Advances & Challenges for AlGaN-based UV-LED technologies

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EQE of UV-LEDs: State-of-the-Art

M. Kneissl et al., Nature Photonics 13, 233 (2019)

External Quantum Efficiency

“Deep UV drop-off”

“UVB gap”

Emission Wavelength (nm)

200 250 300 350 400

0.01% 0.1% 1% 10% 100%

AlN  AlGaN  GaN

Bolb  Cree  Crystal IS  DOWA
Hexatech/Tokuyama  LG Innotek  Mitsubishi  Nichia  Nikkiso
Challenges for deep UV LEDs

- Ohmic (V), UV-reflective p-contacts (LEE)
- Low resistance (V), UV-transparent p-layers
- Efficient carrier injection (CIE)
- High IQE, carrier confinement (CIE), polarization control (LEE)
- Efficient current spreading, n-contact (V)
- Strain management
- Low defect densities (IQE)
- UV transparency & light extraction (LEE)
- Heat extraction, high-power ($P_{\text{max}}$)
Effect of dislocations on the IQE of UV-LEDs

Simulation parameters [3]:
- AlGaN-MQW LEDs
- $\lambda = 280$ nm, $j = 100$ A/cm$^2$
- No SRH from point defects
- Light extraction: $\eta_{extr} = 10\%$

[1] Ban et al., APEX 4, 052101 (2011)
**AlN/sapphire template technologies**

- **MOVPE AlN on sapphire**
  - TDD $\sim 4.0 \times 10^9$ cm$^{-2}$
  - Layer thickness: 1.5 µm

- **sputter. AlN on sapphire**
  - TDD $\sim 8.1 \times 10^8$ cm$^{-2}$
  - Layer thickness: 0.9 µm

- **MOVPE AlN on sapphire**
  - TDD $\sim 1.5 \times 10^9$ cm$^{-2}$
  - Layer thickness: 5.5 µm

- **sputter. AlN on sapphire**
  - HTA AlN**
  - TDD $\sim 8.5 \times 10^8$ cm$^{-2}$
  - Layer thickness: 5.5 µm

* Sylvia Hagedorn et al., phys. stat. sol. (a) 217, 1901022 (2020)
** Hideto Miyake et al., Applied Physics Express 9, 025501 (2016)
** Hiroyuki Fukuyama, Hideto Miyake et al., Jap. J. of Appl. Phys. 55, 05FL02 (2016)
CL of AlGaN MQWs on different templates

- AlGaN MQW heterostructures grown side by side on different AlN/sapphire templates by MOVPE
- TDD visualized by CL as their non-radiative recombination causes dark-spots
  → Lowest dark-spot-density (DSD) on HTA MOVPE ELO AlN/sapphire

planar AlN/sapphire

planar HTA AlN/sapphire

ELO AlN/sapphire

HTA ELO AlN/sapphire

DSD: 3.5 × 10^9 cm^-2

DSD: 1.1 × 10^9 cm^-2

DSD: 1.4 × 10^9 cm^-2

DSD: 0.9 × 10^9 cm^-2

Effects of TDD on IQE for different templates

- Good agreement between TDD determined by HR-XRD, panchromatic CL (DSD), and XTEM
- Clear correlation between IQE and TDD
  - Lowest TDD and highest IQE for MQW on HTA ELO AlN/sapphire

\[ \text{IQE} = \frac{\text{EQE}}{\text{LEE}} \]

Simulation parameters: \( j = 13 \text{ A/cm}^2, \mu_e = 120 \text{cm}^2/\text{Vs}, \mu_h = 6 \text{cm}^2/\text{Vs} \), TDD based on DSD determined by CL of MQWs, Karpov et al. model
Light extraction from UV-LEDs

Extraction via substrate

Paths of created photons

Poor light extraction efficiencies for UV-LEDs
(e.g. flip-chip mounted LED: LEE ~7%)

⇒ Need for enhanced light extraction

Encapsulation with UV-transparent polymers

⇒ Challenges: UV-absorption, low refractive index, long-term stability

UV-reflective contacts & UV-transparent p-side:

⇒ Challenges: Ohmic p-contacts, p-AlGaN layer resistance

LI characteristic of a UVC-LED

Flip-chip LED in SMD package
Non-reflective contacts
λ = 262 nm

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DUV-LEDs for in-vivo disinfection

- Light from DUV LEDs (<235 nm) does not penetrate living skin layers
  - ⇒ in-vivo disinfection without damage to human skin
- In-activation of multidrug resistant bacteria, e.g., MRSA, MSSA
- Disinfection of airborne viruses, e.g., SARS-CoV2, influenza
- Required DUV dose levels: 2 – 40 mJ/cm²

*Irradiation system with an array of 118 DUV-LEDs emitting at 233 nm*

*M.C. Meinke et al., Management & Krankenhaus 9, 20 (2020)*
Performance of 233 nm LEDs on sapphire

- Steep drop in EQE for shorter wavelength LEDs
- Degradation in light extraction (LEE), radiative recombination (RRE) & current injection efficiency (CIE)

=> Fundamental physical limitations or engineering challenge?

Summary

- Sputtered & high-temperature annealed (HTA) AlN layers on sapphire promising low cost, low TDD template technology for UVC-LEDs
- Reduced threading dislocation densities
  - Enhanced IQE, EQE and WPE
  - Improved lifetimes
- Further advances in UVC-LED efficiency will require enhanced light extraction, i.e. UV-reflective contacts, UV-stable encapsulation, …
- Pushing the wavelength limits of deep UV-LEDs (<250 nm)
  - 233 nm LEDs with 1.88 mW output power & EQE = 0.35%
  - Strong decrease in EQE for LEDs wavelength < 250 nm
    - Drop in in LEE, IQE, and CIE for wavelength < 230 nm
    - Advanced heterostructure designs for improved carrier injection
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