TAIPEI TAIWAN LEDforum2015

NIKKISO

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Room 201, National Taiwan University
Hospital International Convention Center

- DUV-LEDs -
Development and Applications

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Presentation Outline

NIKKISO Original technologies

1. Introduction
   - ✓ Going to shorter wavelength
   - ✓ UV-LED vs traditional UV Lamp
2. Development and Performance of DUV-LED
   - ✓ Comparison InGaN-based LED / AlGaN-based LED
   - ✓ Evolutions of DUV-LED performance: IQE, LEE, EE
   - ✓ Characteristics of Commercial DUV-LED
   - ✓ Next Generation DUV-LED
3. Applications for DUV-LED
   - ✓ Module development
   - ✓ Analysis Applications
   - ✓ Disinfection Applications
   - ✓ Market evolution
4. Conclusion

Applications in UV Range

Below 300nm, large volume market for applications such as water, air or surface disinfection, and high added value market in medical or biochemical field

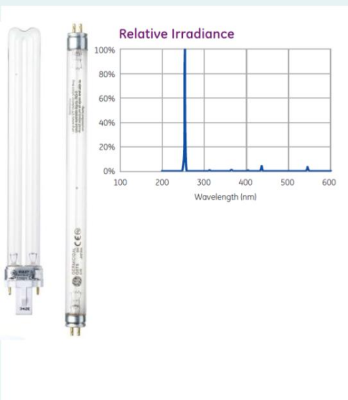
UV Range and UV Sources

Ultraviolet Radiation Range (ISO standard: ISO-21348):

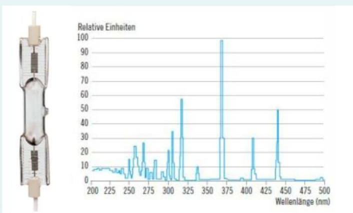
- ✓ 315nm～400nm･･･UVA
- ✓ 280nm～315nm･･･UVB
- ✓ 100nm～280nm･･･UVC

Sources of UV

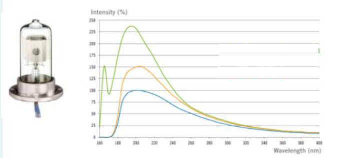
･Gas-discharge lamps	･UV-LED
(Mercury, Deuterium, Xenon…)	InGaN-based UV-LED (>360 nm) AlGaN-based Deep UV (DUV) LED (<360nm)



Germicidal Lamps
www.GElighting.com

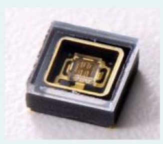


MP Lamp



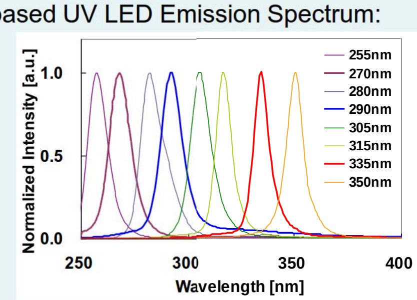
Deuterium Lamp
Hearaus NobelLight HP

TO-46- can package wo/w lens



3,5x3,5mm-sq SMD

AlGaN-based UV LED Emission Spectrum:



With their long history, traditional UV Light sources are well implanted and are able to deliver high output power but …

Advantages of UV-LED Systems

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Compare to traditional UV-Light Sources, UV-LED has significant Advantages:

- ✓ Shock resistant semiconductor
- ✓ Customizable emission wavelength
- ✓ Modulation of UV output power
- ✓ Easy integration (design flexibility, simple driving circuits, low voltage operation)
- ✓ Instant on/off => No warm-up/cool-down cycles, no shutter needed
- ✓ Diode lifetime in excess of 10,000 hours
- ✓ No mercury-filled UV bulbs
- ✓ No ozone production => No system exhaust

KUMAMOTO・MINAMATA 2013

By the Minamata Convention on Mercury, regulation on mercury will be strict from 2020.

=> With their low environmental impact DUV-LEDs are expected to replace mercury lamps in many applications and to access to new markets thanks to their specificity.

From Blue to UV-LED

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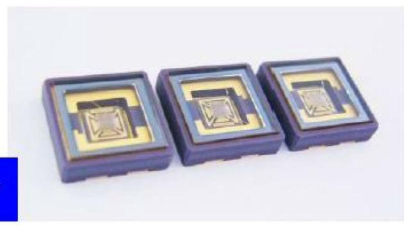
New Technology Frontier Related to Nitrides

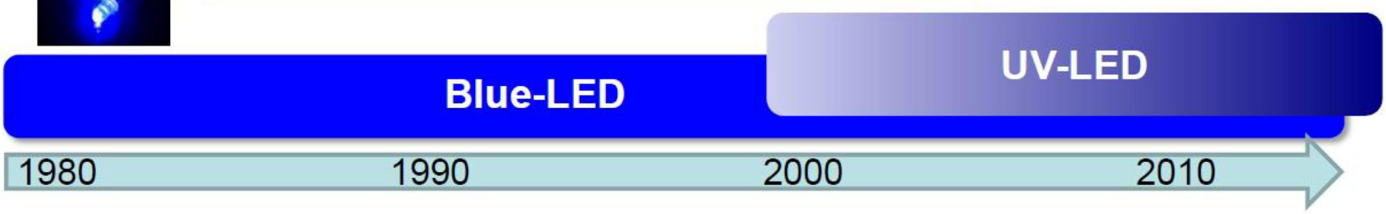
Prof. Akasaki, Meijo Univ.

Prof. Amano, Nagoya Univ.

the 2014 Nobel Laureates in Physics



From blue LED to UV-LED Technology



Background of Nikkiso's UV-LED Business

2006: UV Craftory, Nikkiso's subsidiary has been established as start-up company originating from UV-LED technology by professors Akasaki and Amano in Meijo University who are the 2014 Nobel winners in Physics.

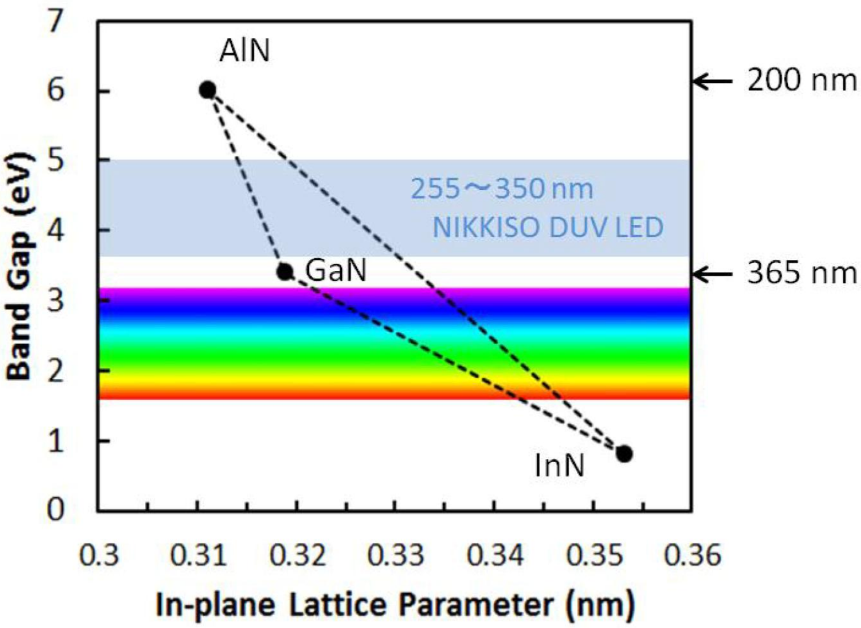
2012: Nikkiso's UV-LED samples were supplied to some domestic customers.

2013: Nikkiso purchased the property (both land and buildings) for UV-LED mass production in Hakusan, Ishikawa, Japan.

2014: Hakusan factory achieved ISO9001:2008 for its quality management system.

2015: Starting Mass Production of 30 mW high power SMD product.

Band Gap and Emission Wavelength



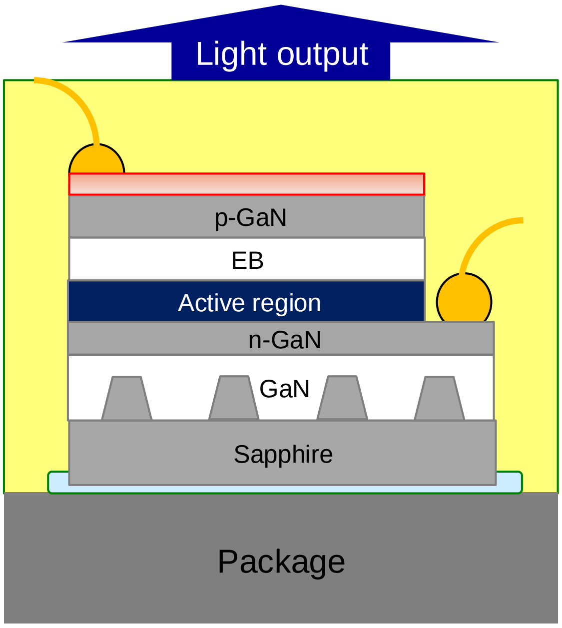
・DUV-LEDs are based on AlGaN ternary alloy. By changing Al% in the active layer, it is possible to tune the emission wavelength

・GaN can not be used as template as it is absorbing wavelength below 365nm.

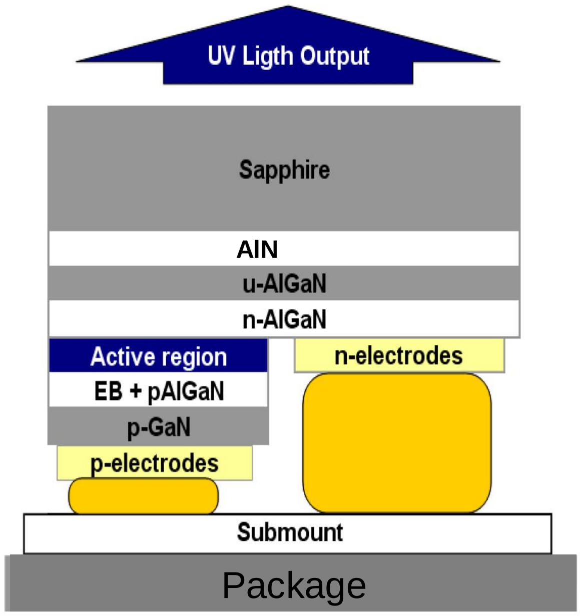
Even small difference in lattice parameter may induce stress, cracks, dislocations:
⇒ fine optimization of growth parameters is necessary to obtain devices with high crystal quality

Device Structure Comparison

InGaN-based LED :



AlGaN-based DUV-LED :



<u>Compare to InGaN-based LED, DUV-LEDs have several constraints:</u>

- Use of PSS substrate difficult for AlN/AlGaN growth
- High resistivity of AlGaN layers with high Al mole fraction
- Very low hole carrier concentration for p-type AlGaN
- Absorption of DUV light by pGaN layer
- No appropriate resin materials transparent and resistant to DUV light

Performance Comparison

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	>90%	<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	$	$$$$

※ Best values are greatly depending on the measurement conditions and on the overall performance.

IQE Optimization (1): AlN Template Fabrication

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- Template will affect the crystal quality, the Al mole fraction and the stress of the overgrowth AlGaN layer

Approach	Growth Method	Crystal quality	Growth Challenge	DUV LED EQE	Availability
AlN on Sapphire	-MEMOCVD -Pulse-flow -High Temp -HVPE	-DD～10^9cm^{-2} -Smooth (DD: Dislocation Density)	Lattice mismatch, cracks	EQE 6.5% (>10% for improved LEE)	Up to 4 inch (demonstrated)
ELO AlN	-on Patterned Sa -on Patterned AlN	-DD<2x10^8cm^{-2} -pits	Need regrowth, and thick layer , coalescence difficult	EQE 3%	Difficult for large diameter, Cost (need process, regrowth, thick growth)
Bulk AlN	-Sublimation -PVT	-DD<10^5cm^{-2} -Smooth	UV Transparent Layer, Low Al% AlGaN regrowth	EQE 3% (270nm)	1 inch available (high cost), 2 inch (R&D stage)

- "High quality AlN is very difficult to grow due to a narrow growth window, strong parasitic reactions at elevated temperature" (Y. A. Xi APL89, 103106, 2006)

➢ At Nikkiso, we developed a stable growth process on Sa in order to have high quality, uniform and reproducible AlN template.

Growth of DUV-LED on sapphire remains the competitive approach

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IQE Optimization(2): Device Structure

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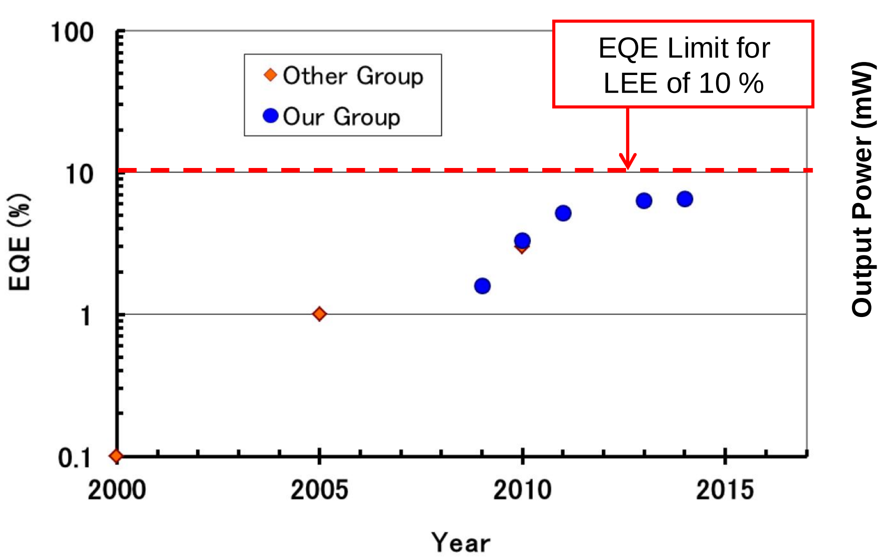
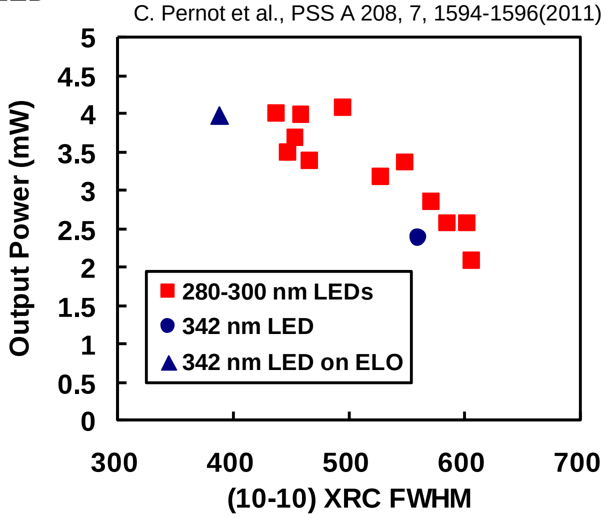
Evolution of EQE

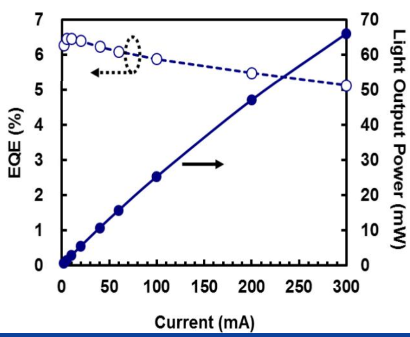
Bare chip measurement under same condition for 280-290nm LED



C. Pernot et al., PSS A 208, 7, 1594-1596(2011)

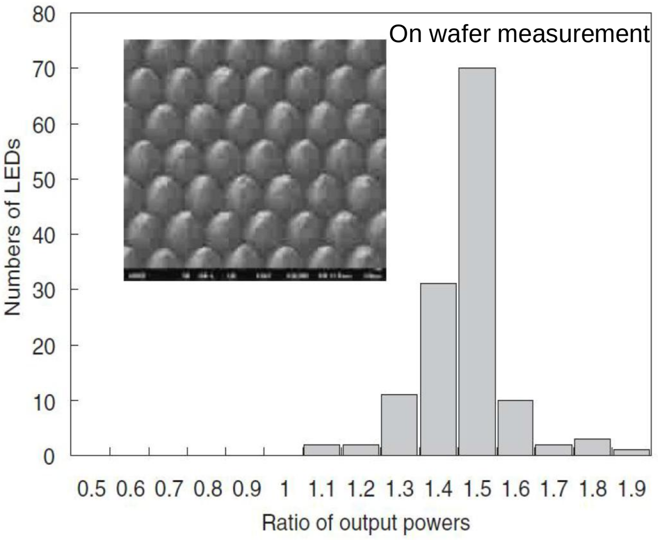


289nm bare chip (2013): EQE = 6.5% @ 10mA
WPE = 5.0 % @ 10mA

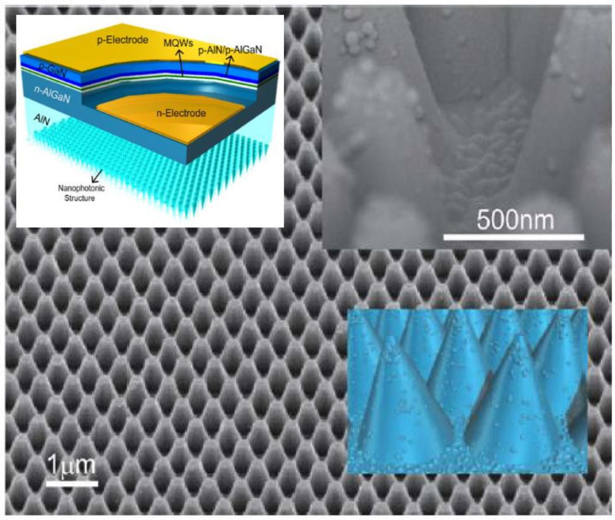


Best EQE results obtained at low current
=> presence of droop at high current

LEE Optimization (1): Surface Roughening



C Pernot et al. Appl. Phys. Express 3 (2010) 061004

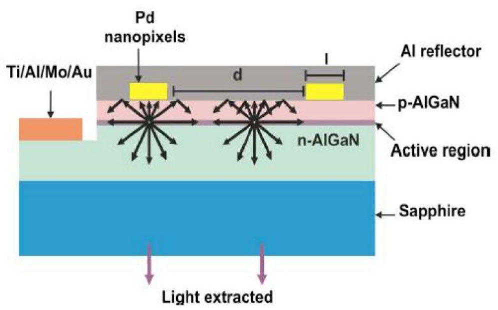


Inoue et al. Appl. Phys. Lett. 106, 131104 (2015)

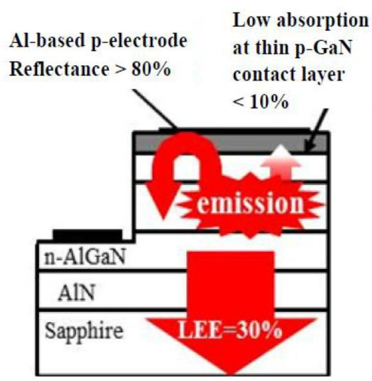
・Sapphire substrate with Moth-eye pattern on back side:
→On wafer Improvement of Output Power by×1.5

・Hybrid nano photonic pattern on back side of AlN substrate
→Output Power×1.96 265nm LED with EQE of 6.3%

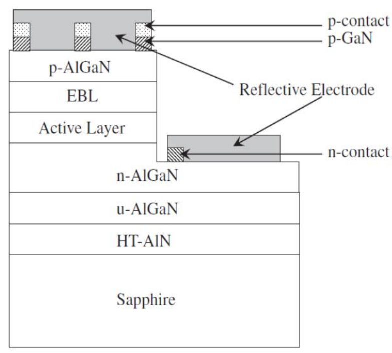
LEE Optimization(2): Reflective Electrodes



Lobo et al. Appl. Phys. Lett. 96, (2010) 081109



Akiba et al. PSS C, 9, (2012) 806



Inazu et al. J. J. Appl. Phys. 50 (2011) 122101

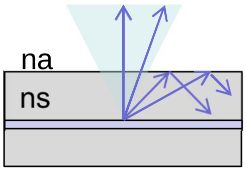
・Nano pixels contacts (390nm LED) with high reflective electrodes
Output Power x 1.9 (Vf increased by about 2V @100mA)

・Very thin p-GaN contact layer with high reflective electrodes
p-GaN thickness < 10nm (>65% transmission) => Output Power x 1.2 (Vf not mentioned)

・Mesh p-GaN contact layer with high reflective electrodes
Output Power x 1.27 (x1.55 when combining with n-reflective electrodes).
Voltage increase by 0.45V (20mA)

=> Trade-off between LEE improvement and Vf increase

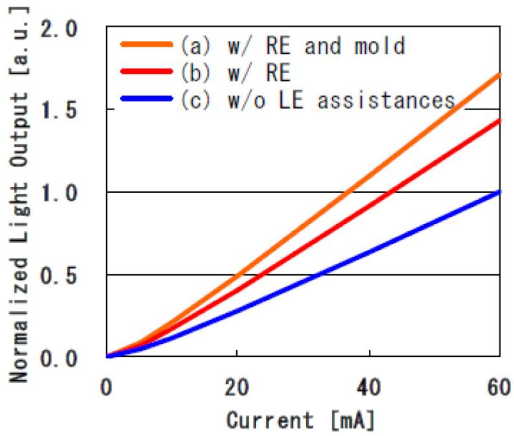
LEE Improvement (3): Encapsulation



internal refractive critical angle: $\alpha_c = n_a/n_s$
$\Rightarrow$ In case of Air/ Sapphire : $\alpha_c = 33.7°$ (@300nm)

To improve light extraction efficiency, resin for encapsulation is actively researched
In addition to LEE, mechanical and electrical reliability can be improved

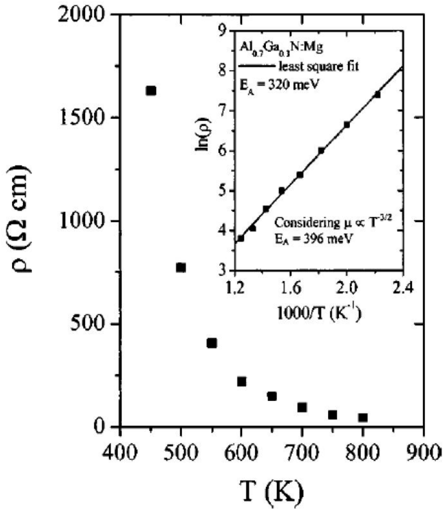
Resin materials should present:
- ✓ Good transparency to DUV radiation
- ✓ Low degradation when exposed to UV light
- ✓ Refractive index between Air and Sa (AlN)
- ✓ Good adherence to the chip
- ✓ Robustness to environment (not too soft)
- ✓ Half-ball shaping for efficient light extraction



Inazu et al. Spring Oyobutsuri Conf. 2011

LEE x 1.2 for 290nm LED on Sa (our group)
LEE x 2 for 270 nm LED on thinned AlN, J.R.Grandusky et al. APEX6 (2013) 032101
LEE x 1.35 for 278nm LED on Sa, M.Shatalov et al. APEX5 (2012) 082101

EE Improvement (1): p-AlGaN



Nakarmi et al. Appl. Phys. Lett. 86, 092108 (2005)

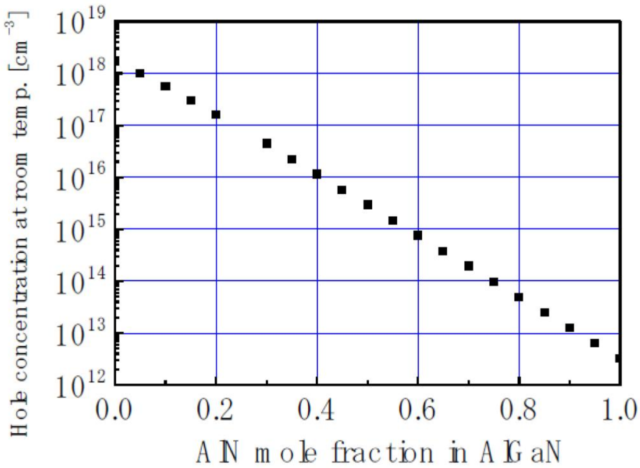
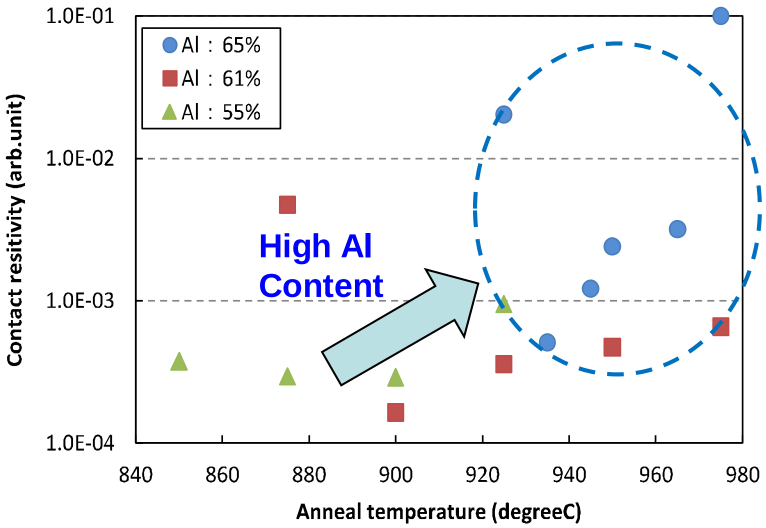


Fig. 8 Maximum hole concentration at room temperature in AlGaN.
H. Amano et al. Proc. Of SPIE Vol. 7216 (2009)

・For Al mole fraction of 70%, activation energy of Mg acceptor is 320 meV.
・Hole carrier concentration decreases as the Al molar fraction increase in Mg-doped AlGaN layers.
=> Current DUV-LED devices are using thin pAlGaN layers for p-clad, and pGaN for contact layer.
・New dopants, short period super lattice , different semiconductors, new approach are under investigations for improving p-type layers.

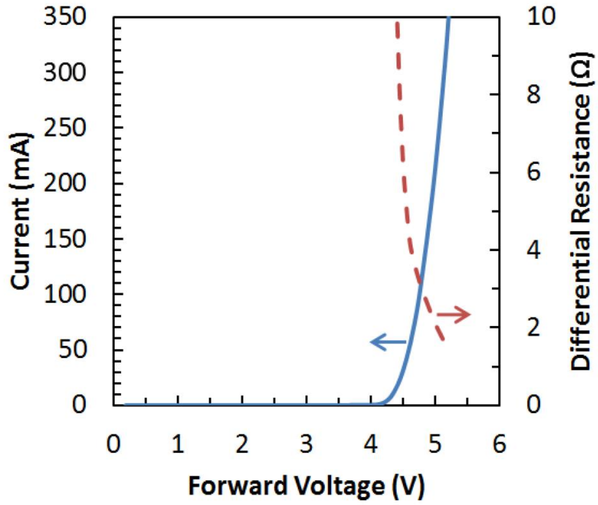
EE Improvement (2): n-AlGaN

n-Contact Resistivity - Annealing Temperature



Inazu et al. Autumn Oyobutsuri Conf. 2015

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

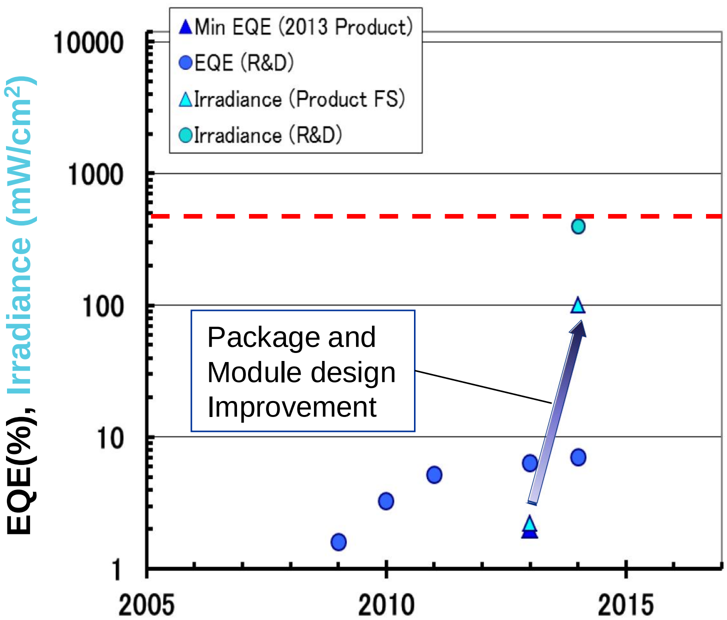


Pernot et al. IEEE. 2015

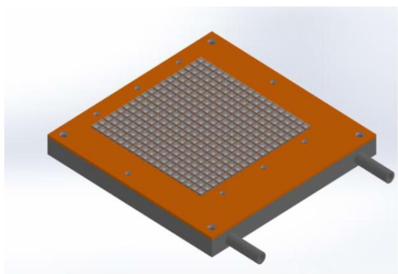
- Up to 70% AlGaN, n-type layers with sheet resistance below 60 Ω/☐ can be fabricated
- Optimization of n-contact annealing temperature is depending on Al mole fraction
- As the Al mole fraction is increased the process window is becoming narrow

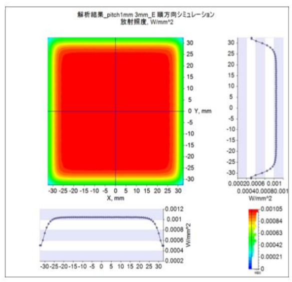
By optimizing every parameters, DUV-LED with low forward voltage can be obtained.

Irradiance Optimization



High Density Packaging Array:





UV-LED 3.5x3.5mm2 SMD x 324pcs

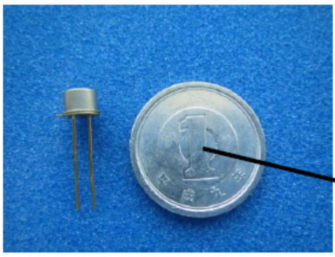
Peak Wavelength	Work Distance	Irradiance	Uniformity of irradiance
265nm	3mm	57mW/cm^2	50mmsq
285nm	3mm	104mW/cm^2	50mmsq
300nm	3mm	104mW/cm^2	50mmsq

- To obtain high Irradiance DUV Module => high density array

⇒In addition to LED high and uniform output Power, Package/Module Thermal management and Vf uniformity are key parameters for high power applications

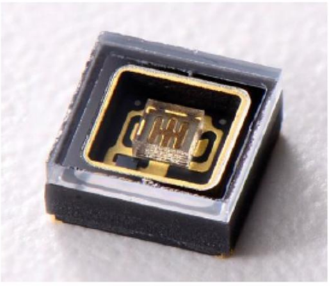
DUV-LED Products and Characteristics

【TO-46 can】



1JPY coin
(20mm dia.)

【3.5 x 3.5 mm-sq SMD】



standard TO-46 can

Item		Unit	265nm	285nm	300nm
Forward current	I_F	mA	15	20	20
Forward voltage	V_F	V	5.0~7.0	4.5~6.0	4.5~6.0
Emission intensity	P_O	mW	0.4	1.3	1.3
Peak wavelength	λ_P	nm	265+/-5	285+/-5	300+/-5
Full width at half maximum	$\Delta\lambda$	nm	<15	<15	<20
Directional half power angle	$2\theta_{1/2}$	deg.	80	80	80

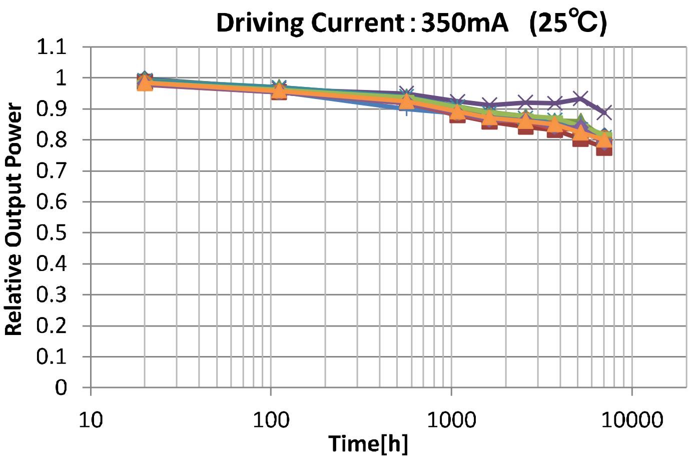
standard SMD

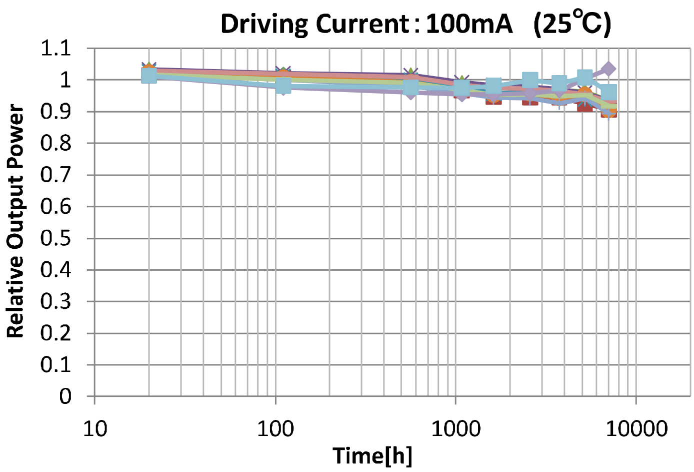
Item		Unit	265nm	285nm	300nm
Forward current	I_F	mA	350	350	350
Forward voltage	V_F	V	5.0~9.0	5.0~8.0	5.0~8.0
Emission intensity	P_O	mW	>10	>25	>25
Peak wavelength	λ_P	nm	265+/-5	285+/-5	300+/-5
Full width at half maximum	$\Delta\lambda$	nm	<13	<15	<17
Directional half power angle	$2\theta_{1/2}$	deg.	130	130	130

DUV-LED Lifetime

Temperature and driving current are affecting lifetime of the DUV-LED device
By growing high quality DUV-LED, lifetime over 10000 hours can be achieved.

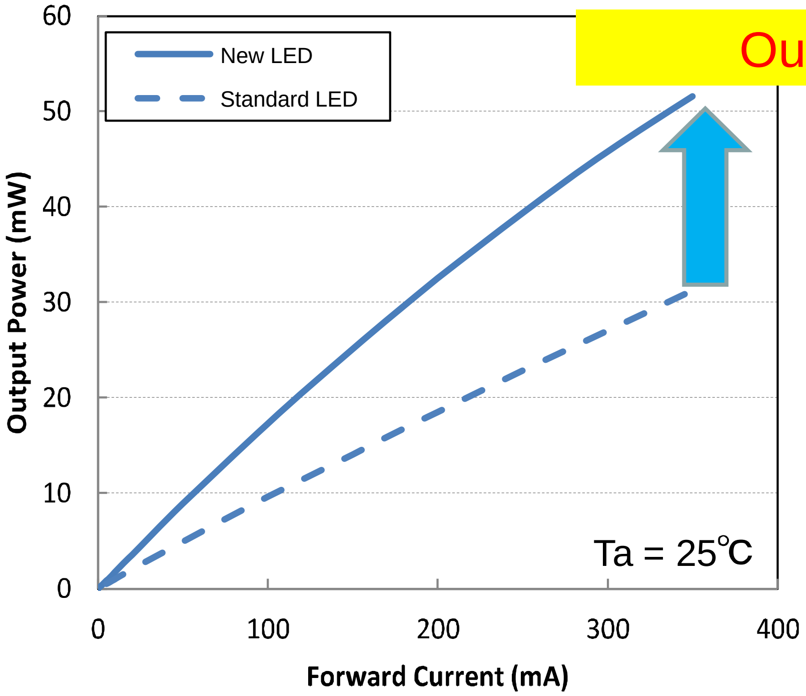
Output power evolution for 285 nm DUV-LED:

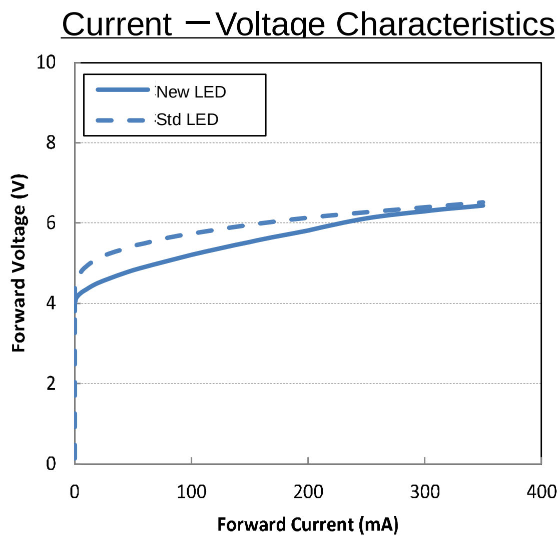




Next Generation DUV LED

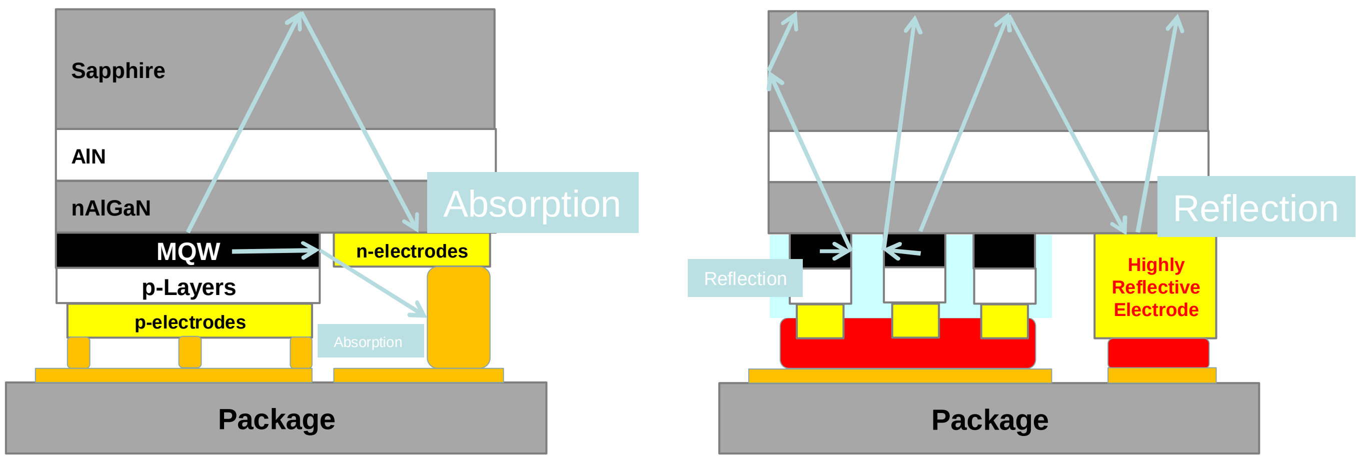
I－L Characteristics





Achievement of 50 mW at 350mA driving current

Optimization of Chip Light Extraction

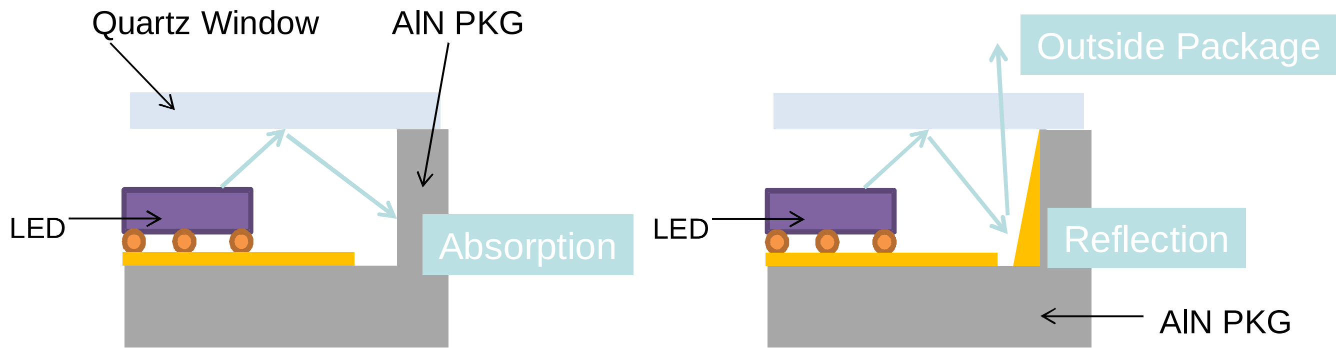


Standard Device

New Device

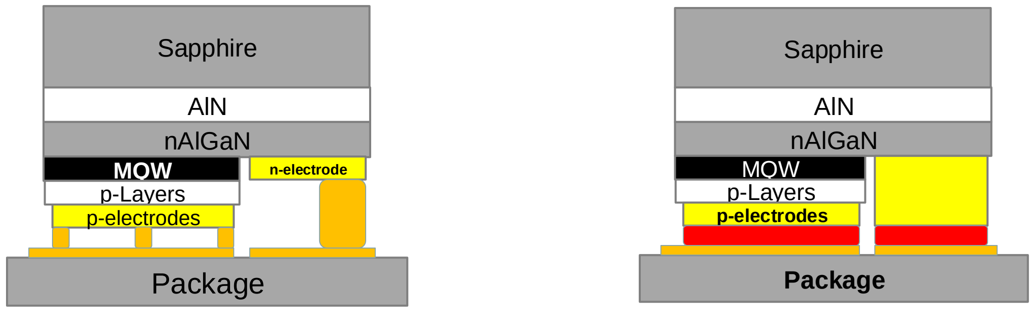
=> By inserting reflective surfaces on the back side of the chip (n-electrodes, mesa side area), it is possible to limit absorption, and to improve the light extraction of the device

Optimization of Package



Standard Device New Device

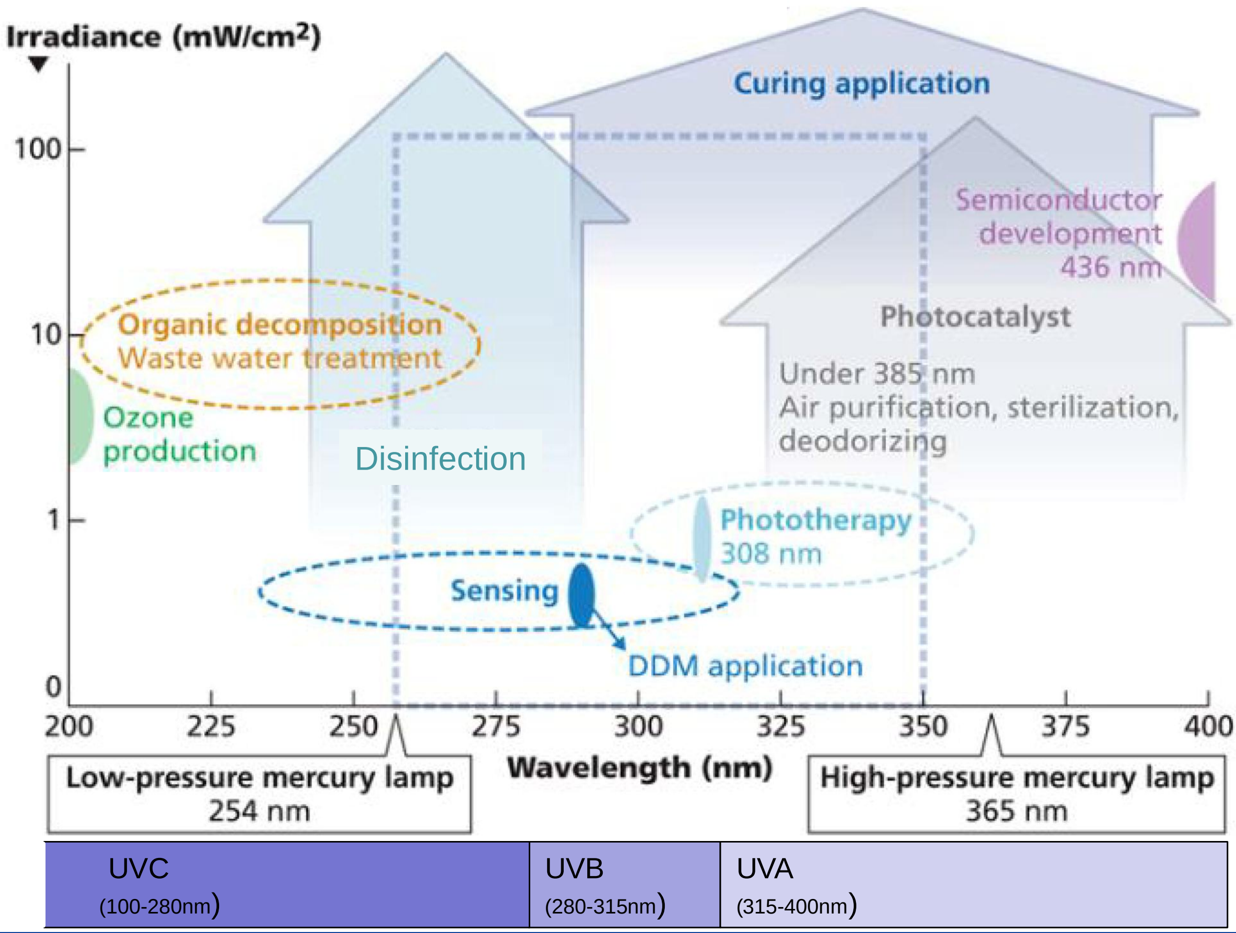
⇒ Improvement in Package Light extraction by using highly reflecting material and shape



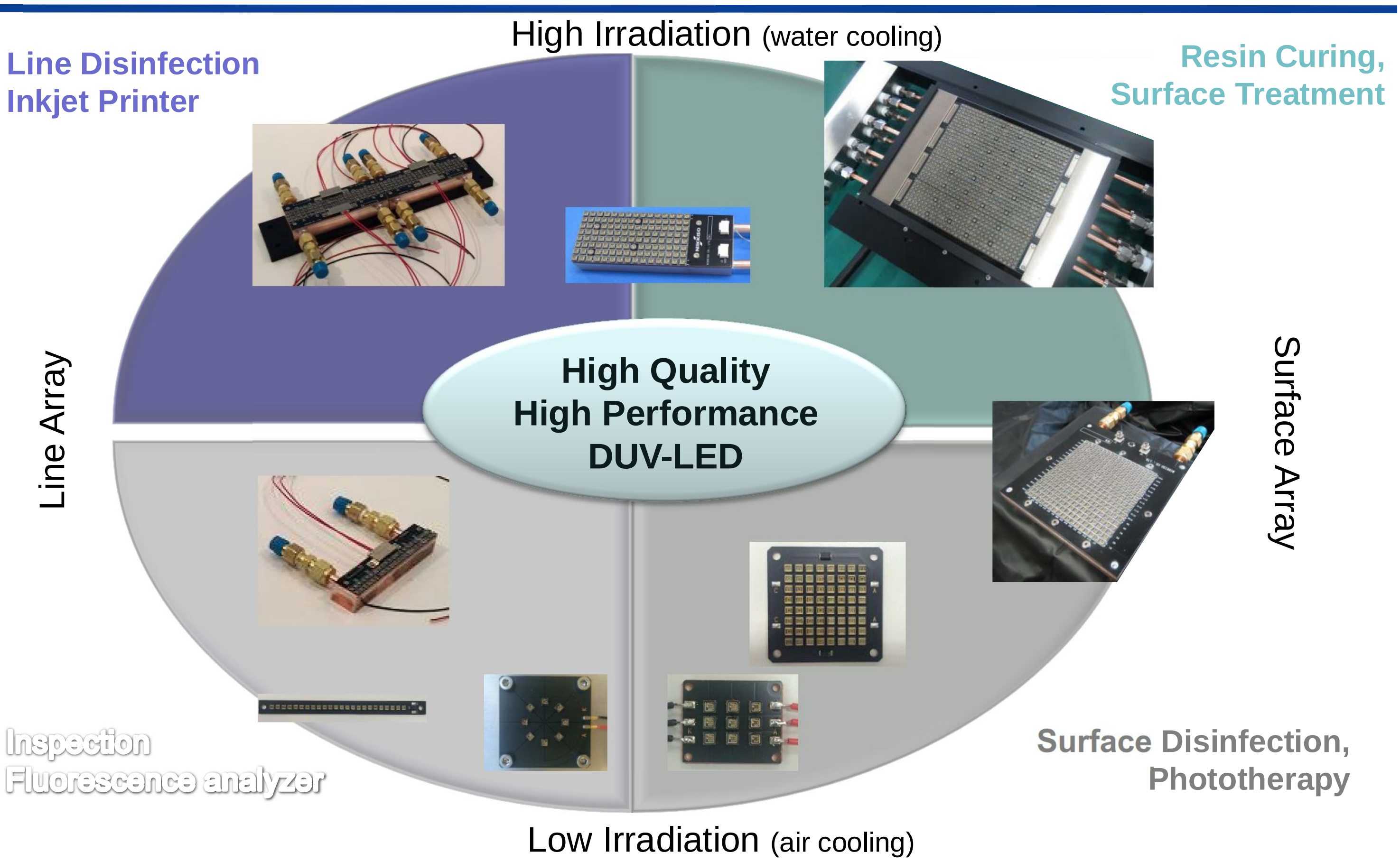
Standard Device New Device

⇒ By increasing the contacting surface area between chip and package, the thermal resistance of the device is significantly decreased (15 K/W => 9 K/W)

UV-LED Applications Map



Module Development

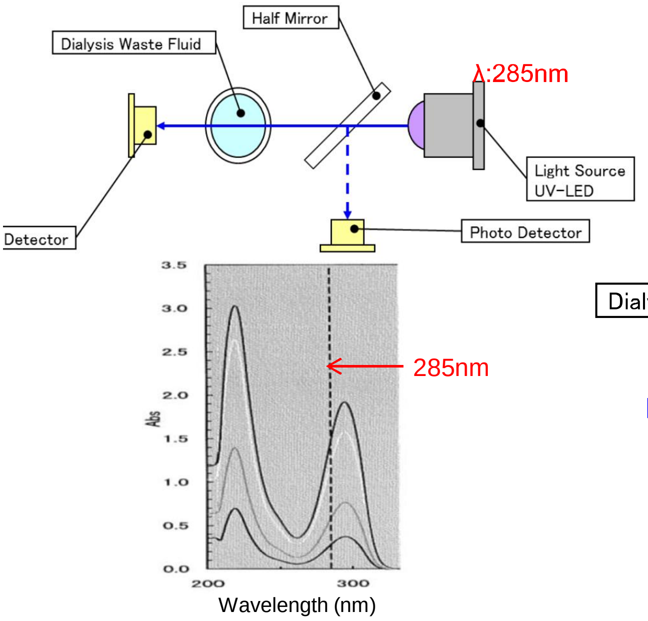


⇒ Depending on applications, development of optimized module solutions

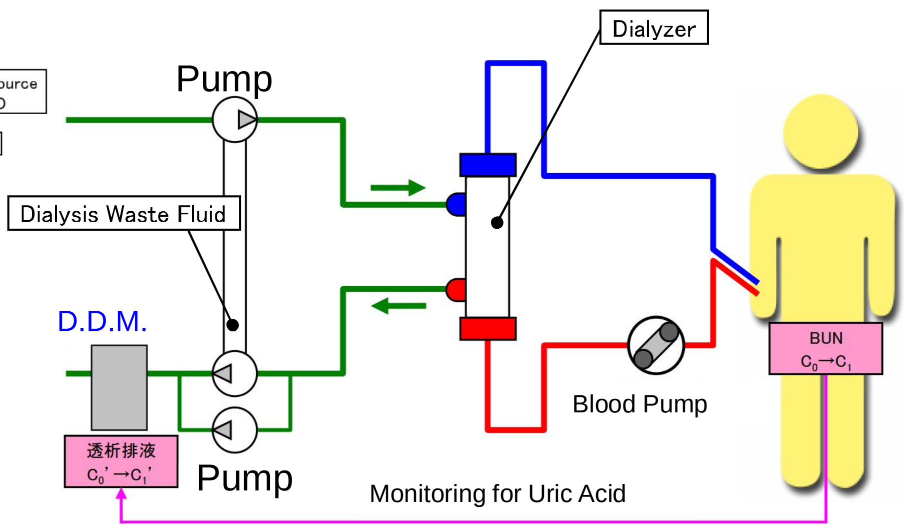
UV-LED for Sensing Application

Example of Dialysis Dose Monitor (DDM)

- Measurement of uric acid concentration contained in dialysis waste fluid
- Uric acid is measured by absorption spectroscopy with DUV-LED as light source



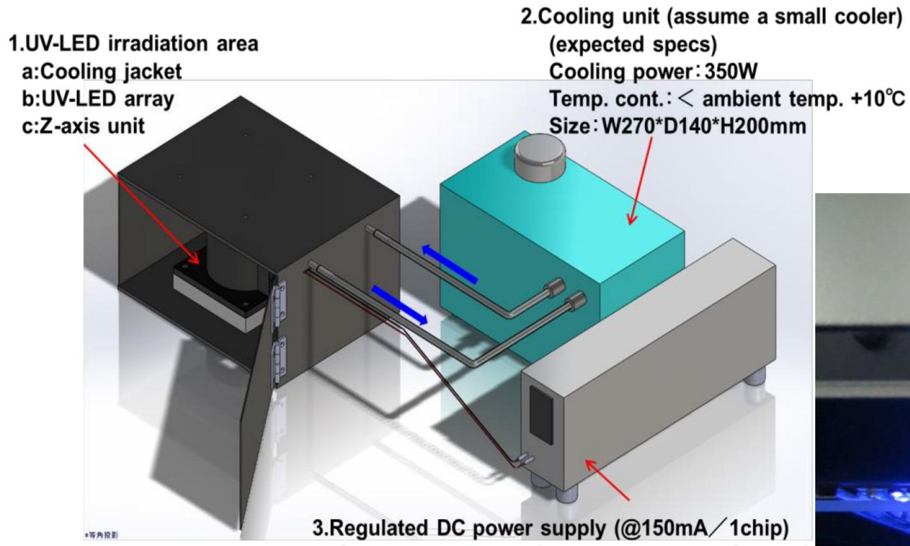
Absorption Spectra of Uric acid



Other Potential Analysis applications include measurement of :

Ozone, Protein, SO_x, NO_x, Chlorine, DNA/RNA, Oil, Bromic acid

Module for Curing Applications



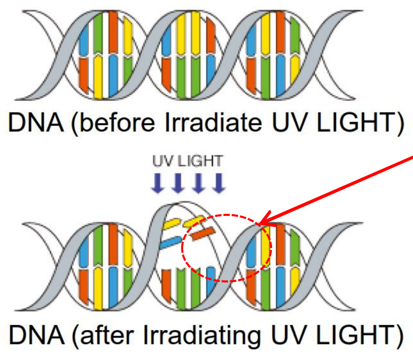
Customized modules designs based on customers needs are possible thanks to Nikkiso's know-how and simulation tools in optics, fluid dynamic and thermal analysis,

960 x 3.5mm-packages
Irradiance of 80 mW/cm^2
at a working distance of 10 mm
over an area of 25 x 25 cm^2

Disinfection by UV Light

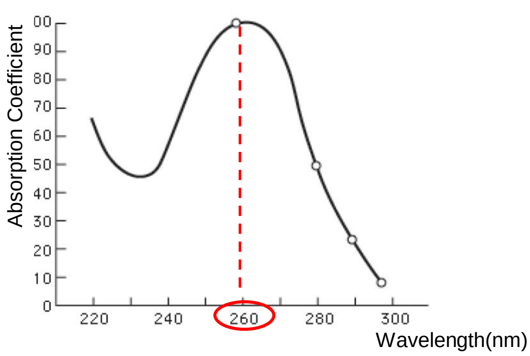
When living microorganisms such as bacteria are exposed to UV-C light between 250nm and 280nm (germicidal action spectra), their DNA can be effectively destroyed and inactivated by UVC; DNA cannot reproduce itself ⇒ Disinfection

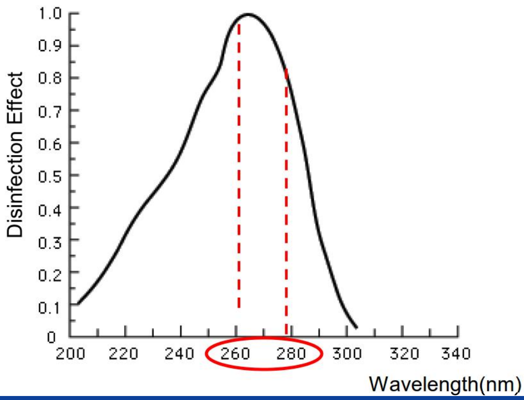
Principle



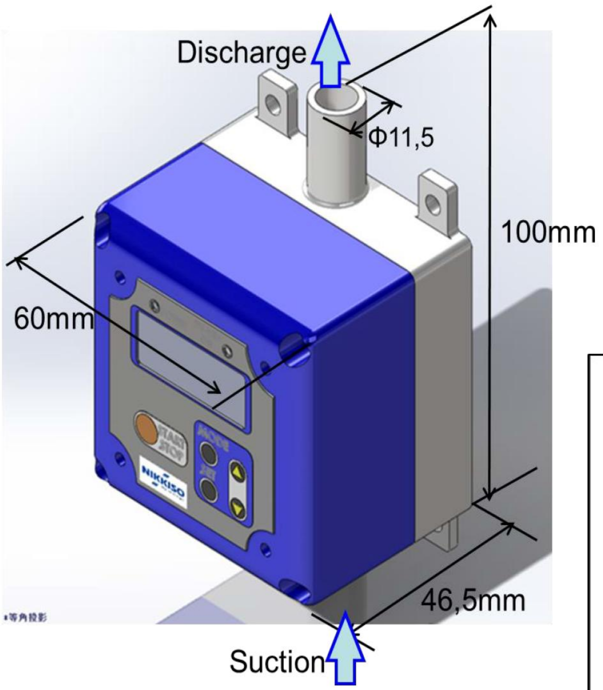
DNA: Deoxyribonucleic Acid

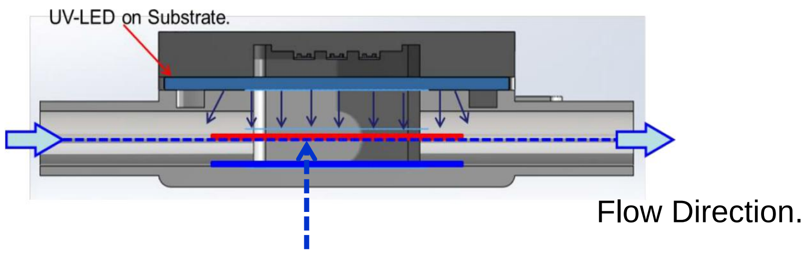
DNA can be destroyed and inactivated by UV light irradiation.



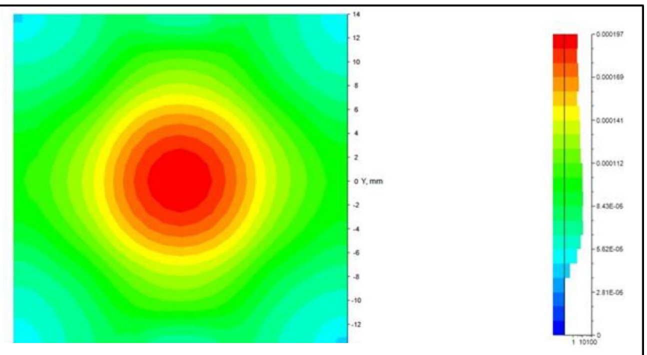


Prototype Module for Water Disinfection: Design





Optical Analysis Surface



Average Irradiance : 10mW/cm²

Product released in 2014

Prototype Module for Water Disinfection: Results

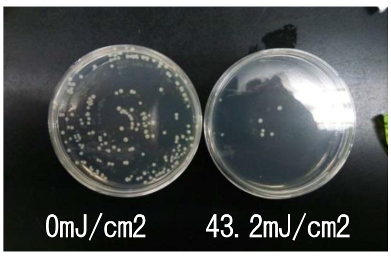
<3x3 LED-array>
Irradiance (center area)
> 40 mW/cm² (285 / 300 nm)
> 15 mW/cm² (265 nm)
If = 350mA
Work distance: 10 mm
Array size: 24 x 29 mm²

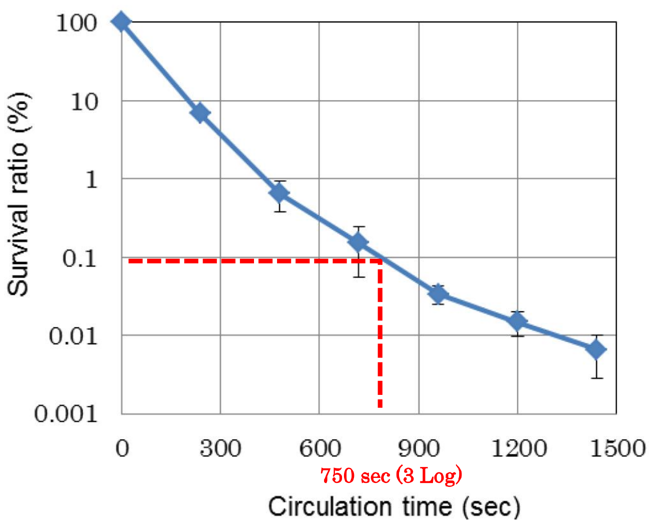
Disinfection data for 10 mW/cm² (wavelength: 285 nm)

Initial number of bacteria: 10Million cfu/ml
(E. Coli : JCM1649)

- Tank size: 1 L
- Flow rate: 2 L / min

Tests conducted at
Japan Food Research Laboratories



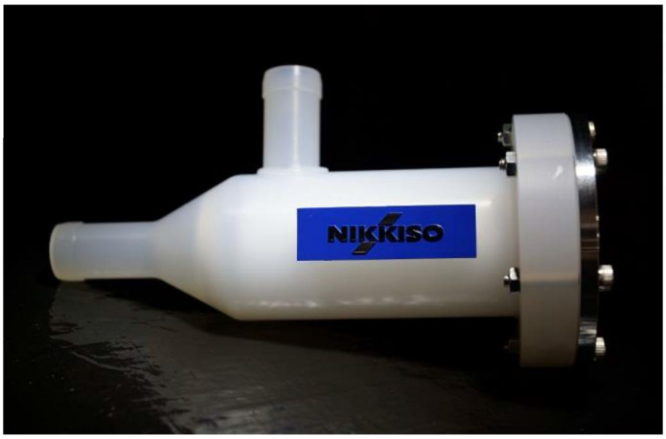


New Modules for Water Disinfection

NIKKISO Original technologies

Low Flow Rate Type (2 L/min):

For integration in drinking water equipment and various systems



Medium Flow Rate Type (10 L/min):

Home, hotel medium flow rate water disinfection

Specifications are subject to change without notice.

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New Modules for Water Disinfection

NIKKISO Original technologies

■ Specifications (Target)

Item		Units	2L/min Type	10L/min Type
Water	Fluid	-	Clear Water	Clear Water
	Density	-	1	1
	Viscosity	mPs・s	1	1
	Transparency	%/cm	Above 95%@280nm	Above 95%@280nm
Germicidal performance * Mortality of E. coli in rated flow		%	99.9%	99.9%
Specifications	Flow	L/min	2	10
	Pressure	MPa	0.5	0.5
	Current	mA	350	700
	Power	W	2.1	8.4
	Size	mm	Φ70 x L160	Φ110 x L215
	Weight	g	200	900
	Piping diameter	mm	Inlet： Φ14 Outlet： Φ14	Inlet: Φ19 Outlet: Φ14

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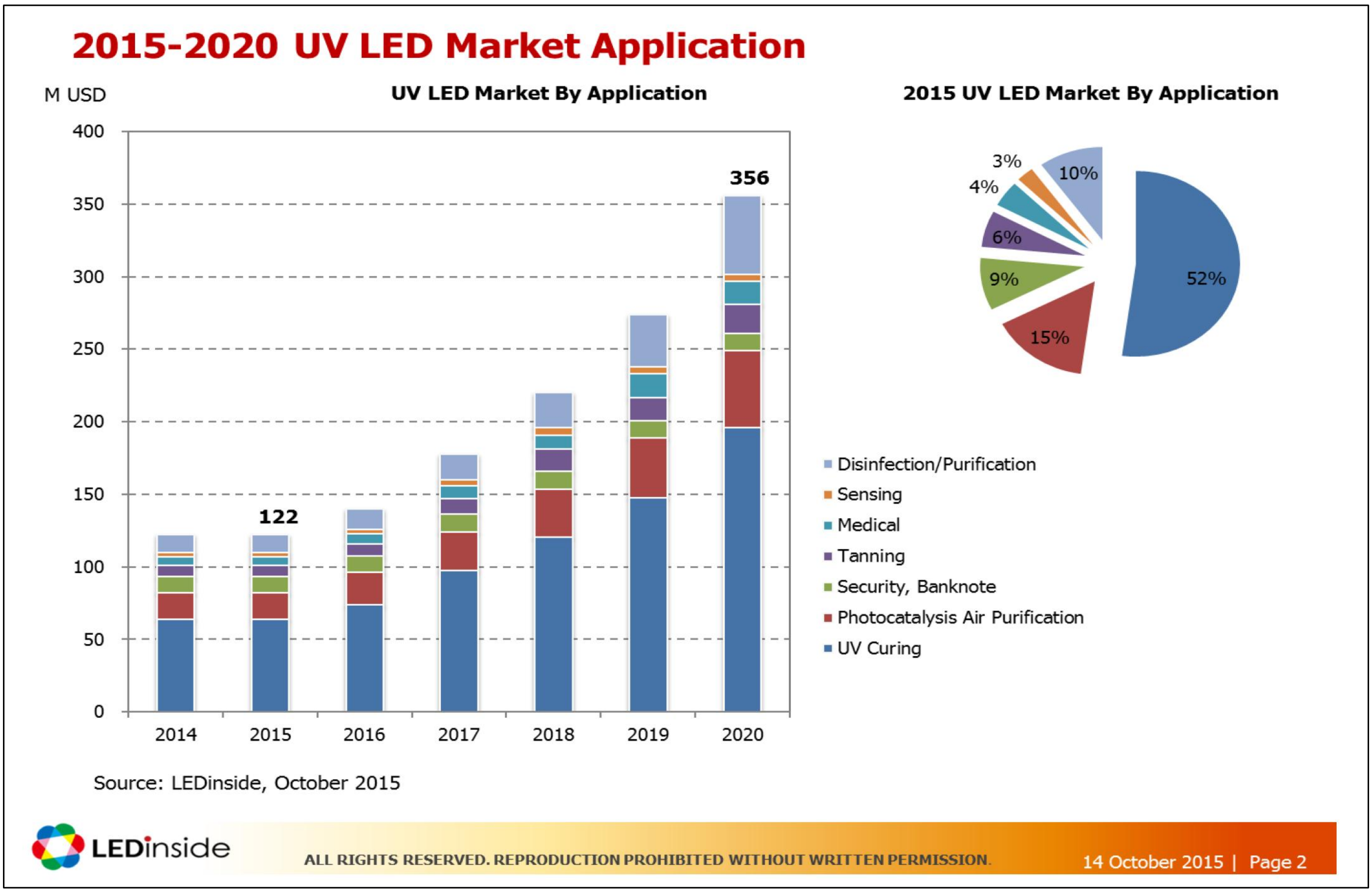
UV-LED Market



Conclusion

- DUV-LED has some clear advantage compared with traditional UV light source
- After several years of continuous improvement, DUV-LED performance reached finally a level allowing industrial applications.

- For DUV-LED devices, thanks to recent improvement in
  - Electrodes design and process
  - Chip and Package Light extraction
  - Device thermal management

⇒ We achieve 285 nm DUV-LED with 50 mW Output Power at 350 mA

- For DUV-LED applications: to access the large potential markets, we are developing specific module solutions for each applications.

⇒ For disinfection market, recent development include water disinfection modules with 99.9% germicidal performance in a single-pass for 2 to 10 L/min flow rate.

Thank you for your attention !