Advances & Challenges for AlGaN-based UV-LED technologies

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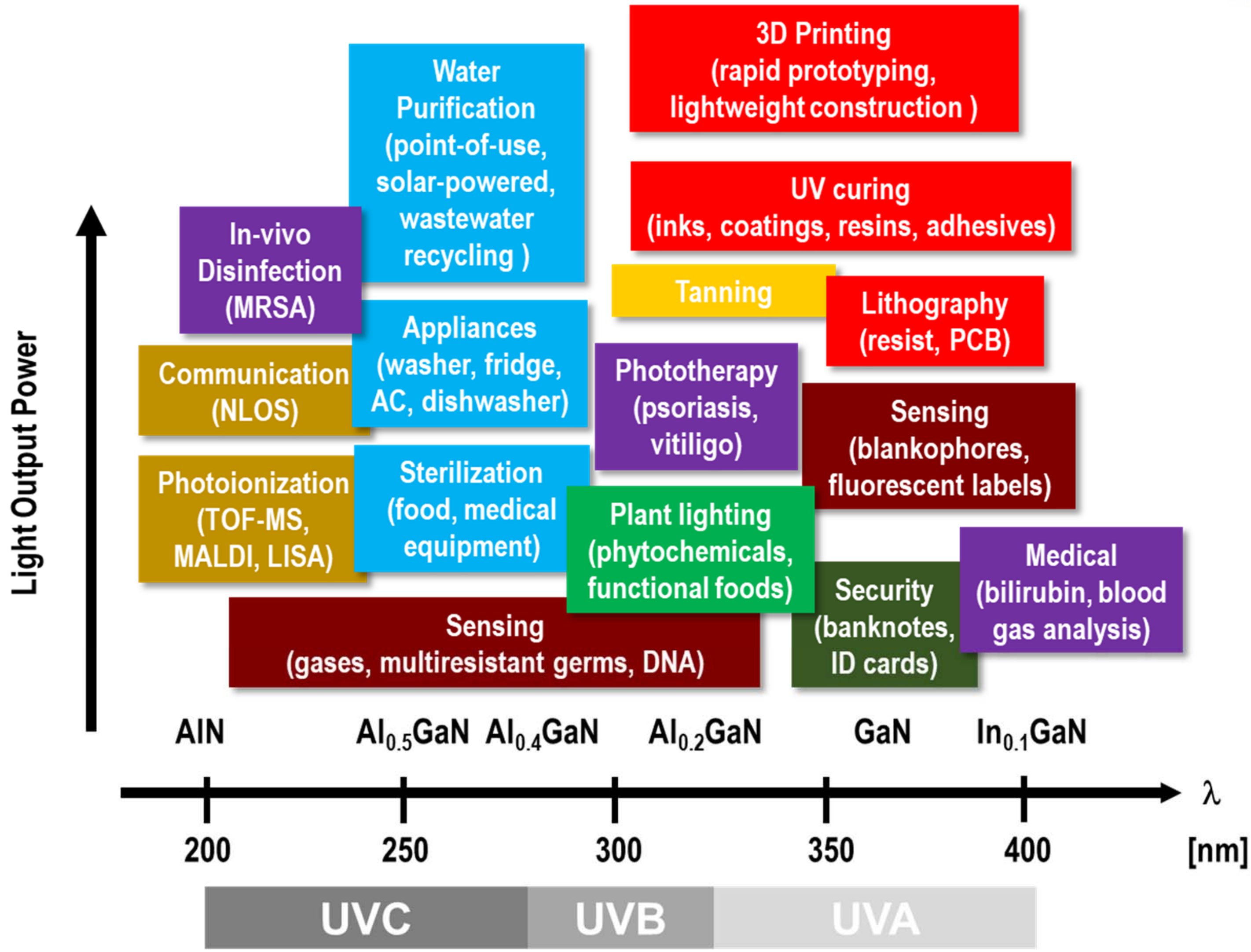
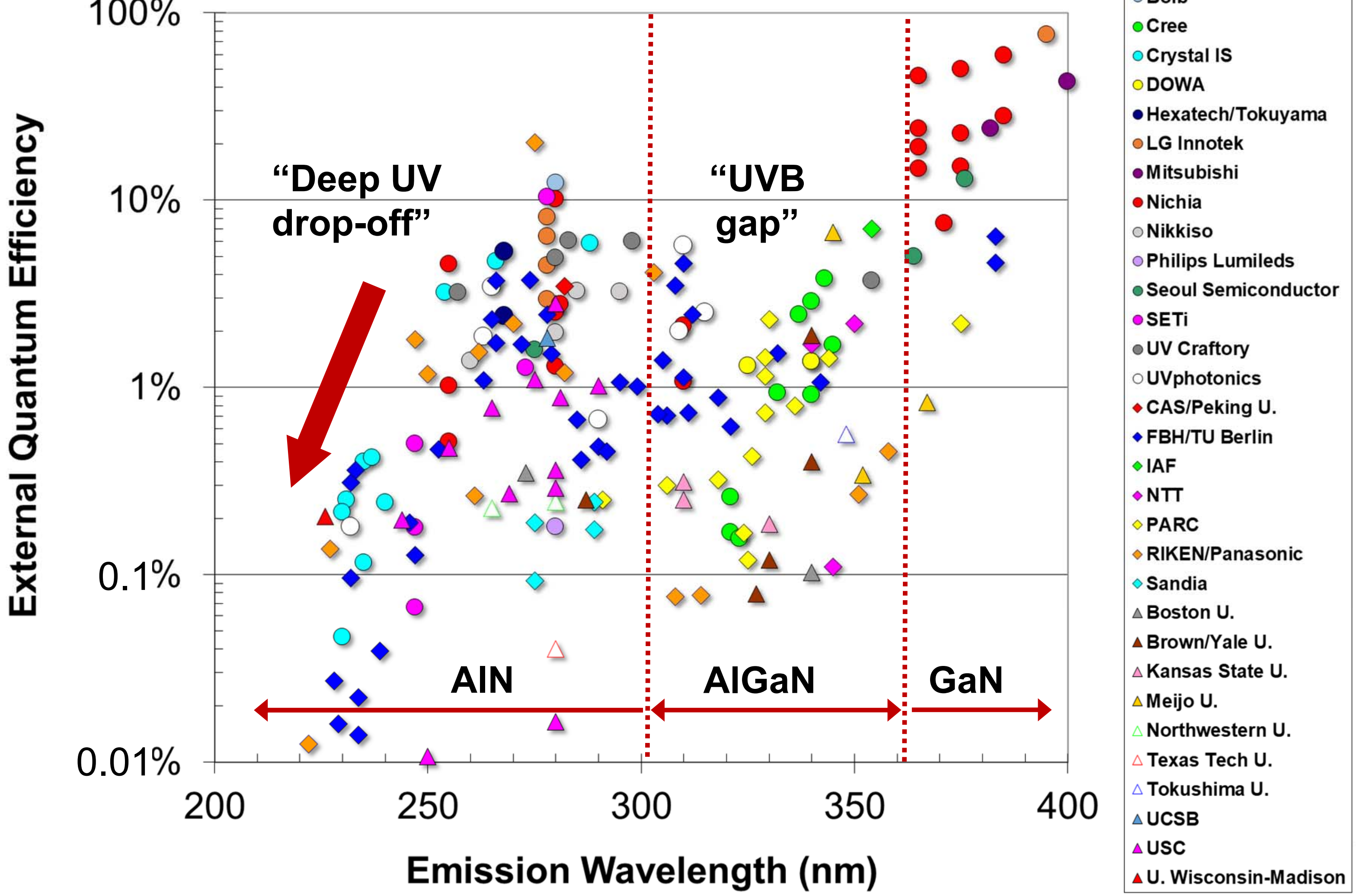
Applications of ultraviolet light emitters

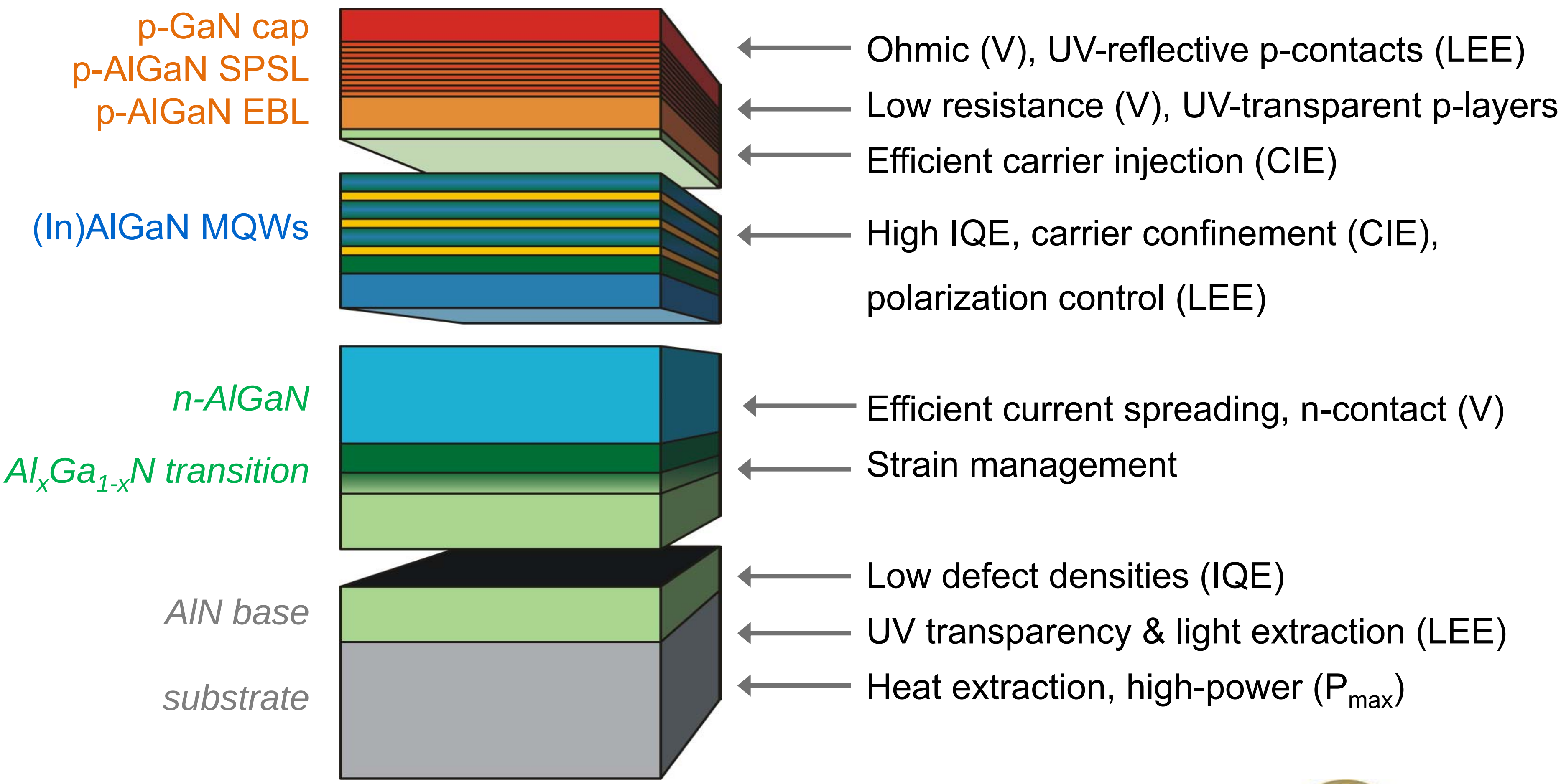


EQE of UV-LEDs: State-of-the-Art

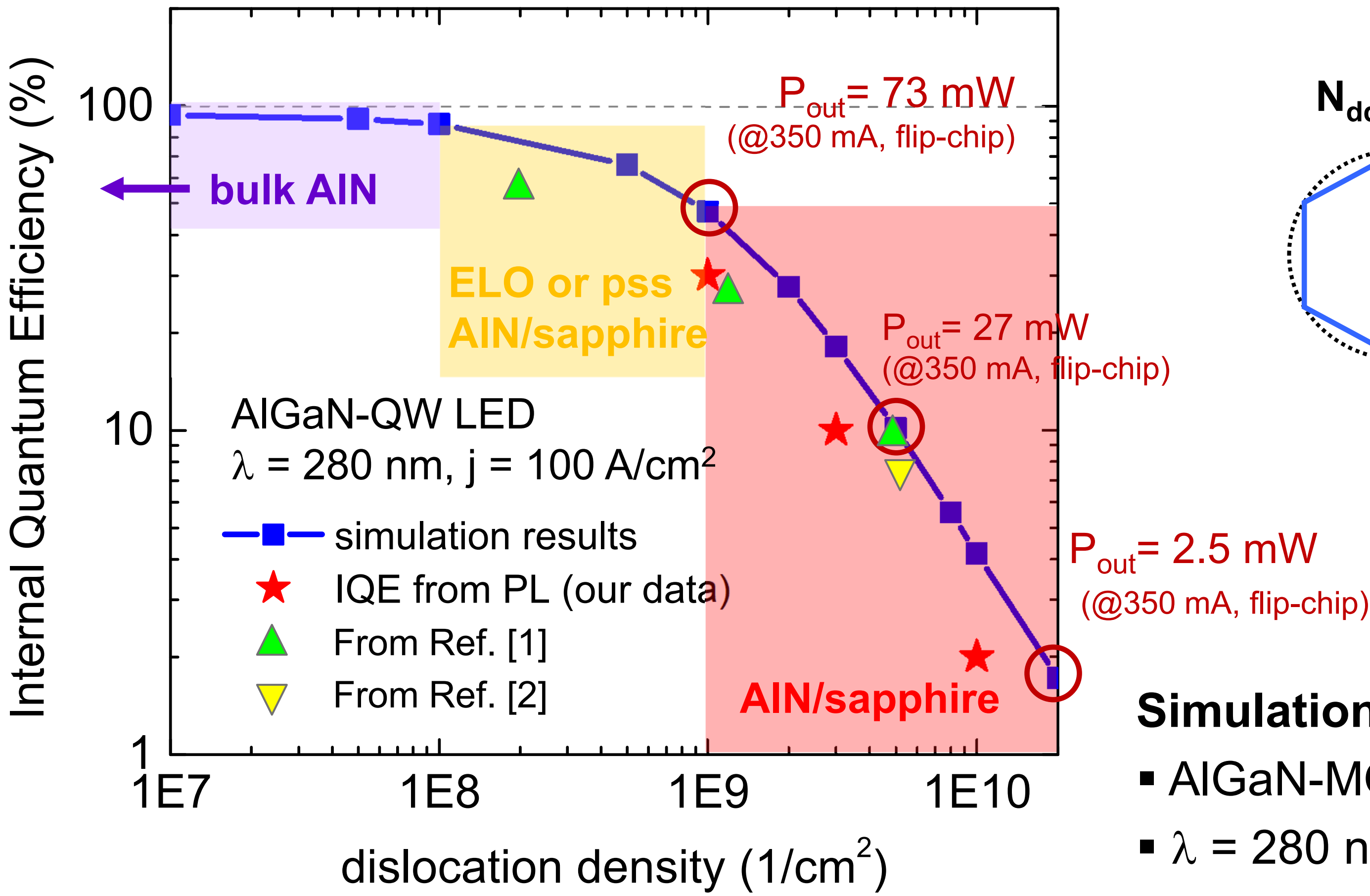
M. Kneissl et al., Nature Photonics 13, 233 (2019)



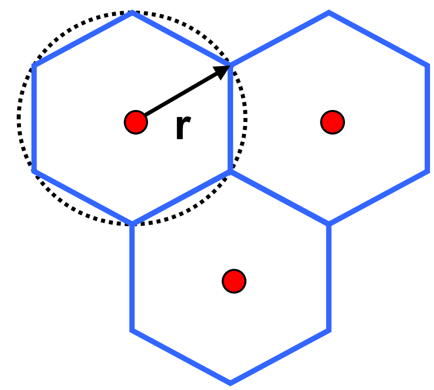
Challenges for deep UV LEDs



Effect of dislocations on the IQE of UV-LEDs



$N_{dd} = 1/\pi r^2$



Simulation parameters [3]:

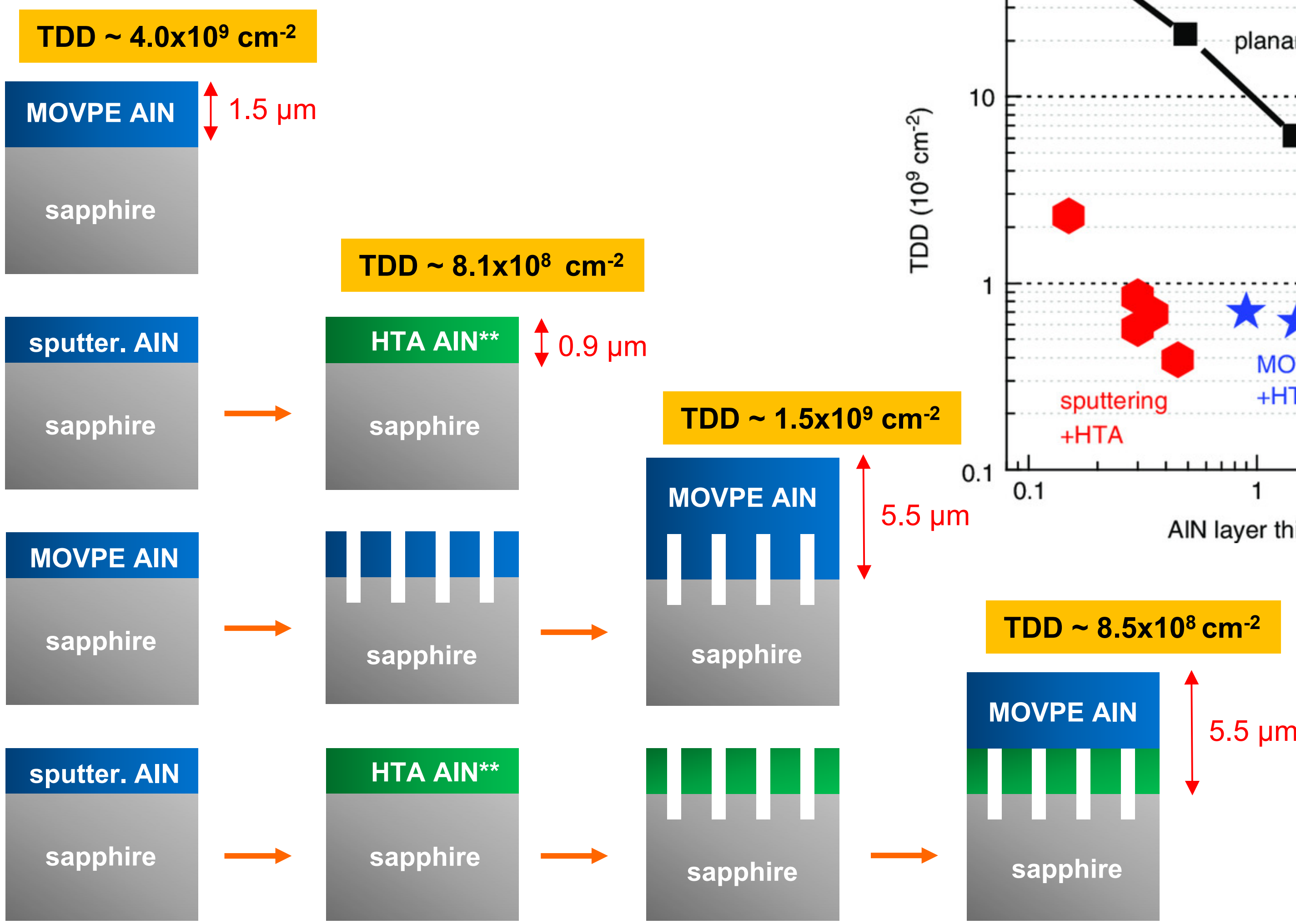
- AlGaN-MQW LEDs
- λ = 280 nm, j = 100 A/cm^2
- **No SRH** from **point defects**
- Light extraction: η_{extr} = 10%

[1] *Ban et al., APEX 4, 052101 (2011)*

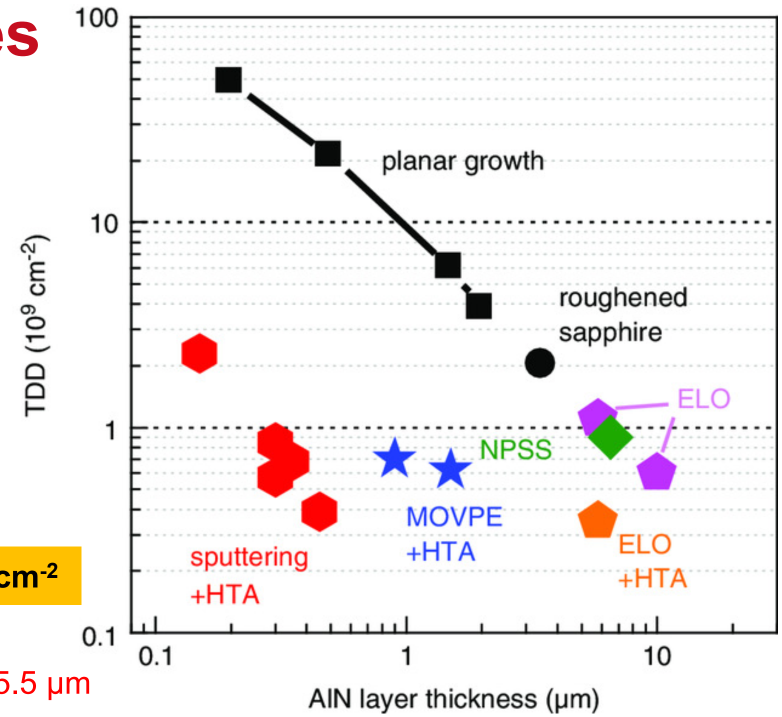
[2] *Mickevicius et al., APL 101, 211902 (2012)*

[3] *Karpov et al., APL* 81, 4721 (2002)

AlN/sapphire template technologies



TDD of AlN/sapphire templates*



*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)

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CL of AlGaN MQWs on different templates

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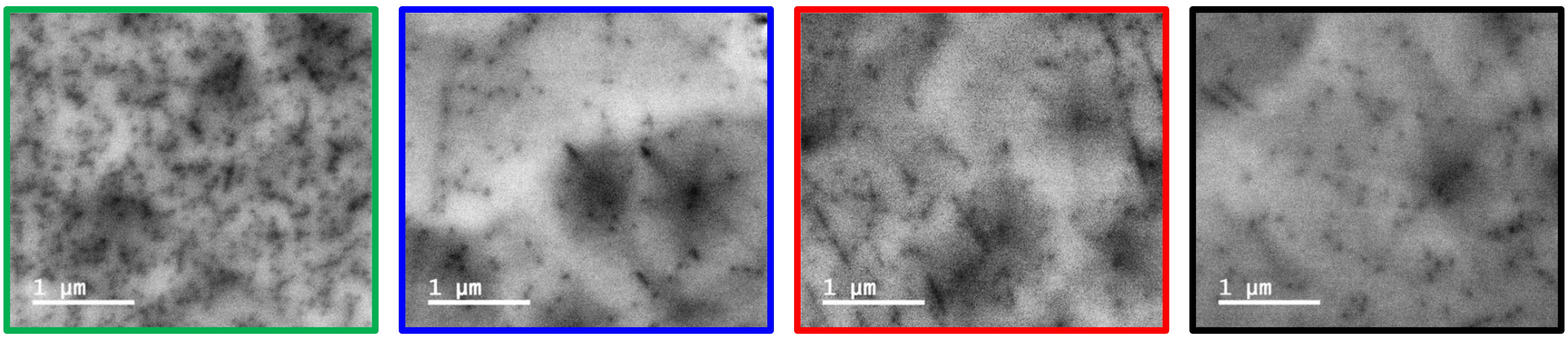
- AlGaN MQW heterostructures grown side by side on different AlN/sapphire templates by MOVPE
- TDD visualized by CL as their non-radiative recombination causes dark-spots
  → Lowest dark-spot-density (DSD) on HTA MOVPE ELO AlN/sapphire

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}**

N. Susilo et al., Appl. Phys. Lett. 112, 041110 *(2018)*

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Effects of TDD on IQE for different templates

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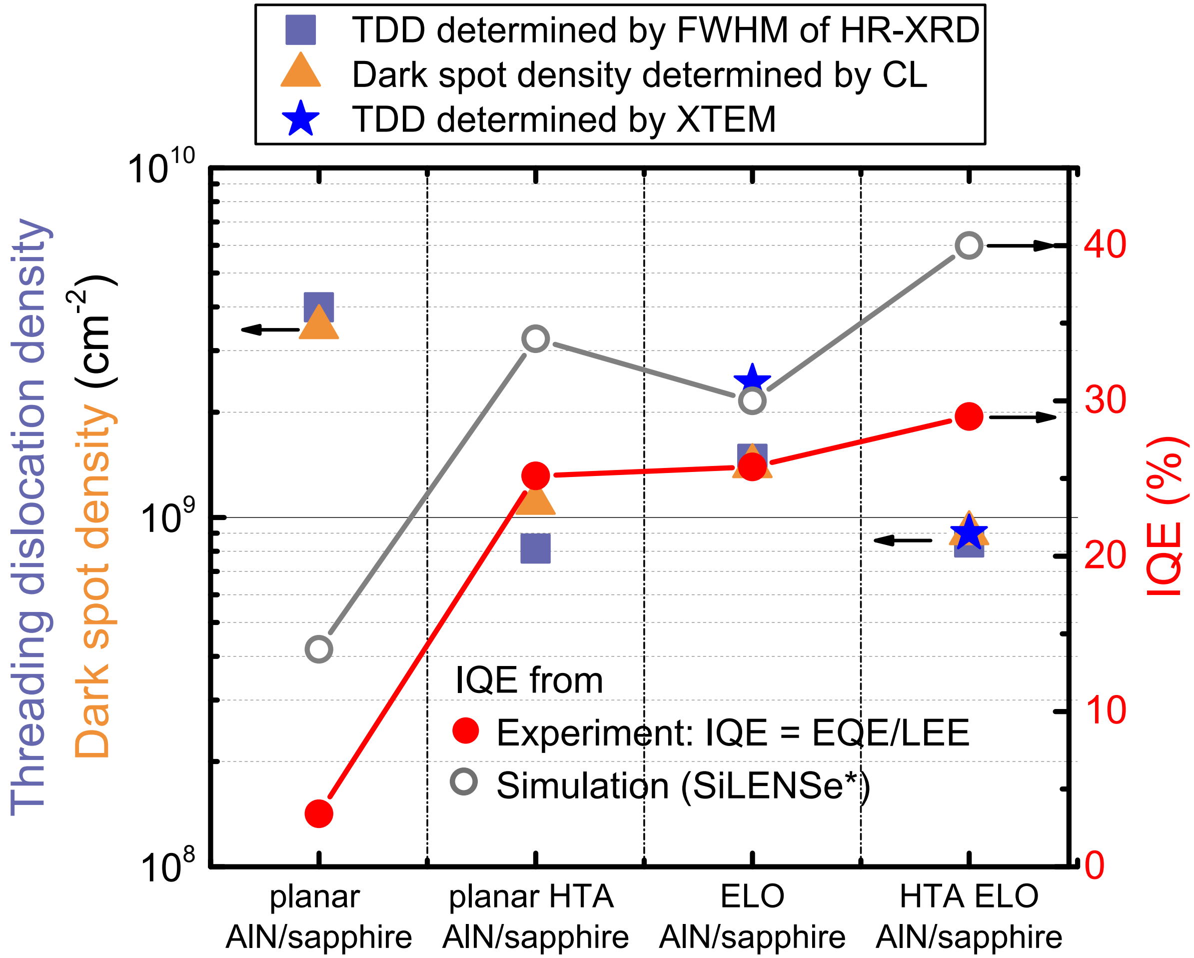

- Good agreement between TDD determined by HR-XRD, panchromatic CL (DSD), and XTEM
- Clear correlation between IQE and TDD

  → Lowest TDD and highest IQE for MQW on HTA ELO AlN/sapphire

*Simulation parameters: j = 13 A/cm², μ_e = 120cm²/Vs, μ_h = 6cm²/Vs, TDD based on DSD determined by CL of MQWs), Karpov et al. model

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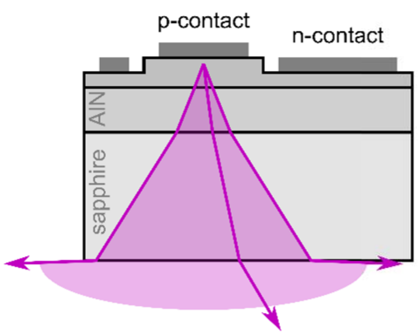
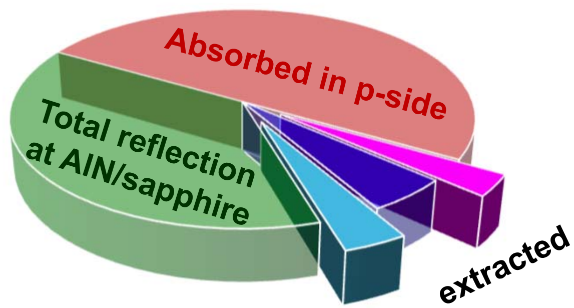
Light extraction from UV-LEDs

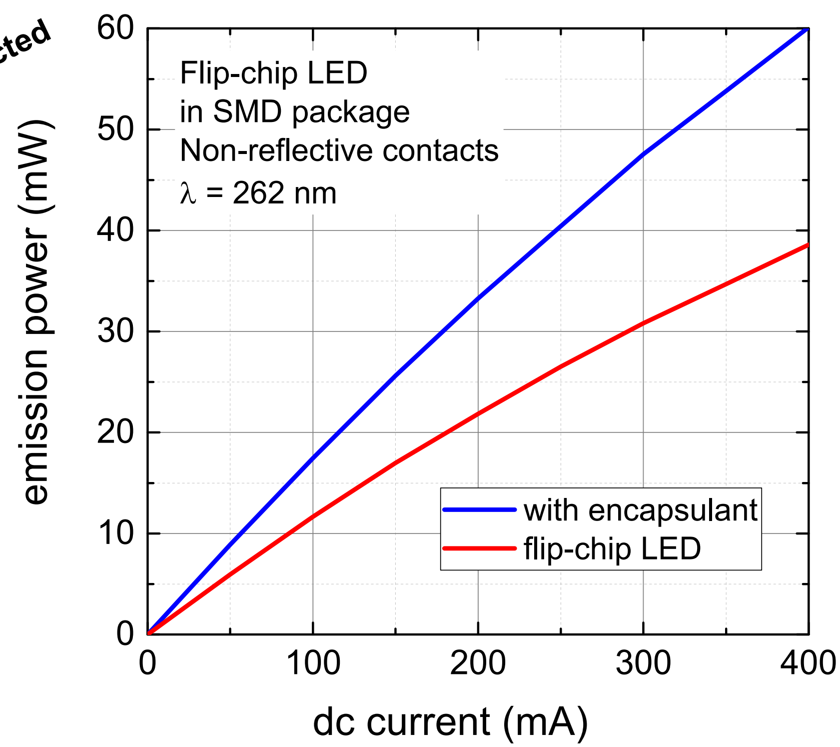
Extraction via substrate



Paths of created photons



LI characteristic of a UVC-LED



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

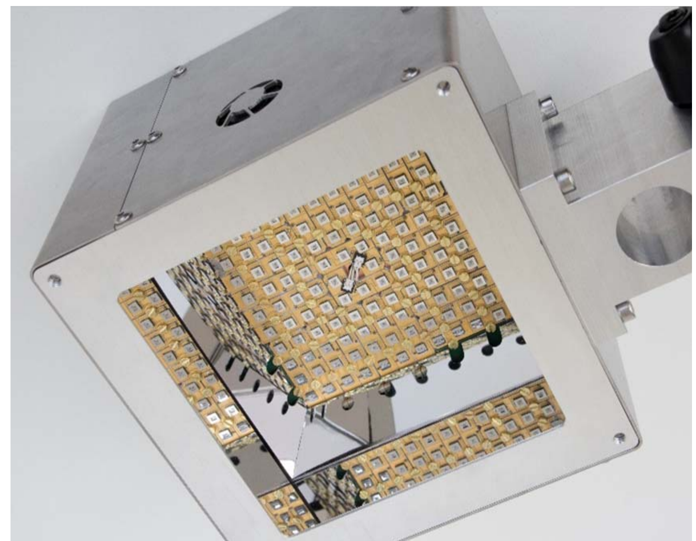
DUV-LEDs for in-vivo disinfection

- Light from DUV LEDs (<235 nm) does not penetrate living skin layers

  ⇒ **in-vivo disinfection without damage to human skin**

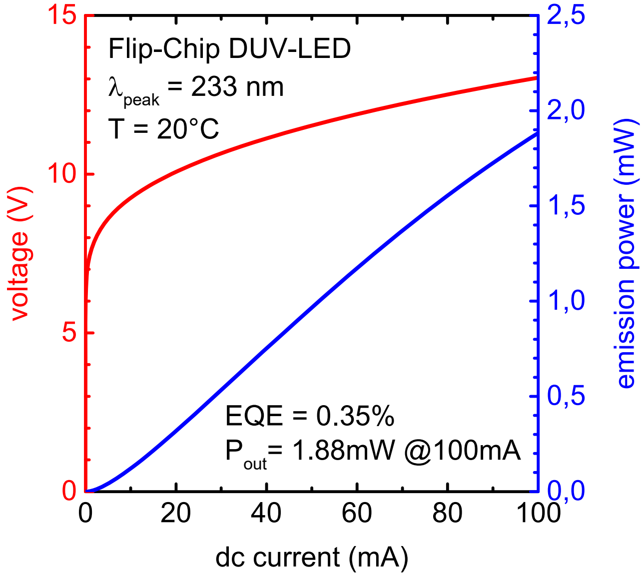
- In-activation of multidrug resistant bacteria, e.g., MRSA, MSSA
- Disinfection of airborne viruses, e.g., SARS-CoV2, influenza
- Required DUV dose levels: 2 – 40 mJ/cm^2

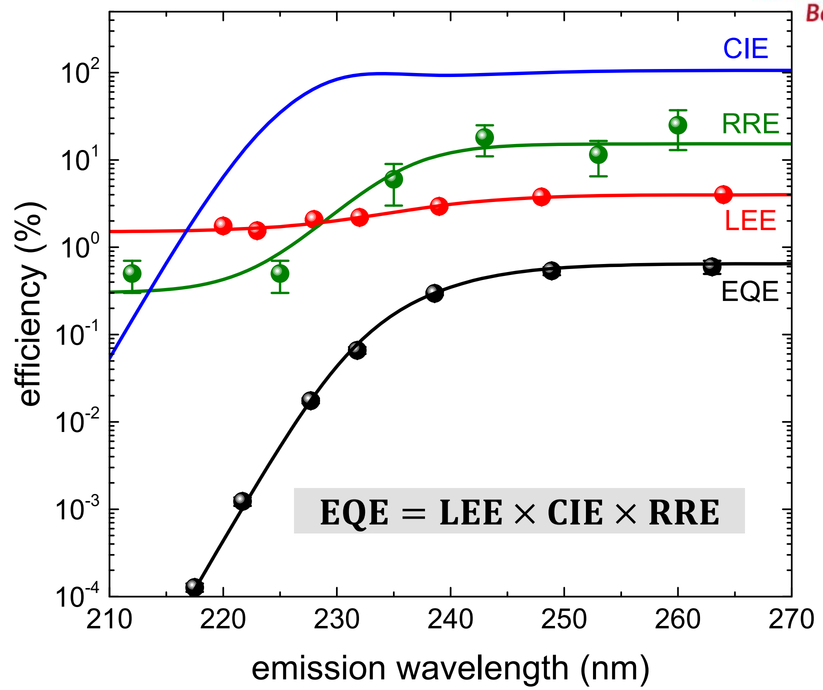
*Irradiation system with an array of 118 DUV-LEDs emitting at 233 nm**

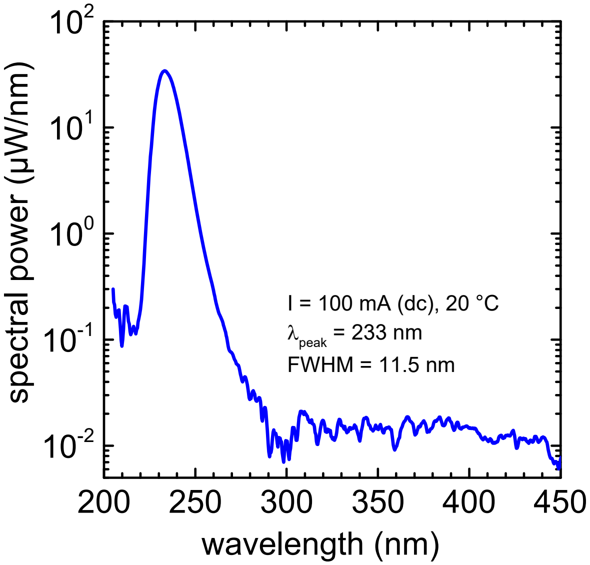


*M.C. Meinke et al., Management & Krankenhaus **9**, 20 (2020)

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?

N. Lobo-Ploch et al., Appl. Phys. Lett. **117**, 111102 *(2020)*
M. Guttmann et al., Jpn. J. Appl. Phys. ***58****, SCCB20 (2019)*

Summary

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- 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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