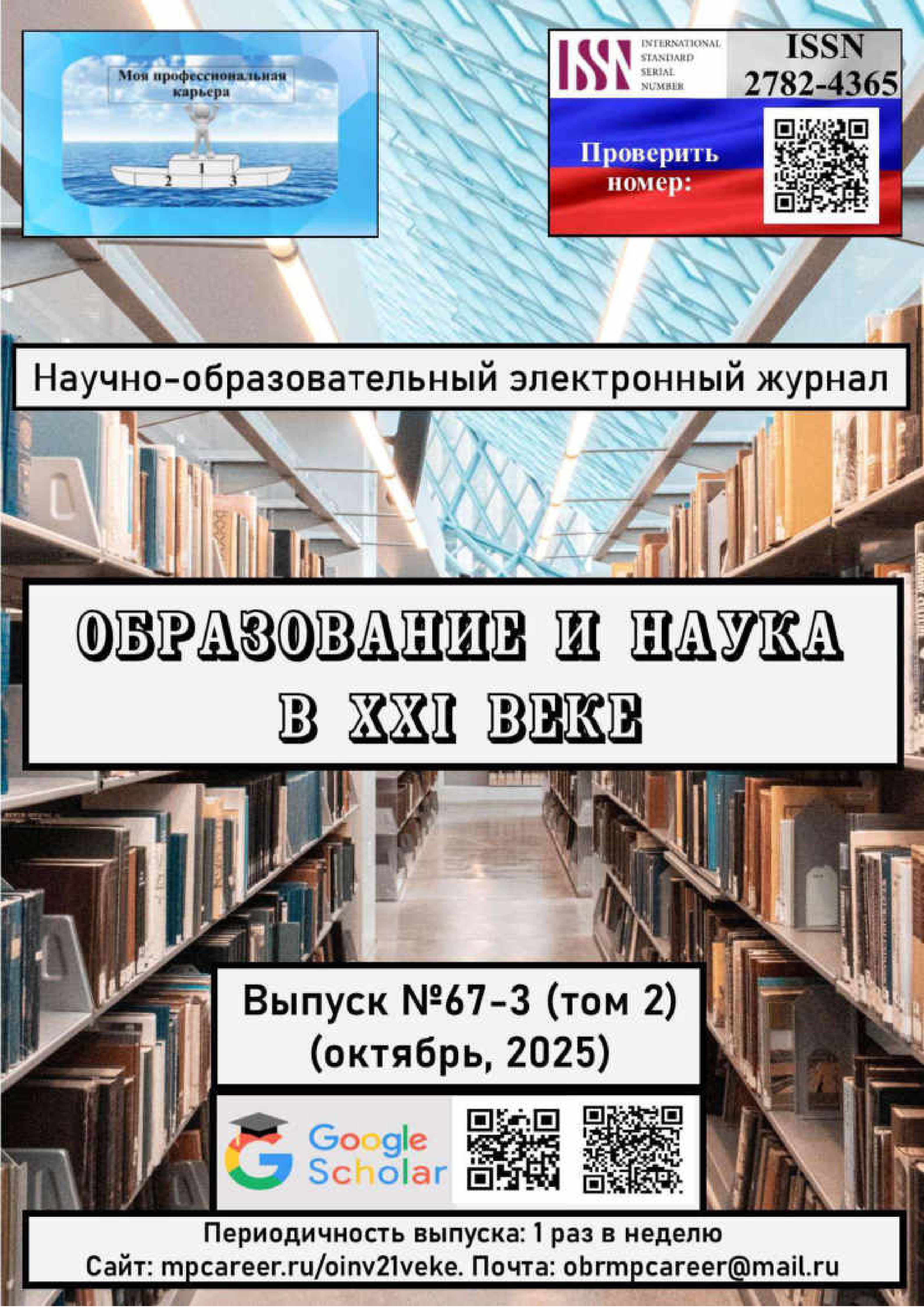

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Название публикации: «QUANTUM DOTS AND THEIR APPLICATIONS IN DISPLAY AND PHOTOVOLTAIC TECHNOLOGIES»

Abstract

Quantum dots (QDs) are nanoscale semiconductor crystals characterized by unique electrical and optical properties resulting from quantum confinement effects. Their size-dependent emission, tunable bandgap, and high quantum yield have enabled transformative advancements in display and photovoltaic technologies. This review critically examines the classification, synthesis methods, optoelectronic properties, and integration of QDs in next-generation display panels and solar cells. The potential of QDs for commercial applications, current limitations, and future prospects are discussed, supported by relevant experimental studies and industry reports.

Introduction

The emergence of quantum dots has marked a paradigm shift in nanotechnology-driven optoelectronic systems. Initially developed as fluorescent markers in biological imaging, QDs now underpin significant innovations in display and photovoltaic devices due to their luminescent efficiency and spectral tunability. The integration of QDs in mature manufacturing sectors, such as display panels and solar photovoltaics, relies on advances in synthesis, surface engineering, and patterning technologies. This review provides an organized synthesis of the literature, detailing the scientific groundwork of QDs and highlighting their transformative impact on commercial devices.

Classification and Synthesis of Quantum Dots

Quantum dots are broadly classified based on material composition and structural design. Core-type QDs are typically single-element or compound nanocrystals, such as CdSe or PbS, displaying innate quantum confinement properties. Core-shell QDs feature a primary core with a secondary shell material that passivates defects and enhances stability, while alloyed QDs exhibit graded or mixed material compositions for tailored electronic properties. Synthesis methods—including colloidal synthesis, molecular beam epitaxy, and chemical vapor deposition—play vital roles in determining QD properties such as size distribution, surface chemistry, and defect density. Advancements in ligand engineering and surface passivation have significantly improved the photostability and charge transport of QDs, expanding their viability for optoelectronic device integration.

Optoelectronic Properties and Quantum Confinement Effects

The fundamental optoelectronic properties of QDs arise from discrete energy levels induced by quantum confinement. This results in size-dependent emission, high quantum yield, narrow emission spectra, and tunable bandgaps. The unique optical responses of QDs, including broad absorption and sharp fluorescence peaks, make them superior to traditional phosphors for color rendition and efficiency in display and photovoltaic devices. Quantum dots also enable multi-exciton generation and have large Stokes shifts, allowing them to convert high-energy photons into lower-energy ones more efficiently. Charge carrier dynamics and photophysical behaviors, such as carrier multiplication and suppressed non-radiative recombination, underpin the superior performance of QD-based devices.

Quantum Dots in Display Technology

Quantum Dot Light-Emitting Diodes (QLEDs)

QLEDs utilize the sharp and efficient emission characteristics of QDs as their active layer in display panels. With recent advances in material synthesis and patterning, colloidal QDs now achieve external quantum efficiencies exceeding 35% for red and green emission, and up to 24% for blue QDs, though efficiency limitations persist for blue emitters due to intrinsic material challenges. Innovations in patterning technologies—including inkjet printing, photolithography, capillary bridge confinement, and microfluidics—enable the precise deposition and spatial arrangement of QDs, critical to realizing high-resolution displays with pixel densities surpassing 5000 pixels per inch.

QLEDs offer several advantages over organic light-emitting diodes (OLEDs) and conventional LED displays, including broader color gamut, higher luminance, and improved energy efficiency, with reduced power consumption for portable devices. Enhanced stability and longer operational lifetimes further position QDs as promising candidates for next-generation display solutions. Industry adoption trends indicate significant commercial momentum toward micro-LED panels and quantum dot films for television, mobile, and augmented reality displays.

Patterning, Stability, and Commercialization Challenges

Despite progress, integrating QDs into mass-produced displays presents notable challenges. Patterned deposition techniques must ensure defect minimization and long-range order, especially for blue QDs, which are more susceptible to non-radiative recombination and charge leakage. Surface ligand engineering and advanced fabrication processes are being developed to mitigate these issues, enabling more stable and reproducible QD microstructures. Moreover, the selection and customization of QD materials, including II–VI, III–V, and perovskite QDs, afford unique pathways for engineering device performance but require careful control over synthesis variables to preserve optoelectronic uniformity across large-scale arrays.

Quantum Dots in Photovoltaic Technology

Quantum Dot-Sensitized Solar Cells (QDSCs)

Quantum dots have revolutionized photovoltaic research, offering the potential for higher energy conversion efficiencies by harnessing their tunable absorption properties and multi-exciton effects. Quantum dot-sensitized solar cells (QDSCs) exploit QDs as the primary light-absorbing material, benefiting from their size-adjustable bandgaps to target optimal regions of the solar spectrum. This allows for customizable absorption profiles that maximize solar energy capture and minimize thermalization losses. QDSCs, including those based on CdSe, PbS, and perovskite

QDs (PQDs), exhibit promising laboratory efficiencies and the capacity for low-cost, scalable fabrication.

Downconversion, Downshifting, and Tandem Structures

A prominent application of QDs in photovoltaics involves downconversion and downshifting, converting high-energy ultraviolet photons into visible or near-infrared photons more readily absorbed by conventional solar cells. This strategy addresses the Shockley–Queisser limit, enhancing photovoltaic efficiency beyond the practical threshold of traditional silicon devices. QDs also find utility as downconverter layers in tandem and multi-junction solar cells, further increasing energy harvesting by extending spectral coverage. Recent studies have validated the efficacy of such architectures, reporting substantial efficiency gains in devices incorporating QD layers, especially when combined with defect-tolerant perovskite materials.

Integration Challenges and Commercial Prospects

While QDs enable groundbreaking performance enhancements, their commercial deployment in solar cells faces hurdles related to material toxicity, cost, scalability, and long-term stability. The instability of certain QD materials, such as those containing lead or cadmium, limits widespread adoption due to environmental and health concerns. Engineering robust core-shell structures and alternative non-toxic QD compositions remain active areas of research. Integration with graphene and carbon nanotubes, aiming to boost charge carrier transport, signifies another frontier in QD-enabled photovoltaics, offering pathways to higher efficiency and reliability.

Comparative Analysis with Conventional Materials

Both in display and photovoltaic applications, QDs outperform traditional materials—phosphors, OLEDs, and silicon—in efficiency, spectral tunability, and integration flexibility. Their ability to produce pure spectrum colors confers distinct advantages for ultra-high-definition displays, while tunable absorption enables more efficient light harvesting in solar cells. However, material cost, stability, and the need for advanced fabrication techniques represent common challenges across both domains. Comparisons must also account for resource constraints and lifecycle analysis, including recycling and environmental impacts.

Future Trends and Perspectives

Advances in QD materials science, synthesis strategies, and device engineering suggest an upward trajectory for their role in optoelectronic technologies. The development of non-toxic, earth-abundant QD materials, alongside scalable manufacturing solutions, will be pivotal in realizing their widespread adoption. Emerging fields such as quantum information processing, biosensing, and energy storage may further benefit from QD properties. In displays, ongoing research into hybrid and tandem architectures, leveraging QD-superlattice and perovskite interfaces, promises to push the boundaries of color fidelity and efficiency.

In photovoltaics, the synergy of QDs with perovskite structures, graphene, and other nanomaterials points toward next-generation solar cells with efficiencies surpassing current theoretical limits. Standardization of QD synthesis, integration methods, and device architectures will be essential for consistent commercial performance.

Conclusion

Quantum dots represent a breakthrough in nanoscale optoelectronics, offering distinctive advantages in both display and photovoltaic technologies. They have enabled significant gains in device performance, resolution, color purity, and energy conversion efficiency. While challenges related to stability, toxicity, and large-scale manufacturing remain, ongoing research into material engineering and device integration is likely to unlock new opportunities for QD-based applications. The future of QDs in display and solar technologies is bright, supported by their tunable properties and ongoing scientific innovation.

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