Deep UV-LED Performance

A 2014 Nobel Prize winning technology

June 2015

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1. Introduction: Going to shorter wavelength

Ultraviolet light emitting diode (UV-LED) market should reach over 500 million $ in 2020 as reported by market analysis [1]. The LED part should reach one-third of the total UV market in 2017 dominated by UVA (315-400nm) LED. In 2020 thanks to the penetration of shorter wavelengths LED, more than half of the total market volume should be dominated by LED.
The advantages of UV-LED compared to conventional UV lamps explain this market penetration expectation. It is a solid-state technology with shock resistant semiconductor and customizable single peak emission wavelength. As it is compact, it is easy to integrate in a system and offer a large design flexibility. It needs simple driving circuits, low voltage operation. No warming time is required: instant on/off allows to increase lifetime and to reduce running cost. The diode lifetime is in excess of ten thousands hours. It is ecology friendly as it doesn't contain hazardous substance such as mercury, and doesn't produce ozone, so no system exhaust is required. In addition, based on the treaty of the Minamata Convention on Mercury, the regulation on mercury will become stricter from 2020. After this date, the manufacturing, importation and exportation of a wide range of mercury-polluted products will not be allowed. [2]
Following the development of gallium nitride (GaN) based visible LED, UV-LED have reached excellent performance in term of output power and reliability, and are already serving many applications such as UV curing related to printing, adhesives and coatings, currency validation and many others. However this recent development is still limited to the UVA range, more precisely to wavelength over 360 nm.
To access wavelength below 360 nm, aluminium gallium nitride (AlGaN) based LED are the most promising candidates as emission wavelength ranging from 200 to 365 nm could be theoretically achieved [3]. In practice, although LED with wavelengths as short as 210 nm have been reported [4], the output power is decreasing significantly for short wavelengths and practical applications below 250 nm are still limited. For UVB (280-315nm) range and long-wavelength part of UVC (100-280nm) range, the recent progress of AlGaN-based semiconductors technology [5] allows LED to address a wider range of applications including air, water and surface disinfection, phototherapy, spectroscopy, UVB and UVC curing, etc (Figure 1). In this paper we will use the acronym DUV (Deep Ultra Violet) for wavelengths below 350nm, although it generally refers to wavelengths below 300nm.

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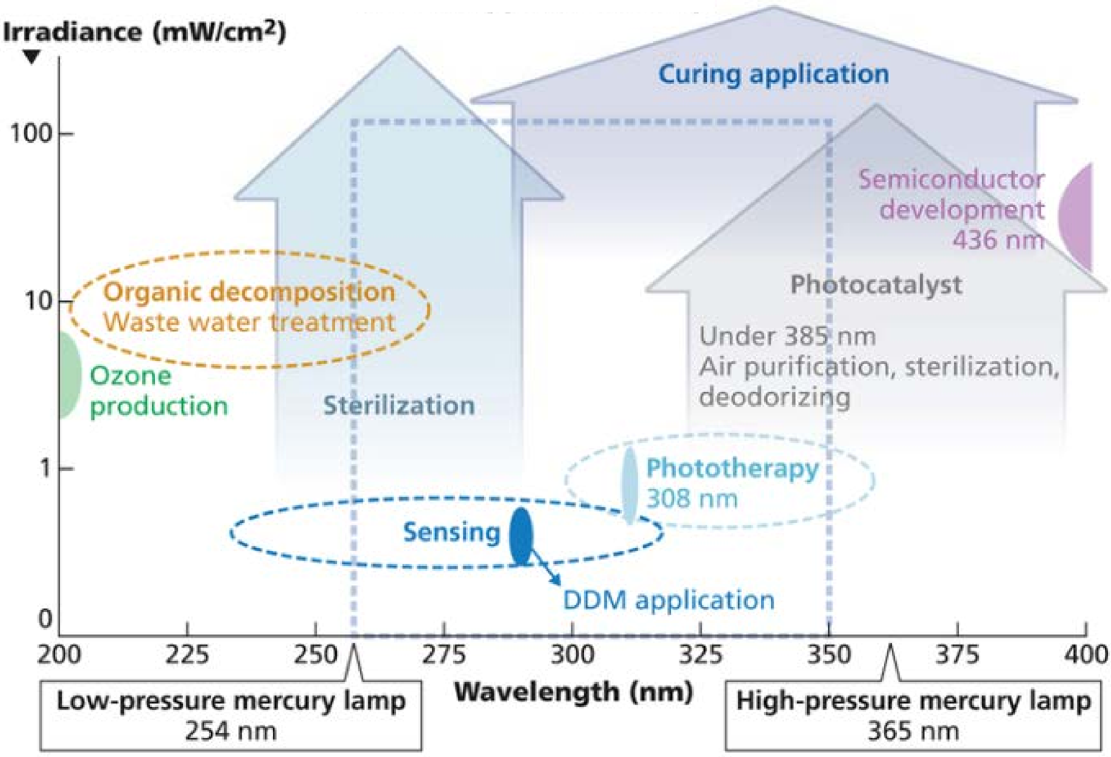

Figure 1: UV-LED applications map [6]

In order to develop an alternative solid-state UV light source to mercury lamps, Nikkiso is involved in the DUV-LED business since 2006. The strong collaboration with Nobel Prize winning Professors Akasaki and Amano to develop the epitaxial growth technology leaded to state-of-the-art DUV-LED chips. Our close cooperation on R&D projects is still very active for the development of devices with better performance. Regarding production, in 2014, Nikkiso invested in a new factory located in Japan, dedicated to DUV-LED manufacturing. It has a vertical integration with new epitaxial growth systems, wafer processing lines and packaging and testing equipment systems. Operation started in 2015 and capacity should reach over 1 million units per year from 2016.

This white paper begins with the presentation of DUV-LED structure and characteristics, then focuses on issues and challenges affecting their performance related to substrate, optical and electrical characteristics, light extraction and package. Finally, focusing on the specificity of UV-LED compare to conventional UV lamps, applications are presented anticipating the progress in device technology and in manufacturing.

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2. DUV-LED structure and characteristics

A LED is a semiconductor device that emits light when an electric current passes through it. It is a p–n junction diode working on the principle of electroluminescence. Compare to visible or infrared LED, UV-LED are relatively recent, and the first DUV-LED appears in the late 1990s.

2.1. Typical DUV-LED configuration

DUV-LED are generally produced on 2 inch diameter wafers using metal organic vapor chemical deposition (MOVCD). Following the crystal growth, the processing steps consist of taking the electrical contact on the p-type and n-type of the semiconductors. Then chips are diced, sorted and mounted into a package.

Figure 2 is showing the typical flip-chip configuration used for DUV-LED as well as the layers structure. In this example, it consists of an aluminium nitride layer grown at high temperature (HT-AlN) on a sapphire substrate. This is followed by an AlGaN-based hetero-structure p-n junction with an active region made of quantum wells (QW), where the photons are generated, and a p-AlGaN electron blocking layer (EBL) to avoid electrons overflow. Finally a p-type GaN layer on top of the structure is necessary to take the electrical p-contact. As the p-GaN layer is absorbing the emitted UV light below 365 nm, the DUV-LED are generally flip-chip on a sub-mount: the light is going out through the substrate. Finally the sub-mount is soldered or glued to the final package. The LED chip can also be directly flip-chip to the package.

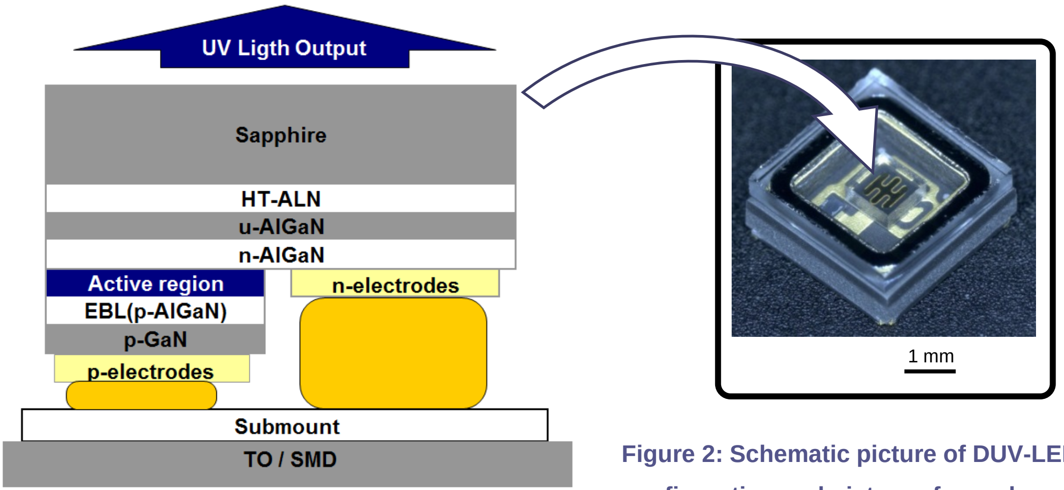

Figure 2: Schematic picture of DUV-LED flip-chip configuration and picture of a packaged DUV-LED

Each part of the LED is impacting the overall performance of the device.

The optical characteristics are depending on the crystal quality of the active region which is related to the substrate (section 3) and to the growth conditions. Design of the layers is critical for output power efficiency and for tuning the wavelength emission peak (section 4). The

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resistivity of the layers and the contact resistances affect the electrical characteristics of the device (section 5). Electrodes, chip and package design affect the light extraction efficiency (section 6) as well as the device thermal characteristics (section 7) which are critical for efficiency and reliability.

2.2. Status of DUV-LED overall performance

Table 1 presents parameters used to characterize the LED performance, as well as the difference between the indium gallium nitride (InGaN) based blue LED and the AlGaN-based DUV-LED.

The values mentioned are a guideline. The best values are greatly depending on the measurement conditions and on the overall performance. For example by driving the LED at very high current it is possible to reach much higher output power but the lifetime will be greatly affected.

Table 1: Performance comparison of Blue and DUV-LED performances

Parameters	UV-LED (InGaN-based)	DUV-LED (AlGaN-based)
IQE: Internal Quantum Efficiency	>80%	<80%
LEE: Light extraction Efficiency	>80%	<25%
EQE: External Quantum Efficiency	>80%	<15%
EE: Electrical Efficiency	>70%	<90%
WPE: Wall Plug Efficiency	>50%	<5%
Max Power /Chip (Irradiance Working Distance >3mm)	>5 W (>16 W/cm^2)	< 100 mW (<500 mW/cm^2)
Lifetime and reliability	> 50000 hours	>10000 hours
Cost/ W	$	$$$

Internal quantum efficiency (IQE) evaluates the efficiency of the active region of the device. It is defined as the number of photons emitted per electrons injected. It expresses the product of the radiative recombination efficiency with the carrier injection efficiency.

Light extraction efficiency (LEE) estimates the light which is going out of the chip. This parameter limits significantly high performance DUV-LED. A substantial difference for blue LED is observed. LEE below 20% is listed in the table 1; however, the values do not exceed 8% for DUV-LED on the market. LEE has contribution of the chip itself (light extraction of the chip: LEC) and of the package (LEP): LEE = LEC x LEP.

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External quantum efficiency (EQE) is the product of IQE and LEE. In comparison to the estimated IQE and LEE values which have more or less accuracy, the EQE value can be directly measured, therefore, it is often use to compare lighting performance of different LED. Wall plug efficiency (WPE), or also known as power efficiency, is the ratio of the light output power to the driving power. It is taking into account the electrical efficiency (EE): WPE = EQE x EE. It evaluates the overall efficiency of the LED. Between blue and DUV-LED, there is more than one order of magnitude difference in WPE. Regarding the maximum output power, the difference is even larger. The driving current of DUV-LED is much lower. This is mainly related to thermal performance, which still need optimization for DUV device.

Although the number of available data for DUV-LED is still limited, lifetimes over 10 thousand hours have already been reported by several groups.

Finally, cost per watt of DUV-LED is higher for three main reasons:

(1) low efficiency of the chip,

(2) package cost which has to be UV compatible, and

(3) low production volume.

The power flow for Nikkiso standard 30 mW LED at 285nm in a3.5mm surface mounted device (SMD) package is shown in Figure 3. 98.5% of input power is dissipated as heat; therefore, thermal management is crucial for stable operation.

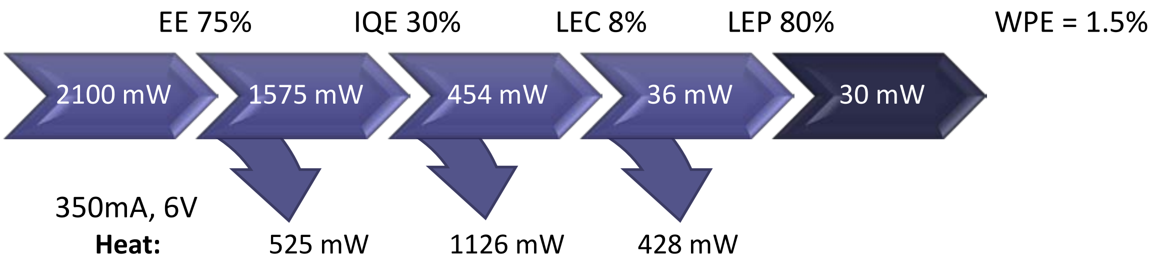

Figure 3: Power-flow for the Nikkiso 285nm DUV-LED in 3.5mm SMD Package

3. Substrate and crystal quality

3.1. III-N semiconductors

III-N semiconductors are formed out of elements from the third column of the periodic table (III) such as In, Ga, Al and atomic nitrogen (N). Gallium nitride (GaN) and its ternary alloys AlGaN and InGaN, are direct band gap semiconductors commonly used in LED.

Although the research on GaN crystal started in the late 1960s, the progress were limited until Professors Akasaki and Amano were able to obtain a high crystalline quality by depositing a buffer layer at low temperatures on sapphire substrate [7]. They demonstrated the p-type doping of GaN [8] and reported the first blue LED based on a GaN p-n junction [9]. Since that point, LED performance has improved dramatically leading to the solid-state lighting revolution enabling bright and energy saving white-light source.

As blue and white LED, DUV-LED are based on III-N semiconductors.

Figure 4 is showing the lattice parameters of III-N semiconductors versus the band gap. They potentially achieve a large spectral band from infrared to visible for InGaN, and in the ultraviolet down to 200 nm for AlGaN. In practice, the III-N semiconductors are used for LED emitting from 250 nm to 550 nm.

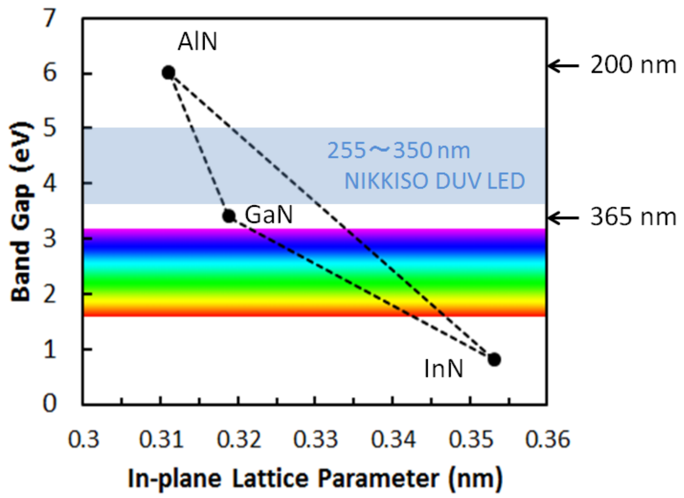

Figure 4: Band Gap versus In-Plane Lattice Parameter

3.2. Substrates for AlGaN-based DUV-LED

It is very important to control the quality of the template used for DUV-LED growth as it will affect the crystal quality, the Al mole fraction and the stress of the overgrowth AlGaN layers. GaN on sapphire is widely used for blue or white LED; it is a very well established technology, giving excellent results. However, for DUV LED, GaN template will absorb the DUV light. In addition, as the lattice parameter of AlGaN layer is smaller than GaN cracks occur.

For these reasons AlN template is used. There are three approaches to fabricate the AlN template:

(1) AlN template grown on sapphire,

(2) AlN template grown on patterned substrate, and

(3) AlN template from AlN bulk crystal

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AlN templates on sapphire have high defect density, as a result of the difference in the lattice constants and thermal expansion coefficients between AlN and sapphire. By optimizing the growth condition, templates with defect density on the order of 10^9 /cm^2 can be fabricated, and state-of-the-art DUV-LED with EQE up to 6.5% for bare chip has been achieved (section 4.1). In addition sapphire as the main substrate used for white LED production, is widely available, even for large diameter.

Epitaxial Lateral Overgrowth (ELO) is a technology widely used for GaN that drastically decreases the dislocation density. It bends the dislocations by using mask and lateral growth to obtain a flat surface. However, although ELO of AlN causes a reduction in the dislocations density by one order of magnitude, it is a very challenging method due to the required additional processing steps. Regrowth step and growth of thick layers take a long time. Coalescence of AlN is difficult and smooth surface are difficult to achieve. Best EQE is 3% now using ELO AlN template, which is half of EQE for DUV-LED on sapphire.

AlN templates fabricated from bulk crystal AlN with low dislocation density (<10^5 /cm^2) are available, but diameter is still limited and cost is very high. In addition, transmission in UV range is low due to impurity incorporation during crystal growth, thus additional step to remove or to thin down the template is necessary. The growth of low defect thick AlGaN layers on top of AlN bulk template remains a challenge due to lattice parameter mismatch.

For these reasons, AlN on sapphire remains the template of choice for the coming years. High quality crack-free AlN templates on sapphire are possible to achieve but the growth is difficult to control due to a narrow growth window. At Nikkiso, we developed a stable growth process that leads to high quality, uniform and reproducible AlN templates.

4. Optical characteristics of DUV-LED

4.1. Internal Quantum Efficiency

The surprising characteristics of the AlInGaN material system is its high radiative efficiency despite the presence of a very high concentration of threading dislocations (10^7 to 10^9 /cm^2). In addition to the threading dislocations of the AlN template, the mismatch between the lattice parameters of each layers of the AlGaN-based DUV-LED creates stress and additional dislocations and defects.

In 2002, Karpov et al. [10] presented a model to simulate the effect of dislocation density on light emission efficiency for GaN QW. Professor Amano's group showed similar results for UV QW [11]. In this model the effect of carrier concentration is also included. In addition to decrease the dislocation density, increasing the non-equilibrium carrier concentration achieves higher efficiency via saturation of the non-radiative recombination channel.

From this model, by decreasing threading dislocation density below $10^9 cm^{-2}$, IQE over 50% can be expected. In 2011, we reported a significant improvement in output power by decreasing the dislocation density of our DUV-LED [12]. We observed that, for a given LED structure, the radiative recombination efficiency was close to its maximum for dislocation density below $10^9 cm^{-2}$.

Using the rate equation analysis of the light output versus the current characteristics [13], we obtained radiative recombination efficiency of 80% for UVB device. IQE cannot be directly measured in LED. After estimating or simulating the LEE and measuring the EQE of the LED, the IQE can be deduced. The LEE of bare DUV-LED chips on sapphire was evaluated by several groups. Typical values between 6 to 10% were obtained. Figure 5 shows EQE and output power for a UVB LED bare chip. In this example, excellent value of IQE up to 65% was obtained at 10 mA driving current by assuming a LEE of 10%. [14]

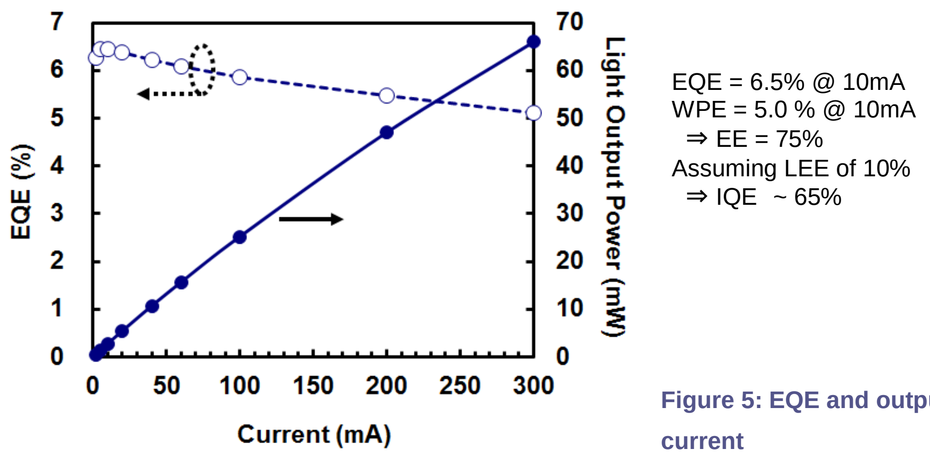

Figure 5: EQE and output power versus driving current

However as it is the case for InGaN-based LED, IQE at high injections current remains hampered by the efficiency-droop problem. Several mechanisms explaining the efficiency-droop phenomenon were proposed, including Auger recombination, density-activated defect recombination as well as carrier leakage. IQE at 350 mA is currently less than 80% of its maximum obtained at low current, but improvement is expected by minimizing the efficiency-droop through the optimization of device layers' structure.

In addition to droop-phenomenon, IQE is also affected by the junction temperature as discussed in section 7, and for Nikkiso standard DUV-LED product operating at 350 mA, the IQE is considered to be in the order of 30%.

4.2. Emission Wavelength

The emission wavelength of LED is determined by the band gap of the layers in the active region. The following equation estimates the emission wavelength:

λ (nm) = 1240 / band gap (eV)

For AlGaN-based UV-LED, by increasing the AlN mole fraction of the active region, the emission peak is shifted to shorter wavelengths (see Figure 4). By tuning the Al mole fraction of the quantum well layers from 0% to 57%, Nikkiso can supply DUV-LED from 350 nm down to 255 nm, with standard products having peak wavelengths at 265, 285 and 300 nm. (Figure 6) Our DUV-LEDs exhibit single peak emission with full width at half maximum (FWHM) typically below 15 nm. In addition, the main peak to parasitic emission ratio is in excess of 1000.

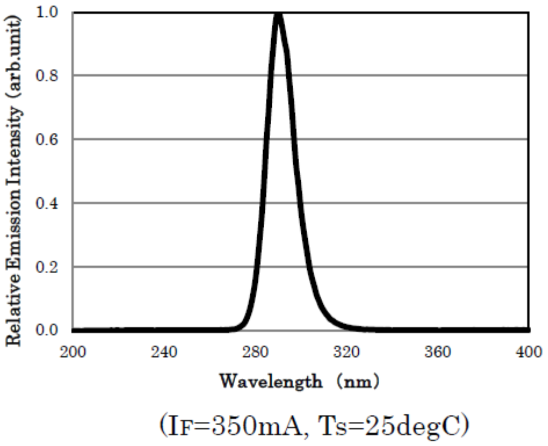

Figure 6: Typical normalized emission spectra for a 285 nm DUV-LED at a forward current of 350 mA.

4.3. Efficiency versus wavelength

Wavelength tuning is possible by adjusting the band gap of the active layers. However, to get high efficiency at a given wavelength, several layers need fine tuning to optimize carrier injection and radiative recombination.

As a general trend, the efficiency is decreasing when going to shorter wavelengths as illustrated in Figure 7. Thus, cost per watt output is higher while delivering less energy. Depending on the application careful consideration of the overall cost performance is necessary before selecting the wavelength.

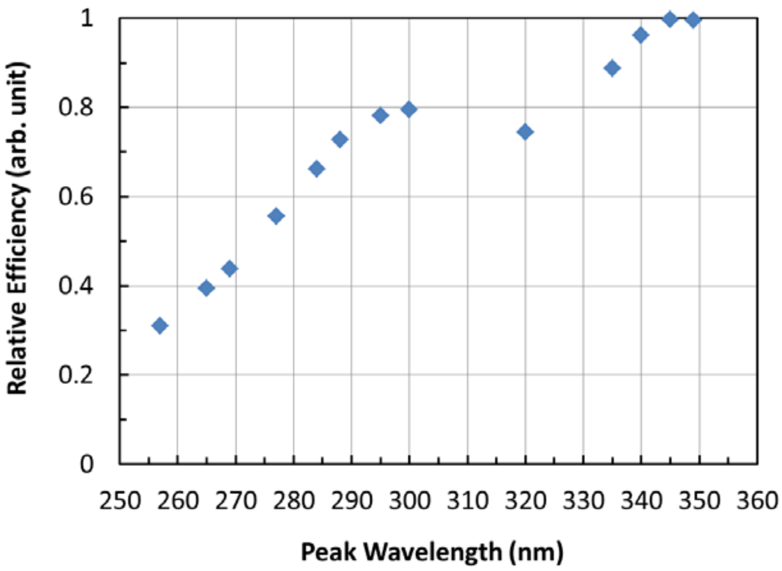

Figure 7: Relative Efficiency versus wavelength

5. Electrical characteristics

5.1. LED series resistance

The energy of an injected electron is converted to optical energy by electron-hole recombination. In ideal case, because of conservation of energy, the forward voltage of a LED is equal to band gap energy and it increases when going to shorter wavelengths (see Figure 4). However, LED has additional series resistance caused by contact resistance, bulk resistance, and resistance caused by hetero-structures. For these reasons, after manufacturing, forward voltage is higher from few hundred of mV to few V compared to the band-gap. This wide discrepancy of I (V) curves is a reason why LEDs are traditionally driven with a bias current and not with a voltage current.

5.2. Doping of AlGaN layers

Doping will affect the resistivity of the layers and the carrier concentration.

High resistivity affects the EE and leads to a phenomenon called current crowding occurring in lateral p-n junction where the carriers do not uniformly spread across the active area, leading to hot spots affecting reliability. In addition, the carrier concentration of each layer has to be fine-tuned to optimize the carrier injection efficiency, thus the IQE. Finally, high carrier concentration at the contact interface will improve the contact resistance.

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5.2.1. p-layers and p-contact

p-doping has always been a challenge for III-N semiconductors. Although it has a high activation energy, Mg is the common acceptor. For GaN only few percent of the acceptor carriers are activated at room temperature. In addition Mg activation energy is further increasing for high Al molar fraction. The low carrier concentration is also a challenge for the contact. For these reasons, although it is absorbing the emitted DUV-light, p-GaN layer is still used at least for the contact. A lot of efforts to reach conducting p-AlGaN layers with equivalent Al mole fraction in the range of 50-70 % are underway.

5.2.2. n-Layers and n-contacts

Si is the common dopant used for n-type. Although the behavior of n-type doping is not as critical as that of p-type doping, there is also a decrease in the conductivity of n-AlGaN layers with increasing Al composition. In addition, the contact resistivity also tends to increase. Thick n-AlGaN layers (over 2 μm) with optimized doping allows to reach low resistivity (below 60 Ω/square) even for UVC, reducing significantly the bulk resistance and limiting the current crowding underneath the electrodes.

5.3. Current-Voltage characteristic

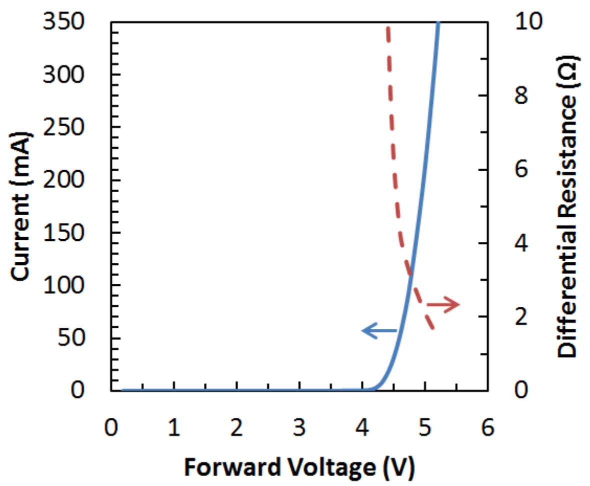

Figure 8: Forward current-voltage characteristics and differential resistance of a 285nm DUV-LED

Figure 8 shows the I-V characteristics of a 285 nm DUV-LED. The turn-on voltage is 4.3 V, close to the band gap, and the differential resistance is below 2 Ω at 350 mA. The typical forward voltage close to 5 V, at 350 mA driving current, is henceforth possible on a production base for UVB LED. The significant improvement in series resistance, that we obtained recently, provides less heat generation (typically 500 mW reduction) leading to a lower junction temperature and ultimately to higher-efficient, longer-lasting devices.

6. Light Extraction

Besides the difficulties to grow high quality AlGaN template and the very low carrier concentration of high aluminum p-type material, light extraction is currently the major limiting factor to achieve high power DUV-LED. Indeed, using the standard flip-chip configuration, the LEE is estimated to be below 10%. Figure 9 is showing the standard far field pattern of a DUV-LED in a 3.5mm package. The emission pattern is related to the chip geometry (thickness, and shape) and to the package design (cavity shape, coating, reflector, and lens).

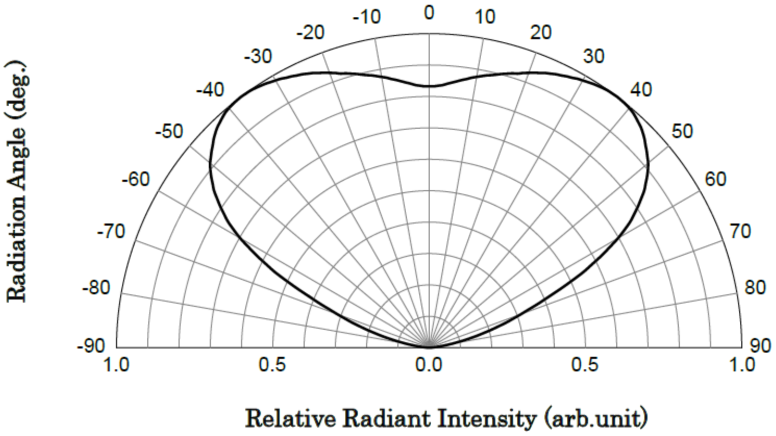

Figure 9: Far field pattern of standard DUV-LED in a 3.5 mm package

6.1. Chip design

UV light generated at the p-n junction level must be extracted from the sapphire.
As LED' semiconductors are high index refractive materials, the internal refractive critical angle given by $\alpha_c = n_a/n_s$ (where n_a and n_s are the refractive index of environment and of semiconductor, respectively) is small. A large part of the light is subject to internal reflection inside the constitutive material of the LED and is lost by absorption, especially in the p-GaN layer.
To improve light extraction, reflective electrodes are a promising approach. To avoid absorption by the p-GaN layer, we proposed the use of mesh p-GaN contact layer and obtained an improvement in LEE by 27% [15]. Other approaches were proposed such as the use of very thin p-GaN contact layer [16], or p-GaN free structure thanks to optimized p-AlGaN layers [17].
Independent of the approach, a significant degradation of the forward voltage is observed. No market available DUV-LED is using reflective electrodes yet.

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The use of micro-scale textured surface on the back side of the chip can enhance light extraction. Using this approach improvement of light extraction efficiency by more than 50% can be expected [5].

6.2. Encapsulation

The encapsulation materials used for blue and white LED, such as epoxy resin or silicone polymer, are damaged by prolonged exposure to UV light and their transmission characteristics typically degrades significantly below 300 nm.

At R&D stage, there are few reports on LEE improvement using resin encapsulation. Figure 10 is showing the improvement we obtained by using both reflective electrodes and encapsulation. We reported an improvement of 20% for 290 nm LED and found low degradation even under 256 nm illuminations [18].

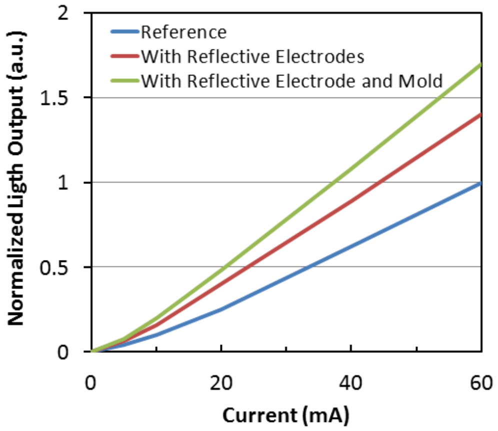

Figure 10: Normalized Output power for 290 nm DUV LED with reflective electrodes and resin encapsulation

In addition to the light extraction efficiency, encapsulation can improve mechanical and electrical reliability. Research on resins is very active. These materials have to fulfill several requirements including:

(1) good transparency to DUV radiation,
(2) refractive index between air and the substrate (sapphire or AlN) ,
(3) half-ball shaping for efficient light extraction,
(4) good adherence to the chip,
(5) being hermetic,
(6) low degradation when exposed to UV light (low solarization),
(7) high temperature stability, and
(8) robustness to environment (not too soft).

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7. Package and Thermal management

The low efficiency of DUV-LED results in significant device self-heating, and, efficient thermal management is necessary when operating the device under high current.

The chip size of Nikkiso DUV-LED is $1x1mm^2$ for a nominal current of 350 mA. As the operating voltage is over 5 V, a thermal power over 1.5 W has to be dissipated, this equates to a few hundred watts per square centimetre which is higher than current microprocessors. The thermal management is a key point, as it affects LED characteristics such as output power, efficiency and lifetime.

7.1. Effect of temperature on LED characteristics

Figure 11a shows the peak wavelength shift with temperature. As temperature increases, the energy gap of semiconductors decreases. The temperature dependence of the energy gap of the semiconductors can be expressed by the formula:

$Eg = Eg_{(T=0K)} - a T^2 / (T + b)$

where a and b are fitting parameters.

The temperature dependence of the forward voltage is shown in Figure 11c. The decrease in forward voltage is due to the decrease of the band gap energy as well as an increase of the conductivity of the p-type layers due to the higher acceptor activation, occurring at high temperatures.

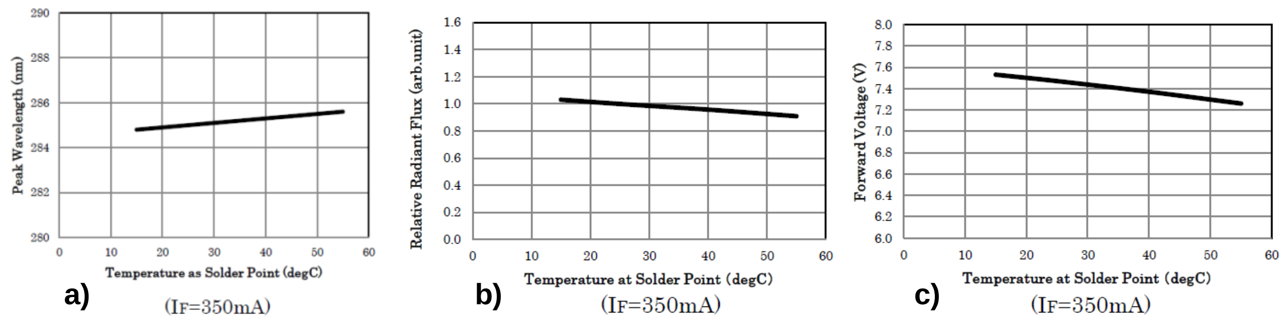

Figure 11 Dependence of LED characteristics (a) peak wavelength, (b) output power and (c) forward voltage on Temperature

In addition, the emission intensity of LEDs decreases with increasing temperature (Figure 11b). The decrease is related to temperature dependent factor including non-radiative recombination via deep levels, and carrier loss over the hetero-structure barriers. The temperature dependence can be described using the phenomenological equation [19]:

$I = I_0 \exp(-T/T_1)$

where T_1 is the characteristic temperature that describe the temperature dependence of the LED. A large T_1 implies small temperature dependence.
The mechanism of derating is not well understood. We observed that our DUV-LED on sapphire has similar thermal derating as UV-LED grown on AlN bulk, showing that derating is not directly related to the dislocation density of the template.

7.2. TO-can and SMD package

At Nikkiso, two kinds of package are available: a TO-can package with or without dome lens for sensing applications and a SMD package for higher power applications (Figure 12).
The TO-46 package is designed for applications where high power is not required, such as spectroscopy and sensing applications. Nominal currents are 15 mA and 20 mA for UVC and UVB DUV-LED, respectively. The nominal viewing angles are 15° and 80° with or without dome lens, respectively.
To achieve higher output power we developed a ceramic-based SMD package. It is designed for high current operation, typically at 350 mA but higher current can be applied as long as thermal management is sufficient to keep the junction temperature (Tj) below 100℃ (the maximum recommanded current is 500 mA).
The junction temperature can not be directly measured, but can be deduced by measuring the solder point temperature (Ts) and by using the following equation:

$$Tj(℃)=Ts(℃)+IF(A)\times VF(V)\times R_{j\text{-}s}\ (℃/W),$$

where $R_{j\text{-}s}$ is the thermal resistivity between the LED junction and the solder point. Note that temperature at the solder point will be affected by the PCB's (Printed Circuit Board) thermal resistance and the ambient temperature. After taking appropriate measures for the heat dissipation, the maximum driving current should be determined according to the solder point temperature. As temperature is significantly affecting the LED characteristics, to get the best performance, we are actively working on the thermal management and targeting to reduce the thermal resistivity $R_{j\text{-}s}$ between Tj and Ts from the current value of 15 ℃/W to below 10 ℃/W for the next device generation.
As the chip is sensitive to static electricity or surge voltage, an electro-static discharge (ESD) protection device is included in the SMD package. However, the use of measures against ESD such as a grounded wrist strap and anti-static gloves are also recommended.

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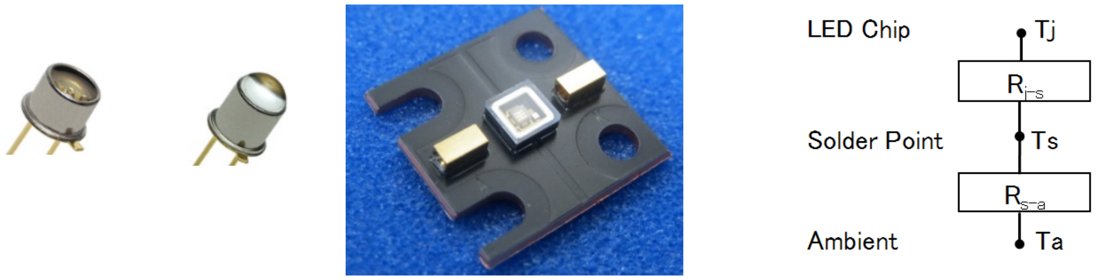

Figure 12: TO-can package without and with dome lens, SMD package on PCB, and thermal resistance model

As it was mentioned in section 6, package is also affecting the light extraction efficiency (LEP). The use of a reflector inside the package as well as anti-reflection coating of the synthetic quartz window can also contribute to improve the performance.

8. Deep UV LED Applications

8.1. Irradiance

When talking about applications, one of the important parameter is the irradiance as it will directly affect the fluence (energy delivered by unit area), following the relation:

Fluence (mJ/cm^2) = irradiance (mW/cm^2) x time of exposure (s)

Irradiance is greatly affected by the working-distance as it follows, in theory for a point source, the inverse square law.

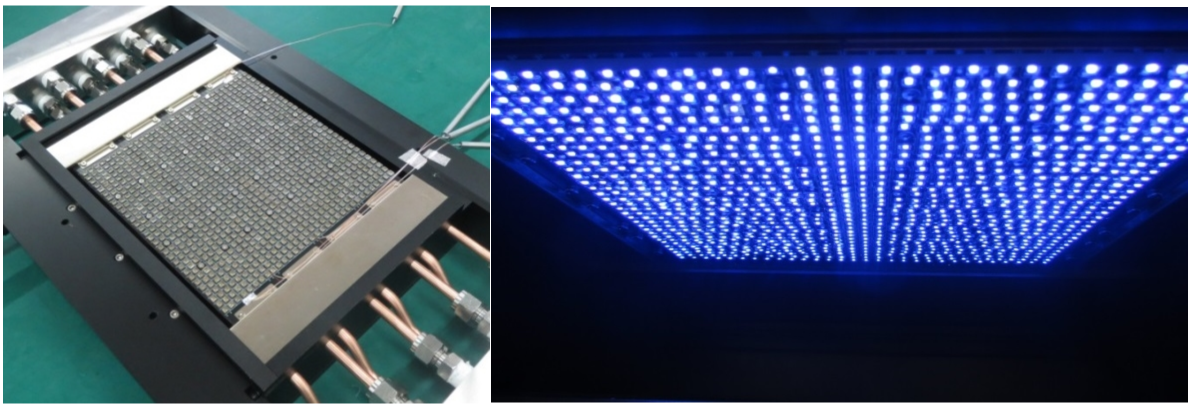

Figure13 285 nm-Lighting module of 996 chips with water cooling (irradiance of 80 mW/cm^2)

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By grouping arrays of LED together high irradiance over large area systems can be created as shown in Figure 13. The array of DUV-LED is composed of 8 modules of 112 3.5mm-packages each and has an irradiance of 80 mW/cm^2 at a working distance of 10 mm over an area of 25 x 25 cm^2. In such module, high packing density results in a significant increase of heat density, affecting lifetime, reliability, efficiency and output. Thus, thermal management implementation is critical. For applications requiring high power densities over large area, water cooling has to be implemented. Water cooling is very efficient for extracting heat; however the drawbacks of such method include needs for chillers (larger floor space) and water pipe, heavier weight.

For smaller modules or applications requiring less power, air cooling can be implemented. It is less effective at extracting heat as water but remains very attractive because of ease of integration and lower cost. Figure 14 shows a prototype module with irradiance of 400 mW/cm^2, over an area of 1 cm^2 operated with air cooling. DUV-LED ongoing efficiency improvements will allow shifting more and more from water to air cooling, which will further improve the overall cost per watt aspect.

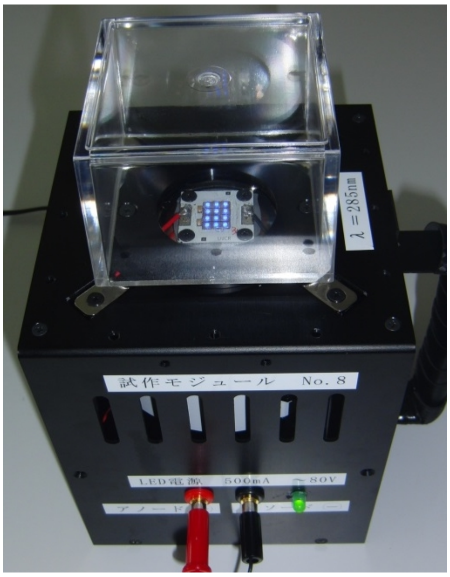

Figure 14: 285 nm prototype module with irradiance of 400 mW/cm^2

8.2. Reliability

Regarding reliability, as it is the case for other semiconductor products, LEDs adhere to the bathtub curve: in the early life of a product the failure rate is high, in the mid-life it is low and constant, and in the late life it increases. Reliability can be divided in extrinsic reliability and intrinsic reliability. Extrinsic failures are especially high at the beginning and are generated by defective materials, deviations in manufacturing process or by incorrect handling, installation or

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operation. After the first hours of operation and before the wear-out period the spontaneous failure for LED is extremely low. The intrinsic failure is referred as degradation. The output power of the LED is decreasing with time. This degradation depends on the operating conditions and the main factors are the junction temperature and the applied current. However, the origin and mechanism of degradation are still unclear.

It is generally accepted that the lifetime of a LED is defined as the time after which a ratio B% of a sample of LEDs emits an output power L% lower than the initial power. B50, L70 means that 50% of the LEDs from the tested sample emit 70% of the initial power after a time t. The test conditions are not yet normalized, therefore, comparison between manufacturers is still difficult. Figure 15 is showing the output power degradation over the time for a 285 nm SMD packaged LED operated at 350 mA. After 4000 hours of operations the degradation is on the order of just 10% and extrapolation shows that L70 is over 10000 hours.

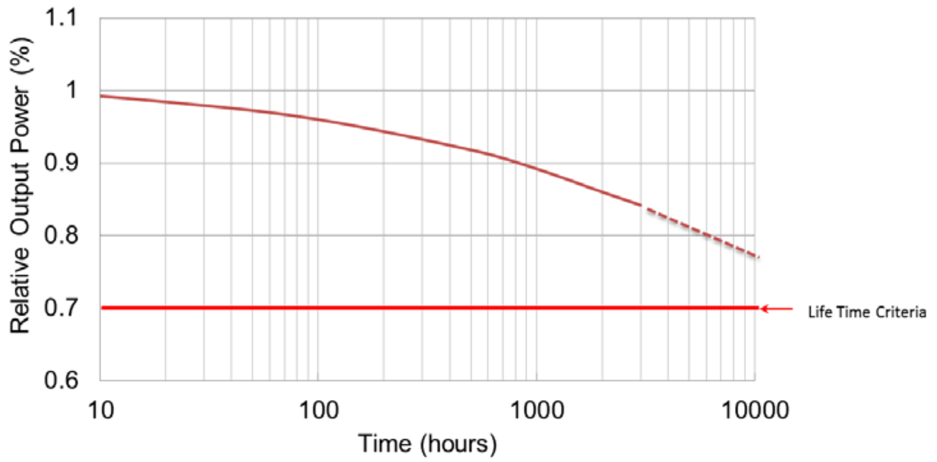

Figure 15: Output power degradation for 285 nm DUV-LED driven at 350 mA with Ts of 40℃

8.3. Application map

For UVA range (> 365nm), UV-LED has already reached irradiance of over 16 W/cm^2 competing with conventional UV light source. Until recently, although few applications could be addressed by DUV-LED, their limited performance, especially their low output power, was hampering their access to a wide range of applications. Nikkiso‘s target market goes from 255 to 350 nm and products with irradiance over 100 mW/cm^2 are already available within UVB range. Figure 1 is showing the UV-LED application map as a function of wavelength and irradiance.

In addition to device performances (wavelength, IQE, and driving voltage) related to layer structure and crystal quality. Chip, package, module design in term of optics and thermal management will strongly affect the maximum irradiance, the reliability and the design flexibility which can be achieved.

8.4. Cost consideration

DUV-LED have clear advantages compared to traditional UV light source. There is a large potential market for DUV-LED: for substitution and for new applications. For substitution, cost is a critical parameter for adoption. In addition to improved performance, DUV-LED systems have to be competitive to mercury lamp systems. As it is the case for visible LED, we can expect that DUV-LED will follow the Haitz's Law: the cost per Watt will decrease by one order in a decade. This is will be driven by technology progress allowing more and more output power per device and by the growing market demand that allows cost reduction due to larger production volume. Regarding technology progress, we observed significant improvement in the DUV-LED performance recently: more optimizations are under development not only in the LED-chip performance but also in thermal management, optical designs and reliability of the chip and of the package. In addition to higher chip performance, higher yield is possible thanks to dedicated and stable production system. For this purpose, in 2015 Nikkiso has started production in a new factory dedicated to DUV-LED allowing to control all the fabrication steps, from wafer epitaxy to chip packaging, including quality control and DUV-LED module development.

9. Conclusion

After several years of continuous improvement, DUV-LED performance reached finally a level allowing industrial applications. In this white paper we discussed about the specificity of the DUV-LED. Specificity compared to the well-known blue-LED in term of material property, fabrication and characteristics; specify of the semiconductor device compared to the conventional UV lamp technology, in terms of performance. Thanks to their small size, longer lifetime, and environmental friendliness, DUV-LED can access new applications such as portable devices or point-of-use disinfection systems where traditional UV lamps cannot be used.

Nikkiso is now ready to supply large quantities of high power single chip packaged DUV-LED with peak wavelengths ranging from 255 to 350 nm. In addition, we develop and provide customized solutions such as DUV-LED arrays, DUV-LED modules, and DUV-LED systems to address a large range of applications. In parallel, we are carrying on research projects to develop higher efficient devices.

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