Bright Future of Deep-Ultraviolet Photonics: *Emerging UVC Chip-Scale Light Source Technology Platforms, Benchmarking, Challenges and Outlook for UV-disinfection*

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Abstract

COVID-19 pandemic has generated great interest in ultraviolet (UV) disinfection, particularly for air disinfection. Although UV disinfection was discovered close to 90 years ago, only very recently it has reached the consumers market and achieved much acceptance from the public starting 2000s. The UV light source of choice has been almost exclusively the low-pressure mercury vapour discharge lamp for this time. Today, however, with emerging deep-UV (DUV) chip-scale technologies, there has been a significant advancement, along with ever-increasing interest, in the development and deployment of disinfection systems employing compact devices that emit in the deep-UV spectral band (200-280 nm) including UV light-emitting diodes (LEDs) and cathodoluminescent (CL) chips. This perspective looks into competing UV technologies (including mercury lamps and excimer lamps as benchmarks) on their optical merits and demerits and discusses the emerging chip-scale technologies of DUV electroluminescent and cathodoluminescent devices, comparing them against the benchmarking and providing an overview of the challenges and prospects. The accelerating progress in chip-scale solutions for deep-UV light sources promises a bright future in UV-disinfection.

Keywords: *Mercury lamp, excimer lamp, UVC LEDs, cathodoluminescent chips, germicidal efficiency*

Introduction to ultraviolet disinfection

Ultraviolet (UV) radiation, which is an which is part of the electromagnetic spectrum, can be divided into three spectral bands comprising the UVA (320-400 nm), the UVB (280-320 nm), and the UVC band (200-280 nm), also commonly known as deep-UV (DUV) (**Fig. 1a**). UVA is nearly visible and is known to cause skin damage. Being a slightly shorter waveband, UVB is a major factor causing sunburn in the daylight and causing skin damage. Both UVA and UVB easily enter the earth's atmosphere and are present in daylight and harmful to our skin because of their long penetration depth into the human tissue (**Fig. 1b**). On the other hand, UVC wavelengths are blocked by ozone in the earth's atmosphere and are not present in sunlight at the surface of the earth, which means pathogens have not evolved defences against UVC radiation. Therefore, because of the germicidal effectiveness of the UVC wavelengths, this phenomenon is also known as ultraviolet germicidal irradiation (UVGI).[1] UVGI can destroy the ability of microorganisms to reproduce by causing photochemical changes in their nucleic acids, which destructively impairs reproducibility and thus render them inactive (inset of **Fig. 1a)**. All wavelengths in the UV range are known to cause some photochemical effects, high-energy photons in the UVC range are specifically damaging to cells because they are absorbed by DNA and RNA (DNA/RNA) as well as proteins (inset of **Fig. 1a)**. The germicidal effectiveness peaks at about 260-265 nm, which also corresponds to the peak of UV absorption for bacterial DNA/RNA (**Fig. 1a**).[1,2] So, technically any UV source emitting in the 260-265 nm band will be in principle more effective for disinfection. Spectral comparisons among various UVC light sources in reference to the standard absorption spectra of DNA/RNA (alternatively referred to as germicidal effectiveness curve (GEC)) and the absorption spectrum of proteins are shown in **Fig. 1c**.

Looking at **Fig. 1c**, low-pressure mercury lamps exhibit high germicidal effectiveness because they radiate the majority (about 85%) of their optical output at the wavelength of 254 nm, which is quite close to the peak of GEC (260-265 nm). Also, recently, excimer lamps have been becoming increasingly popular for their emission at 222 nm, which is considered to be safer because of their limited penetration depth in human tissue **(Fig. 1b).** The peak emission wavelength of UVC LEDs can be tuned by varying the Al concentration in $Al_xGa_{1-x}N$ and recently UVC LEDs emitting at 265 nm have been achieved, although at low-efficiency levels (~1-3%).[3–6] On the other hand, the emission spectrum generated by cathodoluminescent (CL) DUV chips can be wide, fully overlapping with the germicidal UVC range, and can be tuned to peak in the spectral band of 260-265 nm.

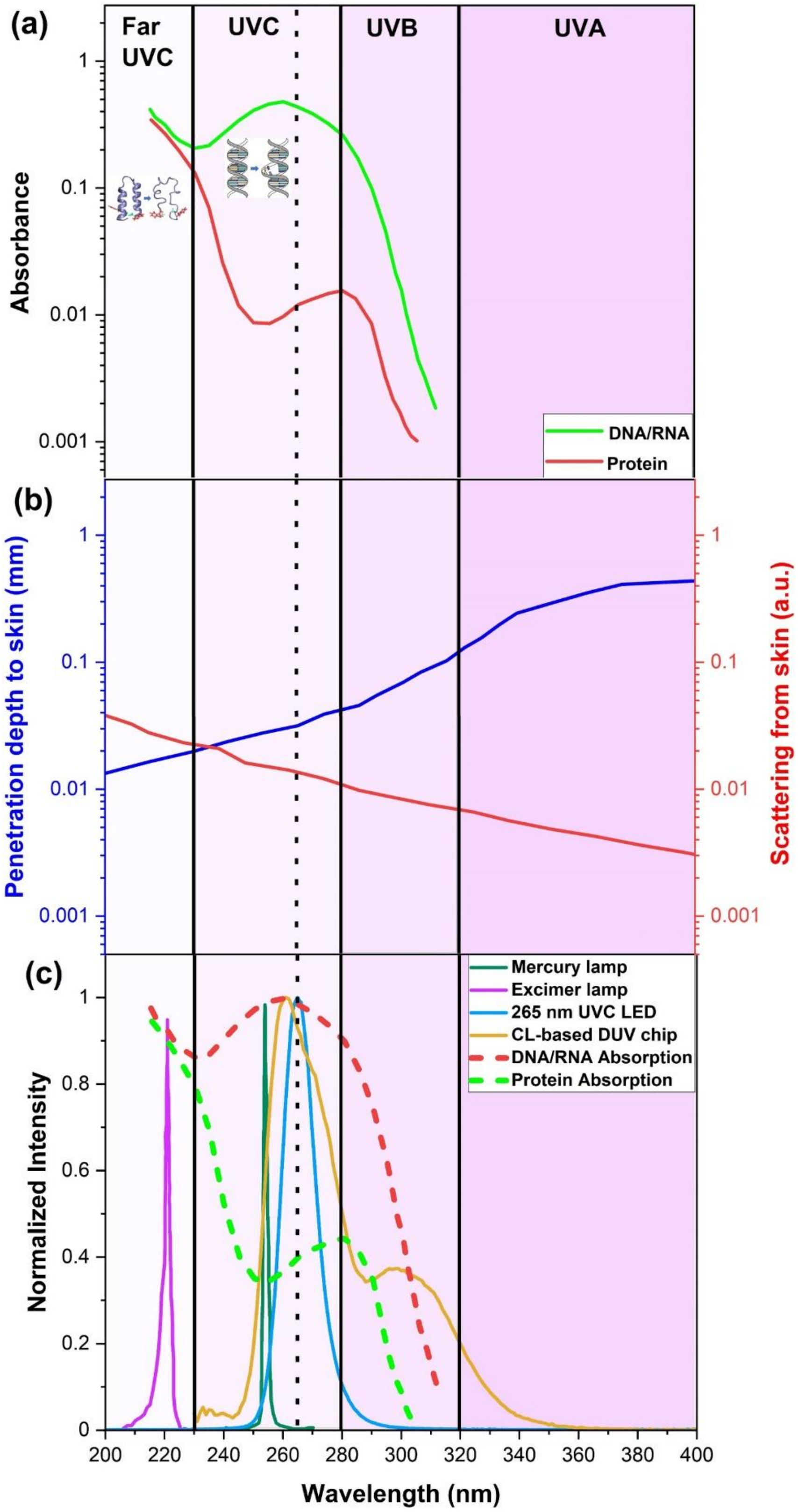

Fig. 1: (a) Standard absorption spectrum of DNA and RNA (also known as germicidal effectiveness curve) peaking at 265 nm (indicated by the dashed vertical line) along with the absorption spectrum of proteins, both increasing towards further shorter wavelengths .[1,2] (**b**) Penetration depth into the human skin and scattering from the human skin across the UV and its values at specific wavelengths of interest are ~18 µm (222 nm), ~27 µm (254 nm) and ~32 µm (265 nm).[7,8] **(c)** Comparison of various UVC lights sources with the standard absorption spectra of DNA/RNA and proteins.

Human skin is commonly divided into three layers: the top layer called epidermis, the middle layer called dermis and the bottom layer known as hypodermis. The stratum corneum is a dead skin layer on the top of the epidermis with a thickness of 10-20 µm.[7,8] The total thickness of the epidermis layer lies between 50-150 µm whereas the thickness of the dermis layer is around 1-4 mm.[7,8] It is clear from **Fig. 1**, that the 254-nm UVC range is mostly absorbed by the DNA/RNA, and it can penetrate deeper into the epidermis layer of human skin and damage the DNA in the skin cells which could, in turn, induce cancer. On the other hand, the 222-nm UVC range is highly absorbed by both proteins and DNA/RNA and will be mostly absorbed by the stratum corneum (dead layer) of the skin, which increases the effectiveness of the 222-nm UVC band compared to the 254-nm UVC against microbes. The germicidal efficiency is known to vary with wavelength and is described by the GEC peaking around 265 nm (denoted by the vertical dashed line in **Figs. 1a-c**). Also, because of the popularity of excimer lamps, the deep-UV wavelength range of 200 to 230 nm is further specified as the far-UVC.

Deep-ultraviolet light sources

The first scientific report on the germicidal effects of UV radiation was published in the year 1877.[9] By the year 1929, UV dosages required to disinfect various bacteria and fungus had been reported.[10–12] The 1930s saw the implementation of UV systems in hospital settings to control infections[13–16] and it had been acknowledged after 20 years that these systems were effective in disinfecting both air and surfaces. Although UVGI systems had been in use in hospitals for decades, only very recently, in 2003, the Centers for Disease Control and Prevention (CDC) formally endorsed that these systems could be used in hospitals under certain guidelines.[17] Low-pressure mercury (Hg) lamps have been exclusively used for disinfection purposes for over 90 years now and dominate the germicidal UV market today. However, now we observe growing health concerns associated with the use of toxic mercury and the Minamata Convention has been implemented across 128 countries to phase out completely or at least phase down Hg-based lamps for health and environment-related issues.[18] This has been strongly motivating the rapid development of various mercury-free DUV technologies for disinfection purposes. The promising DUV technologies include UVC LEDs, and CL-based DUV light chips, which are both chip-scale solutions, as well as excimer lamps, which are not chip-based and are indeed based on old technology but have been recently attracting interest for their far-UVC capability. Figure 2 directly compares the sizes of these different light sources and contains the schematics of all the DUV light sources discussed in this perspective.

We will discuss these technologies in the following sections along with their merits and demerits.

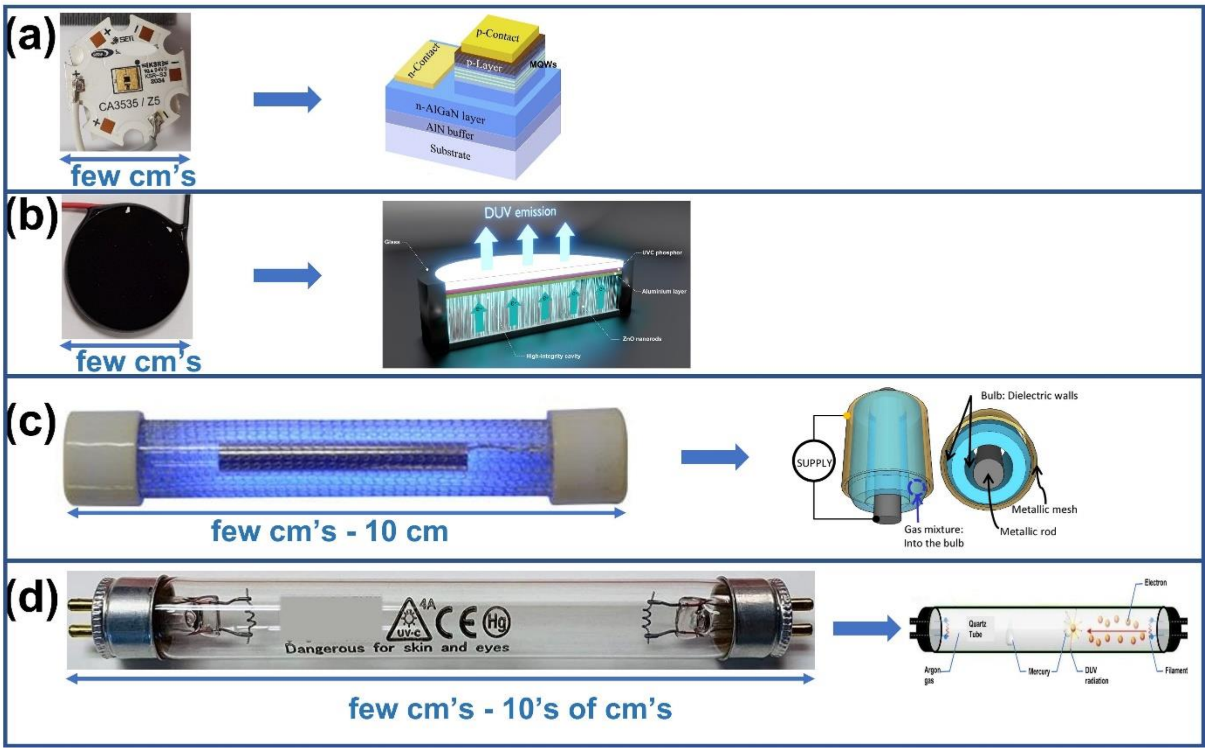

Fig. 2: Size comparison (on the same scale) and schematics of the (a) UVC LED[19] (Adapted with permission from ref 19. Copyright 2017 Elsevier), (b) CL-based DUV chip[20] (Reprinted with permission from ref 20. Copyright 2021 John Wiley and Sons) (c) excimer lamp[21] (Adapted with permission from ref 21. Copyright 2012 IEEE), and (d) mercury lamp[22] (Adapted with permission from ref 22. Copyright 2014 Elsevier).

Mercury lamps for benchmarking in deep-UV

Mercury lamps have enjoyed a monopoly in the disinfection market for over 90 years. They are often referred to as UV lamps or "amalgam" lamps. Their two most common types are medium-pressure (MP) and low-pressure (LP) mercury vapour lamps defined by the mercury gas pressure in them. MP UV lamps contain mercury gas at a pressure of ~ 1,000 torr whereas for LP UV lamps the pressure is ~10 torrs. MP UV lamps have a polychromatic emission pattern with an intense peak around ~365 nm. On the other hand, LP UV lamps have monochromatic emissions centred around 254 nm, as shown in **Fig. 1c**. Therefore, LP UV lamps found usage in disinfection since their emission is close to the peak of the germicidal curve. LP UV lamps consist of a UV-transmitting glass envelope, a pair of electrodes, and a mercury amalgam. The schematic of the standard LP mercury lamp is shown in **Fig. 2d**. The electric current provided by the ballast passes through the electrodes and heats the mercury vapour, which stimulates electronic transitions and causes UV emission. In the LP UV lamps, about 60% of the electrical input power is converted to light, of which about 85% occurs near 254 nm.[23] The typical efficiencies of the LP UV lamps are in the range of ~15-30% with a possibility of variation depending on ambient operating conditions..[24]

Mercury lamps have been the mainstream option for the DUV light sources for many years. However, these lamps contain mercury, which is highly toxic to humans and is environmentally harmful. Therefore, these light sources cannot be used safely in settings close to human end-consumers, for example, in healthcare facilities and public places. Besides, these lamps are undesirably large (tens of cm's) and suffer from long warm-up times (typically minutes) before radiating DUV, making them impractical in certain applications. The adverse effects of mercury on human health and the environment have also been acknowledged worldwide leading to the Minamata Convention on mercury.[18] In 2017, this convention came into force with a target to stop or reduce the use of mercury in existing processes, resulting in robust demand for alternative DUV light sources.

Excimer lamps as a far-UVC source

Excimer lamps are based on a mature technology whose origin goes back to the demonstration of the first excimer laser in the year 1970.[25,26] Excimer lamps found use in a large number of applications including substrate cleaning, UV curing, surface modification, material deposition, and water and air purification. More recently, after the implementation of the Minamata convention, excimer lamps are becoming increasingly popular as an alternative to mercury-based UV lamps.[27,28] Excimer lamps provide high-intensity far-UVC radiation generated by decaying excimer complexes formed in various nonequilibrium discharges.[25] The schematic of coaxial excimer dielectric barrier discharges (DBD) far-UVC lamp is shown in **Fig. 2c**. Different gas mixtures create different light frequencies; thus, the spectra of the excimer lamp are defined by the working excimer molecule. For example, an excimer lamp filled with a mixture of krypton (Kr) and chlorine (Cl) gas primarily makes 222-nm light when energized whereas Kr and Br together will emit at around 207 nm.

Excimer lamps are considered to be safer than mercury lamps because the far-UVC wavelength range has a very limited penetration depth in the human skin (See **Fig. 1b**). Nonetheless, this limited penetration is still much larger than the size of viruses and bacteria, therefore far-UVC light is as efficient in killing pathogens similar to conventional germicidal UV light.[29,30] However, far-UVC light because of the limited penetration, cannot reach or damage living cells in the human skin or the eye, in contrast to the conventional germicidal UV light, which can be a health hazard.[28,31,32] But, till now this claim has not been acknowledged by the governments or authorities worldwide and is still under debate. More research is needed to conclude that excimer lamps are safer than conventional UVC light sources. Also, there are a lot of unknowns about excimer lamps, especially in terms of their germicidal efficacy on different pathogens.

Emerging chip-scale UVC technologies

Electroluminescent devices: UVC LEDs

UV light-emitting diodes (LEDs) are compact environmental-friendly (mercury-free) solid-state light sources with many advantages over mercury lamps. A UVC LED can be deployed in places where space does not permit regular mercury lamps. This is a carefully engineered p-i-n junction that emits in the UV range when forward biased. The schematic of a typical UVC LED is shown in **Fig. 2a**. In principle, UV LED technology is based on the conventional LED technology used for general lighting. The DUV LEDs are built using the same basic material system of III-nitrides as the blue and near-UV LEDs, except that to shift the emission wavelength from the blue (typically 440-460 nm) towards the UV, In (indium) in InGaN must be replaced with increasing amounts by Al (aluminium) in AlGaN. Therefore, to make an LED operating in the DUV spectral region, a relatively large portion of Al must be used. The problem with Al is fundamentally challenging because Al is a smaller atom than In and will not have a good match in the crystal lattice. Therefore, this inherent mismatch leads to major lattice stress and inevitably to crystal defects, and difficulty in *p*-type doping, which in turn leads to a decrease in efficiency. By tuning the right Al concentration, UVC LEDs will emit at the optimum wavelength (~265 nm) for maximizing germicidal effectiveness as shown in **Fig. 1c**.

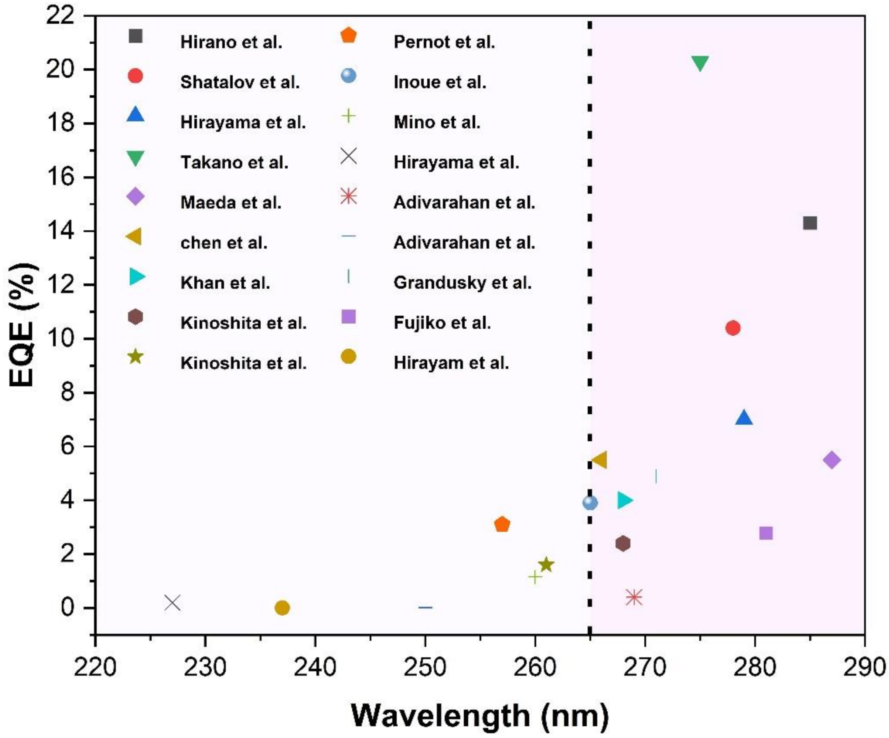

Fig 3: State-of-the-art EQE of UVC-LEDs.[33–51] The dashed vertical line shows the peak of the germicidal effectiveness curve, which serves as a reference for assessing EQE below and above this wavelength (265 nm).

The current benchmarks for UVC LEDs in terms of external quantum efficiency (EQE) are shown in **Fig. 3**. EQE is defined as the ratio of the number of photons emitted from the LED to the number of electrons passing through the device. In other words, EQE is the product of internal quantum efficiency (IQE), carrier injection efficiency (CIE) and light extraction efficiency (LEE). The maximum EQEs achieved for AlGaN-based LEDs is 20.3% at 275 nm.[44] The EQEs of commercially available AlGaN-based UVC-LEDs are much lower compared to the benchmarked GaN-based blue and green LEDs, which is caused by high dislocation densities (poor quality of AlGaN material), low hole concentrations (*p*-type doping problem in AlGaN), and low LEE. [3,6] Furthermore, we see an order of magnitude difference in the EQE of UVC LEDs below the peak of the germicidal effectiveness curve (265 nm) as seen in **Fig. 3**. The EQE drops sharply below 4% at wavelengths shorter than 265 nm (obtained by increased Al content) stemming from the deterioration in the crystalline quality of AlGaN material, the difficulty of *p*-type doping processes, and the degradation of TE mode polarization. *p*-type doping is a major technical problem in obtaining high-efficiency UVC LEDs at higher Al doping concentrations. A considerable research effort is being put in to improve the EQE of UVC LEDs and it is anticipated that high-efficiency UVC LEDs will be realized by mitigating the above difficulties.

Wall-plug efficiency (WPE) is another key performance parameter for UV LEDs. WPE corresponds to the ratio of the optical output power and the electrical input power and is expressed as[4,6]

$$WPE = \frac{P_{out}}{IV} = EQE * \eta_{el} \quad (1)$$

where η_{el} is the electrical efficiency, P_{out} is output optical power, I is operating current, and V is the operating voltage of the LED. WPE of UVC LEDs is further discussed for comparison in the last section of the paper.

Cathodoluminescent devices:

System-level electron-beam driven UVC light sources

One possible approach to overcome the troublesome nature of *p*-type doping processes in UVC LEDs and achieve DUV light emission is by using the electron-beam (EB) pumping technique. In EB-pumped DUV light sources, normally thermal electron-gun (e-gun) emitting via thermionic emission is used as electron emitters. However, recently because of the compactness of EB-pumped light sources for practical applications, the thermal e-gun is replaced with cold field emitters, which emit on the principle of field emission (via a quantum mechanical process known as quantum tunnelling). In both cases, the electrons are accelerated in a high vacuum by the applied electric field towards the anode. The anode can be AlGaN multiple quantum wells (MQWs) that generate DUV light when hit by these electrons (a photon emission process via excitation of high-energy electrons known as cathodoluminescence). Such EB-pumped UVC light sources are also called cathodoluminescent (CL) light sources. Compared with UVC-LEDs, EB-pumped DUV sources offers numerous advantages including (i) complete absence of a *p*-type layer in the structure, (ii) reduction in absorption of the emitted light because of a simple structure, and (iii) a basic thin film anode for epitaxial growth making it suitable for the mass fabrication. Besides AlGaN MQWs, various UVC phosphors have been investigated as potential anodes for EB-pumped DUV light sources.

The development history of EB-pumped DUV light sources is less than 10 years, but the progress made in the power conversion efficiency (PCE) is quite significant (**Fig. 4)**. The power conversion efficiency (PCE) is defined as output optical power to input electrical power and is expressed as[52]

$$PCE = \frac{P_{out}}{IV_A} = (\text{EQE}) * \eta_{eh} \quad (2)$$

where η_{eh} is the yield of converting irradiated electrons into electro-hole pairs, P_{out} is output optical power, I is irradiated current, and V_A is accelerating voltage of EB sources. The most remarkable result reported by Oto *et al.*[52] is the demonstration of 100 mW optical output with a PCE of ~40% from EB-pumped (e-gun) AlGaN/AlN MQWs emitting at ~240 nm operated inside a vacuum chamber. The authors attributed such high PCE to the strong carrier confinement provided by high-quality AlGaN/AlN QWs as well as to the appropriate design of the sample structure for EB excitation. Other than Ref[52], in most of the cases, however, the PCE reported is currently less than ~ 1% for all DUV wavelengths at the system level (**Fig. 4)**. Although the performance levels of such EB-pumped DUV light sources are progressing, many challenges still exist in the development of these light sources for practical applications. First, the size miniaturization of EB-driven DUV light sources is critical for many practical applications. More studies are needed using cold cathodes instead of thermal cathodes in this regard. Second, a requirement of a high vacuum to provide high-energy field emission electron sources raises the difficulty at the system level. Third, to obtain high carrier injection efficiency, it is imperative to match the thickness of the MQW structure to the EB penetration depth. A lot of understanding has been developed on the relation between the EB-penetration depth and MQWs thickness in the last decade. The efficiencies of EB-pumped DUV light sources may surpass those of UVC LEDs and possibly of excimer lamps provided that other phosphors with high efficiencies are developed in the UVC wavelength range. The emission wavelength can be tuned in EB-pumped DUV light sources by changing the anode (the concentration of Al in AlGaN MQWs or the composition of UVC phosphor).

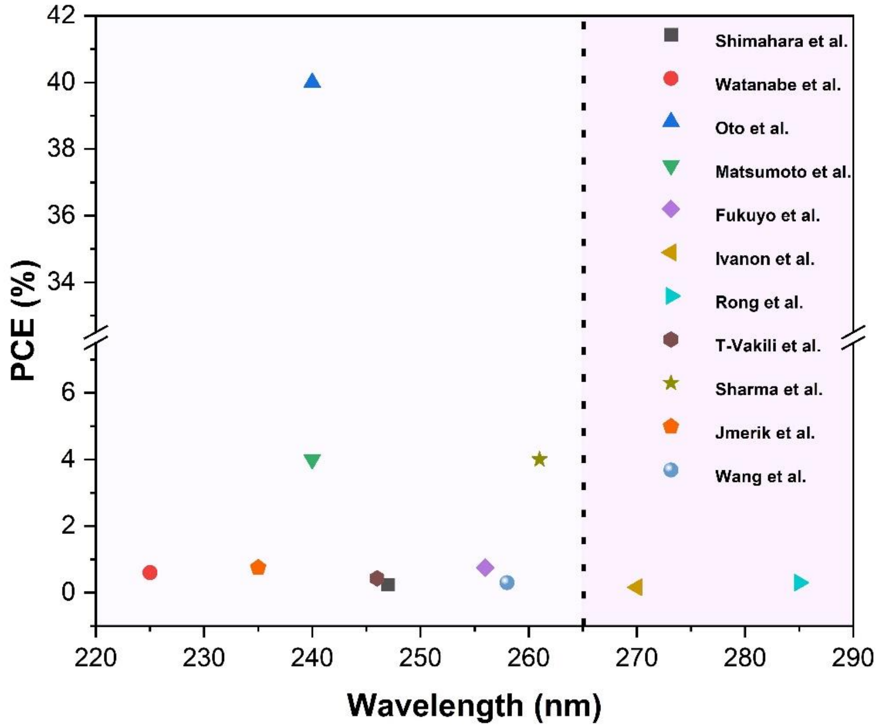

Fig. 4: State-of-the-art PCE of EB-driven DUV light sources.[20,52–61] The dashed vertical line denotes the peak of the germicidal effectiveness curve, which serves as a reference for evaluating PCE below and above this wavelength (265 nm).

Chip-scale integrated cathodoluminescent UVC light sources

For practical applications, in addition to the required high PCE, EB-pumped DUV light sources need to be made compact to compete with UVC LEDs.[3,62] The size miniaturization is the biggest challenge for CL-based DUV light sources. Therefore, in this section, we focus only on the compact packaged CL-based devices fabricated using field-emission cold cathodes (see **Table 1**). Watanabe *et al*.[54] reported a CL-device with a PCE of 0.6% using hexagonal boron nitride (hBN) far-ultraviolet (225 nm) fluorescent powders and Spindt field-emission array cold cathode. Matsumoto *et al*.[53] made a notable improvement in the PCE (~4%) by demonstrating a handheld device emitting at 240 nm with 20 mW power obtained by combining $Al_{0.7}Ga_{0.3}N$/AlN MQWs and graphene nanoneedle cold cathodes. Recently, our group has demonstrated DUV light chips emitting at 261 nm with an output power ≥20 mW at a PCE ~ 4% based on a novel chip-based architecture.[20] In this architecture as shown in **Fig. 2b**, the electron-emitter cold cathode and the DUV photon-emitter anode are integrated inside a compact, high-integrity sealed vacuum cavity for efficient field-emission from the cathode, resulting in efficient cathodoluminescence from the anode. The DUV chips after packaging are less than 30 mm (diameter) in size with 4 mm thickness (**Fig. 2b**), allowing complete design freedom like UVC LEDs. We also found that the performance of the chip remains similar under different temperature conditions (-20 to 80 ^{0}C), which will be useful for a variety of applications requiring operation at extreme temperatures or a large variation of temperature during operation (**Fig. 5a**). Additionally, the lifetime of the tested chips is ~500 hrs and is expected to be longer after further optimizations. (**Fig. 5b**). Moreover, we also found log 6 (99.9999%) germicidal efficacy using these DUV chips owing to the spectral overlap of the phosphor's CL spectrum and the standard germicidal effectiveness curve (GEC) (**Fig. 5c and 5d**). Such EB-driven DUV light sources is an emerging field giving tough competition to UVC LEDs. It is expected that, if the synthesis of UVC phosphors with high efficiency or growth of high-quality defect-free AlGaN/AlN MQWs is realized, the fabrication of compact EB-pumped DUV light sources with higher power and efficiencies will be rapidly developed.

Table 1: Compact packaged CL-based DUV devices fabricated using cold cathodes.

Cathode	Anode	EB Energy	Output Power (mW)	PCE (%)	Wavelength (nm)	Refs.
Spindt field-emission array	hBN powder	9.0 keV, 100 µA	0.2	0.6	225	[54]
Graphene nanoneedles	AlGaN quantum wells	7.5 keV, 80 µA	20	3-4	240	[53]
ZnO nanorods	UVC phosphor ($Lu_2Si_2O_7:Pr^{3+}$)	6.5 keV, 90 µA	20	4	261	[20]

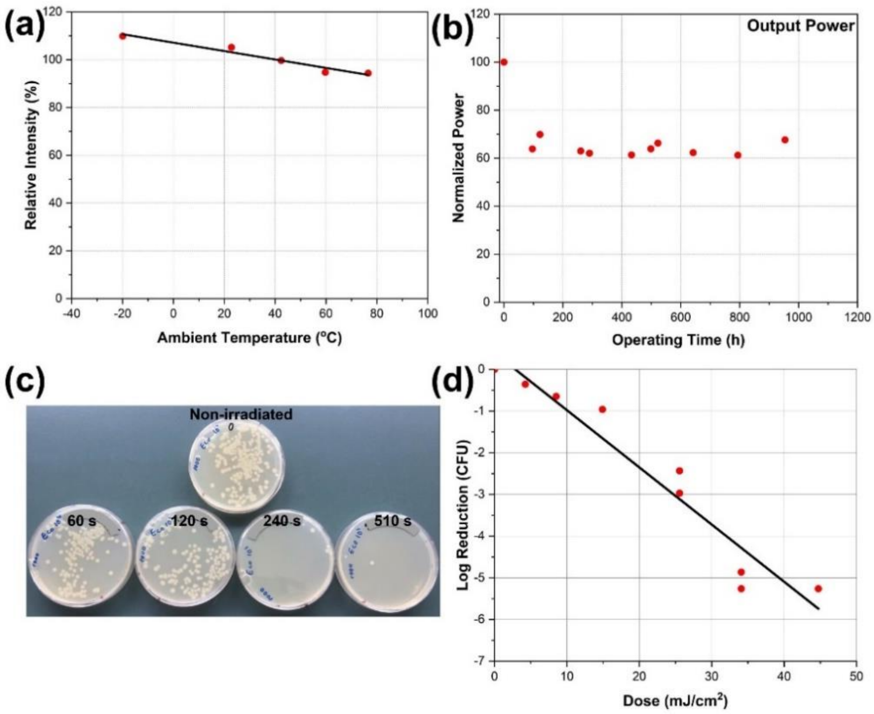

Fig. 5: Chip performance at varying operating (a) temperatures, b) time (lifetime test), c) E.coli bacteria before and after DUV irradiation, and d) log-reduction obtained for E.coli bacteria using these DUV chips.[20] (Adapted with permission from ref 20. Copyright 2021 John Wiley and Sons).

Comparison, Challenges & Future Prospects

All the DUV light sources have their own merits and demerits. Hence, choosing the right one depends on the competitiveness they offer over other UVC light sources in terms of compactness, efficiency, temperature stability, and germicidal efficacy. **Table 2** summarizes the comparison between the four different technologies (mercury lamps, excimer lamps, UVC LEDs, and CL-based DUV chips) discussed in this brief review. Although mercury lamps have several disadvantages, they still enjoy popularity in the market because of their availability. However, the deployment of mercury lamps must scale down because of the Minamata convention adopted by 128 countries throughout the world. So, the UVC LEDs, DUV chips and excimer lamps will play a bigger role in the future UV-disinfection market. UV-LEDs share the same platform as the III-nitride material system with blue LED technologies. Although AlGaN-based UVC LEDs with an impressive EQE of 20.3% at 275 nm are achieved, EQE drops drastically with decreasing wavelength resulting from multiple factors. Thus, there are still many challenges in the development of high-efficiency UVC LEDs. Nonetheless, there seems to be no fundamental blockade preventing the development of high-efficiency UVC LEDs and one can expect these LED's performance levels like InGaN-based blue LEDs soon.

Table 2: Competitive analysis of the existing state-of-the-art technologies: mercury lamps, excimer lamps, UVC LEDs and CL-based DUV chips.

Competitive analysis	Hg lamps (254 nm)	Excimer lamps (222 nm)	CL-based DUV chips (< 265 nm)	UVC LEDs (265 nm)
Technology	Mercury lamps	Kr-Cl gas	Field-emission (Cathodoluminescence)	AlGaN LEDs
Germicidal efficiency (log reduction)	Log 6 (99.9999 %)	Log 3 (99.9 %)	Log 6 (99.9999 %)	Log 3 (99.9 %)
Efficiency	~15-35 %	~5-15 %	~4-5 %	~1-3 %
Operational temperature range	20 to 60 °C	0 to 100 °C	-20 to 100 °C	0 to 80 °C
Instant On/OFF	No	Yes	Yes	Yes
Cost	High (Continues ON)	High (continues ON)	Low (Intermittent operation)	Low (Intermittent operation)
Environment friendly	No	Yes	Yes	Yes

Fig. 6 shows the WPE reported for UVC LEDs and PCE for CL-based DUV chips in the 240-280 nm emission bands and its prediction up to the year 2025. The 240-280 nm emission band is chosen because this range is considered the most effective for UV-based disinfection. By the definition of PCE and WPE, we can directly correlate the PCE of e-beam pumped DUV light sources with the WPE of UVC LEDs. The expected performance of UVC LEDs based on the trajectory of preceding developments is projected to reach WPE ~ 20% for 270-280 nm wavelength whereas for 240-270 nm band it is expected to reach WPE ~ 10% by

2025 (**Fig. 6**).[3,4,6] The main factors driving the WPE improvement will be the increased internal quantum efficiency, reduced operating voltages and enhanced light extraction. On the other hand, recently, EB-pumped DUV light sources (CL-based DUV chips) are making faster progress compared to UVC LEDs. EB-pumped AlGaN-based DUV light sources with an impressive WPE (PCE) of 40% have been demonstrated at a wavelength of 238 nm.[52] Interestingly, such high efficiency was not reported by any other research group, recently few researchers demonstrated portable light sources with efficiency levels as high as ~4-5% at wavelengths below 260 nm, which is relatively higher in comparison to UVC LEDs in this wavelength range.[20,53] Our recent report has also demonstrated that CL-based DUV chips possess an exceptional germicidal performance level of log 6 (99.9999%) as opposed to log 3 (99.9%) level for germicidal efficiency of UVC LEDs. The CL-based devices also provide instant ON/OFF, low-temperature dependence, and compactness offered by UVC LEDs.[20] It is expected that, if DUV phosphors with high efficiency are developed, CL-based DUV chips offer the potential to overtake UVC LEDs (**Fig. 6**).

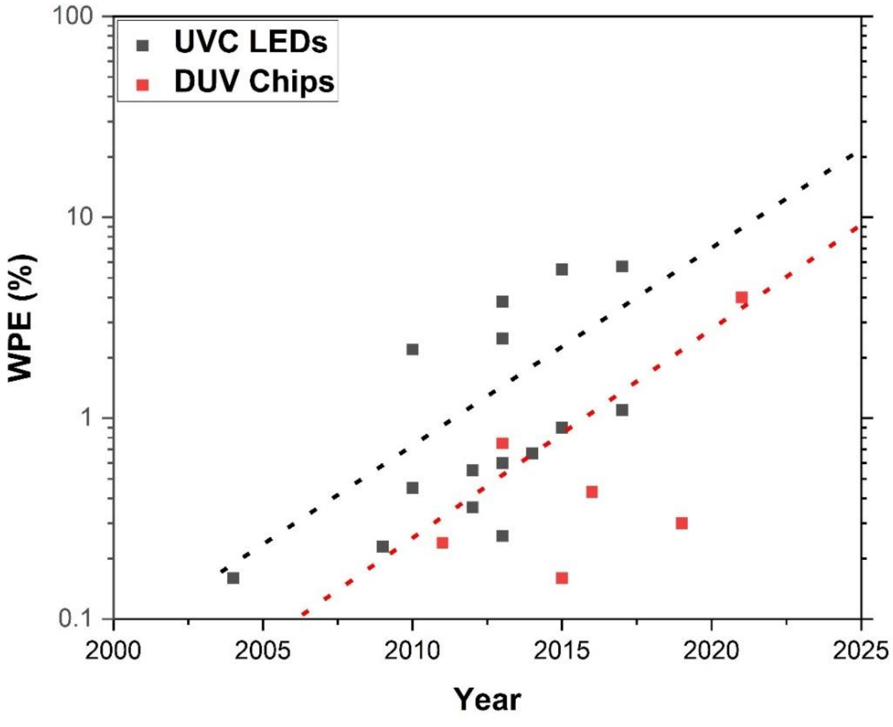

Fig. 6: WPE (PCE) of UVC LEDs and CL-based DUV chips for 240-280 nm UVC emission band. The dashed line provides an estimate of the WPE of UVC LEDs (black line) and CL-based DUV chips (red line) up to the year 2025.

Figure 6 also shows the WPE (PCE) reported for CL-based DUV chips in the 240-280 nm emission bands and is projected to rise to 10% by 2025. Especially for the 240-270 nm wavelength, currently, the EB-pumped DUV chips are having an edge over the UVC LEDs and offer higher performance as of date. Also, if efficient phosphors in the far-UVC range are developed, DUV chips possibly challenge the excimer lamps, too. However, further optimization and advancement in the device structure, fabrication, and high-efficiency UVC phosphor/defect-free AlGaN will be prerequisites to demonstrate further higher performance CL-based DUV devices for practical applications. Finally, excimer lamps are getting much attention nowadays because of their potential for safety when used in open spaces over the other DUV light sources, which allows them to be used in public places. However, a lot more research efforts both in terms of the germicidal efficacy and safety aspects are required before we use them freely in public settings.

Conclusions

In conclusion, although UVC LEDs offer the advantages of being mercury-free, compact, instant-ON, and low-cost, especially in the region of 260-265 nm, which is the most effective range for UV disinfection, the efficiency of these UVC LEDs is still low for practical applications.[4,6] CL-based DUV chips are in the initial stage of development, but the WPE (PCE) reported is already in the range of ~ 4-5% for the packaged chips for the wavelengths shorter than 265 nm. Additionally, these chips also offer similar features offered by UVC LEDs. Although excimer lamps emitting in far-UVC are based on mature technology, only recently it has been attracting much interest because of their potential for safety in human settings over other DUV light sources. Furthermore, studies are needed to evaluate their germicidal effectiveness on various pathogens. Overall, besides mercury lamps, all other technologies coexist in the market based on their competitiveness and trade-offs in terms of compactness, high efficiency, improved germicidal efficacy and wide operation temperature range, long operational lifetimes, and better safety aspects.

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Conflict of Interest

The authors declare no conflict of interest.

References:

(1) Kowalski, W. *Ultraviolet Germicidal Irradiation Handbook*; Springer Berlin Heidelberg: Berlin, Heidelberg, 2009. https://doi.org/10.1007/978-3-642-01999-9.

(2) Harm, W. *Biological Effects of Ultraviolet Radiation*; Cambridge University Press: United Kingdom, 1980.

(3) Li, D.; Jiang, K.; Sun, X.; Guo, C. AlGaN Photonics: Recent Advances in Materials and Ultraviolet Devices. *Adv. Opt. Photonics* **2018**, *10* (1), 43. https://doi.org/10.1364/aop.10.000043.

(4) Amano, H.; Collazo, R.; De Santi, C.; Einfeldt, S.; Funato, M.; Glaab, J.; Hagedorn, S.; Hirano, A.; Hirayama, H.; Ishii, R.; Kashima, Y.; Kawakami, Y.; Kirste, R.; Kneissl, M.; Martin, R.; Mehnke, F.; Meneghini, M.; Ougazzaden, A.; Parbrook, P. J.; Rajan, S.; Reddy, P.; Römer, F.; Ruschel, J.; Sarkar, B.; Scholz, F.; Schowalter, L. J.; Shields, P.; Sitar, Z.; Sulmoni, L.; Wang, T.; Wernicke, T.; Weyers, M.; Witzigmann, B.; Wu, Y. R.; Wunderer, T.; Zhang, Y. The 2020 UV Emitter Roadmap. *J. Phys. D. Appl. Phys.* **2020**, *53* (50). https://doi.org/10.1088/1361-6463/aba64c.

(5) Khan, A.; Balakrishnan, K.; Katona, T. Ultraviolet Light-Emitting Diodes Based on Group Three Nitrides. *Nat. Photonics* **2008**, *2* (2), 77–84. https://doi.org/10.1038/nphoton.2007.293.

(6) 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.

(7) Moan, J. Visible Light and UV Radiation. In *Radiation at home, outdoors and in the work place*; Dag Brune, Ragnar Hellborg, Bertil R. R. Persson, R. P., Ed.; Scandinavian Science Publisher, 2001; p 69.

(8) Finlayson, L.; Barnard, I. R. M.; McMillan, L.; Ibbotson, S. H.; Brown, C. T. A.; Eadie, E.; Wood, K. Depth Penetration of Light into Skin as a Function of Wavelength from 200 to 1000 Nm. *Photochem. Photobiol.* **2021**. https://doi.org/10.1111/php.13550.

(9) Downes, A.; Blunt, T. P. Researches on the Effect of Light upon Bacteria and Other Organisms. *Proc. R. Soc. London* **1877**, *26*, 488–500.

(10) Bedford, T. H. B. The Nature of the Action of Ultra-Violet Light on Micro-Organisms. *Br. J. Exp. Pathol.* **1927**, *8* (6), 437–441.

(11) Gates, F. L. A STUDY OF THE BACTERICIDAL ACTION OF ULTRA VIOLET

LIGHT. *J. Gen. Physiol.* **1929**, *13* (2), 231–248. https://doi.org/10.1085/jgp.13.2.231.

(12) Fulton, HR; Cobelentz, W. THE FUNGICIDAL ACTION OF ULTRA-VIOLET. *J. Agric. Res.* **1929**, *38* (3), 159.

(13) Kraissl, C. J.; Cimiotti, J. G.; Meleney, F. L. CONSIDERATIONS IN THE USE OF ULTRAVIOLET RADIATION IN OPERATING ROOMS. *Ann. Surg.* **1940**, *111* (2), 161–185. https://doi.org/10.1097/00000658-194002000-00001.

(14) Overholt, R. H.; Betts, R. H. A COMPARATIVE REPORT ON INFECTION OF THORACOPLASTY WOUNDS: Experiences With Ultraviolet Irradiation of Operating Room Air. *J. Thorac. Surg.* **1940**, *9* (5), 520–529. https://doi.org/https://doi.org/10.1016/S0096-5588(20)32260-1.

(15) HART, D.; SANGER, P. W. EFFECT ON WOUND HEALING OF BACTERICIDAL ULTRAVIOLET RADIATION FROM A SPECIAL UNIT: EXPERIMENTAL STUDY. *Arch. Surg.* **1939**, *38* (5), 797–805. https://doi.org/10.1001/archsurg.1939.01200110003001.

(16) ROBERTSON, E. C. AIR CONTAMINATION AND AIR STERILIZATION. *Arch. Pediatr. Adolesc. Med.* **1939**, *58* (5), 1023. https://doi.org/10.1001/archpedi.1939.01990100105010.

(17) Chinn, R. Y. W.; Sehulster, L. *Guidelines for Environmental Infection Control in Health-Care Facilities; Recommendations of CDC and Healthcare Infection Control Practices Advisory Committee (HICPAC)*; MMWR Recomm Rep. 52(RR-10):1-42., 2003.

(18) United Nations Environment Programme. Minamata Convention on Mercury. 2019, pp 1–72.

(19) Shatalov, M.; Jain, R.; Saxena, T.; Dobrinsky, A.; Shur, M. Development of Deep UV LEDs and Current Problems in Material and Device Technology. In *Semiconductors and Semimetals*; Elsevier Inc., 2017; Vol. 96, pp 45–83. https://doi.org/10.1016/bs.semsem.2016.08.002.

(20) Sharma, V. K.; Tan, S. T.; Haiyang, Z.; Shendre, S.; Baum, A.; Chalvet, F.; Tirén, J.; Demir, H. V. On-Chip Mercury-Free Deep-UV Light-Emitting Sources with Ultrahigh Germicidal Efficiency. *Adv. Opt. Mater.* **2021**, *9* (15), 1–7. https://doi.org/10.1002/adom.202100072.

(21) Florez, D.; Diez, R.; Hay, K.; Piquet, H. DBD Excimer Lamp Power Supply with Fully Controlled Operating Conditions. In *2012 13th International Conference on Optimization of Electrical and Electronic Equipment (OPTIM)*; IEEE, 2012; pp 1346–

1352. https://doi.org/10.1109/OPTIM.2012.6231836.

(22) Wu, Y.; Yin, X.; Zhang, Q.; Wang, W.; Mu, X. The Recycling of Rare Earths from Waste Tricolor Phosphors in Fluorescent Lamps: A Review of Processes and Technologies. *Resour. Conserv. Recycl.* **2014**, *88* (100), 21–31. https://doi.org/10.1016/j.resconrec.2014.04.007.

(23) Bergman, R. S. Germicidal UV Sources and Systems. *Photochem. Photobiol.* **2021**, *97* (3), 466–470. https://doi.org/10.1111/php.13387.

(24) Schalk, S.; Adam, V.; Arnold, E.; Brieden, K.; Voronov, A.; Witzke, H. UV-Lamps for Disinfection and Advanced Oxidation - Lamp Types, Technologies and Applications. **2005**, *8* (1), 32–37. https://doi.org/https://uvsolutionsmag.com/stories/pdf/archives/080103Schalk_Article_2006.pdf.

(25) Kogelschatz, U. Excimer Lamps: History, Discharge Physics, and Industrial Applications. In *Proc.SPIE*; Tarasenko, V. F., Ed.; 2004; Vol. 5483, pp 272–286. https://doi.org/10.1117/12.563006.

(26) Boyd, I. W.; Liaw, I. I. Development and Application of UV Excimer Lamps from 354nm -126nm. *High-Power Laser Ablation VI* **2006**, *6261* (June 2006), 626104. https://doi.org/10.1117/12.686233.

(27) Masoud, N. M.; Murnick, D. E. High Efficiency Fluorescent Excimer Lamps: An Alternative to Mercury Based UVC Lamps. *Rev. Sci. Instrum.* **2013**, *84* (12). https://doi.org/10.1063/1.4842296.

(28) Childress, J.; Roberts, J.; King, T. Disinfection with Far-UV (222 Nm Ultraviolet Light). *Boeing*. 2020, pp 1–6.

(29) Buonanno, M.; Welch, D.; Shuryak, I.; Brenner, D. J. Far-UVC Light (222 Nm) Efficiently and Safely Inactivates Airborne Human Coronaviruses. *Sci. Rep.* **2020**, *10* (1), 1–8. https://doi.org/10.1038/s41598-020-67211-2.

(30) Barnard, I. R. M.; Eadie, E.; Wood, K. Further Evidence That Far-UVC for Disinfection Is Unlikely to Cause Erythema or Pre-Mutagenic DNA Lesions in Skin. *Photodermatol. Photoimmunol. Photomed.* **2020**, *36* (6), 476–477. https://doi.org/10.1111/phpp.12580.

(31) Buonanno, M.; Ponnaiya, B.; Welch, D.; Stanislauskas, M.; Randers-Pehrson, G.; Smilenov, L.; Lowy, F. D.; Owens, D. M.; Brenner, D. J. Germicidal Efficacy and Mammalian Skin Safety of 222-Nm UV Light. *Radiat. Res.* **2017**, *187* (4), 483–491. https://doi.org/10.1667/RR0010CC.1.

(32) Yamano, N.; Kunisada, M.; Kaidzu, S.; Sugihara, K.; Nishiaki-Sawada, A.; Ohashi, H.; Yoshioka, A.; Igarashi, T.; Ohira, A.; Tanito, M.; Nishigori, C. Long-Term Effects of 222-Nm Ultraviolet Radiation C Sterilizing Lamps on Mice Susceptible to Ultraviolet Radiation. *Photochem. Photobiol.* **2020**, *96* (4), 853–862. https://doi.org/10.1111/php.13269.

(33) Hirayama, H. Growth Techniques of AlN/AlGaN and Development of High-Efficiency Deep-Ultraviolet Light-Emitting Diodes; Kneissl, M., Rass, J., Eds.; Springer International Publishing: Cham, 2016; pp 75–113. https://doi.org/10.1007/978-3-319-24100-5_4.

(34) Shatalov, M.; Sun, W.; Lunev, A.; Hu, X.; Dobrinsky, A.; Bilenko, Y.; Yang, J.; Shur, M.; Gaska, R.; Moe, C.; Garrett, G.; Wraback, M. AlGaN Deep-Ultraviolet Light-Emitting Diodes with External Quantum Efficiency above 10%. *Appl. Phys. Express* **2012**, *5* (8), 10–13. https://doi.org/10.1143/APEX.5.082101.

(35) Adivarahan, V.; Wu, S.; Zhang, J. P.; Chitnis, A.; Shatalov, M.; Mandavilli, V.; Gaska, R.; Khan, M. A. High-Efficiency 269 Nm Emission Deep Ultraviolet Light-Emitting Diodes. *Appl. Phys. Lett.* **2004**, *84* (23), 4762–4764. https://doi.org/10.1063/1.1756202.

(36) Mino, T.; Hirayama, H.; Takano, T.; Noguchi, N.; Tsubaki, K. Highly-Uniform 260 Nm-Band AlGaN-Based Deep-Ultraviolet Light-Emitting Diodes Developed by 2-Inch×3 MOVPE System. *Phys. status solidi* **2012**, *9* (3–4), 749–752. https://doi.org/10.1002/pssc.201100358.

(37) Hirayama, H.; Yatabe, T.; Noguchi, N.; Ohashi, T.; Kamata, N. 231-261 Nm AlGaN Deep-Ultraviolet Light-Emitting Diodes Fabricated on AlN Multilayer Buffers Grown by Ammonia Pulse-Flow Method on Sapphire. *Appl. Phys. Lett.* **2007**, *91* (7), 1–4. https://doi.org/10.1063/1.2770662.

(38) Hirayama, H.; Yatabe, T.; Noguchi, N.; Kamata, N. Development of 230-270 Nm AlGaN-Based Deep-UV LEDs. *Electron. Commun. Japan* **2010**, *93* (3), 24–33. https://doi.org/10.1002/ecj.10197.

(39) Hirano, A.; Nagasawa, Y.; Ippommatsu, M.; Aosaki, K.; Honda, Y.; Amano, H.; Akasaki, I. Development of AlGaN-Based Deep-Ultraviolet (DUV) LEDs Focusing on the Fluorine Resin Encapsulation and the Prospect of the Practical Applications. In *Proc. SPIE*; Lérondel, G., Kawata, S., Cho, Y.-H., Eds.; 2016; Vol. 9926, p 99260C. https://doi.org/10.1117/12.2235398.

(40) Maeda, N.; Hirayama, H. Realization of High-Efficiency Deep-UV LEDs Using

Transparent p-AlGaN Contact Layer. *Phys. Status Solidi Curr. Top. Solid State Phys.* **2013**, *10* (11), 1521–1524. https://doi.org/10.1002/pssc.201300278.

(41) Chen, J. (Jeff); Grandusky, J. R.; Moe, C. G.; Mendrick, M. C.; Jamil, M.; Gibb, S. R.; Schowalter, L. J. High Power Pseudomorphic Mid Ultraviolet Light Emitting Diodes with Improved Efficiency and Lifetime. In *Renewable Energy and the Environment*; OSA: Washington, D.C., 2013; p DM2E.2. https://doi.org/10.1364/SOLED.2013.DM2E.2.

(42) Khan, A. AlInGaN-Based Deep Ultraviolet Light-Emitting Diodes and Their Applications Technology. *2013 Int. Conf. Compd. Semicond. Manuf. Technol. CS MANTECH 2013* **2013**, 41–44.

(43) Inoue, S. I.; Tamari, N.; Taniguchi, M. 150 MW Deep-Ultraviolet Light-Emitting Diodes with Large-Area AlN Nanophotonic Light-Extraction Structure Emitting at 265 Nm. *Appl. Phys. Lett.* **2017**, *110* (14). https://doi.org/10.1063/1.4978855.

(44) Takano, T.; Mino, T.; Sakai, J.; Noguchi, N.; Tsubaki, K.; Hirayama, H. Deep-Ultraviolet Light-Emitting Diodes with External Quantum Efficiency Higher than 20% at 275 Nm Achieved by Improving Light-Extraction Efficiency. *Appl. Phys. Express* **2017**, *10* (3), 0–4. https://doi.org/10.7567/APEX.10.031002.

(45) Hirayama, H.; Maeda, N.; Fujikawa, S.; Toyoda, S.; Kamata, N. Recent Progress and Future Prospects of AlGaN-Based High-Efficiency Deep-Ultraviolet Light-Emitting Diodes. *Jpn. J. Appl. Phys.* **2014**, *53* (10), 100209.

(46) Grandusky, J. R.; Chen, J.; Gibb, S. R.; Mendrick, M. C.; Moe, C. G.; Rodak, L.; Garrett, G. A.; Wraback, M.; Schowalter, L. J. 270nm Pseudomorphic Ultraviolet Light-Emitting Diodes with over 60mW Continuous Wave Output Power. *Appl. Phys. Express* **2013**, *6* (3), 0–3. https://doi.org/10.7567/APEX.6.032101.

(47) Kinoshita, T.; Obata, T.; Nagashima, T.; Yanagi, H.; Moody, B.; Mita, S.; Inoue, S.; Kumagai, Y.; Koukitu, A.; Sitar, Z. Performance and Reliability of Deep-Ultraviolet Light-Emitting Diodes Fabricated on AlN Substrates Prepared by Hydride Vapor Phase Epitaxy. *Appl. Phys. Express* **2013**, *6* (9), 092103. https://doi.org/10.7567/APEX.6.092103.

(48) Kinoshita, T.; Hironaka, K.; Obata, T.; Nagashima, T.; Dalmau, R.; Schlesser, R.; Moody, B.; Xie, J.; Inoue, S. I.; Kumagai, Y.; Koukitu, A.; Sitar, Z. Deep-Ultraviolet Light-Emitting Diodes Fabricated on Aln Substrates Prepared by Hydride Vapor Phase Epitaxy. *Appl. Phys. Express* **2012**, *5* (12), 3–6. https://doi.org/10.1143/APEX.5.122101.

(49) Pernot, C.; Kim, M.; Fukahori, S.; Inazu, T.; Fujita, T.; Nagasawa, Y.; Hirano, A.; Ippommatsu, M.; Iwaya, M.; Kamiyama, S.; Akasaki, I.; Amano, H. Improved Efficiency of 255-280 Nm AlGaN-Based Light-Emitting Diodes. *Appl. Phys. Express* **2010**, *3* (6), 8–11. https://doi.org/10.1143/APEX.3.061004.

(50) Fujioka, A.; Misaki, T.; Murayama, T.; Narukawa, Y.; Mukai, T. Improvement in Output Power of 280-Nm Deep Ultraviolet Light-Emitting Diode by Using AIGaN Multi Quantum Wells. *Appl. Phys. Express* **2010**, *3* (4), 3–6. https://doi.org/10.1143/APEX.3.041001.

(51) Adivarahan, V.; Sun, W. H.; Chitnis, A.; Shatalov, M.; Wu, S.; Maruska, H. P.; Khan, M. A. 250nmAlGaN Light-Emitting Diodes. *Appl. Phys. Lett.* **2004**, *85* (12), 2175–2177. https://doi.org/10.1063/1.1796525.

(52) Oto, T.; Banal, R. G.; Kataoka, K.; Funato, M.; Kawakami, Y. 100 MW Deep-Ultraviolet Emission from Aluminium-Nitride-Based Quantum Wells Pumped by an Electron Beam. *Nat. Photonics* **2010**, *4* (11), 767–771. https://doi.org/10.1038/nphoton.2010.220.

(53) Matsumoto, T.; Iwayama, S.; Saito, T.; Kawakami, Y.; Kubo, F.; Amano, H. Handheld Deep Ultraviolet Emission Device Based on Aluminum Nitride Quantum Wells and Graphene Nanoneedle Field Emitters. *Opt. Express* **2012**, *20* (22), 24320. https://doi.org/10.1364/OE.20.024320.

(54) Watanabe, K.; Taniguchi, T.; Niiyama, T.; Miya, K.; Taniguchi, M. Far-Ultraviolet Plane-Emission Handheld Device Based on Hexagonal Boron Nitride. *Nat. Photonics* **2009**, *3* (10), 591–594. https://doi.org/10.1038/nphoton.2009.167.

(55) Fukuyo, F.; Ochiai, S.; Miyake, H.; Hiramatsu, K.; Yoshida, H.; Kobayashi, Y. Growth and Characterization of AlGaN Multiple Quantum Wells for Electron-Beam Target for Deep-Ultraviolet Light Sources. *Jpn. J. Appl. Phys.* **2013**, *52* (1 PART2), 2–5. https://doi.org/10.7567/JJAP.52.01AF03.

(56) Ivanov, S. V.; Jmerik, V. N.; Nechaev, D. V.; Kozlovsky, V. I.; Tiberi, M. D. E-Beam Pumped Mid-UV Sources Based on MBE-Grown AlGaN MQW. *Phys. Status Solidi Appl. Mater. Sci.* **2015**, *212* (5), 1011–1016. https://doi.org/10.1002/pssa.201431756.

(57) Rong, X.; Wang, X.; Ivanov, S. V.; Jiang, X.; Chen, G.; Wang, P.; Wang, W.; He, C.; Wang, T.; Schulz, T.; Albrecht, M.; Jmerik, V. N.; Toropov, A. A.; Ratnikov, V. V.; Kozlovsky, V. I.; Martovitsky, V. P.; Jin, P.; Xu, F.; Yang, X.; Qin, Z.; Ge, W.; Shi, J.; Shen, B. High-Output-Power Ultraviolet Light Source from Quasi-2D GaN Quantum Structure. *Adv. Mater.* **2016**, *28* (36), 7978–7983.

https://doi.org/10.1002/adma.201600990.

(58) Tabataba-Vakili, F.; Wunderer, T.; Kneissl, M.; Yang, Z.; Teepe, M.; Batres, M.; Feneberg, M.; Vancil, B.; Johnson, N. M. Dominance of Radiative Recombination from Electron-Beam-Pumped Deep-UV AlGaN Multi-Quantum-Well Heterostructures. *Appl. Phys. Lett.* **2016**, *109* (18). https://doi.org/10.1063/1.4967220.

(59) Wang, Y.; Rong, X.; Ivanov, S.; Jmerik, V.; Chen, Z.; Wang, H.; Wang, T.; Wang, P.; Jin, P.; Chen, Y.; Kozlovsky, V.; Sviridov, D.; Zverev, M.; Zhdanova, E.; Gamov, N.; Studenov, V.; Miyake, H.; Li, H.; Guo, S.; Yang, X.; Xu, F.; Yu, T.; Qin, Z.; Ge, W.; Shen, B.; Wang, X. Deep Ultraviolet Light Source from Ultrathin GaN/AlN MQW Structures with Output Power Over 2 Watt. *Adv. Opt. Mater.* **2019**, *7* (10), 1–7. https://doi.org/10.1002/adom.201801763.

(60) Jmerik, V. N.; Nechaev, D. V.; Toropov, A. A.; Evropeitsev, E. A.; Kozlovsky, V. I.; Martovitsky, V. P.; Rouvimov, S.; Ivanov, S. V. High-Efficiency Electron-Beam-Pumped Sub-240-Nm Ultraviolet Emitters Based on Ultra-Thin GaN/AlN Multiple Quantum Wells Grown by Plasma-Assisted Molecular-Beam Epitaxy on c-Al2O3. *Appl. Phys. Express* **2018**, *11* (9), 0–5. https://doi.org/10.7567/APEX.11.091003.

(61) Shimahara, Y.; Miyake, H.; Hiramatsu, K.; Fukuyo, F.; Okada, T.; Takaoka, H.; Yoshida, H. Fabrication of Deep-Ultraviolet-Light-Source Tube Using Si-Doped AlGaN. *Appl. Phys. Express* **2011**, *4* (4), 3–5. https://doi.org/10.1143/APEX.4.042103.

(62) Schubert, E. F.; Cho, J. Electron-Beam Excitation. *Nat. Photonics* **2010**, *4* (11), 735–736. https://doi.org/10.1038/nphoton.2010.254.