AlGaN Ultraviolet Micro-LEDs

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***Abstract*—AlGaN-based UV LEDs have proven to have broad applications in many fields including sterilization, disinfection, purification, and phototherapy, but the performance still needs to be further improved. Benefiting from advantages such as better current spreading, lower self-heating effect and higher light extraction efficiency achieved by the reduced LED size, UV micro-LEDs are expected to improve quantum efficiency and thus can expand more potential applications. In this article, performance enhancement techniques and applications of UV micro-LEDs will be reviewed, providing an outlook for further development of AlGaN-based UV-LEDs. The micro-LED format offers possibilities to address fundamental issues that UV LEDs confront in general, but also demonstrates specific characteristics and performance advantages opening up new areas of application including high-speed optical communication, time-resolved fluorescence lifetime measurement, optical pumping, direct writing and charge management.**

***Index Terms*—AlGaN UV micro-LED, optical communication, mask-free photolithography, time-resolved fluorescence detection, charge management.**

I. INTRODUCTION

ULTRAVIOLET (UV) light-emitting diodes (LEDs) play an important role in many applications such as sterilization, disinfection, purification, and phototherapy, and thus UV LEDs have attracted widespread attention. The global spread of COVID-19 infection has further fueled commitment to UV LED research because deep UV light is a very effective way to destroy viruses and bacteria. UV LEDs are generally categorized into UVA (320-400 nm), UVB (280-320 nm) and UVC (200-280 nm) devices according to their emission wavelengths [1]. Alternatively, they can be specified as deep UV (DUV, 200-300 nm) and near UV (NUV, 300-400 nm) LEDs [2]. UV light with a wavelength between 100 nm and 200 nm belongs to the vacuum ultraviolet (VUV) and is not currently accessible to LED technology. AlGaN-based materials are very suitable for the preparation of UV LEDs from 200-400 nm, however, because the bandgaps of GaN (3.4 eV) and AlN (6.2 eV) correspond to photon wavelengths in the NUV and DUV, respectively. By adjusting the Al component in the AlGaN-based alloy material, the emission wavelength can be continuously changed in the UV band, and the wavelength can be further extended to 400 nm by adding the In component, thus achieving full UV wavelength coverage. Other materials suitable in principle for UV LEDs include ZnO [3], Ga_2O_3 [4], and perovskite [5], although these have not yet demonstrated comparable performance to AlGaN-based UV LEDs. Of these, Ga_2O_3 has been widely used in DUV photodetectors, electroluminescent devices and chemical sensors due to its advantages such as direct wide bandgap, high breakdown electric field, and high electron saturation velocity, but the poor quality of n-type Ga_2O_3 films caused by undesirable oxygen vacancies and defects limits the fabrication of high-performance Ga_2O_3-based DUV-LEDs [4].

The improvement in the epitaxial quality of III-nitride compound semiconductor materials has laid a good foundation for the development of AlGaN LEDs with short emission wavelengths. Following Nakamura *et al.*'s achievement of high-efficiency blue InGaN LEDs [6] and the international development of the technology this engendered, AlGaN-based UV LEDs have also developed rapidly. However, even after a long period of development, UV LEDs, especially UVC LEDs, still suffer from the problems of large threading dislocation density (TDD), inferior p-doping and high transverse magnetic (TM) polarized emission, resulting in much lower quantum efficiency than that of InGaN blue LEDs [7]. Several reviews have been published focusing on improvement in UV LED performance, expansion of the applications of this technology, and exploration of fundamental characteristics and underlying mechanisms [8].

In recent years, so-called micro-LEDs with the size between 1-100 μm have attracted increasing attention, in particular driven by their applications in new forms of electronic visual display technology. Associated underpinning research has demonstrated that micro-LEDs also have a combination of advantageous performance characteristics compared to their larger area counterparts, including better current spreading, lower self-heating effect, higher modulation bandwidth, higher optical power density and higher light extraction efficiency due to the sidewall emission [9, 10]. These developments have motivated consideration of the potential advantages and applications of micro-LEDs operating in the UV. The micro-LED format offers possibilities to address fundamental issues that UV LEDs confront in general, but also offer specific characteristics and performance advantages opening up new areas of application.

In this review, we will focus on aspects of UV micro-LEDs those are expected to improve the low quantum efficiency and

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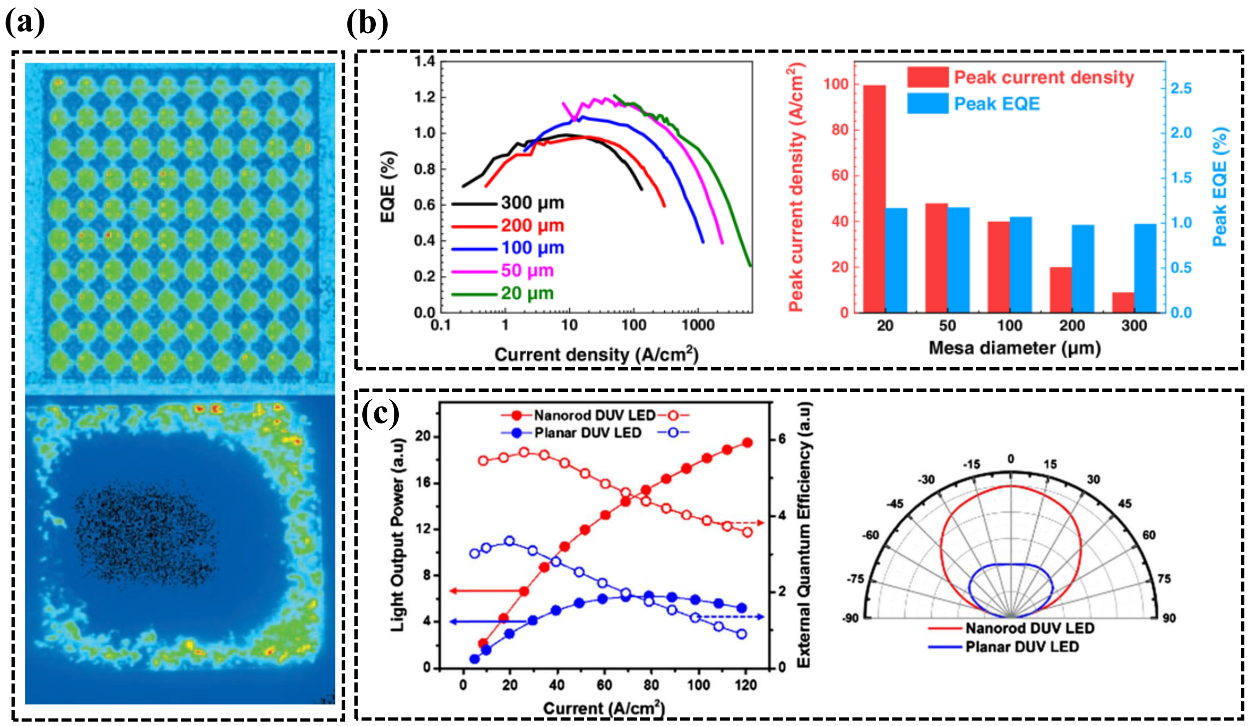


Fig. 1. (a) Images from a CCD of UV micro-LED and conventional LED [12]. (b) (Left) EQE against current density for the UVC LEDs with different sizes. (Right) Peak EQE and peak current density with different sizes [13]. (c) (Left) LOP and EQE against current density with nanorod and planar LED. (Right) Normalized angle-resolved electroluminescence spectra of nanorod and planar LEDs [14]. The figures reprinted with permissions from Refs. [12-14].

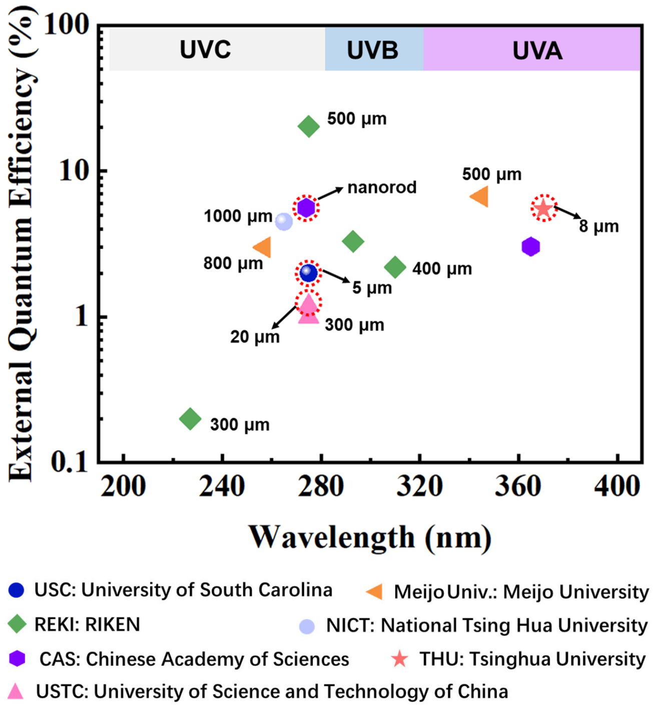


Fig. 2. EQEs of typical UV LEDs including conventional large size UV LEDs and UV micro-LEDs [13, 14, 18-27]. The sizes of the respective devices are given alongside the data points.

expand the application scenarios, and these will be described in detail below.

II. UV MICRO-LEDS

Due to the wide bandgap of AlGaN-based materials ranging from 3.4 to 6.2 eV which, as noted above, covers almost the entire UV spectral range (200–400 nm), AlGaN-based materials are ideally suitable materials for UV LEDs. In addition, compared with conventional UV light sources, AlGaN-based LEDs are expected to be suitable candidates in applications of UV radiation requiring advantages of tunable emission wavelength, low power consumption, long lifetime, environment friendliness and easy integration. However, the external quantum efficiency (EQE) of AlGaN based UV LEDs is still relatively low, especially at shorter wavelength (<365 nm). In recent years, many approaches have been proposed to improve the efficiency of the AlGaN based UV LED. Among these, several works have demonstrated that reducing the chip size to micro-scale could improve the efficiency of LEDs [11–15]. Adivarahan *et al*. reported that an interconnected micro-LED geometry could improve the current spreading in LEDs and reduce the device series resistance and thermal impedance, thereby increasing the maximum light output power [11]. As shown in Fig. 1(a), compared with a conventional UV LED which has a severe lateral current crowding effect, the UV interconnected micro-LED geometry has more uniform current spreading during continuous-wave operation [12]. Usually, in the case of the same overall device size and luminous area, the smaller the device size and the larger the pitch, the better the heat dissipation [16]. However some applications may impose practical constraints on the minimum size or pitch, for example to match the geometry of optics. Yu *et al*. investigated the size dependent optical and electrical properties of UVC AlGaN based LEDs, as shown in Fig. 1(b) [13]. As it is known, the TM polarized emission increases with the increase of Al-content in the active region. Increased TM polarized emission means that photons cannot be easily extracted from the light escape cone, and thus results in low light extraction efficiency (LEE) and EQE. The enhanced LEE for a smaller chip size of LED is attributed to an increase in the out-coupling of TM-polarized photons. In addition, Zhang *et al*. further scaled down the size to nano-scale, and demonstrated that the light output power (LOP) and EQE value of a 274-nm nanorod LED are ∼2.5 times larger than that of large-sized planar LED, as shown in Fig. 1(c) [14]. Fig. 1(c) also shows the optical beam divergence angles of the planar LED and nanorod LED. The larger divergence angle of the nanorod LED further suggests the larger photon vertical extraction by the nanorod LED. It is also worth noting that there have been reports of micro-LEDs comprised of nanowires. Liu et al. demonstrated a relative high EQE of $\sim 5.5\%$ for green nanowire micro-LEDs with device size of 3 μm owing to the efficient surface strain relaxation of nanowires [17], which may offer a viable path for promoting the efficiency of UV emitters. Hence, these studies all indicate that reducing the scale of UV LEDs can improve current spreading and suppress the lateral transport of carriers in MQWs, and is a promising route towards high efficiency UV emitters. In the following section, we will review the current status and challenges of UV micro-LEDs as well as recent techniques for improving the efficiency of UV micro-LEDs.

A. Current state of the art and challenges of UV micro-LEDs

The EQE, defined as the ratio of photons emitted escaping the device to the number of carriers injected into the device, is a key performance parameter of LEDs. Here we summarize the EQE of AlGaN micro-LEDs and conventional LEDs in the UV spectral range (200-400 nm), see Fig.2 [13, 14, 18–27]. To date, most researches mainly focus on the diverse applications of UV micro-LEDs, but relatively few works have investigated the improvement of EQE achievable with UV micro-LEDs. In the UVC band, researchers in University of Science and Technology of China (USTC) fabricated UV LEDs emitting at ∼275 nm with different sizes of 300, 200, 100, 50, and 20 μm and they found that the peak EQE of a 20 μm micro-LED with a value of 1.2%, increased by 20% compared to that of a 300 μm micro-LED [13]. Also, University of South Carolina (USC) has reported a 5 μm micro-LED with a record brightness of 570 $\mathrm{Wcm^{-2}}$ and the peak EQE is ∼2% [18]. At present, for a conventionally sized LED in the UVC region, RIKEN has reported a record high EQE of ∼20% for UVC LED emitting at 275 nm [20]. In the UVA band, researchers at Tsinghua University (THU) have fabricated a high resolution 960 × 540 UV micro-LED array with single pixel size of 8 μm and the peak EQE is 5.5% [19]. Many commercial UV LEDs in the UVA band (320-400 nm), especially in 365-400 nm region, have exhibited high performance. However, most UVB and UVC LEDs still have poor EQEs. Despite reducing the chip size being a powerful technique to increase the efficiency of UV LEDs, the EQE of UV micro-LEDs is still relatively low as shown in Fig. 2 and there is room for improvement.

There are a number of factors that limit the efficiency of UV micro-LEDs. Fig. 3 illustrates the technical challenges posed by every layer of a typical micro-LED structure. First, sapphire is usually used as the substrate for UV micro-LEDs as it is low-cost and transparent in the entire UV spectral region. However, the LEE of the substrate side will be limited due to the restricted extraction cone caused by the sapphire [28]. Secondly, the large lattice mismatch between a sapphire substrate and AlGaN results in a high TDD of the AlGaN layer. The insertion of single-crystal bulk AlN has been adopted for strain management to reduce the defect density in the AlGaN layer [29, 30]. To obtain low defect density AlN on a sapphire substrate, various approaches have been proposed, including hydride vapor phase epitaxy of AlN [31], migration-enhanced metal–organic chemical vapour deposition of AlN [32], and high-temperature metal-organic vapor phase epitaxy of AlN [33]. Nevertheless, the UV absorption of an AlN buffer layer which is induced by residual impurities such as oxygen, carbon and silicon in the AlN layer is still an issue [34]. Thirdly, it is difficult to obtain high n-type and p-type doping efficiencies of AlGaN due to the increasing ionization energies of Si donors and Mg acceptors with rich Al content, which further affects the performance of UV micro-LEDs [35]. The limitation of n-type doping of AlGaN results in high contact resistance and thereby high voltage operation and poor electrical efficiency. Plus the insufficient p-doping of AlGaN causes low hole concentration injected into the active region and therefore poor ohmic contacts. Several research groups have explored the solutions to improve the p-doping efficiency in AlGaN, containing the employment of Mg-doped superlattices [36], Mg-delta doping [37] and replacement of p-AlGaN with Mg-doped hexagonal-boron nitride [38]. Usually, a p-GaN layer has been grown on the top of p-AlGaN to provide better ohmic contact and improved supply of holes. However, the strong absorption of a p-GaN layer to UV light results in poor LEE. These factors are also challenges for conventional-size UV LEDs. In contrast to the conventional sized devices, the UV micro-LED with its micro-size mesa benefits the extraction of TM polarized emission thereby enhancing LEE. Furthermore, the UV micro-LED approach improves current spreading for effective thermal management as mentioned above. In counterpoint to the enhancement of LEE and thermal management in micro-LEDs , the decreased LED size allows carriers to more easily reach the mesa edges, resulting in significant surface nonradiative recombination and thus lower the efficiency at low current density [39]. Moreover, dry etching is usually employed to define the luminous region (active area) of a micro-LED which tends to result in many defects on the sidewall of the mesa, leading to more nonradiative recombination and lowering internal quantum efficiency (IQE) [10]. Therefore, a great deal of effort needs to be devoted to improve the UV micro-LED efficiency.

B. Techniques for improving UV micro-LED efficiency

To achieve effective light extraction, several researches have reported that the inclined mesa sidewall of UV LEDs could extract the strong TM-polarized in-plane emission in an

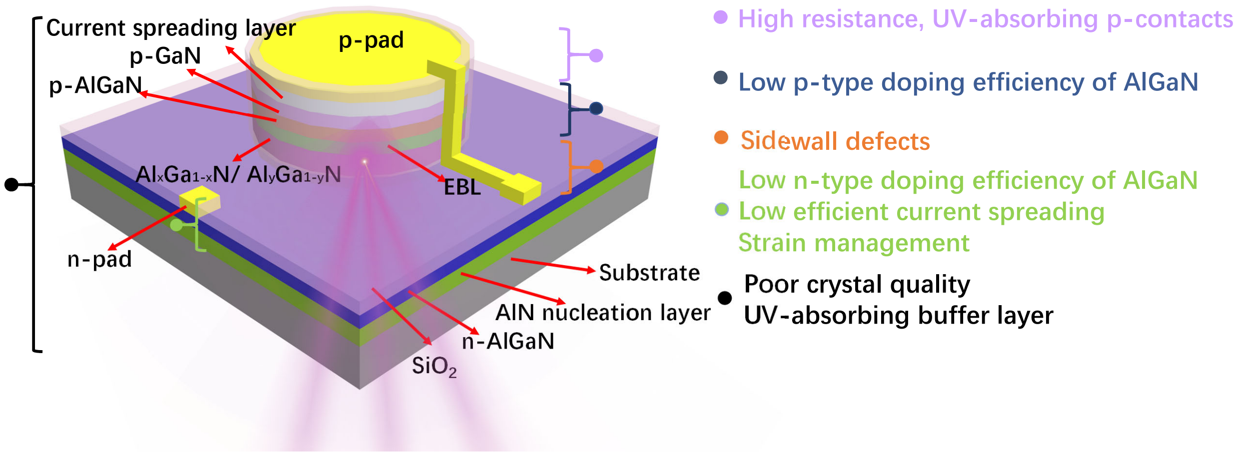


Fig. 3.

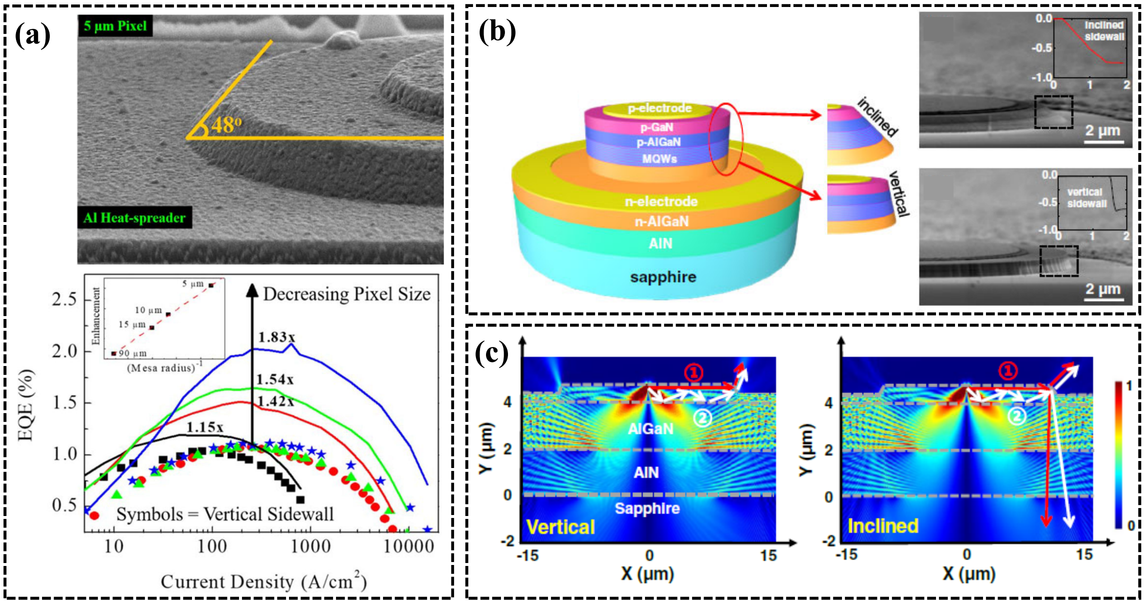


Fig. 4. The improvement of an inclined sidewall UV micro-LED in EQE and LEE, where (a) shows an SEM image of the inclined mesa sidewall with an Al_2O_3/Al coating together with EQE characteristics, (b) shows a structure schematic and SEM images of devices with inclined and vertical sidewalls, and (c) demonstrates the calculated normalized electric field distribution and light extraction pathways. The figures are reprinted with permissions from Refs. [18, 41].

isotropic manner and thus improve LEE, e.g. [40]. To improve the LEE of UV micro-LEDs, Floyd *et al*. investigated the size dependence of a truncated cone architecture for UVC micro-LEDs with chip sizes ranging from 5 to 15 μm [18]. They also explored the effect of an Al_2O_3/Al sidewall reflector on the performance of UVC micro-LEDs. From that work, the SEM image in Fig. 4(a) (top) shows the inclined mesa sidewall of a 5 μm micro-LED with a semi-reflective Al_2O_3/Al sidewall coating. Fig. 4(a) (bottom) demonstrates the associated EQE of different sized micro-LEDs with, respectively, a vertical and inclined sidewall mesa. It is clear that micro-LEDs with an inclined sidewall have higher EQE compared to those with a vertical sidewall. Also, the EQE enhancement of the inclined sidewall is dependent on the mesa size. The size-dependent enhancement is attributed to the shorter lateral absorption length which results in more out-coupling of TM-polarized emission and thereby improvement in the LEE of the device. In addition, the Al_2O_3/Al sidewall reflector could reduce the sidewall reflectivity and minimize self-heating effect to improve the LEE and LOP of the device. Also, Tian *et al*. explored the effect of different sidewall angles on the performance of UVC micro-LEDs [41]. Two kinds of micro-LEDs with sidewall angles relatively vertical (75°) and inclined (33°) are shown in Fig. 4(b). Fig. 4(c) demonstrates the calculation of the normalized electric field distribution in a 20 μm micro-LED in these respective geometries. It can be seen that the small sidewall angle results in more emitted light being reflected downwards towards the sapphire, improving the guiding of TM-polarized photons toward the substrate for extraction and thus improving the LEE. These findings provide effective light extraction strategies of optimizing the LED size and geometry to develop high-performance UV micro-LEDs. Also, as mentioned above, performance degradation of LEDs caused by sidewall damage is an inevitable problem when

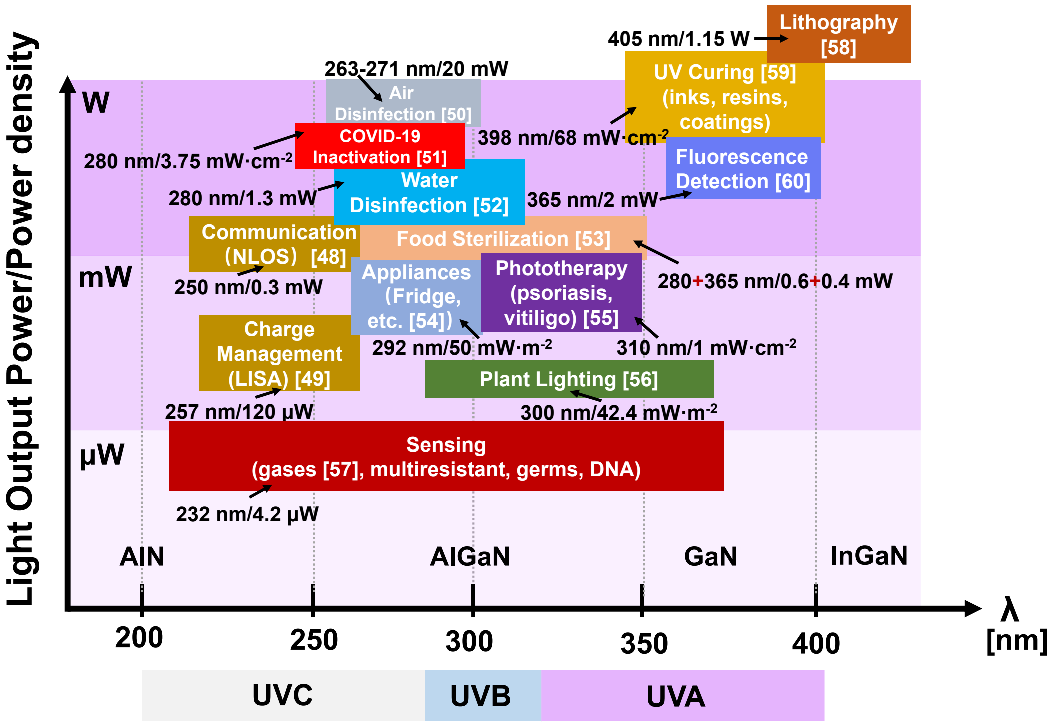


Fig. 5. Applications of UV LEDs plotted as a function of optical power and wavelength, as assembled from Refs. [48-60].

the micro-LEDs are formed by dry etching. Several techniques such as wet chemical treatment have been employed to minimize the sidewall effects in GaN based micro-LEDs [42, 43]. Chee *et al.* have reported that using post-processing methods based on HCl followed by KOH chemical treatment could recondition the sidewall damage, improving the LEE of (in their case) photonic crystal AlGaN UVC LEDs [44]. Therefore, these results demonstrate that chemical treatment may be an effective way to minimize the sidewall effect, improving the efficiency of UV micro-LEDs.

The low LOP of individual UV micro-LEDs may provide limitations for applications requiring high LOP. Thus some studies have employed large arrays of UV micro-LEDs to improve the LOP. The micro-LED array format allows increasing the total output power with minimal reduction in performance due to better heating dissipation between LED pixels [45]. The small UV micro-LEDs have higher optical power density and better heat dissipation, therefore it is expected that the UV micro-LED arrays consisting of smaller LED pixels can achieve higher LOP under the same luminous area as a non-pixellated device. Many recently published works employed micro-LED arrays with such series or parallel connected micro-LED pixels [11, 46]. Hwang *et al.* fabricated a UV LED lamp composed of four-pairs of UV micro-LED arrays in series and parallel, and the maximum LOP was ∼20 mW [46].

III. UV MICRO-LED APPLICATIONS

Traditional UV LEDs have proven to play a role in many fields such as sensing, medical treatment, sterilization, and disinfection. A diagram summarising these and other applications is shown in Fig. 5, compiled from Refs. [47–60]. This figure plots the applications against light output power and wavelength. We draw attention to several of these applications. Sterilization and disinfection effects of UV radiation on water or air are well known, because highly-energetic UV photons within a narrow-range of wavelength destroy the chemical bonds in the bacterial DNA/RNA chain. The most effective emission wavelength for these applications is often around 250 ∼ 280 nm [61], because the photon energy of UV light with a wavelength longer than 280 nm may not be sufficient to destroy chemical bonds, and UV light with a shorter wavelength is easily absorbed by media such as water. In particular, the global spread of COVID-19 infection has further drawn attention to UVC LEDs, and SARS-CoV-2 losing its activity under short-term irradiation of 280 nm UVC-LEDs has been demonstrated [51]. The UV-activated gas sensors have been rapidly developed because UV irradiation enhances the charge carrier number and surface chemical activity of metal-semiconductor materials, thereby improving gas adsorption and eliminating the need for thermal activation. Typical gases such as O_3, NO_2 and NH_3 can be detected by a system comprising UV LEDs and detectors, and the photon energy of the UV LED with a suitable wavelength should match the bandgap of the material used for gas adsorption [57]. Furthermore, UV LEDs can also be used to treat various skin diseases. UVB radiation treatment is the most commonly used method for vitiligo because UVB light has reduced side effects on the human body and a smaller penetration depth, so it is most effective on the epidermis [55]. Also, UVB radiation is an effective promoter of plant secondary metabolism and can be used to facilitate the production and extraction of a variety of functional plant secondary metabolites for use in functional

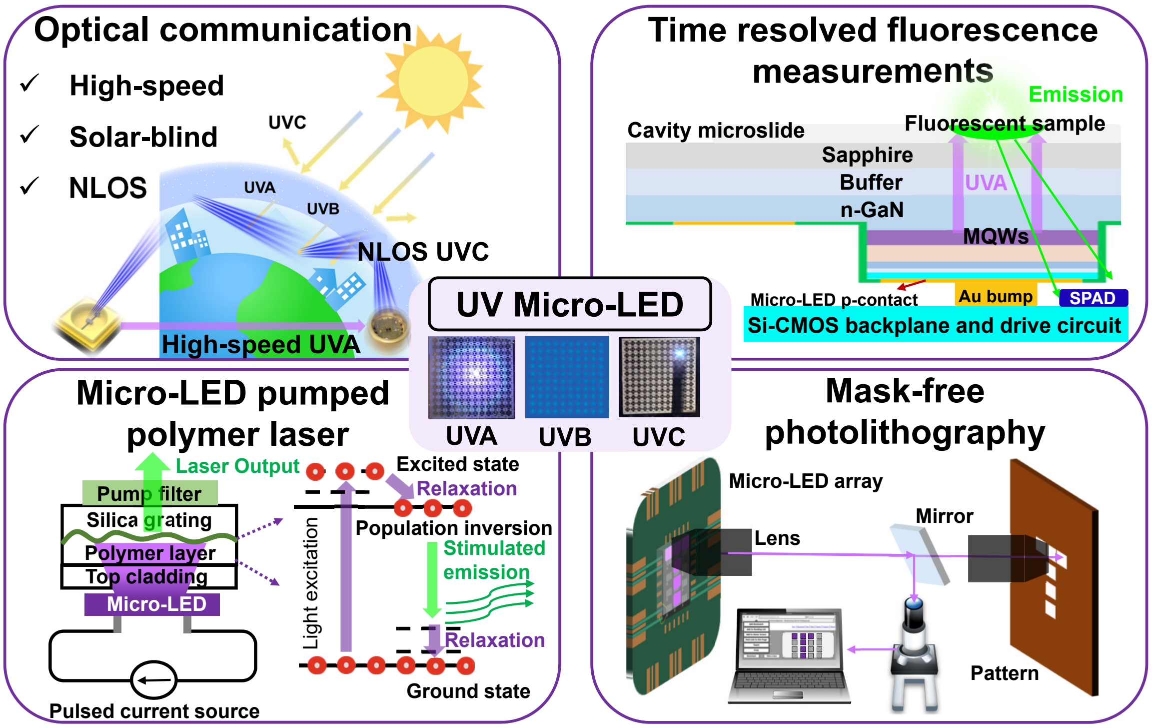


Fig. 6. Several specific applications of UV micro-LEDs. Here NLOS refers to non-line-of-sight and SPAD refers to single photon avalanche diode.

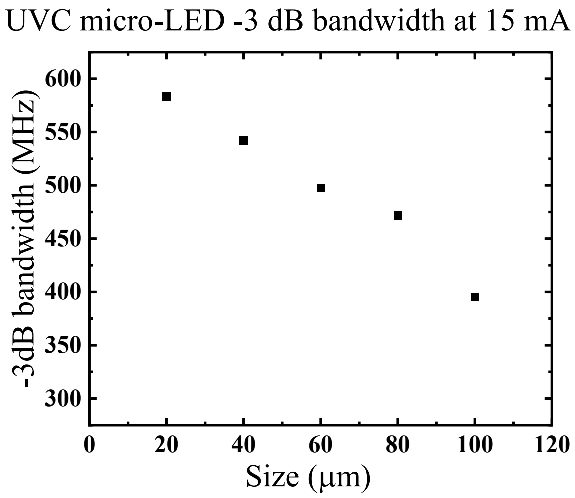


Fig. 7. Plot of modulation bandwidth (expressed as -3dB electrical-to-optical bandwidth) vs. pixel size for UVC micro-LEDs. From Ref. [66].

foods [56]. Moreover, the higher optical power and stronger penetration of UVA light open up the opportunity for the fields of UV curing [59] and photolithography [58].

Unlike traditional large-size UV LEDs, UV micro-LEDs will lead many revolutionary applications due to their unique advantages. On the one hand, micro-LEDs can operate at higher current density due to their low junction temperature and uniform current distribution, thus faster response time and higher modulation bandwidth can be achieved [9, 10]. On the other hand, the small size of the micro-LED allows these devices to be arranged in arrays of high pixel density while performing more precise localized irradiation [62]. Based on these advantages, UV micro-LEDs have also attracted widespread attention in the fields including optical communication, fluorescence lifetime measurement, optical pumping and mask-free photolithography, as shown in Fig.6. These applications will be described in detail below.

A. *Optical communication*

Early work on UV optical communication can be traced back to the 1960s or even earlier [63]. Research on UV communication could enable optical wireless communication systems to utilize more of the electromagnetic spectrum to achieve broad-band communication [64]. Furthermore, UVC communication has the advantage of avoiding ambient light interference. Prior to the development of UV-emitting LEDs, the available UV sources such as mercury flash lamps were of limited use for optical communications due to their very low modulation bandwidths, on the order of tens of kHz. Work from several groups demonstrated that UV-emitting LEDs could be used for wireless data rates on the order of 1 Gbps [57-59]. As a possible route to increasing these data rates yet further, high-bandwidth UV micro-LEDs have been investigated as transmitters for UV optical communication. Previous studies of visible-emitting micro-LEDs have shown that decreasing the pixel diameter leads to higher modulation bandwidths [10, 65]. This has been attributed to smaller micro-LEDs being able to sustain higher operating current densities, in turn leading to shorter carrier recombination times and faster modulation responses. A size-dependent study on UVC micro-LEDs by Maclure *et al.* [66] showed that this behavior is also observed in UV micro-LEDs. Fig. 7 shows the modulation

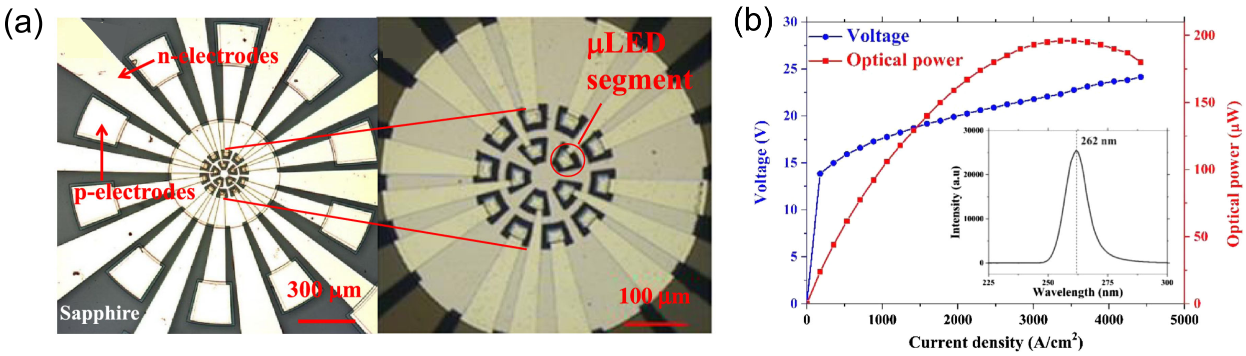


Fig. 8. (a) Plan view microscope image of micro-LED array. (b) Current density-voltage and light output power-current density characteristic curves of the UVC micro-LED pixel with the inset emission spectrum at 1.768 kA/cm^2. The figures reprinted with permissions from [67].

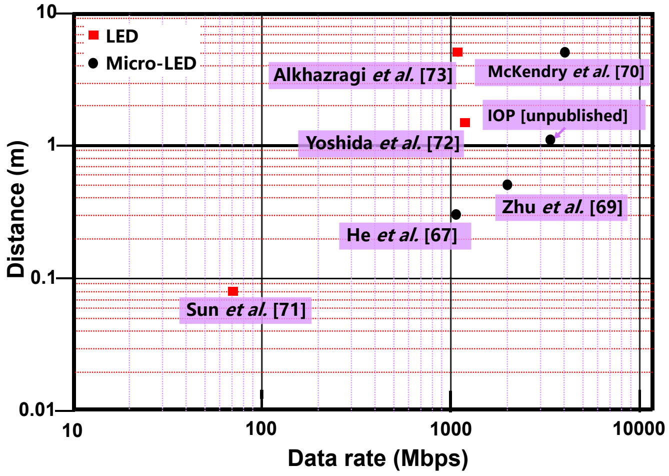


Fig. 9. A summary of literature reports of line-of-sight data rate vs. distance performance of UV-B and UV-C micro-LEDs. Data from Refs. [67, 69-73] and unpublished data from Dawson's group in University of Strathclyde.

bandwidth at a fixed current for UVC pixels of varying size, showing a clear trend to higher bandwidths as the pixel diameter decreases.

UVC micro-LEDs for solar-blind communication and non-line-of-sight (NLOS) communication, as well as the near-UV (violet) micro-LEDs for high-speed communication have been achieved in recent years. The first research on UVC micro-LED communication [67] showed a record 1.1 Gbps data rate at a distance of 0.3 m utilizing an orthogonal frequency division multiplexing (OFDM) modulation scheme. OFDM is a modulation technique that is commonly used in optical wireless communication thanks in part to its efficient use of the available channel bandwidth [68]. In [67] the OFDM data was uploaded to the arbitrary waveform generator and output as an electrical signal that was amplified by an amplifier and then combined with DC bias current by a bias-tee to drive the micro-LED. Afterwards, the light from the micro-LED was collected by a UV lens and focused into a UV-enhanced silicon avalanche photodiode detector. Finally, the received optical signal was converted into an electrical signal and captured by an oscilloscope, which was then downloaded to an offline MATLAB program for performance evaluation. The 262 nm UVC micro-LED used there (see Fig.8), with an emission area of 566 μm^2, could produce an optical power of 196 μW at a current density of 3.4 kA/cm^2 and had a -3 dB bandwidth of 438 MHz at the current density of 71 A/cm^2. However, the relatively low output optical power affected the signal-to-noise ratio and communication performance. Subsequently, by using a 276.8 nm UVC micro-LED with a diameter of 100 μm, Zhu *et al.* improved the light output power to 0.854 mW at a current density of 400 A/cm^2 and the -3 dB bandwidth to 452.53 MHz at a current density of 500 A/cm^2 [69]. This micro-LED device was shown to achieve higher output optical power while maintaining a high modulation bandwidth. With this UVC micro-LED, they obtained a data rate of 2 Gbps over 0.5 m link and 0.82 Gbps over 3 m link by using OFDM with pre-equalization. Very recently, further improvement has been made in the communication performance of UVC micro-LEDs to achieve a data rate of 4 Gbps at a distance of 5 m [70]. The Shannon-Hartley theorem states that the theoretical maximum data rate for a communications channel is a function of both the channel signal-to-noise ratio (SNR) and bandwidth. Therefore, while maintaining the high bandwidth provided by the small-size of UV micro-LEDs, series or parallel connection of such devices to further increase the light output power can increase the transmission data rate of optical communication systems. Fig. 9 summarizes work from these groups and others by plotting the achieved data rates against the demonstrated free-space transmission distance, using UVB and UVC micro-LEDs and standard off-the-shelf commercial LEDs. These demonstrations are all direct line-of-sight or, in the case of Sun *et al.*, diffuse line-of-sight communications links [67, 69–73].

The emission wavelength of the UV micro-LED also has considerable influence on the achievable data rate because of factors including the variation of LOP densities of micro-LEDs at different wavelengths and the responsivity of the detectors at different wavelengths [64, 74]. Shorter wavelengths are also more strongly scattered by air, which may be advantageous for non-line-of-sight optical wireless links that rely on scattered light to overcome physical obstacles such as buildings. In addition to these UV-B and UV-C results, a near-UV micro-LED emitting at 400 nm with an active area of 435 μm^2 has presented a record data rate of 7.91 Gbps over ~0.3 m [75]. These micro-LED pixels can each achieve a light output power of 2.3 mW and maintain a high modulation bandwidth of 655 MHz at a current density of $\sim$12 kA/cm^2. Operation of optical wireless communications at deep ultraviolet wavelengths offers specific application advantages. When used in space-based communications applications in the form recently demonstrated with micro-LEDs at longer wavelengths [76], there is the possibility of micro-LED mediated communication links not being observable from ground level. In addition, at ground level, DUV micro-LED devices offer new capabilities in non-line-of-sight optical wireless communications systems and/or other scenarios taking advantage of minimized solar background. This includes the possibility of systems based on single photon counting.

B. Time-resolved fluorescence detection

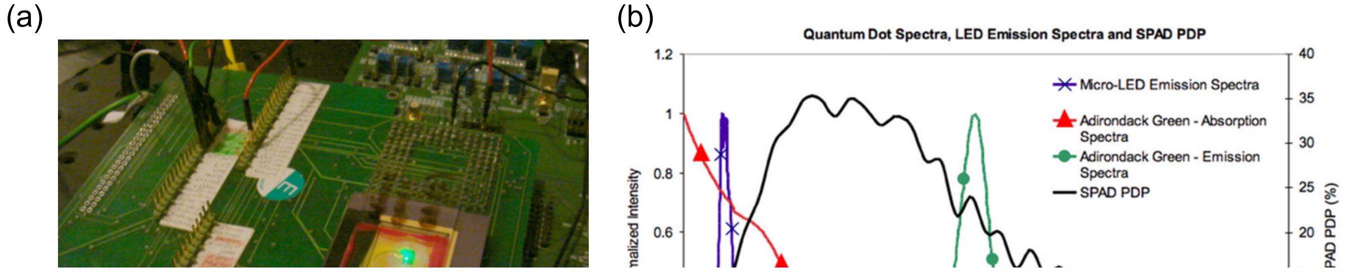
Fluorescence detection can qualitatively and quantitatively provide diagnostic information of biological systems, so it has been widely used in the field of biomedicine. In fluorescence detection analysis, samples either autofluorescence or are labeled with fluorescent molecules that absorb light from an excitation light source and emit a longer-wavelength fluorescent signal, which is then detected and quantified using a photodetector. Among the fluorescence detection techniques, the time-resolved fluorescence detection method measures the characteristic fluorescence decay time (or lifetime) of the fluorescent signal excited by a pulsed light source, which can effectively avoid the interference of natural fluorescence of the detected species [77]. For a fluorescence lifetime analysis system, the selection of the excitation light source is particularly important. The utilized fluorophores mostly are designed to be excited by the light with the wavelengths in ultraviolet, violet or short-wavelength visible band. LED technology provides an inexpensive, compact, efficient, and highly stable light source, the emission of which is spectrally well defined and whose emission wavelength can be adjusted from ultraviolet to infrared, and can therefore serve as a suitable excitation source. But measuring the lifetime of fluorescent molecules after pulsed excitation using LEDs can only be applied to the fluorescent samples which have much longer decay times compared with the duration of the light pulses generated by LEDs. UV micro-LEDs are capable of emitting short-wavelength and ultra-short light pulses and thus have been applied to time-resolved fluorescence detection. Moreover, the micro-LED geometry facilitates emission on a spatial scale comparable to the size of cells and other biological structures and can readily be deployed in array format for high-throughput parallel fluorescence lifetime measurement or compatibility with imaging systems.

To demonstrate the advantages of such systems, a highly integrated time-resolved fluorescence detection microsystem has been developed including a UV micro-LED array as an excitation light source, a fluorescent sample to be detected and single photon avalanche diode (SPAD) detectors, as shown in Fig. 10 (a) [78]. The excitation light source comprises 16 $\times$ 4 individually addressable micro-LED pixels driven by CMOS to realize spatially and temporally-selective irradiation of the samples, each with a diameter of 72 μm, a pitch of 100 μm and an emission wavelength of 370 nm all on one semiconductor chip. CdSe/ZnS quantum dots, being the sample under test in this demonstrator system, are encapsulated in a cavity microslide and placed on top of the micro-LED chip, and then excited by pulsed light emitted by a single UV micro-LED. The UV micro-LED can produce ultra-short pulses with (in this case) a rise time, fall time and pulse width of 2.15 ns, 3.31 ns and 8 ns, respectively, at a drive current of 4 mA. The sapphire substrate of the UV micro-LED array is transparent at this excitation wavelength, so the excited fluorescent light can pass through the device array to the SPAD detector. The SPAD detector at the suitable location has a photon detection probability (PDP) of 7% at 370 nm and a PDP of 25% at the fluorescent light wavelength of 526 nm from the quantum dots. The insensitivity of the SPAD to UV light, as shown in Fig. 10(b), is conducive to filtering the excitation light, thereby enhancing the detection performance. The lifetime of the quantum dot sample measured by the system was 17.2 ns, which is consistent with the lifetime provided by the manufacturer (15–20 ns), confirming the applicability of UV micro-LEDs as the excitation light source for fluorescence detection. This work further demonstrated that by using the integrated UV micro-LED array and SPAD detector, miniature time-resolved fluorescence detection microsystems can be achieved, but microsystems based on UV micro-LED arrays that can be implanted in vivo for cell analysis still need to be developed. It is clear that more sophisticated embodiments of this technology are possible using micro-LED arrays. Such devices could include microfluidic channels to handle samples, ultraparallel operation by parallel pulsing of the micro-LEDs in array format in conjunction with a SPAD array detection and so on. Moreover being in the form of a planar chip, ultracompact and integrated measurement systems can be designed. Shorter wavelength UV light from micro-LEDs can also be suitable for exciting autofluorescence from appropriate samples which may not then need other fluorescent labels to be introduced.

It is worth mentioning that deep-UV surface-enhanced fluorescence could be achieved by localized surface plasmon resonances [79]. The interaction between Al nanospheres and incident light from the molecule increases the local excitation field, quantum yield, and thus fluorescence intensity [80]. In addition, UV light can be used not only for fluorescence detection, but also for gas detection. Some molecules and atomic groups in the gas absorb UV radiation and produce specific fluorescence. The presence and content of these gas molecules can be inferred after detecting the fluorescence, and thus it can be used to detect harmful gases in the air. Optical gas sensors based on UV absorption have the advantages of small drift, fast response, and low cross-reactivity to other gases [81], while the introduction of UV micro-LEDs as UV light sources is expected to further facilitate ultracompact integrated measurement systems.

C. Ultraviolet direct writing

Patterning photoresists via UV light exposure is a critical step in well-established semiconductor manufacturing processes. However, a corresponding hard mask must be designed



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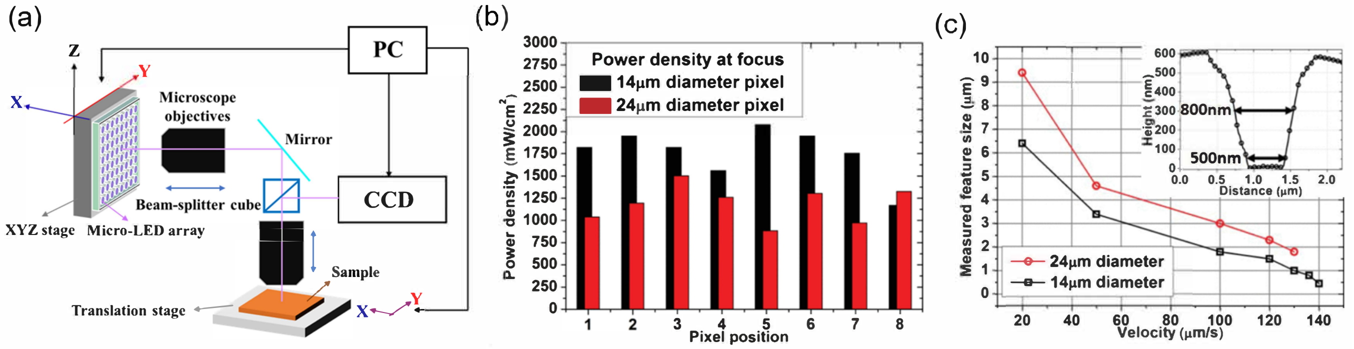

Fig. 11. (a) Diagram of the microprojection exposure system for mask-free photolithography. (b) Optical power densities distribution at a micro-LED drive voltage of 5 V for spots with diameters of 1.4 and 2.4 μm (emitting pixels diameters of 14 and 24 μm) at the focus, respectively. (c) Feature sizes (trench bottom) of the S1805 PR patterns exposed by micro-LED pixels versus direct writing speeds. The inset is the AFM scan profile of the PR pattern direct written at 140 μm/s. The figures of (b) and (c) reprinted with permissions from Ref. [62].

and manufactured in each step of such standard lithography, which increases the cost and reduces the flexibility of pattern fabrication. This has motivated the exploration of alternative maskless approaches, in particular where pattern projection is directly facilitated by an appropriate light source and imaging system, where the source itself or optical relay system may include means to control the position and exposure time and thus produce a spatially and temporally controlled exposure. GaN-based LEDs offer high-efficiency and spectrally discrete light emission at UV wavelengths such as 365 nm and 405 nm, which correspond to the i- and h-lines emitted by mercury lamps used in mature lithography processes. It has been shown that photoresist patterns with feature size less than 20 μm can be achieved by direct writing of both UV large-size LEDs and micro-LEDs [82, 83]. However, the micro-LED format operating at such wavelength offers obvious advantages for such applications, in that irradiation patterns can be directly loaded to the array, refreshed and controlled at high frame rates using drive electronics, and the individual micro-size emitter elements can be directly imaged to produce micro-size exposure spots with/without demagnification as required.

With these advantages in mind, the fabrication of patterns with micrometer or submicrometer features using UV micro-LED direct writing were demonstrated [62, 84]. These photopatterning demonstrations were achieved by using an 8 $\times$ 8 UV micro-LED array with an emission wavelength of 370 nm and a minimum pixel diameter of 14 μm. This UV micro-LED array was driven by an integrated CMOS control chip which was custom designed such that each emission element had its own local electronic driver. Thus control over the emission pattern and dosage could be controlled directly through electronic interfacing. This micro-LED based direct writing system is shown in Fig. 11(a). To give enhanced flexibility in the writing of patterns, the photoresist samples were placed on a horizontal XY translation stage and the micro-LED array was placed vertically on a manual XYZ stage. By adjusting the displacement speed of the sample XY stage, the exposure dose could be controlled and the feature size of the lithography pattern can be adjusted. Horizontally and vertically mounted infinity-corrected microscope objectives were used for light collection and light projection respectively, so that a sufficiently small spot could be obtained on the surface of the photoresist sample. Through a beam-splitter, a CCD camera with a zoom lens could monitor the positions of the sample and micro-LED array for precise exposure position adjustment. From the light intensity profile images taken by the CCD camera, the (demagnified) focused spot sizes of the pixels with diameters of 14 and 24 μm were estimated to be 1.4 and 2.4 μm, respectively, and the corresponding average optical power densities were 1.7 W/cm^2 and 1.2 W/cm^2, as shown in Fig. 11 (b). Feature sizes of S1805 photoresists patterns written at different direct writing speeds are shown in Fig.11 (c). The inset demonstrates that a line width of 500 nm can be achieved using the UV micro-LED with a diameter of 14 μm, relying on demagnification and nonlinear exposure effects in the photoresist. Furthermore, by using this direct writing system, an 8 × 8 LED array with a pixel size of 199 × 199 μm^2 and a pitch of 200 μm was fabricated, which demonstrated the applicability of the UV micro-LED direct writing technology. In addition, recent studies have shown that high pixel density UV micro-LED arrays for high resolution displays can also be used for ultraviolet direct writing, as shown in Fig. 12 [19]. The high-resolution 1920 × 1080 UV microdisplay with the smallest pixel of 5 μm shows the "NTHU" pattern. Using the displayed pattern to expose the photoresist covered on the silicon substrate, a maskless photolithography "NTHU" pattern can be realized. By utilizing a well-designed lens and focusing system, maskless lithography with UV micro-LED displays as the light source can achieve smaller line widths, which proves the multifaceted application of UV micro-LED arrays in the fields of display and direct writing.

UV micro-LED based maskless direct writing technology can not only reduce the cost and complexity of lithography, but also has the advantages of flexibility, parallel direct writing, and the capability of fabricating high-resolution devices, which is of great significance for developing low cost, flexible, high resolution and portable photolithography tools. Moreover, recent extensions to this technology have demonstrated that pattern projection from micro-LED arrays can also locate and identify features of interest on the sample, such as fluorecent markers, which can be used for multi-step alignment processes [85]. DUV micro-LEDs with shorter emission wavelength may enhance the lithography resolution. According to the Rayleigh's equation which determines the resolution limit in photolithography, the minimum feature size depends on the wavelength of light source [86]. Shorter wavelength light could improve the resolution and the current AlGaN-based DUV LED can already achieve an emission wavelength of 222 nm [87], but the related optical and mechanical systems need to be further optimized for higher resolution and automatic operation. Indeed it is possible to foresee a new generation of multi-functional photolithography tools which combine sophisticated and electronically controlled photoexposure with a variety of other measurement and alignment capabilities, all enabled by the particular properties of micro-LED arrays.

D. *Further applications*

In addition to the aforementioned applications of UV micro-LEDs in optical communication, time-resolved fluorescence detection and maskless direct writing, UV micro-LEDs also have wide applications in other fields such as full-color displays, real-time photodetection of UV light, excitation of organic semiconductor lasers and space charge management [88–91].

Micro-LED based displays are considered to be one of the most promising next-generation display technologies. Blue micro-LEDs are often used to excite red and green quantum dots to achieve full-color displays, which however may suffer from low pumping efficiency. Since quantum dots used for color conversion generally exhibit higher absorption for shorter wavelength photons, blue-violet and near-ultraviolet micro-LEDs have been proposed to increase the absorption of excitation light and improve excitation efficiency. At the same time, using a UV micro-LED as the excitation source can effectively avoid the problem of color mixing caused by the strong blue spectrum output by the blue micro-LED, so that a more uniform RGB spectrum can be achieved [88]. Besides, deep UV micro-LEDs have also been used to excite green

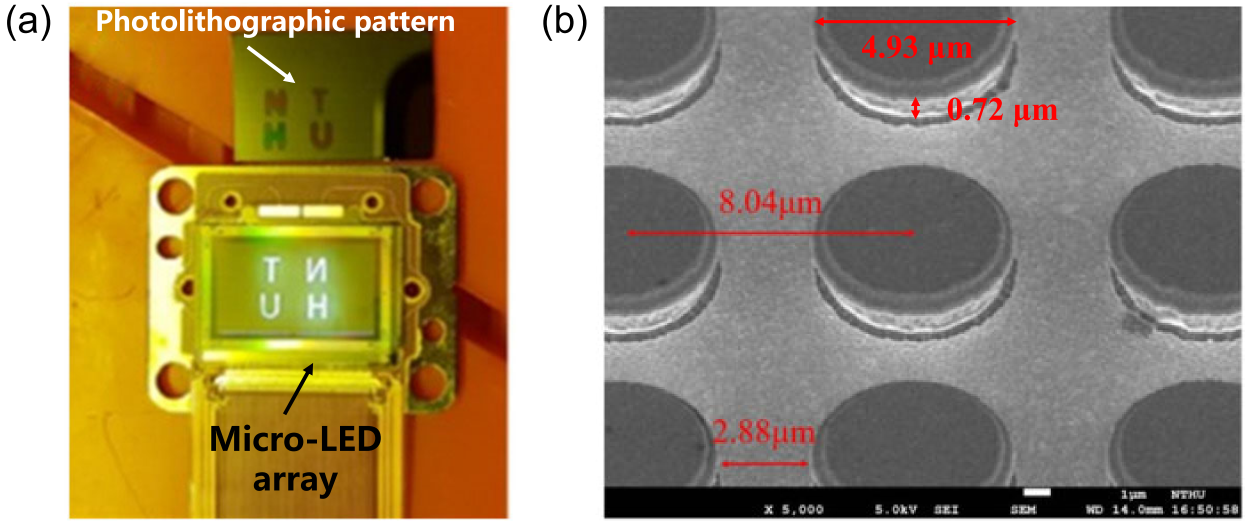

Fig. 12. (a) Maskless photolithography pattern of "NTHU" (the abbreviation for National Tsing Hua University) on a resist-coated Si wafer exposed by the 1920 × 1080 UV micro-LED display. (b) SEM image of the 1920 × 1080 micro-LED array labeled with relevant dimensions. The figures reprinted with permissions from Ref. [19].

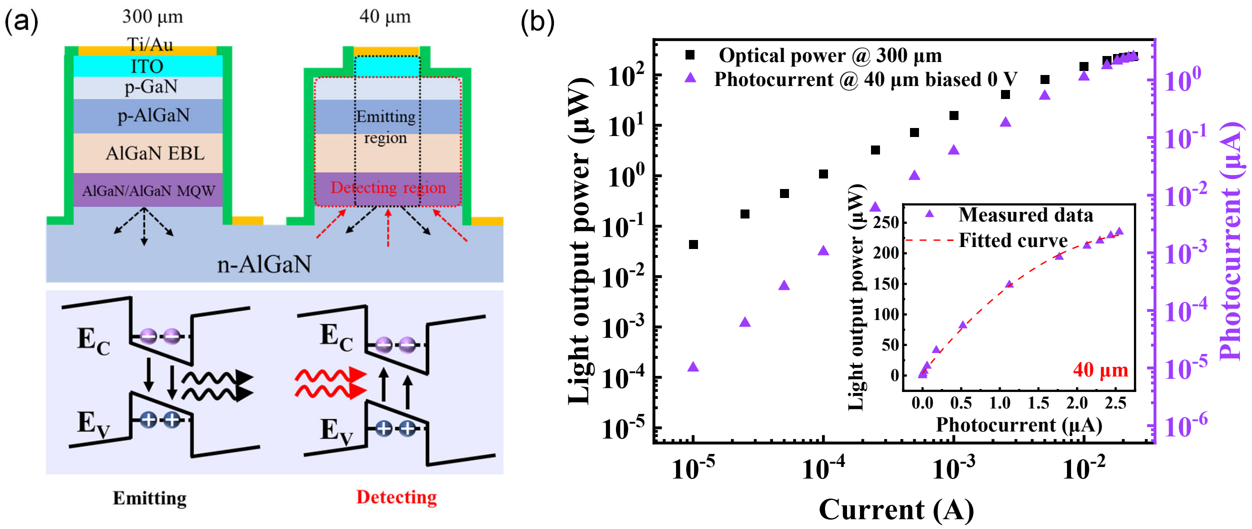

Fig. 13. (a) Schematic diagram of the monolithic integrated chip and its mechanism diagram of the photon emission and photon detection. (b) The optical power of a 300 μm UVC LED and the photocurrent generated by a 40 μm UVC micro-LED biased at 0 V. The inset is the relationship between the photocurrent generated by the UVC micro-LED and the light output power of the UVC LED. The figures reprinted with permissions from Ref. [89].

perovskite quantum dots and a stronger light output intensity was achieved [92].

For UV LEDs, especially UVC LEDs, their high dislocation density and generated point defects can easily degrade the luminous performance, thereby affecting their applications in medical, biological, and other fields that require stable light intensity. Therefore, UV photodetectors that can monitor fluctuations in UV light output in real time is essential. The micro-LED format of device has been proven to have light detection function [93], and UVC light can be transmitted through the AlGaN based waveguide layer in the UVC LED [94]. Based on these research results, Tian's group designed and integrated UVC LEDs with sizes of 40 and 300 μm and emission wavelength of 277 nm on a single chip [89], as shown in Fig. 13(a). The UVC micro-LED in the integrated device can detect the light emitted by the adjacent UVC LED, and the relationship between the photocurrent detected and the optical power output of the UVC LED is shown in Fig. 13(b). We can infer the change of UVC LED luminous performance from the fluctuation of UVC micro-LED photocurrent, and thus realize real-time monitoring. In addition, the technology that integrates UVC LEDs and UVC photodetectors also provides opportunities for the development of miniaturized UV spectrophotometers for gas sensing applications.

Finally, the application of UV micro-LEDs to charge management is very interesting. During the process of space-based gravitational wave detection, electric charges may accumulate on the test mass of the observatory and thus affect the test accuracy. To plate gold on the test mass surface to limit the absorption of photons and to use deep ultraviolet radiation to stimulate the release of electrons is an applicable method for charge management. The deep UV light source is therefore a major component of the charge management system. A UV LED emitting at 257 nm with a optical power of $\sim$120 μW and fibre coupling optical power of $\sim$16 μW has been proven to be possible to meet the stringent requirements of the Laser Interferometric Space Antenna (LISA) [49]. Recently, it is shown that a UVC LED with a peak wavelength of 251 nm and a full width half max (FWHM) around 10 nm can produce 200 pW of optical power at a duty cycle of 6% in pulse mode [91]. However, to meet the minimum optical power requirement of 10 pW, the duty cycle needs to be further reduced thus making precise control difficult. In addition, UVC LEDs for charge management should have high bandwidth to meet the needs of high frequency operation, and also good stability to meet the needs of long-term work in space. UVC micro-LED has better current spreading and higher modulation bandwidth. Moreover, it also has a finer dynamic current adjustment range, which is important to realize more precise light output power control. We have begun carrying out relevant research on the application of UVC micro-LEDs in charge management. We believe that our self-designed UVC micro-LED luminescent detection array combined with the self-feedback circuit can achieve stable and precise light output power to meet the various needs of this application.

More applications of UV micro-LEDs are yet to be fully explored, such as the use of UVC micro-LEDs instead of low-pressure mercury lamps for photochemical activation at low temperature [95]. With the advantages of small size, better current spreading, high modulation bandwidth, high optical power density and high stability, suitability for array format operation and direct electronic interfacing to CMOS, UV micro-LEDs will play an important role in fields including biology, medicine, disinfection, photolithography, instrumentation and UV optical communications.

IV. CONCLUSION

In this article, the development and application of UV micro-LEDs in recent years were reviewed. We briefly summarized the advantages of UV micro-LEDs in comparison to UV LEDs of conventional size. The current status and challenges of UV micro-LEDs as well as recent techniques for improving the efficiency of UV micro-LEDs were also reviewed. Furthermore, we summarized present wide applications of UVC micro-LEDs in high-speed optical communication, time-resolved fluorescence lifetime measurement, optical pumping and direct writing, and proposed some potential applications such as charge management. The development of AlGaN wide bandgap semiconductors provides the possibility for the realization of high-efficiency, compact and inexpensive light sources in the ultraviolet spectral range. Based on these materials, UV LEDs and UV micro-LEDs have been rapidly developed. It has been demonstrated that AlGaN UV LEDs and UV micro-LEDs have a number of advantages and wide applications in many fields.

REFERENCES

[1] R. K. Mondal, S. Adhikari, V. Chatterjee, and S. Pal, "Recent advances and challenges in AlGaN-based ultraviolet light emitting diode technologies," *Materials Research Bulletin*, vol. 140, p. 111258, August 2021.

[2] Y. Muramoto, M. Kimura, and S. Nouda, "Development and future of ultraviolet light-emitting diodes: UV-LED will replace the UV lamp," *Semiconductor Science and Technology*, vol. 29, no. 8, p. 084004, June 2014.

[3] M.-T. Chen, M.-P. Lu, Y.-J. Wu, J. Song, C.-Y. Lee, M.-Y. Lu, Y.-C. Chang, L.-J. Chou, Z. L. Wang, and L.-J. Chen, "Near UV LEDs made with in situ doped pn homojunction ZnO nanowire arrays," *Nano Letters*, vol. 10, no. 11, pp. 4387–4393, October 2010.

[4] C.-H. Lin and C.-T. Lee, "Ga_2O_3-based solar-blind deep ultraviolet light-emitting diodes," *Journal of Luminescence*, vol. 224, p. 117326, August 2020.

[5] L. Wang, Q. Guo, J. Duan, W. Xie, G. Ji, S. Li, C. Chen, J. Li, L. Yang, Z. Tan, L. Xu, Z. Xiao, J. Luo, and J. Tang, "Exploration of nontoxic Cs_3CeBr_6 for violet light-emitting diodes," *ACS Energy Letters*, vol. 6, no. 12, pp. 4245–4254, November 2021.

[6] S. Nakamura, T. Mukai, and M. Senoh, "High-power GaN pn junction blue-light-emitting diodes," *Japanese Journal of Applied Physics*, vol. 30, no. 12A, p. L1998, October 1991.

[7] H. Hirayama, S. Fujikawa, and N. Kamata, "Recent progress in AlGaN-based deep-UV LEDs," *Electronics and Communications in Japan*, vol. 98, no. 5, pp. 1–8, May 2015.

[8] M. Kneissl and J. Rass, "III-nitride ultraviolet emitters: Technology and applications," *Springer Series in Materials Science*, vol. 227, pp. 415–434, 2016.

[9] Z. Gong, S. Jin, Y. Chen, J. McKendry, D. Massoubre, I. M. Watson, E. Gu, and M. D. Dawson, "Size-dependent light output, spectral shift, and self-heating of 400 nm InGaN light-emitting diodes," *Journal of Applied Physics*, vol. 107, no. 1, p. 013103, January 2010.

[10] P. Tian, J. J. McKendry, Z. Gong, B. Guilhabert, I. M. Watson, E. Gu, Z. Chen, G. Zhang, and M. D. Dawson, "Size-dependent efficiency and efficiency droop of blue InGaN micro-light emitting diodes," *Applied Physics Letters*, vol. 101, no. 23, p. 231110, December 2012.

[11] V. Adivarahan, S. Wu, W. Sun, V. Mandavilli, M. Shatalov, G. Simin, J. Yang, H. Maruska, and M. A. Khan, "High-power deep ultraviolet light-emitting diodes based on a micro-pixel design," *Applied Physics Letters*, vol. 85, no. 10, pp. 1838–1840, September 2004.

[12] A. Khan, K. Balakrishnan, and T. Katona, "Ultraviolet light-emitting diodes based on group three nitrides," *Nature Photonics*, vol. 2, no. 2, pp. 77–84, February 2008.

[13] H. Yu, M. H. Memon, D. Wang, Z. Ren, H. Zhang, C. Huang, M. Tian, H. Sun, and S. Long, "AlGaN-based deep ultraviolet micro-LED emitting at 275 nm," *Optics Letters*, vol. 46, no. 13, pp. 3271–3274, June 2021.

[14] L. Zhang, Y. Guo, J. Yan, Q. Wu, Y. Lu, Z. Wu, W. Gu, X. Wei, J. Wang, and J. Li, "Deep ultraviolet light-emitting diodes based on a well-ordered AlGaN nanorod array," *Photonics Research*, vol. 7, no. 9, pp. B66–B72, August 2019.

[15] Z. Qian, S. Zhu, X. Shan, P. Yin, Z. Yuan, P. Qiu, Z. Wang, X. Cui, and P. Tian, "Analysis on efficiency improvement of 273 nm AlGaN UV-C micro-LEDs," *Journal of Physics D: Applied Physics*, 2022.

[16] N. L. Ploch, H. Rodriguez, C. Stolmacker, M. Hoppe, M. Lapeyrade, J. Stellmach, F. Mehnke, T. Wernicke, A. Knauer, V. Kueller *et al.*, "Effective thermal management in ultraviolet light-emitting diodes with micro-LED arrays," *IEEE Transactions on Electron Devices*, vol. 60, no. 2, pp. 782–786, January 2013.

[17] X. Liu, Y. Sun, Y. Malhotra, A. Pandey, Y. Wu, K. Sun, and Z. Mi, "High efficiency InGaN nanowire tunnel junction green micro-LEDs," *Applied Physics Letters*, vol. 119, no. 14, p. 141110, October 2021.

[18] R. Floyd, M. Gaevski, K. Hussain, A. Mamun, M. Chandrashekhar, G. Simin, and A. Khan, "Enhanced light extraction efficiency of micropixel geometry AlGaN DUV light-emitting diodes," *Applied Physics Express*, vol. 14, no. 8, p. 084002, July 2021.

[19] M.-C. Wu and I.-T. Chen, "High resolution 960 × 540 and 1920 × 1080 UV micro-LED displays with the application of maskless photolithography," *Advanced Photonics Research*, vol. 2, no. 7, p. 2100064, March 2021.

[20] T. Takano, T. Mino, J. Sakai, N. Noguchi, K. Tsubaki, and H. Hirayama, "Deep-ultraviolet light-emitting diodes with external quantum efficiency higher than 20% at 275 nm achieved by improving light-extraction efficiency," *Applied Physics Express*, vol. 10, no. 3, p. 031002, February 2017.

[21] C. Pernot, M. Kim, S. Fukahori, T. Inazu, T. Fujita, Y. Nagasawa, A. Hirano, M. Ippommatsu, M. Iwaya, S. Kamiyama *et al.*, "Improved efficiency of 255-280 nm AlGaN-based light-emitting diodes," *Applied Physics Express*, vol. 3, no. 6, p. 061004, June 2010.

[22] S.-i. Inoue, N. Tamari, and M. Taniguchi, "150 mW deep-ultraviolet light-emitting diodes with large-area AlN nanophotonic light-extraction structure emitting at 265 nm," *Applied Physics Letters*, vol. 110, no. 14, p. 141106, April 2017.

[23] H. Hirayama, S. Fujikawa, N. Noguchi, J. Norimatsu, T. Takano, K. Tsubaki, and N. Kamata, "222-282 nm AlGaN and InAlGaN-based deep-UV LEDs fabricated on high-quality AlN on sapphire," *Physica Status Solidi A*, vol. 206, no. 6, pp. 1176–1182, June 2009.

[24] M. A. Khan, T. Matsumoto, N. Maeda, N. Kamata, and H. Hirayama, "Improved external quantum efficiency of 293 nm AlGaN UVB LED grown on an AlN template," *Japanese Journal of Applied Physics*, vol. 58, no. SA, p. SAAF01, November 2018.

[25] M. A. Khan, E. Matsuura, Y. Kashima, and H. Hirayama, "Overcoming the current injection issue in the 310 nm band AlGaN UVB light-emitting diode," *Japanese Journal of Applied Physics*, vol. 59, no. SA, p. SAAD01, November 2019.

[26] X. Lu, J. Li, K. Su, C. Ge, Z. Li, T. Zhan, G. Wang, and J. Li, "Performance-enhanced 365 nm UV LEDs with electrochemically etched nanoporous AlGaN distributed bragg reflectors," *Nanomaterials*, vol. 9, no. 6, p. 862, June 2019.

[27] H. Tsuzuki, F. Mori, K. Takeda, T. Ichikawa, M. Iwaya, S. Kamiyama, H. Amano, I. Akasaki, H. Yoshida, M. Kuwabara *et al.*, "High-performance UV emitter grown on high-crystalline-quality AlGaN underlying layer," *Physica Status Solidi A*, vol. 206, no. 6, pp. 1199–1204, June 2009.

[28] M. R. Krames, O. B. Shchekin, R. Mueller-Mach, G. O. Mueller, L. Zhou, G. Harbers, and M. G. Craford, "Status and future of high-power light-emitting diodes for solid-state lighting," *Journal of Display Technology*, vol. 3, no. 2, pp. 160–175, June 2007.

[29] F. Brunner, H. Protzmann, M. Heuken, A. Knauer, M. Weyers, and M. Kneissl, "High-temperature growth of AlN in a production scale $11 \times 2'$ MOVPE reactor," *Physica Status Solidi C*, vol. 5, no. 6, pp. 1799–1801, May 2008.

[30] J. R. Grandusky, J. Smart, M. Mendrick, L. Schowalter, K. Chen, and E. Schubert, "Pseudomorphic growth of thick n-type Al_xGa_{1-x}N layers on low-defect-density bulk AlN substrates for UV LED applications," *Journal of Crystal Growth*, vol. 311, no. 10, pp. 2864–2866, May 2009.

[31] T. Kinoshita, K. Hironaka, T. Obata, T. Nagashima, R. Dalmau, R. Schlesser, B. Moody, J. Xie, S.-i. Inoue, Y. Kumagai, and Z. Sitar, "Deep-ultraviolet light-emitting diodes fabricated on AlN substrates prepared by hydride vapor phase epitaxy," *Applied Physics Express*, vol. 5, no. 12, p. 122101, November 2012.

[32] J. Zhang, X. Hu, A. Lunev, J. Deng, Y. Bilenko, T. M. Katona, M. S. Shur, R. Gaska, and M. A. Khan, "AlGaN deep-ultraviolet light-emitting diodes," *Japanese Journal of Applied Physics*, vol. 44, no. 10R, p. 7250, October 2005.

[33] K. Nagamatsu, N. Okada, H. Sugimura, H. Tsuzuki, F. Mori, K. Iida, A. Bando, M. Iwaya, S. Kamiyama, H. Amano, and I. Akasaki, "High-efficiency AlGaN-based UV light-emitting diode on laterally overgrown AlN," *Journal of Crystal Growth*, vol. 310, no. 7, pp. 2326–2329, April 2008.

[34] K. Nagata, H. Makino, T. Yamamoto, Y. Saito, and H. Miki, "Origin of optical absorption in AlN with air voids," *Japanese Journal of Applied Physics*, vol. 58, no. SC, p. SCCC29, May 2019.

[35] M. Kneissl, T.-Y. Seong, J. Han, and H. Amano, "The emergence and prospects of deep-ultraviolet light-emitting diode technologies," *Nature Photonics*, vol. 13, no. 4, pp. 233–244, March 2019.

[36] T. Zheng, W. Lin, R. Liu, D. Cai, J. Li, S. Li, and J. Kang, "Improved p-type conductivity in Al-rich AlGaN using multidimensional Mg-doped superlattices," *Scientific Reports*, vol. 6, no. 1, pp. 1–10, February 2016.

[37] M. Nakarmi, K. Kim, J. Li, J. Lin, and H. Jiang, "Enhanced p-type conduction in GaN and AlGaN by Mg-δ-doping," *Applied Physics Letters*, vol. 82, no. 18, pp. 3041–3043, April 2003.

[38] R. Dahal, J. Li, S. Majety, B. N. Pantha, X. Cao, J. Lin, and H. Jiang, "Epitaxially grown semiconducting hexagonal boron nitride as a deep ultraviolet photonic material," *Applied Physics Letters*, vol. 98, no. 21, p. 211110, May 2011.

[39] S. Hang, C.-M. Chuang, Y. Zhang, C. Chu, K. Tian, Q. Zheng, T. Wu, Z. Liu, Z.-H. Zhang, Q. Li *et al.*, "A review on the low external quantum efficiency and the remedies for GaN-based micro-LEDs," *Journal of Physics D: Applied Physics*, vol. 54, no. 15, p. 153002, January 2021.

[40] J. W. Lee, J. H. Park, D. Y. Kim, E. F. Schubert, J. Kim, J. Lee, Y.-l. Kim, Y. Park, and J. K. Kim, "Arrays of truncated cone AlGaN deep-ultraviolet light-emitting diodes facilitating efficient outcoupling of in-plane emission," *ACS Photonics*, vol. 3, no. 11, pp. 2030–2034, October 2016.

[41] M. Tian, H. Yu, M. H. Memon, Z. Xing, C. Huang, H. Jia, H. Zhang, D. Wang, S. Fang, and H. Sun, "Enhanced light extraction of the deep-ultraviolet micro-LED via rational design of chip sidewall," *Optics Letters*, vol. 46, no. 19, pp. 4809–4812, September 2021.

[42] J. Yu, T. Tao, B. Liu, F. Xu, Y. Zheng, X. Wang, Y. Sang, Y. Yan, Z. Xie, S. Liang *et al.*, "Investigations of sidewall passivation technology on the optical performance for smaller size GaN-based micro-LEDs," *Crystals*, vol. 11, no. 4, p. 403, April 2021.

[43] M. S. Wong, C. Lee, D. J. Myers, D. Hwang, J. A. Kearns, T. Li, J. S. Speck, S. Nakamura, and S. P. DenBaars, "Size-independent peak efficiency of III-nitride micro-light-emitting-diodes using chemical treatment and sidewall passivation," *Applied Physics Express*, vol. 12, no. 9, p. 097004, August 2019.

[44] K. W. Chee, W. Guo, J. R. Wang, Y. Wang, Y.-e. Chen, and J. Ye, "Tuning photonic crystal fabrication by nanosphere lithography and surface treatment of AlGaN-based ultraviolet light-emitting diodes," *Materials & Design*, vol. 160, pp. 661–670, December 2018.

[45] P. Tian, A. Althumali, E. Gu, I. M. Watson, M. D. Dawson, and R. Liu, "Aging characteristics of blue InGaN micro-light emitting diodes at an extremely high

current density of 3.5 kA cm^{-2}," *Semiconductor Science and Technology*, vol. 31, no. 4, p. 045005, March 2016.

[46] S. Hwang, M. Islam, B. Zhang, M. Lachab, J. Dion, A. Heidari, H. Nazir, V. Adivarahan, and A. Khan, "A hybrid micro-pixel based deep ultraviolet light-emitting diode lamp," *Applied Physics Express*, vol. 4, no. 1, p. 012102, December 2010.

[47] M. Kneissl, "A brief review of III-nitride UV emitter technologies and their applications," *III-nitride ultraviolet emitters*, pp. 1–25, November 2016.

[48] G. Chen, F. Abou-Galala, Z. Xu, and B. M. Sadler, "Experimental evaluation of LED-based solar blind NLOS communication links," *Optics Express*, vol. 16, no. 19, pp. 15 059–15 068, September 2008.

[49] K.-X. Sun, B. Allard, S. Buchman, S. Williams, and R. L. Byer, "LED deep UV source for charge management of gravitational reference sensors," *Classical and Quantum Gravity*, vol. 23, no. 8, p. S141, March 2006.

[50] S. S. Nunayon, H. H. Zhang, and A. C. Lai, "A novel upper-room UVC-LED irradiation system for disinfection of indoor bioaerosols under different operating and airflow conditions," *Journal of Hazardous Materials*, vol. 396, p. 122715, September 2020.

[51] H. Inagaki, A. Saito, H. Sugiyama, T. Okabayashi, and S. Fujimoto, "Rapid inactivation of SARS-CoV-2 with deep-UV LED irradiation," *Emerging Microbes & Infections*, vol. 9, no. 1, pp. 1744–1747, December 2020.

[52] K. Oguma, R. Kita, H. Sakai, M. Murakami, and S. Takizawa, "Application of UV light emitting diodes to batch and flow-through water disinfection systems," *Desalination*, vol. 328, pp. 24–30, November 2013.

[53] M. P. Akgün and S. Ünlütürk, "Effects of ultraviolet light emitting diodes (LEDs) on microbial and enzyme inactivation of apple juice," *International Journal of Food Microbiology*, vol. 260, pp. 65–74, November 2017.

[54] M. Shur, "Biomedical and biotechnology applications of deep ultraviolet light emitting diodes," in *2021 IEEE Research and Applications of Photonics in Defense Conference (RAPID)*, August 2021, pp. 1–2.

[55] T. F. Mohammad, M. Al-Jamal, I. H. Hamzavi, J. E. Harris, G. Leone, R. Cabrera, H. W. Lim, A. G. Pandya, and S. M. Esmat, "The vitiligo working group recommendations for narrowband ultraviolet B light phototherapy treatment of vitiligo," *Journal of the American Academy of Dermatology*, vol. 76, no. 5, pp. 879–888, May 2017.

[56] M. Schreiner, I. Mewis, S. Neugart, R. Zrenner, J. Glaab, M. Wiesner, and M. A. Jansen, "UV-B elicitation of secondary plant metabolites," in *III-Nitride Ultraviolet Emitters*, November 2016, pp. 387–414.

[57] E. Espid and F. Taghipour, "UV-LED photo-activated chemical gas sensors: a review," *Critical Reviews in Solid State and Materials Sciences*, vol. 42, no. 5, pp. 416–432, November 2017.

[58] S. S. Fahmida, J. Y. Tan, and K. Jungkwun, "Multidirectional UV-LED lithography using an array of high-intensity UV-LEDs and tilt-rotational sample holder for 3-D microfabrication," *Micro and Nano Systems Letters*, vol. 8, no. 1, pp. 1–12, April 2020.

[59] C. Dreyer and F. Mildner, "Application of LEDs for UV-curing," in *III-Nitride Ultraviolet Emitters*, November 2016, pp. 415–434.

[60] M. Kfouri, O. Marinov, P. Quevedo, N. Faramarzpour, S. Shirani, L. W.-C. Liu, Q. Fang, and M. J. Deen, "Toward a miniaturized wireless fluorescence-based diagnostic imaging system," *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 14, no. 1, pp. 226–234, February 2008.

[61] K. Song, M. Mohseni, and F. Taghipour, "Application of ultraviolet light-emitting diodes (UV-LEDs) for water disinfection: a review," *Water Research*, vol. 94, pp. 341–349, May 2016.

[62] B. Guilhabert, D. Massoubre, E. Richardson, J. J. McKendry, G. Valentine, R. K. Henderson, I. M. Watson, E. Gu, and M. D. Dawson, "Sub-micron lithography using InGaN micro-LEDs: mask-free fabrication of LED arrays," *IEEE Photonics Technology Letters*, vol. 24, no. 24, pp. 2221–2224, October 2012.

[63] G. Harvey, "A survey of ultraviolet communication systems," Tech. Rep., 1964.

[64] P. Qiu, S. Zhu, Z. Jin, X. Zhou, X. Cui, and P. Tian, "Beyond 25 Gbps optical wireless communication using wavelength division multiplexed LEDs and micro-LEDs," *Optics Letters*, vol. 47, no. 2, pp. 317–320, January 2022.

[65] J. J. McKendry, D. Massoubre, S. Zhang, B. R. Rae, R. P. Green, E. Gu, R. K. Henderson, A. Kelly, and M. D. Dawson, "Visible-light communications using a CMOS-controlled micro-light-emitting-diode array," *Journal of Lightwave Technology*, vol. 30, no. 1, pp. 61–67, November 2011.

[66] D. M. Maclure, J. J. McKendry, J. Herrnsdorf, X. He, E. Xie, E. Gu, and M. D. Dawson, "Size-dependent characterization of deep UV micro-light-emitting diodes," in *2020 IEEE Photonics Conference (IPC)*, November 2020, pp. 1–2.

[67] X. He, E. Xie, M. S. Islim, A. A. Purwita, J. J. McKendry, E. Gu, H. Haas, and M. D. Dawson, "1 Gbps free-space deep-ultraviolet communications based on III-nitride micro-LEDs emitting at 262 nm," *Photonics Research*, vol. 7, no. 7, pp. B41–B47, June 2019.

[68] J. Armstrong, "OFDM for optical communications," *Journal of Lightwave Technology*, vol. 27, no. 3, pp. 189–204, February 2009.

[69] S. Zhu, P. Qiu, Z. Qian, X. Shan, Z. Wang, K. Jiang, X. Sun, X. Cui, G. Zhang, D. Li *et al.*, "2 Gbps free-space ultraviolet-C communication based on a high-bandwidth micro-LED achieved with pre-equalization," *Optics Letters*, vol. 46, no. 9, pp. 2147–2150, May 2021.

[70] J. J. McKendry, E. Xie, M. S. Islim, X. Sun, D. MacLure, E. Gu, H. Haas, and M. D. Dawson, "4 Gbps wireless optical communications up to 5 m using a UV-C micro-light-emitting diode array," in *2021 IEEE Photonics Conference (IPC)*, 2021, pp. 1–2.

[71] X. Sun, Z. Zhang, A. Chaaban, T. K. Ng, C. Shen, R. Chen, J. Yan, H. Sun, X. Li, J. Wang *et al.*, "71-Mbit/s ultraviolet-B LED communication link based on 8-QAM-

OFDM modulation," *Optics Express*, vol. 25, no. 19, pp. 23 267–23 274, September 2017.

[72] Y. Yoshida, K. Kojima, M. Shiraiwa, Y. Awaji, A. Kanno, N. Yamamoto, S. F. Chichibu, A. Hirano, and M. Ippommatsu, "An outdoor evaluation of 1-Gbps optical wireless communication using AlGaN-based LED in 280-nm band," in *2019 Conference on Lasers and Electro-Optics (CLEO)*, 2019, pp. 1–2.

[73] O. Alkhazragi, F. Hu, P. Zou, Y. Ha, C. H. Kang, Y. Mao, T. K. Ng, N. Chi, and B. S. Ooi, "Gbit/s ultraviolet-C diffuse-line-of-sight communication based on probabilistically shaped DMT and diversity reception," *Optics Express*, vol. 28, no. 7, pp. 9111–9122, March 2020.

[74] D. M. Maclure, J. J. McKendry, M. S. Islim, E. Xie, C. Chen, X. Sun, X. Liang, X. Huang, H. Abumarshoud, J. Herrnsdorf, E. Gu, H. Haas, and M. D. Dawson, "10 Gbps wavelength division multiplexing using UV-A, UV-B and UV-C micro-LEDs," *Photonics Research*, 2021.

[75] M. S. Islim, R. X. Ferreira, X. He, E. Xie, S. Videv, S. Viola, S. Watson, N. Bamiedakis, R. V. Penty, I. H. White *et al.*, "Towards 10 Gb/s orthogonal frequency division multiplexing-based visible light communication using a GaN violet micro-LED," *Photonics Research*, vol. 5, no. 2, pp. A35–A43, March 2017.

[76] A. D. Griffiths, J. Herrnsdorf, R. K. Henderson, M. J. Strain, and M. D. Dawson, "High-sensitivity inter-satellite optical communications using chip-scale LED and single-photon detector hardware," *Optics Express*, vol. 29, no. 7, pp. 10 749–10 768, March 2021.

[77] B. R. Rae, K. R. Muir, Z. Gong, J. McKendry, J. M. Girkin, E. Gu, D. Renshaw, M. D. Dawson, and R. K. Henderson, "A CMOS time-resolved fluorescence lifetime analysis micro-system," *Sensors*, vol. 9, no. 11, pp. 9255–9274, November 2009.

[78] B. Rae, C. Griffin, J. McKendry, J. Girkin, H. Zhang, E. Gu, D. Renshaw, E. Charbon, M. Dawson, and R. Henderson, "CMOS driven micro-pixel LEDs integrated with single photon avalanche diodes for time resolved fluorescence measurements," *Journal of Physics D: Applied Physics*, vol. 41, no. 9, p. 094011, April 2008.

[79] Y. Wei, H. Pei, and Q. Dai, "Deep ultraviolet surface-enhanced fluorescence spectroscopy using aluminum nanospheres dimer," *Optik*, vol. 217, p. 164883, September 2020.

[80] L. Meng, M. Sun, J. Chen, and Z. Yang, "A nanoplasmonic strategy for precision in-situ measurements of tip-enhanced Raman and fluorescence spectroscopy," *Scientific Reports*, vol. 6, no. 1, pp. 1–7, January 2016.

[81] S. Khan, D. Newport, and S. Le Calvé, "Gas detection using portable deep-UV absorption spectrophotometry: A review," *Sensors*, vol. 19, no. 23, p. 5210, November 2019.

[82] C. Jeon, E. Gu, and M. Dawson, "Mask-free photolithographic exposure using a matrix-addressable micropixellated AlInGaN ultraviolet light-emitting diode," *Applied Physics Letters*, vol. 86, no. 22, p. 221105, May 2005.

[83] R. M. Guijt and M. C. Breadmore, "Maskless photolithography using UV LEDs," *Lab on a Chip*, vol. 8, no. 8, pp. 1402–1404, June 2008.

[84] D. Elfström, B. Guilhabert, J. McKendry, S. Poland, Z. Gong, D. Massoubre, E. Richardson, B. Rae, G. Valentine, G. Blanco-Gomez *et al.*, "Mask-less ultraviolet photolithography based on CMOS-driven micro-pixel light emitting diodes," *Optics Express*, vol. 17, no. 26, pp. 23 522–23 529, December 2009.

[85] M. Stonehouse, A. Blanchard, B. Guilhabert, Y. Zhang, E. Gu, I. Watson, J. Herrnsdorf, and M. Dawson, "Automated alignment in mask-free photolithography enabled by micro-LED arrays," *Electronics Letters*, vol. 57, no. 19, pp. 721–723, 2021.

[86] T. Ito and S. Okazaki, "Pushing the limits of lithography," *Nature*, vol. 406, no. 6799, pp. 1027–1031, August 2000.

[87] H. Hirayama, N. Maeda, S. Fujikawa, S. Toyoda, and N. Kamata, "Recent progress and future prospects of AlGaN-based high-efficiency deep-ultraviolet light-emitting diodes," *Japanese Journal of Applied Physics*, vol. 53, no. 10, p. 100209, September 2014.

[88] H.-V. Han, H.-Y. Lin, C.-C. Lin, W.-C. Chong, J.-R. Li, K.-J. Chen, P. Yu, T.-M. Chen, H.-M. Chen, K.-M. Lau *et al.*, "Resonant-enhanced full-color emission of quantum-dot-based micro LED display technology," *Optics Express*, vol. 23, no. 25, pp. 32 504–32 515, December 2015.

[89] X. Shan, S. Zhu, P. Qiu, Z. Qian, R. Lin, Z. Wang, X. Cui, R. Liu, and P. Tian, "Multifunctional ultraviolet-C micro-LED with monolithically integrated photodetector for optical wireless communication," *Journal of Lightwave Technology*, vol. 40, no. 2, pp. 490–498, January 2022.

[90] J. Herrnsdorf, Y. Wang, J. J. McKendry, Z. Gong, D. Massoubre, B. Guilhabert, G. Tsiminis, G. A. Turnbull, I. D. Samuel, N. Laurand *et al.*, "Micro-LED pumped polymer laser: a discussion of future pump sources for organic lasers," *Laser & Photonics Reviews*, vol. 7, no. 6, pp. 1065–1078, September 2013.

[91] S. P. Kenyon, B. Letson, M. Clark, T. Olatunde, L. Ritten, J. Schindler, P. J. Wass, J. W. Conklin, S. Barke, G. Mueller *et al.*, "A charge management system for gravitational reference sensors–design and instrument testing," in *2021 IEEE Aerospace Conference (50100)*, 2021, pp. 1–9.

[92] F. Feng, K. Zhang, Y. Liu, K.-W. Chan, Z. Liu, and H.-S. Kwok, "Investigation of AlGaN-based deep-UV micro-LED as highly efficient excitation source for green perovskite quantum dots display," in *SID Symposium Digest of Technical Papers*, vol. 52, 2021, pp. 633–636.

[93] X. Liu, R. Lin, H. Chen, S. Zhang, Z. Qian, G. Zhou, X. Chen, X. Zhou, L. Zheng, R. Liu *et al.*, "High-bandwidth InGaN self-powered detector arrays toward MIMO visible light communication based on micro-LED arrays," *ACS Photonics*, vol. 6, no. 12, pp. 3186–3195, October 2019.

[94] R. Floyd, K. Hussain, A. Mamun, M. Gaevski, G. Simin, M. Chandrashekhar, and A. Khan, "Photonics integrated circuits using $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$ based UVC light-emitting diodes, photodetectors and waveguides," *Applied Physics Express*, vol. 13, no. 2, p. 022003, January 2020.

[95] Y.-H. Kim, J.-S. Heo, T.-H. Kim, S. Park, M.-H. Yoon, J. Kim, M. S. Oh, G.-R. Yi, Y.-Y. Noh, and S. K. Park, “Flexible metal-oxide devices made by room-temperature photochemical activation of sol–gel films,” *Nature*, vol. 489, no. 7414, pp. 128–132, September 2012.

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