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Studies of Quantum Dots in Light-Emitting Diodes

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Abstract:

Quantum dots are regarded as a revolutionary material especially in display and lighting applications due to their excellent optical properties. Their high quantum efficiency, high color purity, low-cost solution processability, and tunable emission wavelength, facilitate the realization of their potential for display applications. Therefore, researchers have made a lot of effort in the development and characterization of quantum dot light-emitting diodes (QD-LEDs) to achieve high color purity and brightness in light-emitting devices. Meanwhile, with the aim of commercialization, inefficiency, instability, and cost seem to be inevitable challenges that need to be faced. Progression and challenges of using quantum dots in light-emitting diodes are two aspects that are concentrated on in this review. It also affords methods to tackle these challenges. Lastly, the potential applications of QD-LEDs in displays and lighting are investigated. Their potential to revolutionize various industries are also highlighted. By overcoming current limitations and capitalizing on emerging opportunities, QD-LEDs technology will have further applications. This work will help promote in-depth research on QD-LEDs.

Keywords: Quantum dots; light-emitting diodes; display technology; solid-state lighting.

1. Introduction

Quantum dots (QDs) are semiconductor nanocrystals with a special set of optical properties. This material has been selective to make light-emitting diodes with high exploring potential due to its distinctive optical properties. In recent research, the progresses of quantum dots in lighting and display technology, offer higher energy efficiency and longer lifespans in light-emitting diodes. Hence, the quest for even better performance of light-emitting diodes has resulted in the progression of quantum dot light-emitting diodes (QD-LEDs).

QD-LEDs are self-emissive devices driven by current [1]. QD-LEDs take advantage of the properties of QDs, including high quantum efficiency, high colour purity and low-cost solution processing [2]. QD-LEDs can achieve better performance on flexible band gaps, excellent color gamut, light-emitting efficiency, wavelength tunability, and cost when compared to traditional LEDs [3]. Moreover, the commercialization of QD-LEDs must be taken into considerations.

This paper introduces the development of QDs in QD-LEDs. It highlights recent breakthroughs that have pushed the boundaries of this technology. However, the path to widespread adoption of QD-LEDs still exhibits hurdles. This work will explore the key challenges that currently hinder their commercialization, including material stability, efficiency limitations, and cost-effective fabrication methods. Moreover, it will also discuss ongoing research efforts which aimed at overcoming these challenges to release the full potential of QD-LEDs. Some valuable insights into the current state of this revolutionary technology have been offered in this work.

2. Quantum Dots in Light-Emitting Diodes

2.1 Quantum Dots

Quantum dots are semiconductor materials in the nanoscale dimension with unique optical properties. The band gap of quantum dots is relative to their size due to the quantum confinement effect. Quantum confinement effect expresses electrons in terms of energy levels, valence bands, conduction bands, and electron energy band gaps [4]. It leads to discrete electrons and holes, which quantize energy levels. It can be tuned by changing the particle size of QDs [5]. The smaller size of the QDs represents a larger band gap, which means that shorter wavelength light is required to excite the electron from the valence band to the conduction band. Therefore, QDs can emit light with a shorter wavelength. The larger size of the QDs represents a smaller band gap. Therefore longer wavelength of light is required for excitation and emitting light with a longer wavelength, as shown in Fig. 1 [6].

Their size-dependent bandgap allows for precise tuning of their emission spectrum, making them ideal materials for light-emitting applications. Unlike traditional fluorescent dyes, QDs exhibit narrow emission bandwidth, high quantum yield, and tunable luminescence for various display and lighting technologies [7].

The luminescence of QDs in QD-LEDs occurs when electrons, excited by an external energy source, recombine with holes, releasing photons which are forms of energy. The band gap relative to the diameter of the QDs determines the energy and therefore the colour of the emitted light.

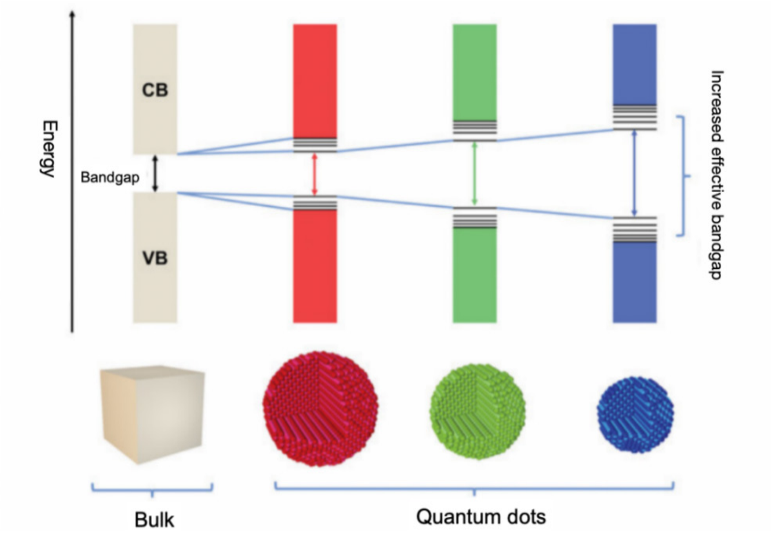

Fig. 1 Comparison between the size of the band gap in QDs and bulk materials [6].

2.2 Development of QDs in QD-LEDs

2.2.1 Principles of QD-LEDs

Light emitted from diodes is sourced from the transfer of electrons and holes between two electrodes. Electrons and holes are released from the cathode to the anode of the device. They move through conductive layers until they reach the QDs emissive layer [8]. Then, they combine to cause excitation of electrons. Afterwards, photons are released, which then produce light. This light escapes the device, resulting in the illumination, as shown in Fig. 2 [9]. Different wavelengths caused different colors of light emitted from the devices.

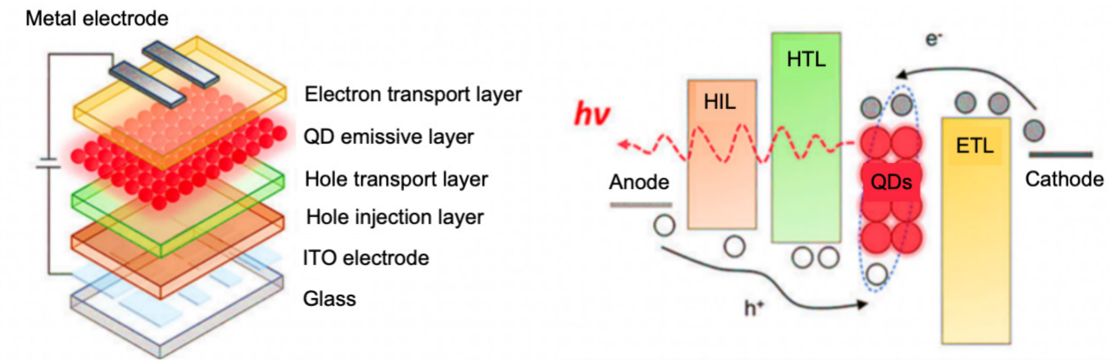

Fig. 2 Structure and energy level diagram of QD-LEDs [9].

2.2.2 Development of QDs in QD-LEDs

In the early 1980s, researchers first discovered nanoscale semiconductors in a glass matrix. Quantum tunability leads to the research of many optical and optoelectronic devices. Later, Luis E. Brus proposed that the band gap is inversely proportional to the width of the quantum dot. Since then, the properties of QDs have been applied in a wide range of fields, including field-effect transistors, solar cells, and light-emitting materials [10]. However, QDs are not widely used at first because of the instability. The external quantum efficiencies in 1994 of QD-LEDs were upgraded to be no more than 20% theoretically [11]. Thereafter, advancements in synthesis of QDs led to the further application of QDs, paving the way for their integration into LED structures.

2.3 Progress in Achieving High Brightness and Color Purity

QD-LEDs can achieve higher brightness and color purity in comparison to the conventional LED. The advancement of QD-LEDs can be divided into three parts, including the discovery of material synthesis, device optimization and innovative manufacturing processes. Firstly, precise control over core size of QDs has enabled the realization of narrow emission spectra, resulting in vibrant and saturated colors. The width of the emission spectra could determine the extent of color purity. It is well acknowledged that a narrower spectrum corresponds to a purer color [12]. Secondly, the enhancement of charge injection efficiency can improve the performance of device. As a result, it demonstrated remarkable progress concerning with brightness and color gamut of QD-LEDs. They are supposed to be an excellent selective material for the next generation of display and illuminating technologies. Moreover, in the future, it is necessary to build up an effective method for arranging quantum dot pixels with three primary colors on the base layer of display[13, 14].

3. Challenges and Strategies

In sight of commercialization, there are several factors need to be considered, such as stability, efficiency, and cost.

3.1 Stability of QDs Material

Quantum dot material is degraded over time due to factors like oxidation. Oxygen and water physically or chemically absorb on the surface of QDs, and the optical performance of this material is weakened. Therefore, this material should be isolated from oxygen and water. Some ideas have been raised to tackle this problem in terms of isolation.

As to the design of shell, increasing the thickness might be a method. For instance, in terms of the CdSe and ZnS/ZnS alloyed QDs, increasing the thickness of the shell by 1.9 nm result in the enhancement of the quantum yield from 44% to 88%. The shell of a quantum dot serves as a protective layer, significantly impacting the overall stability of QDs. A thicker and more robust shell can enhance resistance to oxidation, photodegradation, and ion migration. Careful selection of shell materials with high lattice matching to the core is crucial to prevent defects and strain, which can accelerate degradation.

Additionally, incorporating elements with high electron affinity into the shell can improve charge carrier balance and reduce non-radiative recombination [15]. Secondly, adding ligands to the surface of QDs could stabilize the surface by reducing fragile dangling bonds, and additional functional groups are added to improve their performance. Ligands are molecules attached to the QD surface, which can be added to vary the stability of QDs and device performance. Long-chain ligands can provide steric hindrance, protecting the core of QDs from external factors. However, these ligands can also impede charge transport. Balancing ligand length with charge mobility is essential. Furthermore, exploring alternative ligand chemistries with stronger binding affinities to the surface of QDs can enhance stability without compromising the performance.

Thirdly, overcoating is an efficient method by isolating the surface from water, air, and heat to reduce contact with other substances [16]. Overcoating is an effective strategy to isolate QDs from environmental factors and improve device lifetime. Inorganic overlayers, such as metal oxides or nitrides, can provide a robust barrier against moisture, oxygen, and ions. Organic overcoats, like polymers or cross-linkable materials, can offer flexibility and processability. The selection of overcoating material relies on the desired application and properties. Hybrid overcoats combining inorganic and organic components may offer synergistic benefits in terms of stability and device performance.

3.2 Device Efficiency

The degradation of quantum dot materials caused by oxygen and water not only affects the stability of these materials but also the efficiency of QD-LEDs. Surface engineering represents a potential avenue for enhancing the efficiency of these devices. The integration of an inorganic charge transport layer for a QD emissive layer has been proposed as a means of improving device efficiency. This approach can enhance carrier mobility within the QD-LED mechanism, thereby resulting in higher efficiency of the device [17]. Additionally, these layers are important to facilitate the efficient injection and transport of charge carriers into the quantum dot emissive layer [18].

Effective charge transport layers exhibit high charge carrier mobility, appropriate energy level alignment for efficient injection, and excellent stability. By carefully selecting or designing these layers, researchers can significantly improve the performance of QD-LEDs. For instance, incorporating materials with high carrier mobility can accelerate charge carrier movement, reducing recombination losses and increasing light emission efficiency. Moreover, precise energy level engineering of the charge transport layers can enhance charge injection, minimizing energy barriers and maximizing the number of charge carriers reaching the emissive layer.

Additionally, the interface between the charge transport layers and the quantum dot layer is critical. Minimizing interfacial defects and optimizing energy level matching at this interface can further enhance charge injection and reduce non-radiative recombination pathways. By interface engineering and layer optimization, researchers can develop highly efficient QD-LEDs with superior performance and extended lifetimes.

However, the excess electrons cause imbalanced charge transport which are a main bottleneck to improve the efficiency and are a direction to explore in the future research [19].

3.3 Cost

Cost is a significant factor that need to be reduced as much as possible in commercial applications. The fabrication and the maintenance of QD-LEDs are two aspects included in the cost. In terms of the fabrication, one promising approach is to develop lower-cost QDs materials that maintain high performance. This involves finding alternative core-shell structures or utilizing more abundant elements in the composition. Additionally, optimizing the synthesis process to increase the yield and purity can significantly reduce material costs.

To reduce cost, finding a scalable and cost-effective fabrication might be a way. The typical ways of synthesizing QD-LEDs are vacuum and spin-coating deposition techniques. However, those techniques are complicated and expensive. In this way, finding an efficient and cost-efficient decomposition technique is effective. A decomposition technique called the ultrasonic spray is proposed. It is a technique that retains all the material deposited on the substrate, and it could obtain successive deposition of QDs over a wide range of wavelengths [20]. Furthermore, simplifying the fabrication process by developing solution-based deposition techniques instead of vacuum-based methods can lower equipment and energy expenses. Integrating QD-LEDs with flexible substrates could also reduce production costs by enabling large-area, low-temperature processing.

4. Potential Application

QD-LEDs hold immense promise for revolutionizing the display industry and beyond. Their superior color gamut, high efficiency, and long lifetime make them ideal material for a wide range of applications including biomedicine, photodetection, new energy, and information display [21]. One of the most prominent applications lies in display technology. QD-LEDs can deliver superior image quality with vibrant colors and deeper blacks compared to traditional LCD or OLED displays, making them ideal for high-end televisions. Beyond displays, QD-LEDs have potential in solid-state lighting. Their high luminous efficiency and tunable emission spectrum allow for the creation of energy-efficient and customizable light sources. QD-LED-based lighting could find applications in residential, commercial, and automotive sectors, providing improved lighting experiences and energy savings. Additionally, QD-LEDs can contribute to advancements in augmented and virtual reality (AR/VR) devices. Their compact size, high brightness, and wide color gamut enable the development of immersive and realistic displays for these technologies. Furthermore, the potential of QD-LEDs for flexible and transparent displays opens opportunities for innovative wearable devices and interactive interfaces.

5. Conclusion

QDs have undeniably demonstrated immense potential as the next-generation luminescent material for light-emitting diodes (LEDs). Their unique optical properties, including tunable emission spectra, high color purity, and narrow emission linewidths, position them as strong contenders to surpass traditional LED technologies. The synthesis of high-quality QDs with controlled size distribution and enhanced stability has been a vital process of research, leading to significant advancements in recent years.

However, several challenges persist in the development of commercially viable QD-LEDs. Improving device efficiency, particularly at high luminance levels, remains a critical hurdle. Additionally, addressing the stability issues associated with QDs, such as degradation under operating conditions, is essential for extending device lifetime. Furthermore, the cost-effective production of high-quality QDs on a large scale is imperative for widespread adoption.

Despite these challenges, the potential benefits of QD-LEDs are substantial. The prospect of displays with unparalleled color accuracy, wider color gamuts, and higher energy efficiency is tantalizing. In the realm of lighting, QD-LEDs offer the promise of customizable light sources with improved color rendering indices. Moreover, their potential applications extend beyond displays and lighting, encompassing areas such as biomedical imaging, sensing, and solar cells.

To fully realize the potential of QD-LEDs, continued researches are essential. This includes exploring novel QD materials, optimizing device architectures, and developing efficient charge injection mechanisms. Despite these hurdles, ongoing researches are steadily addressing these issues. Overcoming these obstacles will not only revolutionize display technology but also widen new possibilities in areas such as lighting, augmented reality, and medical imaging.

References

[1] Dai X, Deng Y, Peng X, et al. Quantum-dot light-emitting diodes for large-area displays: Towards the dawn of commercialization. Advanced Materials, 2017, 29 (14): 1-22.

[2] Yang Z, Gao M, Wu W, et al. Recent advances in quantum dot-based light-emitting devices: Challenges and possible solutions. Materials Today, 2019, 24: 69-93.

[3] Jang E, Jang H. Review: Quantum dot light-emitting diodes. Chemical Reviews, 2023, 123(8): 4663-4692.

[4] Tomasulo A, Ramakrishna M V. Quantum confinement effects in semiconductor clusters. II. The Journal of Chemical Physics, 1996, 105(9): 3612-3626.

[5] Talapin D V, Steckel J. Quantum dot light-emitting devices. MRS Bulletin, 2013, 38(9): 685-691.

[6] Tian D, Ma H, Huang G, et al. A review on quantum dot light-emitting diodes: From materials to applications. Advanced Optical Materials, 2022, 11(2): 1-18.

[7] Sadeghi S, Kumar B G, Melikov R, et al. Quantum dot white LEDs with high luminous efficiency. Optica, 2018, 5(7): 793-802.

[8] Yuan Q, Wang T, Yu P, et al. A review on the electroluminescence properties of quantum-dot light-emitting diodes. Organic Electronics, 2021, 90: 1-22.

[9] Chen Z, Li H, Yuan C, et al. Color revolution: Prospects and challenges of quantum-dot light-emitting diode display technologies. Small Methods, 2023, 8(2): 1-43.

[10] Han C Y, Yang H, et al. Development of colloidal quantum dots for electrically driven light-emitting devices. Journal of the Korean Ceramic Society, 2017, 54(6): 449-469.

[11] Cheng Y, Wan H, Liang T, et al. Continuously graded quantum dots: Synthesis, applications in quantum dot light-emitting diodes, and perspectives. The Journal of Physical Chemistry Letters, 2021, 12(25): 5967-5978.

[12] Han J H, Kim D, Lee T W, et al. Color purifying optical nanothin film for three primary colors in optoelectronics. Acs Photonics, 2018, 5(8): 3322-3330.

[13] Bang S Y, Suh Y H, Fan X B, et al. Technology progress on quantum dot light-emitting diodes for next-generation displays. Nanoscale Horizons, 2021, 6(2): 68-77.

[14] Cui J, Huang Q, Veinot J C, et al. Anode interfacial engineering approaches to enhancing anode/hole transport layer interfacial stability and charge injection efficiency in organic light-emitting diodes. Langmuir, 2002, 18(25): 9958-9970.

[15] Ko J, Jeong B G, Chang J H, et al. Chemically resistant and thermally stable quantum dots prepared by shell encapsulation with cross-linkable block copolymer ligands. NPG Asia Mater, 2020, 12(1): 1-11.

[16] Moon H, Lee C, Lee W, et al. Stability of quantum dots, quantum dot films, and quantum dot light-emitting diodes for display applications. Advanced Materials, 2019, 31(34): 1-14.

[17] Qian L, Zheng Y, Xue J, et al. Stable and efficient quantum-dot light-emitting diodes based on solution-processed multilayer structures. Nature Photonics, 2011, 5(9): 543-548.

[18] Dai X, Zhang Z, Jin Y, et al. Solution-processed, high-performance light-emitting diodes based on quantum dots. Nature, 2014, 515(7525): 96-99.

[19] Huang Q, Pan J, Zhang Y, et al. High-performance quantum dot light-emitting diodes with hybrid hole transport layer via doping engineering. Optics Express, 2016, 24(23): 25955-25963.

[20] Ji W, Liu S, Zhang H, et al. Ultrasonic spray processed, highly efficient all-inorganic quantum-dot light-emitting diodes. ACS Photonics, 2017, 4(5): 1271-1278.

[21] Sun Y, Jiang Y, Sun X W, et al. Beyond OLED: Efficient quantum dot light-emitting diodes for display and lighting application. The Chemical Record, 2019, 19(8): 1729-1752.