

Prospects And Challenges Analysis of UV LED Technology in Practical Applications

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Abstract. Owing to the enhanced benefits of ultraviolet light-emitting diodes (UV LEDs) over conventional mercury lamps, the latter have been considered suitable for replacement, contributing to the growth of UV-related markets. Due to their broad applications and advanced development, many new investigations have focused on UV LEDs. However, these LEDs face challenges such as high costs, low efficiency, and limited output power, which hinder their widespread adoption. This paper discusses the potential for UV LEDs to replace traditional mercury-based UV light sources, considering environmental impact, safety, energy consumption, and longevity, along with the need for new solutions. Key applications of UV LEDs in water treatment, medical disinfection, and optical communication are explored, highlighting their potential in large-scale water treatment systems and bandwidth prospects in communication. The paper also addresses challenges such as high dislocation density and introduces directions for optimizing electrode and P-type layer structures, as well as new methods and materials. Lastly, future research directions for UV LEDs are outlined.

Keywords: Ultraviolet, LED, mercury, disinfection.

1. Introduction

UV LED technology has developed rapidly in the past few years with its wide applications in water treatment, medical disinfection, and optical communication. Compared to traditional mercury lamps, UV-LEDs have several advantages which include high efficiency, low energy consumption, and the fact that they do not contain toxic substances hence making the working environment safer and more environmentally friendly. This is especially the case in the present world where health safety issues are of paramount concern, therefore is a need to come up with efficient UV disinfection technology. Further, the fast growth of UV LEDs in the area of optical communications makes them a vital technology for the provision of high broadband and high-speed data transfer.

Some successful case studies of UV LED technology in application include water treatment and medical disinfection, yet, there are many issues that hinder its usage. For instance, in large-scale water treatment systems, UV LED technology has not yet been able to replace mercury lamps in their entirety due to a number of factors such as high costs, low output power, and low WPE [1]. In the context of medical disinfection, the intensity of UV LED disinfection depends on the chemical content of the solution and the bacterial concentration in it, whereas complex surface topologies may reduce the effectiveness of disinfection [2]. In optical communication, although UV LEDs have the advantages of increasing bandwidth and data transmission rate, there is still a need for the further development of materials and device structures regarding the efficiency and reliability of transmission [3].

At present, material selection and structural optimization for UV LEDs have made great improvements and GaN and AlGaIn are widely used in the fabrication of UV LEDs. Nevertheless, the current literature also presents a number of limitations, specifically, those concerning efficiency and reliability. However, due to the material properties, and difficulty in the processing of UV LEDs, the external quantum efficiency (EQE) and (WPE) are quite low at around 20% and 5% respectively [4, 5]. However, the high dislocation density (DD) in UV LEDs is still a major factor that restricts the improvement of device performance [6].

This paper seeks to give an overview of the opportunities and limitations of UV LED technology in different application environments with the aim of informing further research towards the realization of the widespread practical application of UV LEDs.

2. Theoretical basic analysis

2.1. Definition of ultraviolet LED

A Light light-emitting diode (LED) is a special type of LED, whose fundamental structure is also a PN junction. The difference lies in that, within the conventional LED structure, an additional multiple quanta well layer is often incorporated in the middle of the PN junction. The primary functions of this layer include effectively confining and evenly distributing carriers, improving luminous efficiency, enhancing the stability of the emission wavelength, and reducing non-radiative recombination, thereby significantly enhancing the performance of the LED [7]. The basic structure is shown in Figure 1.

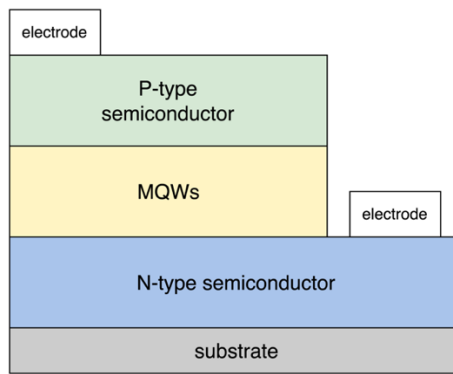


Figure. 1 The basic structure of LED lamps

When a forward voltage is applied to the PN junction of a light-emitting diode (LED), the depletion region narrows under the influence of the external electric field, causing electrons to diffuse into the P region. As electrons in the conduction band recombine with holes in the valence band, they transition from a higher energy state to a lower energy state. During this process, the excess energy of the electrons is released in the form of emitted photons, resulting in electroluminescence [8]. The wavelength of the emitted light is determined by the type of semiconductor material and the doping elements used. The peak wavelength specifically depends on the bandgap energy of the material.

$$\lambda = \frac{hc}{E_g(eV)} \quad (1)$$

In the equation, λ represents the peak wavelength, h denotes Planck's constant, c stands for the speed of light, and E_g represents the bandgap energy of the material. Ultraviolet (UV) light refers to electromagnetic waves with wavelengths ranging from 10 nm to 400 nm. Currently, there are two primary materials used for manufacturing UV-LEDs. The first is Gallium Nitride (GaN), which can emit near-UV light (UVA) in the range of 320-400 nm. The second is Aluminum Gallium Nitride (AlGaN), which can emit mid-UV light (UVB) in the range of 280-320 nm and far-UV light (UVC) in the range of 200-280 nm. AlGaN is currently considered an ideal material for producing UV-LEDs.

2.2. Advantages of UV LED Compared to Traditional Mercury Lamps

In the conventional ultraviolet (UV) light industry, low-pressure mercury lamps and medium-pressure mercury lamps are generally the most widespread to be employed. However, they have several disadvantages that can be considered to be quite crucial.

It is a fact that mercury lamps are very dangerous for the health of human beings. Exposure to mercury is dangerous even at low levels, and this metal poses a great risk of causing harm. Mercury

can have a negative impact on several organs of the human body such as the liver, kidney, heart, immune system, and nervous system. In the course of producing mercury lamps, workers are prone to various health complications because of the high concentration of mercury vapor in the working environment [9]. On the other hand, the process of manufacturing LED lamps includes semiconductor fabrication that does not pollute and does not result in toxic gas emissions thus safer.

Mercury lamps also have a negative effect on the environment. It discharges mercury into the environment as it is in use thus posing environmental concerns. On a daily basis, four billion lamps are lit for eight hours, thereby releasing 1.97 tons of mercury every year, 1.17 tons from the coal-fired power generation, and 0.8 tons from discarded mercury lamps. Also, a significant amount of mercury is trapped in used lamps and if these used lamps are not disposed of properly, mercury will get into the environment and cause a great deal of pollution [10]. On the other hand, LED lamps do not have mercury in them and therefore the process of disposal is less complicated.

Most conventional mercury lamps are rather power-hungry. The input power of conventional medium-pressure mercury lamps can attain 60 000W while that of low-pressure mercury amalgam lamps is between 40W and 500W. By contrast, LED lamps have a power consumption of not more than 5 watts. A higher power consumption results in higher temperature, whereas medium pressure mercury lamps have surface temperatures between 500°C to 950°C and low-pressure mercury lamps have between 90°C to 120°C. Both types need effective cooling systems when in use while LED lamps produce less heat and, in some cases, no cooling system is necessary [11].

There are several other drawbacks of traditional mercury lamps which add on to their problems. They are less durable than the others with the medium-pressure mercury lamps having a life expectancy of about 5,000 hours at best and the optimized low-pressure mercury lamps that have a life expectancy of about 16,000 hours. Mercury lamps also take from long time to flash on and off, and the lamps need some time to stabilize their output before they can be used, which is a significant limitation for applications requiring instant-on capability. Also, mercury lamps have an unstable UV output since the light output changes with the variation in temperature [11].

3. Application scenario analysis

3.1. Water treatment

Drinking water safety is a critical global issue, with increasing water pollution making the development of efficient water disinfection technologies more urgent. Ultraviolet (UV) water disinfection is an effective solution that does not produce harmful by-products like traditional chlorination or electrochemical oxidation. However, conventional UV disinfection commonly uses mercury UV lamps, which face limitations due to high energy consumption, fragility, and mercury pollution.

With advancements in LED technology, UV-LEDs have emerged as a new light source for water disinfection, offering environmental friendliness, durability, and low power consumption, making them an ideal replacement for mercury UV lamps. Unlike mercury UV lamps, which have established methods for assessing disinfection capabilities, UV-LED disinfection research lacks standardized materials and methods, complicating the comparison of different study results [12]. One notable characteristic of UV-LEDs is their flexibility in wavelength and radiation intensity. The research by K. Song indicates that selecting a combination of wavelengths could enhance UV-LED disinfection efficiency. Optimal wavelength combinations and peak wavelength radiation power can be chosen to target different bacteria, combined with specific irradiance levels. Additionally, the high-frequency switching capability of UV-LEDs allows for pulsed irradiation, significantly enhancing sterilization effects. For instance, combined irradiation at 254 nm and 365 nm has shown a marked increase in pathogen inactivation rates [12]. These features may greatly influence the establishment of standards for UV-LED water disinfection.

For household water disinfection, UV-LEDs have demonstrated considerable efficiency. The research by S. Vilhunen indicates that even at lower optical power, UV-LEDs can reduce common E.

coli counts by 3 to 4 log units within five minutes. As shown in Figure 2, although the increase in turbidity and absorbance of the water sample slows down the rate of bacterial inactivation, the difference in inactivation rates becomes insignificant after prolonged treatment. Moreover, given the less stringent turbidity limits for drinking water, UV-LEDs can achieve ideal disinfection results in home environments [13].

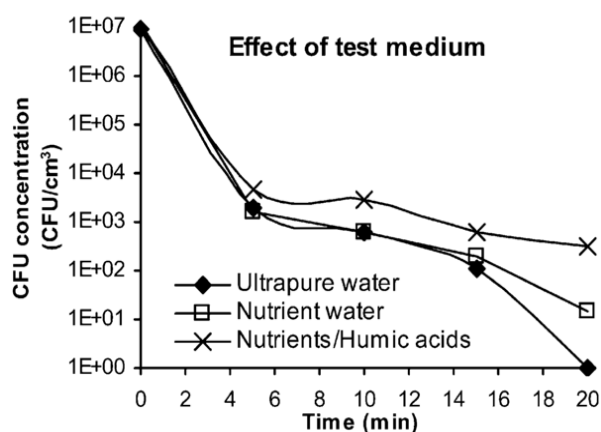


Figure. 2 Effect of test medium on *E. coli* destruction [13]

In the field of large-scale water treatment, UV-LED technology faces challenges such as high costs, low output power, and low wall plug efficiency, but it also holds significant potential for improvement. P. Jarvis's research has shown that full-scale UV-LED reactors are at least as effective as traditional mercury UV reactors in inactivating MS2 viruses. By increasing the LED driving current, performance degradation can be effectively mitigated. The study also found a strong linear relationship between UV intensity measured using chemical actinometry and the performance of traditional mercury LPUV systems. Full-scale UV-LED reactors demonstrated significant inactivation efficiency and operational flexibility, indicating substantial prospects for application in large-scale water treatment systems. With future design optimization and performance enhancements, UV-LED technology is expected to become mainstream in municipal water treatment [1].

3.2. Medical Disinfection

Hospitals require a high standard of hygiene, and conventional hospital disinfection often relies on chemical agents. However, these chemical agents can lead to the development of resistant bacteria, reducing the effectiveness of disinfection. In recent years, UV disinfection has become increasingly popular in hospitals. UV disinfection is more effective at eliminating bacteria and does not have the same drawbacks as chemical agents.

Stethoscopes are common medical instruments in hospitals, but G. Messina's studies have shown that the level of microbial contamination on stethoscopes is comparable to that on doctors' dominant hands. Furthermore, up to 90% of doctors do not disinfect their stethoscopes after examinations. This is primarily because disinfecting medical instruments can be cumbersome, and stethoscopes are used frequently, making frequent chemical disinfection impractical. Using UV-LED disinfection is a good alternative. Research indicates that UV-LEDs can achieve satisfactory disinfection capabilities and can miniaturize disinfection devices, allowing them to be carried around for frequent use. Even though the disinfection is not as complete as the chemical one, UV-LEDs are a feasible approach for often-used tools [14].

In the case of overall hospital disinfection, the efficacy may vary with different environments. The study conducted by H. Duering suggests that UV-LEDs are generally effective in disinfection of the liquid as well as the dry surface samples but the efficiency is not the same in both cases. The efficiency of UV-LEDs for disinfection purposes depends on the chemical content of the environment where the microorganisms are growing. It shows that proteins, salts, and glucose can negatively affect the sterilization efficiency of UV-C LEDs in the medium. Contaminants such as organic and inorganic also reduce the effectiveness of disinfection. In the event that the number of microorganisms in the

environment is high, then there is the need to use higher levels of brightness of the UV-LED. UV-C sterilization may be rendered less efficient by the complexity of the surface structures, particularly in cases where there are many crevices and joints on the surface. Nonetheless, repositioning LEDs to provide coverage for a larger surface can help reduce the effects of the complexity of the surfaces on the sterilization efficacy, thus enhancing overall disinfection capability [2].

The inherent factors that are associated with UV-LED and traditional mercury lamps, including microbial species, are comparable to the extrinsic factors including growth conditions and microbial load. While UV-LEDs cannot be fully implemented in place of chemical disinfection, they can be used to also complement manual cleaning. The adjustable wavelength and customizable geometric shapes of LEDs can effectively disinfect shadowed areas of medical equipment and surfaces [2].

3.3. Optical Communication

Apart from their fast growth in conventional disinfection areas, UV-LEDs are also revealing their potential in optical communication applications. Conventional UV optical communication has the following major drawbacks. The UV light is very much absorbed and scattered in the atmosphere and this makes it have a short transmission range which is mainly used for short-range communication. UV light is a threat to the skin and the eyes and thus proper precautions need to be taken when handling the equipment. Although UV is expected to offer high bandwidth, the actual bandwidth utilization is very poor due to the low bandwidth of conventional mercury UV lamps. This has however been made easier by the availability of UV-LEDs.

L. Guo in his research reveals that as the diameter of micro-UV-LEDs decreases from 120 μm to 60 μm , the differential resistance of the micro-UV-LED array increases by almost four times, the EQE by approximately 30%, and the bandwidth increases from 174 MHz to 380 MHz. This work also shows that the bandwidth of parallel flip-chip AlGaIn-based micro-UV-LED arrays can be improved by optimizing the boundary dimensions, which will contribute to the use of these devices in UV communication. This makes micro-UV-LED arrays suitable for long-distance and high-speed communication applications [3].

X. He has fabricated a concentric cluster array of 15 LEDs using a two-step ICP etching process. Each LED has an emission area of 566 μm^2 , equivalent to a 27 μm diameter μLED . This array can output 196 μW of optical power at a current density of up to 3400 A/cm² and achieve a 3 dB electrical modulation bandwidth of 438 MHz at a current density of 71 A/cm², which is three times higher than that of traditional deep UV LEDs. This UV-C LED has achieved data transmission rates of 800 Mbps under OOK modulation and 1.1 Gbps under OFDM modulation in free-space deep UV communication systems, showcasing its tremendous potential in deep UV communication [15].

4. Challenges and Optimization Analysis

The current field of ultraviolet (UV) LEDs still faces numerous challenges, particularly with materials commonly used in manufacturing UV LEDs, such as AlGaIn, which have several defects that need improvement. Presently, the external quantum efficiency (EQE) of most UV LEDs does not exceed 20%, and the wall-plug efficiency (WPE) generally remains around 5%. This low efficiency is primarily due to two factors: the difficulty of p-type doping and the high threading dislocation density (TDD).

4.1. Low Efficiency

Magnesium is the primary element used for p-type doping, but the efficiency of AlGaIn: Mg is limited by its low hole concentration. Consequently, GaIn: Mg is typically used as the contact layer for UV-LEDs. In this structure, the GaIn: Mg layer strongly absorbs all light emitted towards the p-type layer from the multiple quantum wells (MQWs), and a portion of the light is reflected from the interface. This results in a light extraction efficiency (LEE) of only 9%, whereas popular LEDs usually achieve an LEE of over 20% [4, 5].

Studies by M. A. Khan have established that through the use of p-MQB EBL structure and high reflective Ni/Al electrodes, the UVB LEDs' efficacy can be improved to 9.6% with a light output power of 40 mW. These significant improvements are primarily attributed to three factors: such as the graded aluminum p-MQB EBL, the compliant polarization p-AlGa_{0.5}N hole source layer, and the high-reflectivity Ni/Al electrodes. Thus, numerical simulations and experimental validation in this work demonstrated that the proposed design could significantly improve the efficiency of high-power UVB LEDs and other optoelectronic structures. Optimized UVB LEDs are widely applicable, and future improvements may be obtained by using standard LED packaging, photonic crystal structures, and flip-chip technology, which may enhance the external quantum efficiency to more than 21% [16].

Another study by X. Bao indicates that the performance of AlGa_{0.5}N-based deep-ultraviolet LEDs can be improved by introducing p-type and thickened last quantum barriers (LQBs). As shown in Figure 3, the new structure utilizes new p-type doping (with a doping concentration of $5 \times 10^{17} \text{ cm}^{-3}$) on the last quantum barrier (LQB) in the active region, and the thickness has been increased to 15 nm.

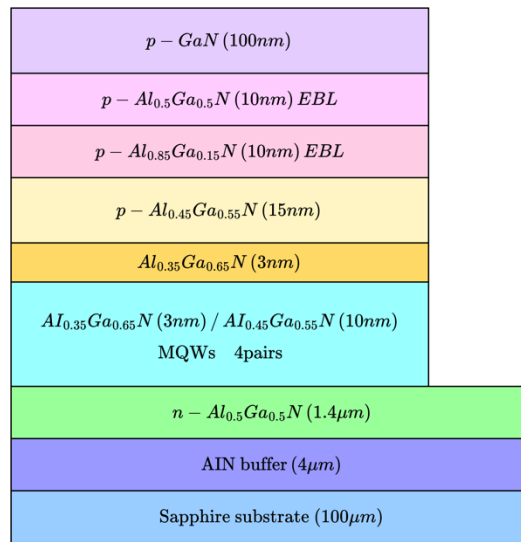


Figure. 3 The new structure by X. Bao

The modified structure demonstrated significant improvements in light output power, internal quantum efficiency, and electroluminescence intensity compared to conventional structures. Specifically, the new structure achieved a light output power of 404 mW at a current of 200 mA, which is twice that of the basic structure, and exhibited a slower decline in IQE at high currents. Despite the experimental challenges in achieving high aluminum content p-type AlGa_{0.5}N materials, this method offers new possibilities and research directions for enhancing deep-ultraviolet LED efficiency [17].

4.2. High Dislocation Density

The high dislocation density (DD) in AlGa_{0.5}N-based ultraviolet LEDs is primarily due to the stress caused by lattice mismatch and thermal expansion coefficient differences, especially when AlGa_{0.5}N materials are grown on mismatched substrates such as sapphire or silicon. As the aluminum content increases, lattice mismatch and material brittleness also intensify, further increasing the dislocation density. Studies by K. Ban have shown that high DD significantly impacts LED performance. It has been observed that reducing dislocation density markedly improves the internal quantum efficiency (IQE). This trend is consistent across DUV/UV MQWs emitting at wavelengths ranging from 230 to 350 nm. Therefore, reducing dislocation density is crucial for significantly boosting the internal quantum efficiency of DUV/UV active layers, which is vital for achieving high-efficiency deep-ultraviolet LEDs [18].

For ultraviolet LEDs, an AlN buffer layer is typically used to reduce the dislocation density in the epitaxial material. However, AlN can generate a higher threading dislocation density (TDD), which in turn decreases device performance. S. Walde has found that metal-organic chemical vapor deposition (MOVPE) can be used to grow Si-doped AlN (Si: AlN) and n-type AlGaIn layers on hydride vapor phase epitaxy (HVPE) grown AlN templates. By adjusting the thickness of the regrown Si: AlN, the lattice constants can be altered to reduce TDD. This study successfully verified the effectiveness of strain engineering and dislocation density optimization in enhancing device performance [19].

Besides the above solutions, H. Chang has recently proposed new research that suggests the use of graphene (Gr)-driven strain pre-storage engineering to obtain low dislocation density (DD) and strain-free AlN films. Graphene effectively removes dislocations in AlN films and stores the tensile stress during the initial growth stage to compensate for the compressive stress arising from heteroepitaxial mismatch. Therefore, a low-strain deep-ultraviolet (DUV) optoelectronic device structure was successfully fabricated on a strain-free AlN template using graphene. This work provides insights into the complex beneficial effects of graphene on nitride epitaxial growth and offers a solution for overcoming major problems associated with conventional heteroepitaxial growth. This progress is of great importance for the development of nitride-based optoelectronic devices [6].

5. Conclusion

UV-LEDs have broad application prospects across various fields. Compared to traditional mercury lamps, UV-LEDs offer higher environmental friendliness, lower energy consumption, and better safety, making them an ideal choice to replace conventional mercury lamps. However, UV-LEDs still face several challenges. Issues such as low efficiency, difficulty in achieving high power output, and material limitations continue to hinder their development. This paper discusses in detail the advantages and challenges of UV-LEDs in different application scenarios, explores the current difficulties in the field of UV-LEDs, and provides directions for optimization.

In the field of water treatment, although the cost is high and the wall-plug efficiency is low, the disinfection efficiency and the operational flexibility of UV-LEDs are shown in large-scale water treatment systems. In medical disinfection, UV-LEDs are more efficient than chemical disinfectants and do not contribute to the development of resistance as compared to others particularly demonstrating portability and usability in disinfection of frequently used medical instruments. In the field of optical communication, the bandwidth and speed of UV-LEDs are much higher than that of mercury lamps, hence are ideal in long distance and high-speed data transfer. For the efficiency aspect, using new p-MQB EBL structures, high reflectivity electrodes and better p-type and thick LQB structures are effective ways of increasing the efficiency of UV-LEDs.

There are still some issues remain in the current research including the need for further improvement in the fabrication of UV-LEDs that is more efficient and cost effective. Further work should aim at the development of material science which is to investigate the possibility of using graphene and other materials to enhance the reduction of dislocation density and enhance the performance of the device. Also, concerning the issues of high-power output and the durability of UV-LEDs, future work should be done on the development of efficient multiple quanta well structures and the new types of electrodes. Due to the improvements made in the technology and the processes in place, there is a high possibility that UV-LEDs will be applied in additional and more real-life situations in the near future and thus boost the whole UV technology industry.

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