ISSN #: 3107-9881

SRI SATHYA SAI
UNIVERSITY FOR
HUMAN EXCELLENCE

AWARENESS

Newer Horizons in Human Excellence

SRI SATHYA SAI UNIVERSITY FOR HUMAN EXCELLENCE

योगः कर्मसु कौशलम्

VOL 3 | ISSUE 1 | JANUARY 2026 https://awarenessjournals.com

VOL 3 | ISSUE 1 | JANUARY 2026

About the Journal

The journal Awareness is dedicated to promoting and disseminating knowledge derived from innovative research that serves humanity, all forms of life, and their environments. It aims to foster deeper understanding by integrating empirical, experimental, experiential, and spiritual dimensions of knowledge across diverse disciplines. At its core, the journal seeks to expand the horizons of collaborative and empirical research, motivated by a love for humanity, child-like curiosity, and an unwavering commitment to truth. Awareness aims to be a publicly accessible platform for fresh, creative knowledge and shared scholarly exchange, thus embracing the principle that knowledge, like light, must be shared freely and openly to dispel ignorance and inspire the pursuit of human excellence. Only through such open exchange can the journal fulfill its commitment to the ideals of the University for Human Excellence. The journal also provides a forum for exploring critical issues related to the advancement of human excellence, welcoming a wide range of perspectives across multiple fields. It publishes original research articles, reviews, perspectives, editorials, commentaries, and book reviews, all of which reflect the personal views of the authors. These contributions do not represent the official stance of the University or the institutions affiliated with the authors, editors, or reviewers, preserving the journal's commitment to intellectual independence and diversity of thought.

JOURNAL PARTICULARS

Title	AWARENESS – Newer Horizons in Human Excellence
Frequency	Bi – Annual
ISSN	3107-9881
Publisher	Sri Sathya Sai University for Human Excellence
Chief Editor	Prof. Kanwaljeet J. S. Anand
Starting Year	2024
Subject	Multidisciplinary
Language	English
Publication format	Online
E-mail ID	awareness.journals@sssuhe.ac.in
Website	https://awarenessjournals.com/
Author Guidelines	https://awarenessjournals.com/author-instructions
Privacy Policy	https://www.awarenessjournals.com/public/img/pdf/privacy-policy.pdf
Copyrights	https://www.awarenessjournals.com/public/img/pdf/copyrights-permissions-policy.pdf

SRI SATHYA SAI
UNIVERSITY FOR
HUMAN EXCELLENCE

AWARENESS
Newer Horizons in Human Excellence

Table of Contents

1. The Onslaught of Artificial Intelligence in Healthcare — Kanwaljeet J. S. Anand and Shaun P. Setty 1

2. Indian Jews: A Case Study of Unique Religious Tolerance — Nicole Hirschkorn 7

3. IXOHOXI Magic Square in Pādukā Sahasram by Sri Vedānta Desika — N Kannan, K Srikanth 15

4. Advancements and Challenges in AlGaN and Phosphor-Based Deep Ultraviolet LEDs: Towards Broader Applications and Higher Efficiencies — K Vineela, P.V.N.M Kaushik, K. Jayanthi 21

5. Emotional Freedom Techniques (EFT) and Dopamine Detox: A Neurobehavioral Tool for Stress Management — Rajeshwari Ullagaddi 39

6. Confidence in Connectivity: Tracing Government Commitment through India's UDAN Scheme — Jacob Arndt 53

Narrative Review

Advancements and Challenges in AlGaN and Phosphor-Based Deep Ultraviolet LEDs: Towards Broader Applications and Higher Efficiencies

K Vineela, P.V.N.M Kaushik, K. Jayanthi

Department of Physical and Chemical Sciences, Sri Sathya Sai University for Human Excellence, Navanihal, Okali Post, Kamalapur, Kalaburagi, Karnataka - 585313

Abstract: Recent progress in deep ultraviolet light-emitting diodes (DUV LEDs) has revolutionized applications in sterilization, water purification, and biomedical imaging. Their effectiveness in viral and bacterial inactivation, notably demonstrated during the COVID-19 pandemic, underscores their critical role in public health and environmental safety. DUV light sources offer mercury-free operation, compactness, and wavelength tunability, positioning them as sustainable alternatives to traditional mercury lamps. Over the past decade, significant advances in substrate engineering, optimized epitaxial growth of AlGaN layers, and the discovery of efficient inorganic phosphor materials have enhanced device performance, with reported wall-plug efficiencies improving from below 1% to over 8% for AlGaNbased LEDs operating in the 250–280 nm range. The present review provides overview on the recent progress, advancements and existing challenges in AlGaN and other inorganic phosphor based DUV LEDs, focusing on efficiency device design strategies and overall lifetime. Despite these achievements, challenges such as limited external quantum efficiency (typically below 10%), high threading dislocation densities, and inefficient light extraction remain major issues to be resolved. Recent strategies like nanostructured quantum wells, polarization engineering, advanced reflective electrodes, hybrid AlGaN phosphor architectures and nano-patterned sapphire substrates, combined with optimized doping, thermal management, and quantum barrier engineering, have significantly enhanced DUV LED efficiency, stability, and reliability. Looking forward, future research is expected to focus on integrating advanced nanofabrication techniques, improving thermal management, and developing cost-effective large-area substrates to achieve high-efficiency, scalable DUV LED systems suitable for next-generation photonic, environmental, and biomedical applications.

Keywords: Deep Ultraviolet LEDs (DUV LEDs), Semiconductors, Phosphor Materials, Sterilization and Biomedical Applications, External Quantum Efficiency (EQE)

Corresponding Author: K. Jayanthu, Email: jayanthi.k@sssuhe.ac.in

Citation: K Vineela, P V N M Kaushik, K Jayanthi; ***Awareness***, 3 (1): 21-38

1. Introduction

The genesis of DUV technology finds its origin tracing to the conventional mercury lamp sources, and eventually evolved with the discovery of wide band-gap semiconductors. Based on their emission wavelength, UV LEDs have proved to support wider range of applications. UV emission is classified into three bands: UV-A (400 nm – 315 nm), UV-B (315 nm – 280 nm) and UV-C (280 nm – 200 nm). [1] UV-A and UV-B LEDs initiate the process of polymerization reactions in industrial processes such as coatings, adhesives, inks and 3D printing. [2] Apart from displaying greater energy efficiencies, the main reason that led to the development of DUV LEDs is their efficacy against the chlorine resistant pathogens such as cryptosporidium, which proved to cause numerous gastro-intestinal illnesses. [3] DUV LED is a well-known suitable light emitter in the UV-C spectrum (280 nm to 200 nm). [4] When emitted in this wavelength range, these LEDs find application, primarily for sterilisation of microbes, water purification, curing etc. [5,6]

The commonly used traditional UV light sources such as mercury vapour lamps generally pose environmental hazards, due to the stated toxic nature of mercury. [7] Additionally, poor energy efficiencies of mercury lamps guided researchers for developing novel DUV LED materials, that are toxic free. [8,9] The Minamata Convention in 2013 further enhanced the development of mercury free alternative materials, thereby placing DUV LEDs as a sustainable solution. [10] The main reason of preferring UV LEDs over mercury lamps is due to their efficiency, compactness and environmental safety. [6]

Traditional water treatment methods like filtration and dependence on chlorine show almost no effect in neutralizing the microbes. [11] UV-C LEDs, when emitted in DUV region, are extremely effective for inactivation of viruses, bacteria and spores by inducing photochemical changes (disrupt the DNA/RNA replication) in their nucleic acids. Kim et al. [12] have reported that a dose of 40 mJ/cm2 is just enough for neutralizing most of the microbes and pathogens, making these suitable for water purification and surface disinfection for household portable systems [13]. Similarly, Stanley's electric DUV LED material emitting 265 nm at 40mW output, had shown 99.9% inactivation rate for the bacteria E.Coli, within 120 seconds. 8 Such parameters were to be adopted in healthcare disinfectant systems, water purification and sterilisation. Researchers have developed several organic and inorganic based DUV light emitting materials for obtaining greater efficiencies.

III-V and IV-VI compound semiconductors / insulators are distinguished by their ultra-wide band-gaps, that enable higher optical transparencies and efficient operation in DUV spectral region. [14] DUV LEDs which are based on group-III nitrides and inorganic phosphors offer compact form factors, operate at moderate direct currents, exhibit longer operational lifetimes, environmentally friendly and provide tunable emission wavelengths through the compositional engineering of active materials. This intrinsic property makes them ideal in the field of solar-blind photodetectors and other notable DUV sensing technologies [15]. Strong structures give these materials high thermal and chemical stability, thereby enabling a consistent performance under extreme conditions and intense DUV irradiation. Adding to their stability factor, these compounds also exhibit distinct nonlinear optical behaviours, such as strong 2^{nd} harmonic generation and phase matching capabilities, that are essential in efficient frequency conversion for photonic DUV systems. [16–18] Additionally, the environmental compatibility and ease of high-quality crystal growth further enhance their suitability for scalable and sustainable integration into next-generation DUV optoelectronic systems devices.

The detailed comprehensive analysis of the efficiency between conventional mercury lamps and DUV LEDs is presented below:

- **Spectrum analysis**

Conventional mercury lamps emit broad UV spectrum, which disables deeper curing penetration and involves toxic mercury and ozone generation. DUV LEDs emit narrowband wavelengths (typically 255nm to 280 nm for AlGaN LEDs) with no toxic materials, enabling environmental benefits and deeper penetration. [19]

- **Lifetime**

Traditional Mercury lamps have a relatively shorter operational lifetimes, typically around 1,000 to 12,000 hours, depending on the pressure and lamp type, with medium-pressure lamps usually lasting less than the low-pressure lamps. [20] DUV LEDs offer much longer lifetimes, typically up to 50,000 to 100,000 hours for certain devices. [21] This implies fewer replacements of these bulbs and lower maintenance costs. LEDs operate without warmup or cooldown periods, whereas mercury lamps require warmup time, and these degrade progressively with more usage.

- **Energy Efficiency**

The conventional mercury lamps have a typical wall-plug efficiency (WPE), ranging from 10% to 40%, depending on the lamp type (whether low type, or medium type, or pressure type) and application, with emissions mainly cantered around 254 nm. [22,23] DUV LEDs currently have a WPE around 1% to 3%, but the ongoing technological advances expect to increase this beyond 10% in the future. [10] LEDs consume significantly less power than mercury lamps, contributing to lower operational costs and better energy conservation.

In addition, few advantages of III-V and IV-VI materials are summarized in the tabular column below.

Table 1 Advantages of III-V and IV-VI materials

Merit	Description	Reference
Wide Bandgap & DUV Transparency	Enables DUV emission and solar-blind detection	[24]
Chemical & Thermal Stability	Ensures reliability of the device in harsher environments	[25]
High Sensitivity & Swift Response	Provides ultrafast and selective DUV detection	[26]
Enhanced Nonlinear Optical Properties	Enables efficient DUV frequency conversion	[27]
Environmentally Friendly & Crystal Growth	Assists in scalable fabrication and eco-friendly material design	[28]

2. Synthesis of DUV LEDs using substrate engineering and epitaxial growth

A milestone in GaN technology in the late 1980s gave rise to blue LEDs, which enabled the production of efficient artificial white light LEDs. [29] Gallium, when alloyed to AlN gives AlGaN based LED materials, which typically emit in UV range giving rise to several notable applications. [30] The synthesis of high performance DUV LEDs mainly depends on minimizing the crystalline defects present in the AlGaN layers, which directly have an impact on their Internal Quantum Efficiency

(IQE). The dislocation density parameter, with its value lesser than 2×10^8 cm^{-3}, is crucial in minimizing the non-radiative recombination. AlN substrates typically have low lattice mismatch as compared to AlGaN and have become the basis for DUV LED fabrication.

Before we further proceed on discussion on several advancements in substrate engineering, it is essential to understand that the main degradation mechanism in DUV LEDs mainly emerges from defect related non radiative recombination, thermally induced nonuniform composition and leakage current led optical losses. [31] The main factors that significantly minimize EQE and device reliability can be stated as point-defects, Al ion migration and Shockley-Read-Hall recombination under thermal and electrical stress. [32] Several notable effects such as advanced thermal management designs, carefully modified silicone / ceramic packing and graded AlGaN superlattice structures have been developed by researchers to mitigate the previously stated factors. These processes not only prevent leakage, improve heat dissipation and reduce defect densities, but also help in achieving greater device stabilities and longer device lifetimes.

Recent advancements in engineering the substrate for AlN had shown an enhancement in the power output of DUV LEDs. A pseudo 2D growth of good quality AlN films on graphene substrate had a reduced effect on the dislocation density and strain, thus achieving a remarkable 22% increase in the output power for 272 nm devices, which was achieved through improved IQE and light extraction efficiency (LEE). [33] Choosing sapphire over AlN substrates had minimized the lattice mismatch, thus giving a 100-fold power enhancement for 280 nm DUV LEDs, through enhancing the carrier injection efficiency. [34] Further optimization of the AlN crystal plane orientation had shown benefits of anisotropic light extraction, thus boosting the emission intensity of 210 nm LEDs, which was achieved through the minimization of photon losses at specific crystallographic interfaces. [35] In addition, high-temperature annealing of hydride vapor phase epitaxy (HVPE) grown AlN substrates had demonstrated an improvement in the surface morphology, thus enhancing LEE by 8% for 265 nm flip-chip LEDs, achieved through reduced interfacial roughness. [36] The stated innovations collectively report the critical role of the quality of substrate, via graphene integration, lattice matching, crystallographic tuning, and post-growth processing, for advancing DUV LED performance in applications for disinfection, spectroscopy, sensing etc. Between 2013 and 2023, the power output exhibited by DUV LEDs ranged between 10 mW to 200 mW, which was mainly due to the result of the enhancement of the AlN substrate quality. [13]

It is crucial to acknowledge that substrate engineering is a key factor in improving the internal and external quantum efficiencies of AlGaN-based DUV-LEDs, mainly achieved by optimizing the Aluminium composition within the active and buffer layers. Results from recent research studies show that growth on AlN substrates drastically reduces the threading dislocation density, that is very much crucial for achieving high IQE in Al-Rich AlGaN layers. [37] This results in improvement up to one order of magnitude compared to the conventional sapphire substrate. Though Sapphire is cost-effective, it results in significant lattice mismatch, thereby lowering IQE in DUV compositions due to enhanced defect densities. [38] In addition, the refining of the surface and advanced photonic structures on the substrates contribute to greater values of EQE, through promoting better light extraction. Thus, advanced substrate engineering techniques directly address, not only the crystal quality and optical management, but also deliver marked quantum efficiency gains throughout the composition range of AlGaN.

Amongst various synthesis methods of DUV materials, epitaxial growth is a unique method preferred, as it offers precise control on the crystallinity of the material, thickness of the layers and interface quality. These factors are crucial and important for the performance of DUV materials. DUV carbon materials like carbon nanostructures and wide band-gap graphene, are emerging as key components in high-performance optoelectronics, photodetectors, and next-generation quantum devices.

A promising approach involves the epitaxial growth of graphene on silicon carbide (SiC). In this technique, SiC is heated to elevated temperatures under ultra-high vacuum conditions, leading to the sublimation of silicon atoms. The remaining carbon atoms then re-organize into well-ordered graphene layers on the SiC substrate.Though this method results in graphene with excellent structural and electronic properties, attaining uniformity in larger area and maintaining consistent layer thickness is a significant hurdle for scalable DUV applications. However, this limitation is overcome by another innovative technique known as remote epitaxy, which involves growing crystalline films on a substrate that is coated with 2D material such as graphene.[39] Another promising epitaxy strategy is known as the Van der Waals epitaxy, that relies on weak interlayer forces between the substrate and the deposited film, and is most ideal for integration in DUV systems. [40] Recent studies have also reported the epitaxial growth of carbon nano-fibres using carbon nanotubes, through the deposition of pyrolytic carbon in the gaseous phase, followed by high-temperature annealing. [41] Using this method, researchers have produced nanofibers with excellent thermal and mechanical flexibility, suited for extreme DUV environments. [41] Further film quality and reproducibility can be enhanced through substrate surface engineering techniques like application of buffer layers, surface coatings, or chemical treatments. These techniques help in minimizing defects, control the film thickness and improve the homogeneity of epitaxial layers, which are crucial for consistent DUV device fabrication. [42] Future efforts must focus on refining the epitaxial control through exploration of novel substrates and incorporation of real-time growth monitoring of the DUV carbon materials.

3. Thermal management techniques for high power DUV LEDs

High-power operations typically generate significant heat at the junctions, leading to reduced LED lifetime; hence, efficient thermal management is essential. To address this issue, thermal-based heat sinks are commonly employed, while the mercury-free design of DUV LEDs further supports sustainable development goals. Efficient thermal management in high-power DUV LEDs largely depends on advancements in both material selection and packaging design, which help lower the junction temperature and improve device reliability. [43] Ceramic substrates such as Aluminium nitride (AlN) offer high thermal conductivity and enable dense packing, making them highly suitable for efficient heat dissipation in DUV applications. [44] However, their relatively high cost compared to Aluminium or Aluminium-based ceramics limits their widespread use. To further enhance heat dissipation and spreading, standard industrial techniques such as thermal arrays, copper planes, and active cooling methods (including liquid cooling and forced convection) are employed. [45] Moreover, microchannel cooling structures and phase-change materials have gained considerable attention for mitigating thermal gradients and localized hotspots in compact, high-power device configurations. [46] Overall, substantial progress has been achieved over the past few decades through the integration of high-thermal-conductivity ceramic materials with advanced cooling structures, resulting in enhanced thermal management at both the device and system levels.

4. Wavelength conversion using phosphor materials

Though phosphors are essential ingredients in development of visible LEDs, they also play a crucial and important role in DUV LEDs. Band-gap engineering in GaN is essential to achieve excellent optoelectronic properties for applications in lasers, LEDs and several high-power devices. Thus, bandgap engineering in AlGaN-based deep ultraviolet (DUV) materials enables tunable emission from 200-280 nm by systematically varying aluminium composition from GaN (3.4 eV) to AlN (6.2 eV). [47]

Techniques like strain-engineering have reported a compressive strain in GaN/AlGaN nanowires, that can induce band-gap shifts up to 240 meV. [48] Similarly, it was reported that uniaxial strain of GaN nanowires leads to a linear decline of the band-gap. [49] Several doping and co-doping strategies like co-introduction of C-Ge or C-Sn create meta-stable states, which narrow the band-gap and enhance the visible light absorption. [50] The phenomenon of Quantum confinement observed in GaN nanostructures has also shown an increase in the band-gap with reduced size due to surface effects. [51] These reported strategies have collectively enabled precise control over GaN band structure for DUV device applications.

4.1 GaN based DUV LEDs

Yi Lu et al. [52] reported monolithic integration of DUV and visible LEDs for the radiative sterilization applications. This was accomplished by cascading AlGaN/AlGaN/AlGaN multiple QWs and GaN/InGaN/GaN QWs through the compositional grading AlGaN cascade region, as shown in figure 1.

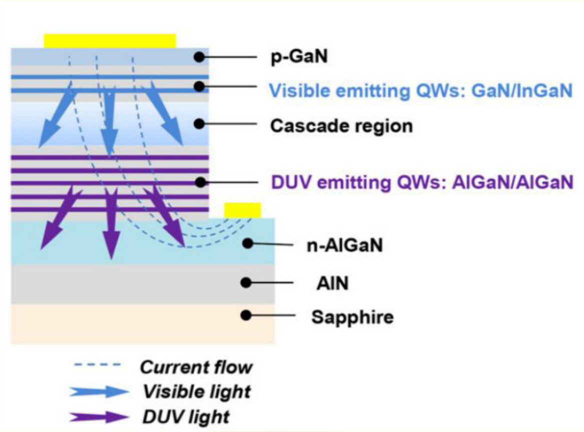

Figure 1 Schematic structure of the proposed LED, containing visible emitting QWs grown on top of the DUV emitting QWs.

The inevitable overflown electrons from DUV QWs are deliberately introduced into the visible QWs, allowing for the electron–hole recombination and the simultaneous emission of visible light. Both experiment and simulation results confirmed the feasibility of the proposed dual-wavelength LED integration. The proposed DUV & visible LED showed an EQE and WPE of 2.03% and 1.54% at 40 mA, respectively.

Ke Jiang et al. [53] fabricated AlGaN-based DUV LEDs with different wavelength on high-temperature-annealed (HTA) AlN/Sapphire templates. The AlN/AlGaN superlattices were employed between the template and upper n-AlGaN to release the strong compressive stress (SCS), improving the crystal quality and interface roughness. DUV LEDs with the wavelength of 256, 265, and 278 nm, corresponding to the light output power of 6.8, 9.6, and 12.5 mW, were realized. They argued that GaN/AlN QWs possess strong quantum confinement in one-monolayer limit which dramatically enhances the exciton binding energy (up to 230 meV). This provides extreme 2D confinement of excitons, being ideally suited for light generation in the deep ultraviolet. Toropov et al. [54] have reported a single monolayer of GaN in AlN as a heterostructure fabricated by molecular beam epitaxy [55] which provides extreme 2D confinement of excitons, which is ideal for light generation in the DUV region. They have also reported an internal quantum yield of 75% at room-temperature, due to excitonic emission at 235 nm. Lu et al. [56] demonstrated a truncated pyramid nanostructure in (AlN)8/(GaN)2 digital alloys, fabricated using nanoimprint lithography and etching techniques. They further stated that the design enhanced LEE by 191%, compared to planar structures, as shown in figure 2.

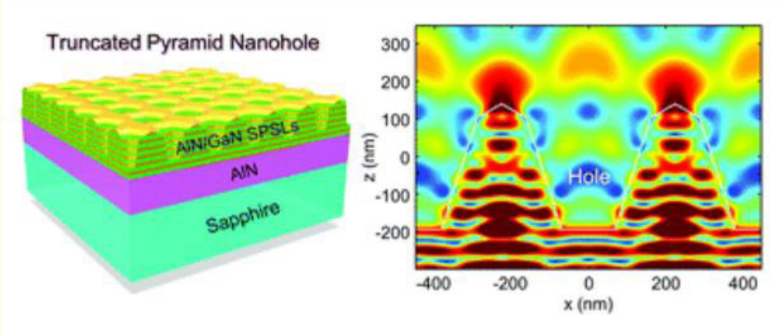

Figure 2 Truncated pyramid nanostructure of AlGaN DUVs

Chenguang He et al.[57] achieved self-organized high crystalline quality of AlGaN quantum wire arrays, by engineering the surface morphology of AlN templates, that resulted in IQE of 70% for DUV emission.

4.2 Band gap engineering in AlGaN based DUV LEDs

The energy band gap of $Al_xGa_{1-x}N$ alloys increases steadily as more Aluminium is added from about 3.4 eV in pure GaN (x = 0) to about 6.2 eV in pure AlN (x = 1). This change in composition lets us adjust the light emission wavelength from 365 nm (near-ultraviolet) to 210 nm (deep ultraviolet), which is useful for things like killing germs, cleaning water, and detecting chemicals. The increase in band gap happens because the conduction band moves up and the valence band moves down as Aluminium content rises as illustrated in figure 3. This shift makes the emitted photons more energetic, producing shorter wavelengths. In LED devices made from AlGaN, the light-emitting region called the multiple quanta well can be designed with specific Aluminium levels to control the colour of light. This idea, known as "Emission Tunability via Al Content Engineering" is key to making advanced deep-UV light sources. Experiments and computer models show that the band gap doesn't change in a straight line, it bends slightly, which scientists describe using the Varshni equation and a bowing factor.

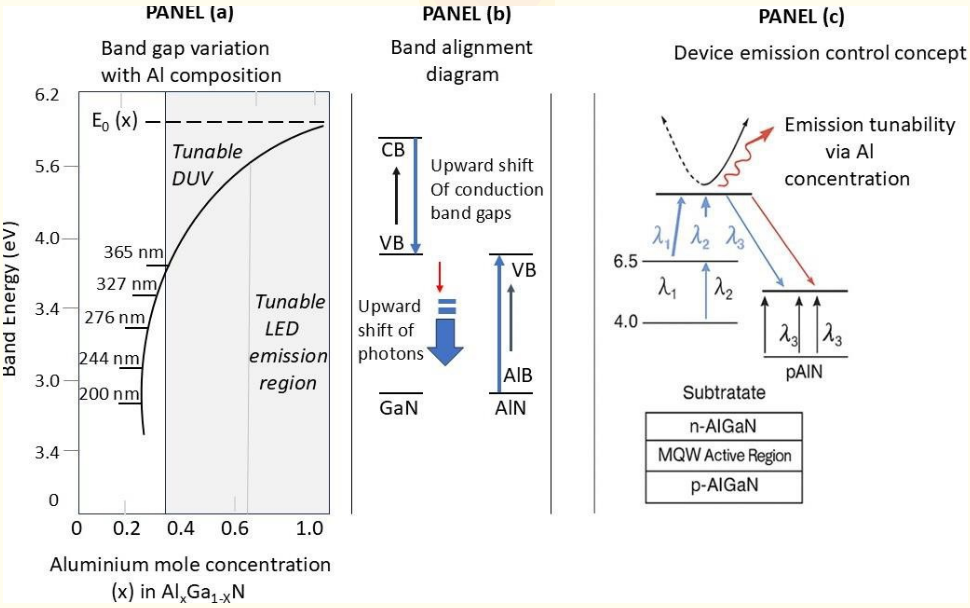

Figure 3: (a) Band-gap energy (Eg) increases smoothly from ~3.4 eV (GaN) to ~6.2 eV (AlN) as a function of Al mole fraction (x). Emission wavelength with band gaps 365 to 210 nm are shaded highlighting the tunable DUV emission window (range: 200 to 300 nm). **(b)** Band alignment for GaN, AlGaN and AlN illustrating conduction band upward shifts and valence band downward shifts with increasing Al content, Arrows show electric transitions of DUV photons with varying energy (λ1, λ2, λ3). **(c)** AlGaN based LED structure emphasizing emission tunability via Al composition in multi-quantum wall layers.

4.3 Research Gap in AlGaN and Phosphor-Based DUV LEDs

AlGaN-based DUV LEDs face inherent challenges such as low hole injection efficiency and UV absorption in p-layers. Recent advancements, including nanoscale structuring, reflective contact design, substrate engineering, and the incorporation of molecular p-type dopants such as DPI–TPFB and F4TCNQ to enhance hole mobility and reduce injection barriers. [58] Strategies for interfacial engineering such as energy-level tuning of hole transport layers and valence state optimization via UV zone treatment have collectively led to significant improvements in charge balance and defect reduction. [59] Up to fourfold enhancements in EQE and device lifetime in blue PeLEDs and solution-processed QLEDs advance the overall reliability and performance of optoelectronic devices.

The maximum efficiency reported for DUV LEDs varied across different studies, with significant advancements in recent years. The highest EQE achieved reported was 11% for 278 nm AlGaN based DUV LEDs, due to the improvement in material quality and light extraction techniques. [60] Such lower values of EQE generally limits the antibacterial and sterilization effectiveness. Other notable efficiencies include 7.2% for a 255 nm tunnel junction LED, which represents a substantial increase over previous designs. [61] Additionally, a 254 nm tunnel junction LED demonstrated an IQE of approximately 88%, marking a significant milestone in DUV LED technology. [62] The typical challenges of these include higher threading dislocation densities due to lattice mismatch with substrates, low light extraction efficiency (LEE), and carrier injection issues reducing IQE. [63] To combat these issues, packaging of these LEDs, device reliability, efficiency improvement in hole injection, control of electron leakage and optical extraction are the active research avenues for the researchers. The main reason in using of AlGaN based DUV LEDs lies in raising the WPE parameter and stable outputs comparable to the mercury lamps, to enable broader industrial and biomedical applications.

4.4 Inorganic Phosphors / Nanophosphors based DUV LEDs

Phosphate-based phosphors, such as Bi doped yttrium phosphate (YPO_4), Pr activated $Ca_2Al_2SiO_7$, and Pr^{3+}-doped $Li(Al_7B_4O_{17})$ have proved to be a potential material for tunable emission spectra. [47–49] When activated by Bi or Pr, these inorganic phosphors emit DUV-C light under UV excitation, thus offering methods for development of multifunctional DUV devices, for potential applications for both illumination and disinfection. [50] However, phosphors based DUVs require excellent stability when irradiated with higher energies, which is an area of further research. Xu et al. [64] have stated in their work the unique features in the atomic and electronic configurations of DUV light emitters. They have reported the fundamental genetic reasons as to why DUV light emitters are extremely rare. They have studied the design and synthesis of several DUV light emitters and established the genetic nature of ultrawide band-gap semiconductors. They have also worked and arrived at a high-throughput computational search for DUV light emitters, based on specially designed screening criteria relating to electronic structure. Through this approach, they have identified 5 promising material candidates that exhibit comparable or higher radiative recombination coefficients than AlN, like $BeGeN_2$, Mg_3NF_3, $KCaBr_3$, KHS, and RbHS. Lin et al. [65] reported β-Ga_2O_3 p–i–n heterostructure grown on p-GaN by sequential vapor-cooling condensation of i-Ga_2O_3 and Si-doped Ga_2O_3, followed by 900°C annealing. The device showed strong deep-UV electroluminescence peaking at 248 nm. They have also measured and reported the electron concentrations to be $\sim 1\times10^{15}$ cm^{-3} in i-Ga_2O_3 and 2.2×10^{17} cm^{-3} in n-Ga_2O_3:Si. Mohammad M. Afandi et al. [66] have also reported DUV electroluminescent device using Bi^{3+} doped yttrium phosphate (YPB) phosphor. They have optimized dopant concentration, phase-morphological, and electro-optical properties of the developed YBP phosphor. They also reported that under AC-driven sinusoidal waveform, the EL emits a narrowband DUV spectrum peaking at 243 nm. Rojas-Hernandez et al. [67] reported in their work that undoped

$ZnAl_2O_4$ fibers which were synthesized though cost-efficient wet chemical route. The rare-earth-free $ZnAl_2O_4$ nanofibers exhibited a strong UV emission with two bands, peaking at 5.4 eV (230 nm) and 4.75 eV (261 nm) respectively. The emission intensity was controlled through tuning the Zn/Al ratio. Xulong Lv et. al. [68] synthesized $ScBO_3$:Bi^{3+} phosphors via a high-temperature solid-state reaction method. These phosphors exhibit intense and long-lasting DUV-C luminescence centred at 299nm due to the presence of various defect levels and external stimulus, which show excellent energy storage capabilities. Yan-Min Yang et al. [69] developed Pr-doped polycrystalline fluoride lepidolite persistent phosphors (Cs_2NaYF_6:Pr^{3+}) which was prepared by high temperature solid-state reaction method. This phosphor showed strong UV-C emission at 250 nm, with an initial power density over 10 mW/m^2 and an afterglow greater than 2 hours. Wang et al. [70] reported Pr^{3+} doped Li(Al7B4O17) nanocrystals (NCs), embedded with fluoride in the glass matrix. These nano-GCs reported DUV emission at 250 nm, with the photoluminescence quantum yield of 25.93%.

DUV LEDs have emerged as a green and sustainable alternative to conventional mercury-based lamps, particularly for applications such as disinfection and sterilization. This transition has sparked significant research interest, aimed at enhancing the performance and efficiency of DUV LED devices. Amongst them, AlGaN-based DUV LEDs have gathered particular attention, as researchers strive to address persistent challenges related to reliability, efficiency, and thermal management. For example, Li et al. have reviewed AlGaN DUV LEDs and reported that these materials typically have EQEs below 10%, due to polarization fields and poor p-type doping. [55] Selective promising techniques such as thermal annealing of reflective electrodes [38,71] have shown promise, by offering significant gain in the EQE. Researchers have also relied on several computational screening methods for identifying potential DUV light emitters with desirable properties.

Progress in UV-C emitting phosphors and study of nonlinear optical (NLO) crystals like $Rb_2ScB_3O_6F_2$ have opened new arenas for next-generation DUV photonic devices. These advancements promise potential applications, from water purification to high-resolution, maskless photolithography, etc. Recent studies have shown the development of several NLO based materials [72–76] for application in DUV devices. Additionally, there are few more prominent review papers [77–81] published in the recent years, that discuss the development and evolution of DUV C LEDs.

4.5 AI-based approaches for design of novel DUV emitters

In the past decade, researchers have stated and proved that computational and AI-based methods are gaining pivotal role in designing novel DUV emitters due to their ability in handling complex datasets of various materials, used in applications related to optimize the device architectures. Several notable Machine learning (ML) frameworks such as stacking ensemble models and Light GBM regression models have been found to rapidly screen ultra-wide bandgap (UWBG) semiconductors, thus enabling identification of promising DUV materials amongst the thousands of similar materials. [82] Integration of ML with first-principles calculations (such as DFT) fine tunes the predictions for ideal (and practical) bandgaps, optical properties and stability. [83] Also, effective AI approaches like SHAP uncover the structure property relationships which reform the material selection. [84] Deep learning models and convolutional neural networks (CNNs) have been often used to extract crucial features that affect the luminous performance of AlGaN-based DUV LEDs, thus predicting the device efficiencies. Additionally, numerous data-driven optimization methods, including genetic algorithms or reinforcement learning, fine-tune layer structures and compositions, significantly accelerate the discovery and advancing of high-performance DUV emitters. [85]

5. Conclusion

DUV LEDs have emerged as sustainable light sources, offering significant advantages over the conventional mercury lamps, in terms of ecofriendly nature and high efficiency. The present review focusses on advancements in AlGaN-based quantum structures which emerged as promising approaches to develop novel LEDs for notable applications in various fields, such as sterilization, biomedical imaging, and environmental monitoring, as reported in the past decade. The article also discusses the synthesis of novel inorganic phosphor materials which have expanded the application scope of DUV LEDs. Future progress centres on optimizing quantum well designs, enhancing the crystal quality, and improving light extraction methodologies. Additionally, the incorporation of innovative phosphors and nanostructures also revealed new performance metrics, mainly for emission tunability and efficiency. The discussion in this article centres and concludes with innovation of DUV LEDs for application in next-generation devices for global health, safety and sustainability.

6. Future Directions

Research on DUV LEDs must focus on overcoming the efficiency barrier through several factors like optimization of quantum well structures, improving high Al content in the AlGaN crystal quality and enhancing the light extraction techniques. The integration of novel inorganic phosphors and nanostructures offer promising approached for enhancing the emission efficiency as well as tunability of the spectra towards DUV region. Development of robust, compact, and low-cost packaging materials is essential for real world applications. With an increased demand for applications related to sterilization, biosensing, and environmental monitoring, notable interdisciplinary strategies involving cross cultural disciplines such as materials science, photonics, and device engineering will be essential. The stated advancements will aim for developing next-generation DUV LEDs with enhanced performance, safety, and global applicability.

Acknowledgment

The author, K. Jayanthi, gratefully acknowledges the financial support provided by the Department of Science and Technology (DST), Government of India, under the DST-Women Scientist Scheme-B (Project No. DST/WOS-B/ER-6/2021(G)).

References

1. Knuschke, P. UV Exposure. In Kanerva's Occupational Dermatology; John, S. M., Johansen, J. D., Rustemeyer, T., Elsner, P., Maibach, H. I., Eds.; Springer International Publishing: Cham, 2020; pp 1145–1178. https://doi.org/10.1007/978-3-319-68617-2_76.
2. Kopyciński, B. UV-Curable Coatings – Environment-Friendly Solution for Sustainable Protection of Metal Substrates. COROSSION PROTECTION 2023, 1 (6), 4–13. https://doi.org/10.15199/40.2023.6.1.
3. Pramod, S.; M.Z, K.; A.K, C. LED Revolution: Deep UV LED. IRJET 2019, 6 (5), 6486–6490.
4. Chiappa, F.; Frascella, B.; Vigezzi, G. P.; Moro, M.; Diamanti, L.; Gentile, L.; Lago, P.; Clementi, N.;

Signorelli, C.; Mancini, N.; Odone, A. The Efficacy of Ultraviolet Light-Emitting Technology against Coronaviruses: A Systematic Review. Journal of Hospital Infection 2021, 114, 63–78. https://doi.org/10.1016/j.jhin.2021.05.005.

5. Song, K.; Mohseni, M.; Taghipour, F. Application of Ultraviolet Light-Emitting Diodes (UV-LEDs) for Water Disinfection: A Review. Water Research 2016, 94, 341–349. https://doi.org/10.1016/j.watres.2016.03.003.
6. Chen, J.; Loeb, S.; Kim, J.-H. LED Revolution: Fundamentals and Prospects for UV Disinfection Applications. Environ. Sci.: Water Res. Technol. 2017, 3 (2), 188–202. https://doi.org/10.1039/C6EW00241B.
7. Hu, Y.; Cheng, H. Mercury Risk from Fluorescent Lamps in China: Current Status and Future Perspective. Environment International 2012, 44, 141–150. https://doi.org/10.1016/j.envint.2012.01.006.
8. Deep ultraviolet LEDs for water sterilization attracting attention. https://www.stanley-electric.com/en/technology/energizing/.
9. Shatalov, M.; Lunev, A.; Hu, X.; Bilenko, O.; Gaska, I.; Sun, W.; Yang, J.; Dobrinsky, A.; Bilenko, Y.; Gaska, R.; Shur, M. PERFORMANCE AND APPLICATIONS OF DEEP UV LED. Int. J. Hi. Spe. Ele. Syst. 2012, 21 (01), 1250011. https://doi.org/10.1142/S0129156412500115.
10. Sharma, V. K.; Demir, H.V. Bright Future of Deep-Ultraviolet Photonics: Emerging UVC Chip-Scale Light-Source Technology Platforms, Benchmarking, Challenges, and Outlook for UV Disinfection. ACS Photonics 2022, 9 (5), 1513–1521. https://doi.org/10.1021/acsphotonics.2c00041.
11. Li, Q.; Yu, S.; Li, L.; Liu, G.; Gu, Z.; Liu, M.; Liu, Z.; Ye, Y.; Xia, Q.; Ren, L. Microbial Communities Shaped by Treatment Processes in a Drinking Water Treatment Plant and Their Contribution and Threat to Drinking Water Safety. Front. Microbiol. 2017, 8, 2465. https://doi.org/10.3389/fmicb.2017.02465.
12. Kim, H.-J.; Yoon, H.-W.; Lee, M.-A.; Kim, Y.-H.; Lee, C. J. Impact of UV-C Irradiation on Bacterial Disinfection in a Drinking Water Purification System. J Microbiol Biotechnol 2023, 33 (1), 106–113. https://doi.org/10.4014/jmb.2211.11027.
13. Kneissl, M.; Seong, T.-Y.; Han, J.; Amano, H. The Emergence and Prospects of Deep-Ultraviolet Light-Emitting Diode Technologies. Nat. Photonics 2019, 13 (4), 233–244. https://doi.org/10.1038/s41566-019-0359-9.
14. Ping, L. K.; Berhanuddin, D. D.; Mondal, A. K.; Menon, P. S.; Mohamed, M. A. Properties and Perspectives of Ultrawide Bandgap Ga2O3 in Optoelectronic Applications. Chinese Journal of Physics 2021, 73, 195–212. https://doi.org/10.1016/j.cjph.2021.06.015.
15. Korotcenkov, G. Handbook of II-VI Semiconductor-Based Sensors and Radiation Detectors: Volume 1, Materials and Technology, 1st ed.; Springer International Publishing AG: Cham, 2023.
16. Dalai, B.; Dash, S. K. Deep-Ultraviolet (DUV) Nonlinear Optical (NLO) Crystals: An Application

in Photonic Technologies. Optical Materials 2023, 143, 113909. https://doi.org/10.1016/j.optmat.2023.113909.

17. Zhai, T.; Fang, X.; Liao, M.; Xu, X.; Zeng, H.; Yoshio, B.; Golberg, D. A Comprehensive Review of One-Dimensional Metal-Oxide Nanostructure Photodetectors. Sensors 2009, 9 (8), 6504–6529. https://doi.org/10.3390/s90806504.
18. Jain, N.; Kumar, D.; Bhardwaj, K.; Sharma, R. K.; Holovsky, J.; Mishra, M.; Mishra, Y. K.; Sharma, S. K. Heterostructured Core-Shell Metal Oxide-Based Nanobrushes for Ultrafast UV Photodetectors. Materials Science and Engineering: R: Reports 2024, 160, 100826. https://doi.org/10.1016/j.mser.2024.100826.
19. Bhattarai, T.; Ebong, A.; Raja, M. A Review of Light-Emitting Diodes and Ultraviolet Light-Emitting Diodes and Their Applications. Photonics 2024, 11 (6), 491. https://doi.org/10.3390/photonics11060491.
20. Sosnin, E. A.; Sorokin, D. A. Current Sources of Vacuum Ultraviolet Radiation: State and Prospects (A Review). Plasma Phys. Rep. 2024, 50 (7), 880–893. https://doi.org/10.1134/S1063780X24601068.
21. Khan, A.; Kneissl, M.; Amano, H. UV/DUV Light Emitters. Applied Physics Letters 2023, 123 (12), 120401. https://doi.org/10.1063/5.0174270.
22. Sun, W.; Jing, Z.; Zhao, Z.; Yin, R.; Santoro, D.; Mao, T.; Lu, Z. Dose–Response Behavior of Pathogens and Surrogate Microorganisms across the Ultraviolet-C Spectrum: Inactivation Efficiencies, Action Spectra, and Mechanisms. Environ. Sci. Technol. 2023, 57 (29), 10891–10900. https://doi.org/10.1021/acs.est.3c00518.
23. Zollner, C. J.; DenBaars, S. P.; Speck, J. S.; Nakamura, S. Germicidal Ultraviolet LEDs: A Review of Applications and Semiconductor Technologies. Semicond. Sci. Technol. 2021, 36 (12), 123001. https://doi.org/10.1088/1361-6641/ac27e7.
24. Shi, J.; Zhang, J.; Yang, L.; Qu, M.; Qi, D.; Zhang, K. H. L. Wide Bandgap Oxide Semiconductors: From Materials Physics to Optoelectronic Devices. Advanced Materials 2021, 33 (50), 2006230. https://doi.org/10.1002/adma.202006230.
25. Fang, W.; Li, Q.; Li, J.; Li, Y.; Zhang, Q.; Chen, R.; Wang, M.; Yun, F.; Wang, T. Deep Ultraviolet Photodetector: Materials and Devices. Crystals 2023, 13 (6), 915. https://doi.org/10.3390/cryst13060915.
26. Lee, H. K.; Park, T.; Yoo, H. Device Applications Enabled by Bandgap Engineering Through Quantum Dot Tuning: A Review. Materials (Basel) 2024, 17 (21), 5335. https://doi.org/10.3390/ma17215335.
27. Jing, Q.; Zhu, M.; Li, L.; Ji, X.; Duan, H.; Chen, H.; Lee, M.-H. Two Noncentrosymmetric Alkali Metal Phosphates MZnPO4 (M = Rb, Cs) with Honeycomb-like Structures. Optical Materials 2024, 147, 114620. https://doi.org/10.1016/j.optmat.2023.114620.
28. Sudha Gulati; Richa Jain. Solar Cells for Ecological Sustainable Development: A Review. J. Adv. Zool. 2023, 44 (S6), 1109–1121. https://doi.org/10.17762/jaz.v44iS6.2366.
29. Nanishi, Y. The Birth of the Blue LED. Nature Photon 2014, 8 (12), 884–886. https://doi.org/10.1038/nphoton.2014.291.

30. Aly, Z. Development of Aluminium Nitride Based Materials and Application to the Fabrication of Ultraviolet Light Emitting Diodes, Université Côte d'Azur, 2024.

31. Gong, M.; Sun, X.; Lei, C.; Liang, T.; Li, F.; Xie, Y.; Li, J.; Liu, N. Study on the Degradation Performance of AlGaN-Based Deep Ultraviolet LEDs under Thermal and Electrical Stress. Coatings 2024, 14 (7), 904. https://doi.org/10.3390/coatings14070904.

32. Abbas, M.; Xu, X.; Rauf, M.; Kyaw, A. K. K. A Comprehensive Review on Defects-Induced Voltage Losses and Strategies toward Highly Efficient and Stable Perovskite Solar Cells. Photonics 2024, 11 (1), 87. https://doi.org/10.3390/photonics11010087.

33. Chang, H.; Chen, Z.; Liu, B.; Yang, S.; Liang, D.; Dou, Z.; Zhang, Y.; Yan, J.; Liu, Z.; Zhang, Z.; Wang, J.; Li, J.; Liu, Z.; Gao, P.; Wei, T. Quasi-2D Growth of Aluminum Nitride Film on Graphene for Boosting Deep Ultraviolet Light-Emitting Diodes. Advanced Science 2020, 7 (15), 2001272. https://doi.org/10.1002/advs.202001272.

34. Li, Y.; Dvořák, M.; Nesterenko, P. N.; Nuchtavorn, N.; Macka, M. High Power Deep UV-LEDs for Analytical Optical Instrumentation. Sensors and Actuators B: Chemical 2018, 255, 1238–1243. https://doi.org/10.1016/j.snb.2017.08.085.

35. Taniyasu, Y.; Kasu, M. Improved Emission Efficiency of 210-Nm Deep-Ultraviolet Aluminum Nitride Light-Emitting Diode. NTT Technical Review 2010, 8 (8), 7–11. https://doi.org/10.53829/ntr201008sf2.

36. Yue, W.; Liu, R.; Li, P.; Zhou, X.; Liu, Y.; Yang, B.; Liu, Y.; Wang, X. Power Enhancement of 265 Nm DUV-LED Flip-Chip by HVPE-AlN High-Temperature Annealing. Micromachines 2023, 14 (2), 467. https://doi.org/10.3390/mi14020467.

37. Huang, C.-Y.; Hagedorn, S.; Walde, S.; Tsai, C.-L.; Fu, Y.-K.; Weyers, M. The Optimal Threading Dislocation Density of AlN Template for Micrometer-Thick Al0.63Ga0.37N Heteroepitaxy. Journal of Crystal Growth 2022, 600, 126910. https://doi.org/10.1016/j.jcrysgro.2022.126910.

38. Mouloua, D.; Martin, M.; Beruete, M.; Jany, C.; Hassan, K.; Baron, T. Exploring Strategies for Performance Enhancement in Micro-LEDs:A Synoptic Review of III-V Semiconductor Technology. Advanced Optical Materials 2025, 13 (6), 2402777. https://doi.org/10.1002/adom.202402777.

39. Lee, H.; Kang, S. B.; Lee, S.; Zhu, K.; Kim, D. H. Progress and Outlook of Sn–Pb Mixed Perovskite Solar Cells. Nano Convergence 2023, 10 (1), 27. https://doi.org/10.1186/s40580-023-00371-9.

40. Kim, J.; Ju, X.; Ang, K.-W.; Chi, D. Van Der Waals Layer Transfer of 2D Materials for Monolithic 3D Electronic System Integration: Review and Outlook. ACS Nano 2023, 17 (3), 1831–1844. https://doi.org/10.1021/acsnano.2c10737.

41. Ko, F. K.; Kuznetsov, V.; Flahaut, E.; Peigney, A.; Laurent, C.; Prinz, V. Y.; Mani, R. C.; Sunkara, M. K.; Baldwin, R. P.; Capelli, E.; Orlando, S.; Mattei, G.; Scilletta, C.; Corticelli, F.; Ascarelli, P.; Bhimarasetti, G.; Graham, U.; Suh, C.; Rajan, K.; Usoltseva, A. N.; Rudina, N. A.; Alekseev, M. Yu.; Lutsev, L. V.; Acatay, K.; Simsek, E.; Akel, M.; Menceloglu, Y. Z.; Krestinin, A. V.; Kislov, M. B.; Ryabenko, A. G.; Çamurlu, H. E.; Aydogdu, A.; Topkaya, Y.; Sevinç, N.; Vyshnyakova, K. L.; Pereselentseva, L. N. Formation of

Nanofibers and Nanotubes Production. In Nanoengineered Nanofibrous Materials; Guceri, S., Gogotsi, Y. G., Kuznetsov, V., Eds.; NATO Science Series; Springer Netherlands: Dordrecht, 2004; Vol. 169, pp 1–129. https://doi.org/10.1007/978-1-4020-2550-1_1.

42. Chang, H.; Liu, Z.; Yang, S.; Gao, Y.; Shan, J.; Liu, B.; Sun, J.; Chen, Z.; Yan, J.; Liu, Z.; Wang, J.; Gao, P.; Li, J.; Liu, Z.; Wei, T. Graphene-Driving Strain Engineering to Enable Strain-Free Epitaxy of AlN Film for Deep Ultraviolet Light-Emitting Diode. Light Sci Appl 2022, 11 (1), 88. https://doi.org/10.1038/s41377-022-00756-1.

43. Qin, Y.; Albano, B.; Spencer, J.; Lundh, J. S.; Wang, B.; Buttay, C.; Tadjer, M.; DiMarino, C.; Zhang, Y. Thermal Management and Packaging of Wide and Ultra-Wide Bandgap Power Devices: A Review and Perspective. J. Phys. D: Appl. Phys. 2023, 56 (9), 093001. https://doi.org/10.1088/1361-6463/acb4ff.

44. Sheng, P.; Nie, G.; Li, Y.; Wang, L.; Chen, J.; Deng, X.; Wu, S. Enhanced Curing Behavior, Mechanical and Thermal Properties of 3D Printed Aluminum Nitride Ceramics Using a Powder Coating Strategy. Additive Manufacturing 2023, 74, 103732. https://doi.org/10.1016/j.addma.2023.103732.

45. Bahru, R.; Zamri, M. F. M. A.; Shamsuddin, A. H.; Shaari, N.; Mohamed, M. A. A Review of Thermal Interface Material Fabrication Method toward Enhancing Heat Dissipation. Int J Energy Res 2021, 45 (3), 3548–3568. https://doi.org/10.1002/er.6078.

46. Orville, T.; Tajwar, M.; Bihani, R.; Saha, P.; Hannan, M. A. Enhancing Thermal Efficiency in Power Electronics: A Review of Advanced Materials and Cooling Methods. Thermo 2025, 5 (3), 30. https://doi.org/10.3390/thermo5030030.

47. Huang, Y.; Li, Y.; Xiang, D. A Review of Recent Research Advances on AlGaN-Based Deep Ultraviolet Light-Emitting Diodes. IEEE Access 2024, 12, 131188–131204. https://doi.org/10.1109/ACCESS.2023.3348273.

48. Rigutti, L.; Jacopin, G.; Largeau, L.; Galopin, E.; De Luna Bugallo, A.; Julien, F. H.; Harmand, J.-C.; Glas, F.; Tchernycheva, M. Correlation of Optical and Structural Properties of GaN/AlN Core-Shell Nanowires. Phys. Rev. B 2011, 83 (15), 155320. https://doi.org/10.1103/PhysRevB.83.155320.

49. Xia, S.; Liu, L.; Kong, Y.; Wang, M. Uniaxial Strain Effects on the Optoelectronic Properties of GaN Nanowires. Superlattices and Microstructures 2016, 97, 327–334. https://doi.org/10.1016/j.spmi.2016.06.040.

50. Car, T.; Nekić, N.; Jerčinović, M.; Salamon, K.; Bogdanović-Radović, I.; Marion, I. D.; Dasović, J.; Dražić, G.; Ivanda, M.; Bernstorff, S.; Pivac, B.; Kralj, M.; Radić, N.; Buljan, M. Closely Packed Ge Quantum Dots in ITO Matrix: Influence of Ge Crystallization on Optical and Electrical Properties. Mater. Res. Express 2016, 3 (6), 065003. https://doi.org/10.1088/2053-1591/3/6/065003.

51. Huang, P.; Shi, J.; Wang, P.; Zhang, M.; Ding, Y.; Wu, M.; Lu, J.; Wang, X. Origin of the Wide Band Gap from 0.6 to 2.3 eV in Photovoltaic Material InN: Quantum Confinement from Surface Nanostructure. J. Mater. Chem. A 2016, 4 (44), 17412–17418. https://doi.org/10.1039/C6TA07700E.

52. Lu, Y.; Guo, Y.; Liu, Z.; Yan, J.; Wang, J.; Li, J.; Li, X. Monolithic Integration of Deep Ultraviolet and Visible Light-Emitting Diodes for Radiative Sterilization Application. Applied Physics Letters 2024, 124 (11), 111102. https://doi.org/10.1063/5.0180411.
53. Jiang, K.; Liang, S.; Sun, X.; Ben, J.; Qu, L.; Zhang, S.; Chen, Y.; Zheng, Y.; Lan, K.; Li, D.; Xu, K.; State Key Laboratory of Luminescence and Applications, Changchun Institute of Optics, China. Rapid Inactivation of Human Respiratory RNA Viruses by Deep Ultraviolet Irradiation from Light-Emitting Diodes on a High-Temperature-Annealed AlN/Sapphire Template. OEA 2023, 6 (9), 230004–230004. https://doi.org/10.29026/oea.2023.230004.
54. Toropov, A. A.; Evropeitsev, E. A.; Nestoklon, M. O.; Smirnov, D. S.; Shubina, T. V.; Kaibyshev, V. Kh.; Budkin, G. V.; Jmerik, V. N.; Nechaev, D. V.; Rouvimov, S.; Ivanov, S. V.; Gil, B. Strongly Confined Excitons in GaN/AlN Nanostructures with Atomically Thin GaN Layers for Efficient Light Emission in Deep-Ultraviolet. Nano Lett. 2020, 20 (1), 158–165. https://doi.org/10.1021/acs.nanolett.9b03517.
55. Li, J.; Gao, N.; Cai, D.; Lin, W.; Huang, K.; Li, S.; Kang, J. Multiple Fields Manipulation on Nitride Material Structures in Ultraviolet Light-Emitting Diodes. Light Sci Appl 2021, 10 (1), 129. https://doi.org/10.1038/s41377-021-00563-0.
56. Lu, S.; Jiang, X.; Wang, Y.; Huang, K.; Gao, N.; Cai, D.; Zhou, Y.; Yang, C. C.; Kang, J.; Zhang, R. Enhancing Deep-UV Emission at 234 Nm by Introducing a Truncated Pyramid AlN/GaN Nanostructure with Fine-Tuned Multiple Facets. Nanoscale 2022, 14 (3), 653–662. https://doi.org/10.1039/D1NR06188G.
57. He, C.; Wu, H.; Zhang, K.; Liu, Y.; Wang, Q.; He, L.; Li, Q.; Dong, B.; Zhang, S.; Zhao, W.; Chen, Z.; Shen, B. Efficient Deep Ultraviolet Emission from Self-Organized AlGaN Quantum Wire Array Grown On Ultrathin Step-Bunched AlN Templates. Crystal Growth & Design 2024, 24 (4), 1551–1559. https://doi.org/10.1021/acs.cgd.3c00990.
58. Chen, Q.; Xu, X.; Bo, Z. Application of n-Type or p-Type Dopants in Organic Photovoltaics. ChemSusChem 2025, 18 (10), e202402525. https://doi.org/10.1002/cssc.202402525.
59. Xia, J.; Sohail, M.; Nazeeruddin, M. K. Efficient and Stable Perovskite Solar Cells by Tailoring of Interfaces. Advanced Materials 2023, 35 (31), 2211324. https://doi.org/10.1002/adma.202211324.
60. Shatalov, M.; Sun, W.; Lunev, A.; Hu, X.; Dobrinsky, A.; Bilenko, Y.; Yang, J.; Shur, M.; Gaska, R.; Moe, C.; Garrett, G.; Wraback, M. 278 Nm Deep Ultraviolet LEDs with 11% External Quantum Efficiency. In 70th Device Research Conference; IEEE: University Park, PA, USA, 2012; pp 255–256. https://doi.org/10.1109/DRC.2012.6257013.
61. Pandey, A.; Gim, J.; Hovden, R.; Mi, Z. An AlGaN Tunnel Junction Light Emitting Diode Operating at 255 Nm. Applied Physics Letters 2020, 117 (24), 241101. https://doi.org/10.1063/5.0036286.
62. Ayub, K.; Khan, B.; Liu, Y.; Nawaz Sharif, M.; Ajmal Khan, M.; Hirayama, H. Achieving Zero Efficiency Droop in Highly Efficient N-Polar AlGaN Tunnel Junction-Based 254 Nm DUV LED. Optics & Laser Technology 2025, 180, 111567. https://doi.org/10.1016/j.optlastec.2024.111567.
63. Park, J.; Pristovsek, M.; Cai, W.; Cheong, H.; Tanaka, A.; Furusawa, Y.; Han, D.; Seong, T.; Amano, H.

Impact of Sidewall Conditions on Internal Quantum Efficiency and Light Extraction Efficiency of Micro-LEDs. Advanced Optical Materials 2023, 11 (10), 2203128. https://doi.org/10.1002/adom.202203128.

64. Xu, X.; Liang, H.-P.; Huang, Q.-S.; Liu, Z.; Zhao, B.-Q.; Xu, S.-Y.; Li, C.-N.; Zhou, Z.-K.; Li, J.; Wei, S.-H.; Zhang, X. Computational Screening of Promising Deep-Ultraviolet Light Emitters. J. Am. Chem. Soc. 2024, 146 (18), 12864–12876. https://doi.org/10.1021/jacs.4c03711.

65. Lin, C.-H.; Lee, C.-T. Ga2O3-Based Solar-Blind Deep Ultraviolet Light-Emitting Diodes. Journal of Luminescence 2020, 224, 117326. https://doi.org/10.1016/j.jlumin.2020.117326.

66. Afandi, M. M.; Kim, J. DUV Electroluminescence from Bi3+-Doped Bi-Phase Yttrium Phosphate. Optical Materials 2024, 156, 115960. https://doi.org/10.1016/j.optmat.2024.115960.

67. Rojas-Hernandez, R. E.; Rubio-Marcos, F.; Romet, I.; Del Campo, A.; Gorni, G.; Hussainova, I.; Fernandez, J. F.; Nagirnyi, V. Deep-Ultraviolet Emitter: Rare-Earth-Free ZnAl2 O4 Nanofibers via a Simple Wet Chemical Route. Inorg. Chem. 2022, 61 (30), 11886–11896. https://doi.org/10.1021/acs.inorgchem.2c01646.

68. Lv, X.; Liang, Y.; Zhang, Y.; Chen, D.; Shan, X.; Wang, X.-J. Deep-Trap Ultraviolet Persistent Phosphor for Advanced Optical Storage Application in Bright Environments. Light Sci Appl 2024, 13 (1), 253. https://doi.org/10.1038/s41377-024-01533-y.

69. Yang, Y.-M.; Li, Z.-Y.; Zhang, J.-Y.; Lu, Y.; Guo, S.-Q.; Zhao, Q.; Wang, X.; Yong, Z.-J.; Li, H.; Ma, J.-P.; Kuroiwa, Y.; Moriyoshi, C.; Hu, L.-L.; Zhang, L.-Y.; Zheng, L.-R.; Sun, H.-T. X-Ray-Activated Long Persistent Phosphors Featuring Strong UVC Afterglow Emissions. Light Sci Appl 2018, 7 (1), 88. https://doi.org/10.1038/s41377-018-0089-7.

70. Wang, S.; Wu, Z.; Sun, L.; Ren, J.; Zheng, X.; Zhang, J.; Ren, J. UV-C Emitting Phosphors of Pr3+ -Doped Fluoroborate Nano-Glass Composites for Disinfection and as Fast Scintillators. J. Mater. Chem. C 2025, 13 (12), 6302–6308. https://doi.org/10.1039/D4TC04607B.

71. Peng, X.; Guo, W.; Xu, H.; Chen, L.; Yang, Z.; Xu, L.; Liu, J.; Tang, K.; Guo, C.; Yan, L.; Guo, S.; Chen, C.; Ye, J. Significantly Boosted External Quantum Efficiency of AlGaN-Based DUV-LED Utilizing Thermal Annealed Ni/Al Reflective Electrodes. Appl. Phys. Express 2021, 14 (7), 072005. https://doi.org/10.35848/1882-0786/ac0b07.

72. Hu, C.; Cheng, M.; Jin, W.; Han, J.; Yang, Z.; Pan, S. A Cation-Driven Approach toward Deep-Ultraviolet Nonlinear Optical Materials. Research (Wash D C) 2023, 6, 0053. https://doi.org/10.34133/research.0053.

73. Zhang, Q.; An, R.; Long, X.; Yang, Z.; Pan, S.; Yang, Y. Exploiting Deep-Ultraviolet Nonlinear Optical Material Rb2 ScB3 O6 F2 Originated from Congruously Oriented [B3 O6] Groups. Angew Chem Int Ed 2025, 64 (2), e202415066. https://doi.org/10.1002/anie.202415066.

74. Tran, T. T.; Yu, H.; Rondinelli, J. M.; Poeppelmeier, K. R.; Halasyamani, P. S. Deep Ultraviolet Nonlinear Optical Materials. Chem. Mater. 2016, 28 (15), 5238–5258. https://doi.org/10.1021/acs.chemmater.6b02366.

75. Kang, L.; Lin, Z. Deep-Ultraviolet Nonlinear Optical Crystals: Concept Development and Materials Discovery. Light Sci Appl 2022, 11 (1), 201. https://doi.org/10.1038/s41377-022-00899-1.

76. Liu, X.; Yang, Z.; Pan, S. A Perspective on Deep-Ultraviolet Nonlinear Optical Materials. Journal of Applied Physics 2024, 135 (12), 120902. https://doi.org/10.1063/5.0195432.

77. Xu, R.; Kang, Q.; Zhang, Y.; Zhang, X.; Zhang, Z. Research Progress of AlGaN-Based Deep Ultraviolet Light-Emitting Diodes. Micromachines 2023, 14 (4), 844. https://doi.org/10.3390/mi14040844.

78. Maraj, M.; Min, L.; Sun, W. Reliability Analysis of AlGaN-Based Deep UV-LEDs. Nanomaterials (Basel) 2022, 12 (21), 3731. https://doi.org/10.3390/nano12213731.

79. Feng, F.; Liu, Y.; Zhang, K.; Yang, H.; Hyun, B.-R.; Xu, K.; Kwok, H.-S.; Liu, Z. High-Power AlGaN Deep-Ultraviolet Micro-Light-Emitting Diode Displays for Maskless Photolithography. Nat. Photon. 2025, 19 (1), 101–108. https://doi.org/10.1038/s41566-024-01551-7.

80. Mondal, R. K.; Adhikari, S.; Chatterjee, V.; Pal, S. Recent Advances and Challenges in AlGaN-Based Ultra-Violet Light Emitting Diode Technologies. Materials Research Bulletin 2021, 140, 111258. https://doi.org/10.1016/j.materresbull.2021.111258.

81. Xiong, P.; Peng, M. (INVITED) Recent Advances in Ultraviolet Persistent Phosphors. Optical Materials: X 2019, 2, 100022. https://doi.org/10.1016/j.omx.2019.100022.

82. Lin, R.; Liu, Z.; Han, P.; Lin, R.; Lu, Y.; Cao, H.; Tang, X.; Wang, C.; Khandelwal, V.; Zhang, X.; Li, X. A Machine Learning Study on Superlattice Electron Blocking Layer Design for AlGaN Deep Ultraviolet Light-Emitting Diodes Using the Stacked XGBoost/LightGBM Algorithm. J. Mater. Chem. C 2022, 10 (46), 17602–17610. https://doi.org/10.1039/D2TC02335K.

83. Yin, Y.; Wang, A.; Sun, Z.; Xin, C.; Jin, G. Machine Learning Regression Model for Predicting the Band Gap of Multi-Elements Nonlinear Optical Crystals. Computational Materials Science 2024, 242, 113109. https://doi.org/10.1016/j.commatsci.2024.113109.

84. Qayyum, F.; Khan, M. A.; Kim, D.-H.; Ko, H.; Ryu, G.-A. Explainable AI for Material Property Prediction Based on Energy Cloud: A Shapley-Driven Approach. Materials 2023, 16 (23), 7322. https://doi.org/10.3390/ma16237322.

85. Saqr, A. E.-S.; Saraya, M. S.; El-Kenawy, E.-S. M. Enhancing CO2 Emissions Prediction for Electric Vehicles Using Greylag Goose Optimization and Machine Learning. Sci Rep 2025, 15 (1), 16612. https://doi.org/10.1038/s41598-025-99472-0.

SRI SATHYA SAI UNIVERSITY FOR HUMAN EXCELLENCE

योगः कर्मसु कौशलम्