Deep UV-LEDs based on group III-nitride for water disinfection applications

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Deep UV-LEDs based on nitrides for water disinfection

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OUTLINE:

UV disinfection concept

UV light sources

State of the art in nitride based UV-LEDs

UV-LEDs: Material and device issues

Discussion
UV disinfection

Covalently bonded thymine neighbors

Wavelength (nm)

UV absorbance (a.u.)

ADENINE
GUANINE
THYMINE
CYTOSINE

UV photon

UVC
100 – 290 nm
UVB
290 – 320 nm
UVA
320 – 400 nm

Deep UV
200-300 nm

Water absorption coefficient 1/cm

Average DNA absorption spectrum
Actual UV system

LP (LPHO) Hg-lamps
- narrow emission peak, $\lambda=254$ nm
- operating power = 15-200 W
- operating temperature = 40°C
- conversion = 30-35 %
- Ideal for small treatment volume

MP Hg-lamps
- wide emission, $\lambda=190\div350$ nm
- operating power = 0.4-7 kW
- operating temperature = 600-900°C
- conversion = 15 %
- treatment volume = 600 m$^3$/h

Spectral power distribution
What is a LED?

Solid-state light source which converts input electrical energy into output optical radiation at the desired wavelength, depending on the semiconductor material.

Light Emitting Diode (LED)

- Multiple chip LED lamp
- 32 LEDs array
- 5-9 mm chip diameter
- ~15 nm FWHM

Graph showing:
- CW Optical Power (mW) vs. CW Current (mA)
- SPD (mW/nm) vs. Wavelength (nm)
- Case Temperature (°C)
deep UV-LEDs vs Hg-Lamps

Robustness
Compact light source
Environmentally safe
Faster start-up time
Longer lifetime (26,000 h)
Low power consuming
Low cost

Emission wavelength tunability

Highly toxic (disposal problems)
Fragile
Bulky
Limited lifetime (4,000-12,000 h)
High power consuming

UV-LEDs vs Hg-Lamps

Selectivity
Ideal material system

Al$_x$Ga$_{1-x}$N based UV-LEDs
UV-LEDs: disinfection performances

4 multi-chip LED lamps
200 mW

λ=275-285nm
chip 1.5mm x 1.5mm
active area 1 mm²

First commercial prototype (May 2012)

λ=275nm

ETA SET i

λ=275-285nm

SET i

NSF testing procedures

Aquinonics and Dot Metrics Technologies
State of the art for UV nitride LEDs

\[ WPE = \frac{\text{output}_\text{optical}_\text{power}}{\text{input}_\text{electrical}_\text{power}} = \eta_{\text{EQE}} \frac{\hbar \omega}{eV} \]

\[ \eta_{\text{EQE}} = \eta_{\text{inj}} \times \eta_{\text{rad}} \times \eta_{\text{ext}} \]

Material quality

Device

Electrical Power

Optical Power
Al\textsubscript{x}Ga\textsubscript{1-x}N/GaN epitaxial growth process

MOCVD (Metal Organic Chemical Vapour Deposition)

Epitaxy=highly ordered growth

Material Issues

Lack of a suitable substrate (high lattice and thermal mismatch)

Low Al species surface mobility (3-D island growth)

Quantum confined stark effect

UV absorption of p-GaN contact layer

Precursor molecules
TMGa
TMAI
NH\textsubscript{3}

1. \text{energy}
2. \text{1180°C}
3. M
4. M

M: material to be deposited

Sapphire Al\textsubscript{2}O\textsubscript{3}

\eta_{rad}

\eta_{ext}
Al$_x$Ga$_{1-x}$N/GaN growth process at NNL-CNR group

High Temperature AlN buffer layer on sapphire substrate

- Reduce interfacial energy
- Increase nucleation density
- Enhance lateral growth

High quality continuous films
Flat growth
Low defect density $\sim 10^7$ cm$^{-2}$

1. Nucleation
2. Lateral growth
3. Coalescence
4. Quasi 2-D growth
Material: structural and optical properties

- Linewidth of X-Ray Rocking curve ~60 arcsec
- Density of threading dislocations ~$10^7$ cm$^{-2}$
- Root mean square surface roughness: 0.6 nm over 10x10 µm$^2$

HRXRD

HRXRD

AFM

UV-vis transmittance

SEM

J. Appl. Phys. 105, 063510 2009
Planned strategy

Design of an ideal architecture

Refinement of microfabrication process
(transparent p-contact based on graphene, optimization of carrier injection)

Development of Al\textsubscript{x}Ga\textsubscript{1-x}N based UV-LEDs with high optical power
CONCLUSIONS

- UV-LED device represents an attractive substitute to the commercial UV light sources for water disinfection applications because of its emission wavelengths tunability, compact form, non-toxicity, long lifetime and low power consumption.

- Bench-scale tests have demonstrated the effectiveness of UV-LEDs on different microorganisms using low flow rate but higher optical powers are required for wide scale implementation.

- By improving device design and material quality should be possible to achieve adequate value of EQE and to customize it for appropriate microbial target.

- Nitride based UV-LEDs have advanced from less than 0.1% EQE to 14% over the past ten years and further improvements are expected in the future as occurred for visible LEDs.