Recent Progress in Chalcogenide Light-Emitting Diodes

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Abstract: Light Emitting Diode (LED), as an efficient light energy conversion device, has been widely used in lighting, display, and other fields. This paper will introduce the basic structure of LEDs, analyze their long development, and the great role they can play in different fields. This paper will also show the reader the current use of LEDs in the field of anti-counterfeiting and optics, as well as the mature use of large-area preparation. At the end of this paper, it will also look forward to the future and discuss, analyze the future of China in different areas of more in-depth research. With the progress of the times, the application of light-emitting diodes extends to a variety of fields, from lower luminous flux indicators to display screens, and then from outdoor displays to medium luminous flux power signal lamps and white light sources for special lighting, and finally develops to high luminous flux general illumination light sources.

1 INTRODUCTION

In recent years, the research and development of new light-emitting materials and their functional devices have demonstrated broad application prospects. Global R&D funding for semiconductor materials increased by 12.5% year-on-year in 2023, further boosting the progress of related technologies. With the continuous investment in basic research on optoelectronic materials worldwide, especially the chalcogenide light-emitting diodes (PeLEDs), they have become the key breakthrough direction for next-generation display technology due to their unique carrier transport properties and solution-processable advantages.

China's semiconductor field is currently booming, with significant breakthroughs in both optical anti-counterfeiting and display. At the same time, luminescence efficiency and stability, as well as pure red light and green light outside the quantum field, can be significant improvements. The improvement in luminous efficiency also leads to higher energy efficiency and lower energy consumption. Large-area preparation also makes the luminescence field more commercialization prospects.

This paper will analyze the current advantages and shortcomings in the field of chalcogenide light-emitting diodes in China, and by analyzing the latest research progress of other scholars, it aims to explore the future development direction of China's light-emitting field.

2 LIGHT EMITTING DIODE STRUCTURE

Light-emitting diode is a typical semiconductor device that can convert electrical energy into light energy. Its basic structure includes a chip, packaging materials, leads, and a housing. Its working principle is based on the fact that photons will be generated and energy will be released when the electrons and holes of the PN junction are combined.

The chip is the core part of the LED, composed of multiple layers of different semiconductor materials, where a PN junction is formed between the N-type layer and the P-type layer. When a positive voltage is applied to the PN junction, electrons jump from the N-type layer to the P-type layer, combining with holes to produce photons, which emit light. In order to improve the luminous efficiency and stability, modern LED chips usually use the double heterojunction (DH) structure, which can effectively limit the carriers and light waves, thus improving the luminous efficiency.

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Encapsulation materials are used to fix and protect the chip, and commonly used encapsulation materials include epoxy resin, silicone, and polystyrene. These materials need to have good thermal conductivity, UV resistance, and moisture resistance to ensure the normal operation of the LED.

The lead wire connects the chip to the external circuit and plays the role of current conduction. Lead wires are generally made of metal materials, such as gold or copper. The soldering quality of the lead wires has an important impact on the performance and life of the LEDs, and it is necessary to ensure a good connection to reduce the contact resistance and thermal resistance.

The shell not only protects the internal structure, but also plays the role of a light guide and heat dissipation. The design of the housing can affect the distribution and direction of light. Some housings are designed in the shape of a convex lens to concentrate the light.

3 MULTIPLE APPLICATIONS

3.1 Mature Applications in Optical Anti-Counterfeiting

Optical anti-counterfeiting technology is an important branch of modern anti-counterfeiting technology, which mainly realizes anti-counterfeiting marking by using the optical properties of materials. Chalcogenide materials have been widely studied in the field of optical anti-counterfeiting due to their excellent optical properties, and such materials can be tuned in their composition and structure to achieve broad spectral tuning in the ultraviolet to near-infrared region. Zhou et al. (2024) successfully synthesized CsPbX3 halide quantum dots (PeQDs) in an anionic metal-organic framework (MOF). Thanks to the porous nature of MOF, the quantum dots were confined by micropores during the synthesis process, which ensured their dimensional homogeneity and made the luminescence more stable and efficient.

3.2 Prospects for Emission Display

Because of its excellent photoelectric properties, chalcogenide material has become a research hotspot in the field of emissive display, especially in blue light-emitting diodes (LED) shows great potential. For blue light-emitting diodes, Liu et al. (2024) pointed out that chalcogenide materials are regarded as a new generation of light-emitting materials because of their excellent photoelectric properties. The luminescence wavelength of chalcogenide materials can be controlled by component engineering and dimensional engineering, in which quasi-two-dimensional chalcogenide materials show great potential in realizing high-efficiency blue light emission due to their excellent thin film surface morphology and multilayered quantum well structure. For transparent light-emitting diodes (TLEDs), transparent display is one of the development directions of future displays, and has great potential for application in smart windows, wearable electronics, virtual reality technology, touch screens, and other fields (Li et al., 2023). With the emergence of new light-emitting materials such as organic, quantum dots, chalcogenide, etc., the brightness, efficiency, and stability of light-emitting diodes are developing rapidly.

3.3 Compound Application

Light-emitting diodes currently play a great role in two important fields: military and agriculture. In the military, light-emitting diodes can be used as a source of illumination. Zhou et al. (2024) found in practice that due to the lack of infrared radiation in LED light sources, they are easy to conceal. In the field under difficult conditions, it has the advantages of vibration resistance, suitable for battery power supply, solid structure, and easy to carry, and will be in the special lighting light source will have greater development, which will directly help the army at night with light. Secondly, in the field of agriculture, light-emitting diodes can be used for greenhouse supplemental light. Chen et al. (2019) found that light is one of the most important environmental factors for plant growth and development by comparing it with other categories, and it has a regulatory effect on the growth and development of plants, morphogenesis, photosynthesis, material metabolism, and gene expression, etc. The electrical energy conversion efficiency of LED can be up to 80%-90%, which is much higher than that of incandescent lamps and Fluorescent lamps. Under the same brightness, LED power consumption is only 1/10 of incandescent lamps, and energy energy-saving effect is outstanding. At the same time, LED does not contain mercury, lead, and other toxic substances, no risk of environmental pollution after disposal. While fluorescent lamps contain mercury, improper handling may jeopardize the ecology. Therefore, greenhouse fill light is an important way to achieve high-quality and high-yield plants.

4 DOUBLE BREAKTHROUGH IN EFFICIENCY AND STABILITY

4.1 Green Light External Quantum Efficiency (EQE)

Green light exo-quantum, as the most mature application area of light-emitting diodes, has been intensively investigated nowadays. Lu et al. (2024) proposed a NaBr-assisted crystallization method, which can effectively regulate the top-down crystallization process of Q-2D chalcogenide films and precisely regulate the phase distribution of Q-2D chalcogenide films in vertical space. Passivating surface bromine vacancy defects and suppressing non-radiative complexation is facilitated by the strong interaction between Na+ and PbBr64-. The device's transport capabilities are effectively improved by this. Finally, the EQE of the device reaches 26.5%, and the efficiency reaches 19.2% even when the effective light-emitting area of the device is enlarged by more than 50 times. At an initial brightness of 100 cd m-2, the small-area and large-area devices achieve a T50 of 612 h and 112 h, respectively.

4.2 Suppression of Efficiency Roll-Off in Pure Red Q-2D PeLEDs

The efficiency roll-off suppression of pure red Q-2D PeLEDs is one of the key challenges to enhance their performance. Lu et al. (2024) improved the carrier density of the composite centers by adjusting the thickness of the quantum wells and the Eb of the Q-2D chalcogenide films using p-F-PEA and PBA with different carbon chain lengths. In addition, the defects, such as halogen vacancies in the chalcogenides, can be passivated by introducing TOPO to enhance the stability of the materials. Ultimately, highly efficient and stable pure red Q-2D PeLEDs were obtained, and the optimized devices achieved a peak external quantum efficiency of 19.78% and a T50 of 241.2 hours. When the effective area is enlarged by a factor of 900, the efficiency remains high at 14.82%, representing one of the best performances of pure red Q-2D PeLEDs to date.

4.3 Significant Improvement in Luminescence Performance

Liu & Bian (2024) found from experimental results that FA + doping enables CsPbBr 3 chalcogenide quantum dots to convert electrical energy into light energy more efficiently and contributes to the improvement of the stability and optical properties of chalcogenide quantum dots. This provides an effective way to enhance the white light emission performance of fully inorganic chalcogenide quantum dots. This class of quantum dots has good application prospects in fluorescence conversion materials for white light LD emitting layers, which can not only significantly extend the service life of the devices, but also realize higher energy utilization efficiency and reduce energy consumption.

5 COLOR PURIFICATION AND DISPLAY TECHNOLOGY INNOVATION

Full-color active displays can be achieved by combining blue active light-emitting diodes with inkjet-printed red and green quantum dots. Blue subpixels and red and green subpixel quantum dots are both excitation sources in this structure, using active matrix blue OLEDs (AM-BOLEDs). He et al. (2025) obtained homogeneous green and red quantum dots with a thickness of micrometers using polymer-based quantum dot inks. The efficiency of converting blue to green and red light can be adjusted by changing the thickness of the quantum dot layer. This structure led to the successful manufacture of a 6.6-inch full-color, large-size quantum dot display with a color gamut of 95% of the BT.2020 standard. The use of quantum dots in display technology can be expanded by designing a full-color display rationally with blue active light-emitting diodes, as demonstrated by these results.

Liu & Bian (2024) concluded that the stability of quasi-two-dimensional devices is better than that of three-dimensional devices, mainly due to the introduction of organic macrocations that somewhat insulate the water oxygen in the air. A reasonable selection of organic cations can improve the stability of the devices, but their effect is limited. Meanwhile, the factors affecting the stability of quasi-two-dimensional blue light devices are diverse.

6 PROGRESS IN LARGE-AREA PREPARATION AND INDUSTRIALIZATION

To fabricate high-performance large-area PeLEDs using the blade coating method, Chen et al. (2025)

proposed a strategy to improve the uniformity and crystalline quality of perovskite nanopolycrystalline films. The method increases the steric hindrance of solutes in the solution of the encapsulated precursor, which slows down the crystallization rate and improves the crystal quality. Based on these methods, an EQE of 25.91% was achieved for small area green PeLEDs, which marks the highest efficiency currently available for the production of pack-crystal green PeLEDs using the blade coating method. In addition, the method successfully prepares larger area photoluminescent films (9 cm × 9 cm) and larger area PeLEDs (5 cm × 7 cm) showing excellent brightness and uniformity. This research result is a key step toward the large-scale commercial application of encapsulated crystalline luminescent films.

Wang et al. (2024) in the YIP research group used organotrichlorosilane immersion of aluminum halide films to fill defects and modulate spectra. By varying the immersion time, aluminum gallium halide films with different luminescence peaks were obtained, and higher device efficiencies were achieved.

7 OUTLOOK

The development of light-emitting diodes is still insufficient. Although it is more economical to use in the long run, the manufacturing cost of LED is significantly higher than that of traditional light sources. At the same time, LED chip manufacturing relies on rare earth elements; its mining and processing may cause resource depletion and environmental pollution. LED after the disposal of the recycling system is not yet perfect, and electronic components, if not handled properly, may still produce pollution. Figure 1 gives the growth trend of the external quantum efficiency of chalcogenide diodes, although the current light-emitting diodes have great potential for development, there are still a variety of defects exist, and the excited state radiation-free compounding associated with the defects has been the main factor limiting the luminescence efficiency of chalcogenide films and devices (Li et al., 2023). In addition, organic light-emitting diodes (OLEDs) are very promising in the field of flat panel displays and solid-state lighting due to their unique advantages such as self-luminescence, faceted light source, fast response time, wide viewing angle, and thickness, etc. Jeonghun et al. mentioned in their article that OLEDs have a promising future for a wide range of applications in lighting, and that due to the growth of lighting demand for existing consumption, solid-state lighting has the potential to provide better power efficiency than conventional light sources. Power efficiency of conventional light sources. Tu (2022) stated that device lighting has become a leading technology in the solid state lighting market, attracting widespread attention from manufacturers, product designers, and end users. The devices have entered the high-end lighting market, such as illuminated artwork, automotive taillights, aerospace lighting, high-end architectural lighting, and other lighting applications.

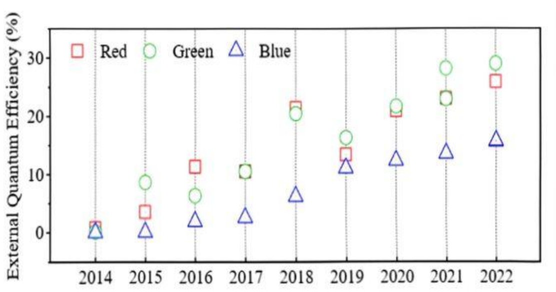

Figure 1: Trend of growth of external quantum efficiency (Photo/Picture credit: Original).

8 CONCLUSION

The breakthroughs in efficiency, stability, and application scenarios of chalcogenide light-emitting diodes (PeLEDs) have propelled them from the laboratory to industrialization. With the progress of material design, process optimization, and environmental protection technology, PeLEDs are expected to achieve large-scale applications in ultra-high-definition display, flexible electronics, biomedicine, and other fields, and become the core pillar of the next generation of optoelectronic technology. New light-emitting materials and their development of innovative devices with attractive prospects for development, people's attention to the development of new materials is increasing day by day, the government of the development of semiconductor materials to provide economic and policy support for the future with the deepening of the understanding of the material and the advancement of process technology is expected to further improve the efficiency and stability of the device, and promote its industrialization. Shortly, chalcogenide LED will become a new generation of display and lighting competitor with its excellent performance and low cost, and occupy an important position in a variety of fields in the future, which will directly promote the accelerated development of China's agriculture, military industry, and other industries.

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