High Performance UV-C LEDs and Their Applications

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Bolb Corporate Overview

- Founded in 2014, production facility located in Livermore, California
- World's only UVC LED manufacturer utilizing emission-transparent epi since 2017.
- Bolb's in-production UV-C LEDs are more than twice as efficient as the nearest competitor
- Bolb products enable new and innovative disinfection solutions for air, water and surface applications

Topics Covered

- High performance UVC LEDs:
  - Past approaches to reduce p-side optical absorption
  - Bolb’s approach and results
  - Importance of packaging in market success
  - Looking ahead
- UVC LED Applications:
  - Examples: Air, water and surface disinfection
- Summary

Dilemma: More light or lower voltage?

Deep acceptor level in AlGaN → P-GaN as p-contact layer → Low LEE (2-5% for FSS)

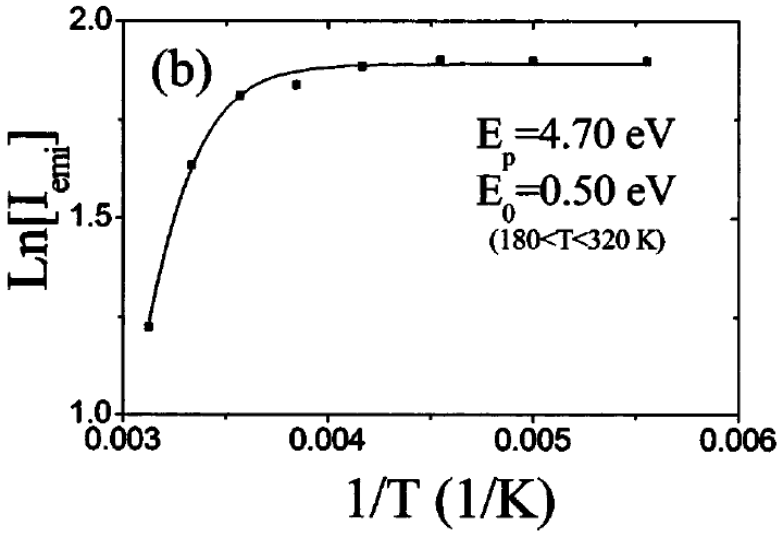


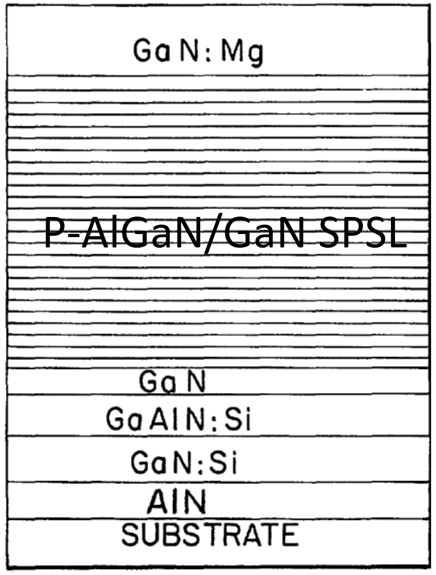
FIG. 2. The Arrhenius plots [ln(I_{emi}) vs 1/T] for two emission lines in Mg-doped AlN: (a) 4.70 eV at T<150 K and (b) 5.54 eV at T>150 K. The solid lines are the least squares fits of data with Eq. (1). The fitted activation energies (E_0) are indicated in the figure.

K. B. Nam et al APPLIED PHYSICS LETTERS 83, 878 (2003)

- Practical high power (> 100mW@350mA and Vf<7V) UVC LEDs only started appearing within the past 2-3 years on the market
- Major technology challenges:
  - **Low carrier concentration in high-Al% structures → low light extraction efficiency from absorbing p-GaN**
  - Trapped TM polarized light
  - Lack of high reflectivity contacts in UVC band
  - High temperature annealing required for N ohmics
  - Lack of suitable UVC-transparent packaging material

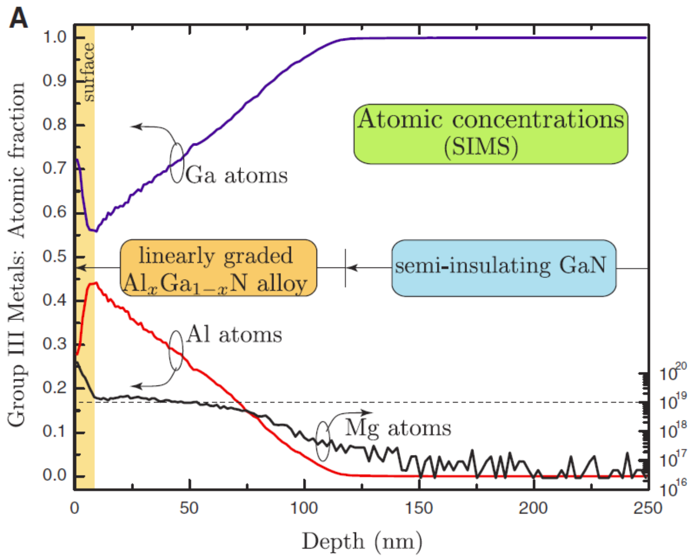
Early efforts to replace p-GaN

P-AlGaN/GaN SPSL



M. Razeghi ,US patent No. 5,831,277

Compositionally-graded P-AlGaN



J. Simon, et al, Science 327, 60 (2010)

P-AlGaN

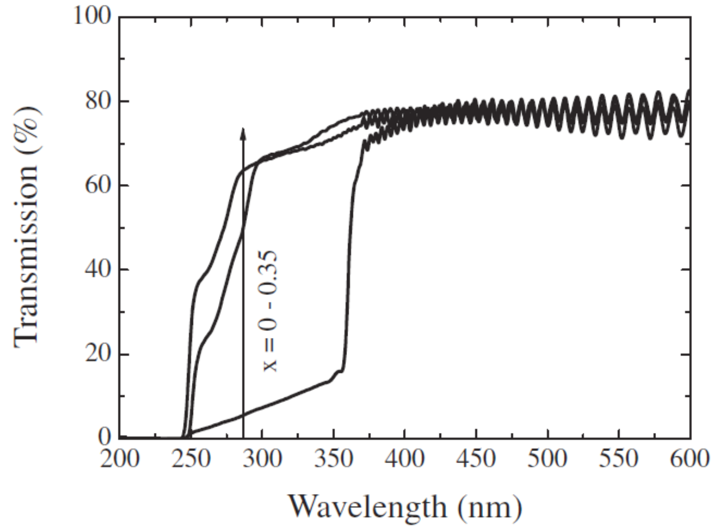


Fig. 1. Optical transmission spectra of DUV LED structures with different compositions of p-AlGaN layer.

M. Shatalov, et al, Applied Physics Express 5, 082101 (2012)

Dilemma: More light or Practical working voltage?

- Simply replacing p-GaN with p-AlGaN, extraction is enhanced, but V_F also increased, device reliability problematic

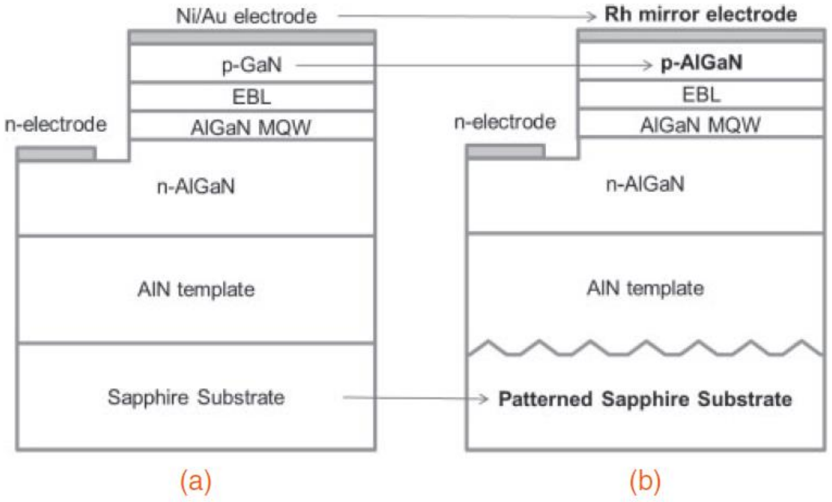
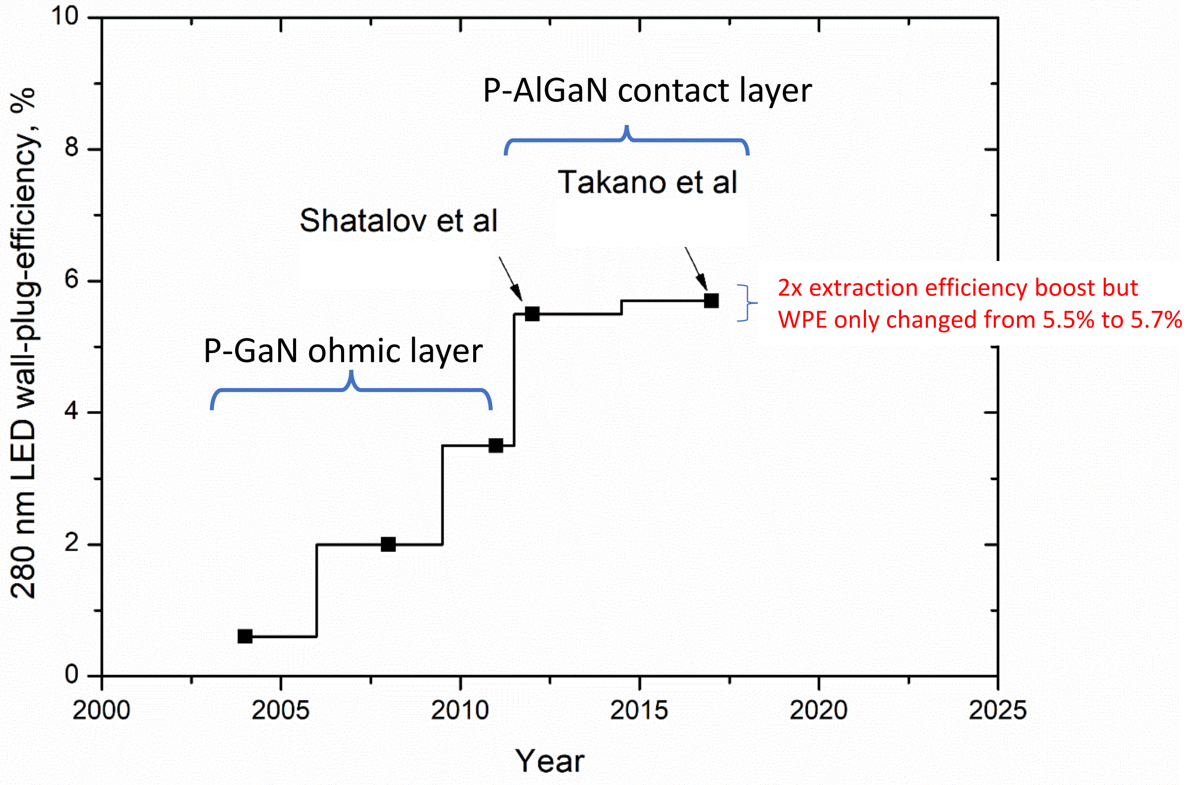


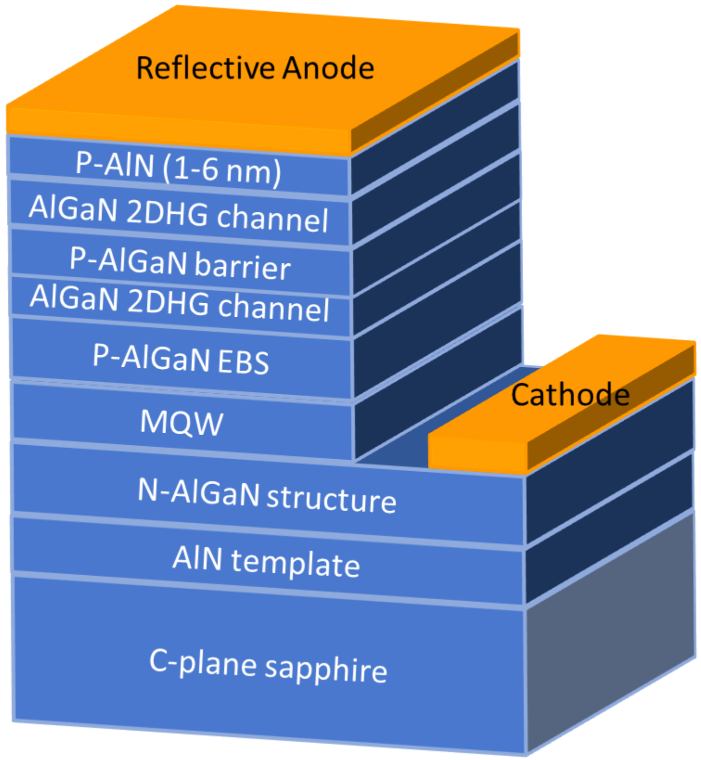
Fig. 1. Schematics of (a) conventional and (b) novel UV-LED structures. In the novel UV-LED structure, we introduced a transparent p-type AlGaN:Mg contact layer, a Rh mirror electrode, a PSS, and encapsulation resin.

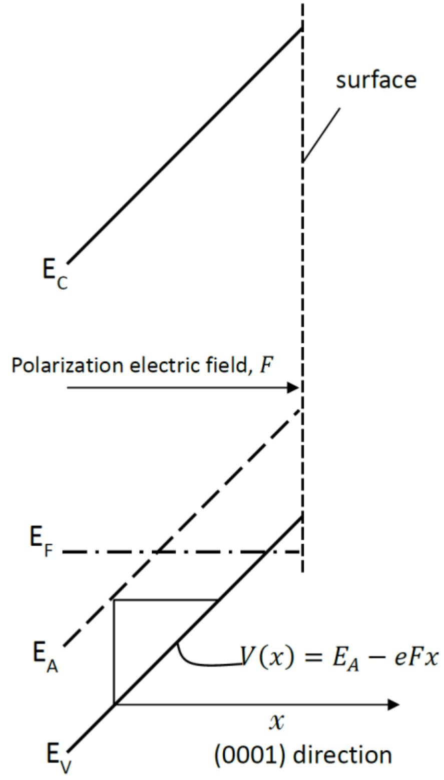
T. Takano, et al, Applied Physics Express 10, 031002 (2017)



BOLB's Transparent UV-C LED Structure

Lifting the fundamental performance ceiling of UVC LEDs





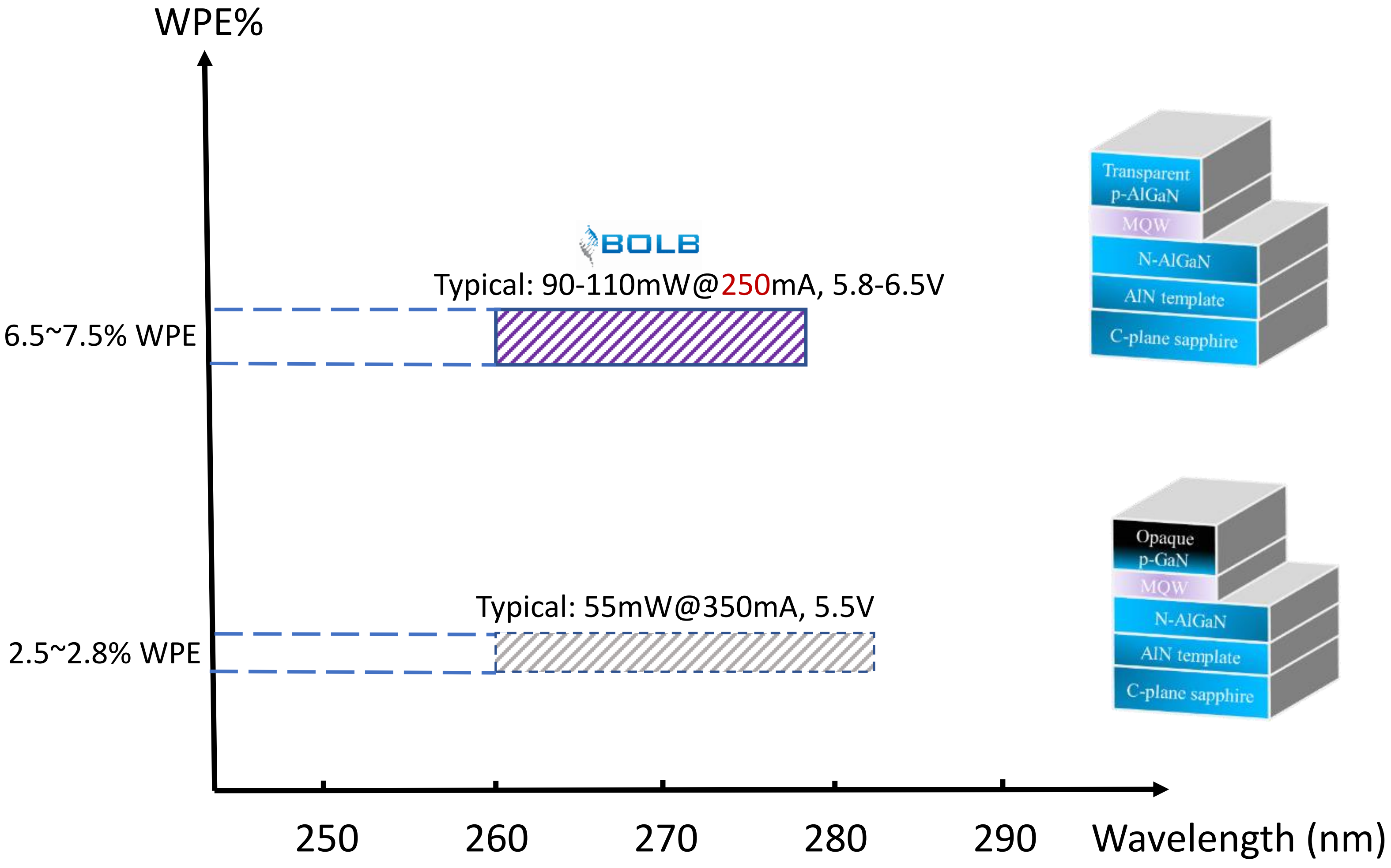
- Use a strained thin p-AlN cap layer
- Creating a very high charge density on AlN surface
- Very high piezoelectric and spontaneous fields enhance tunneling probability

Result:

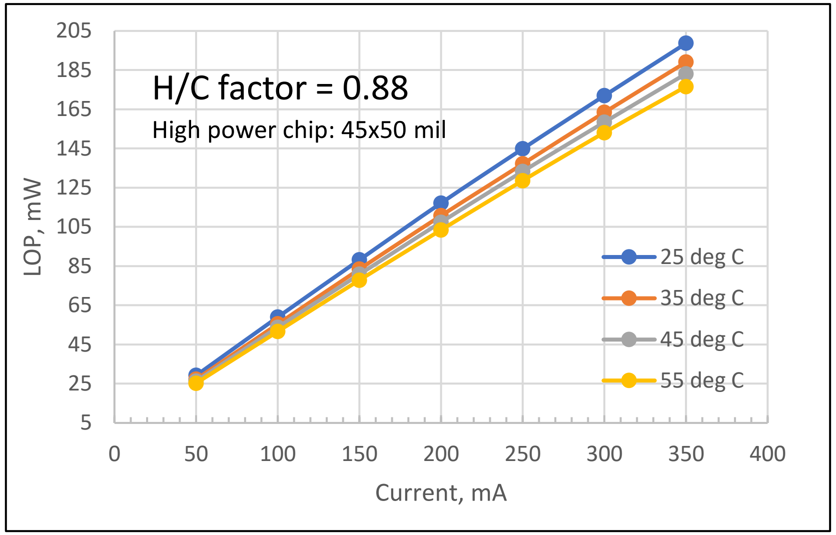
- P ohmic contact without annealing on high-Al% material
- Get high transparency *AND* good working voltage
- Lifts efficiency ceiling by >10x

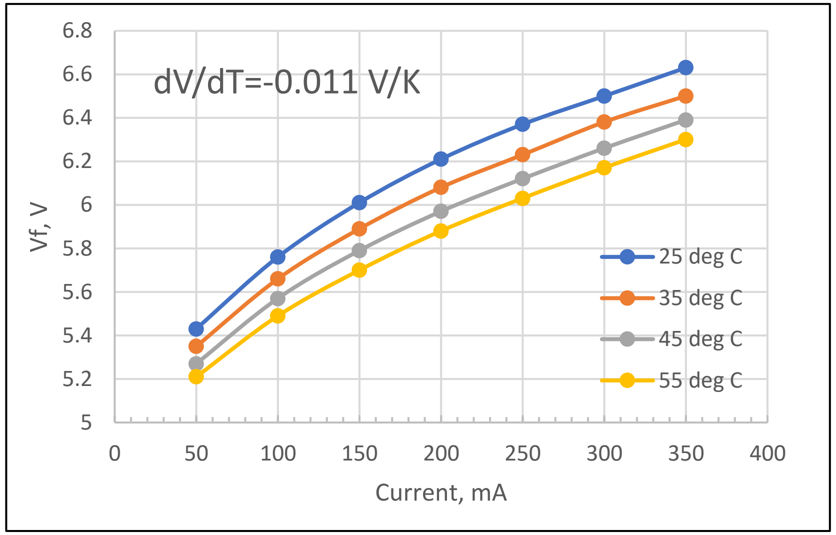
Reference: "Surface hole gas-enabled transparent deep ultraviolet light-emitting diode" by J. Zhang et. al., Semiconductor Science and Technology, Vol. 33(7), June 2018

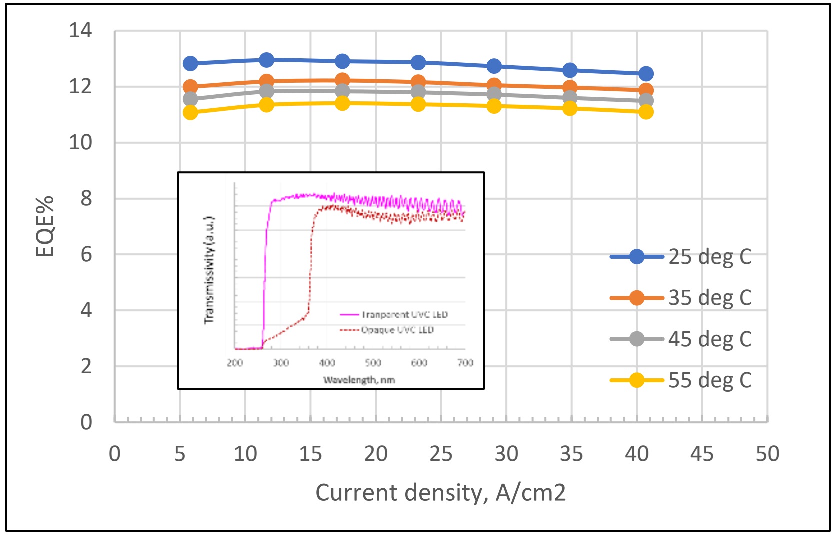
State-of-the-art Production UVC LED Performance

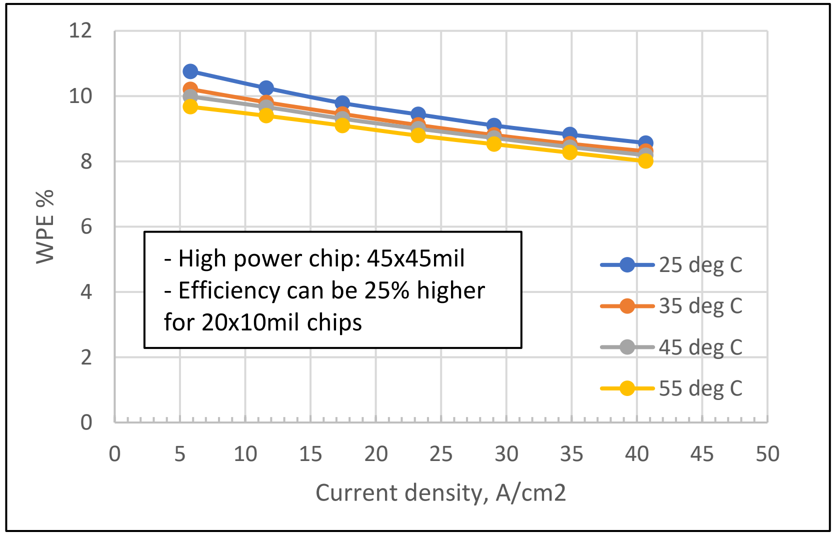


200mW @ 350mA, 273nm Packaged Single LED

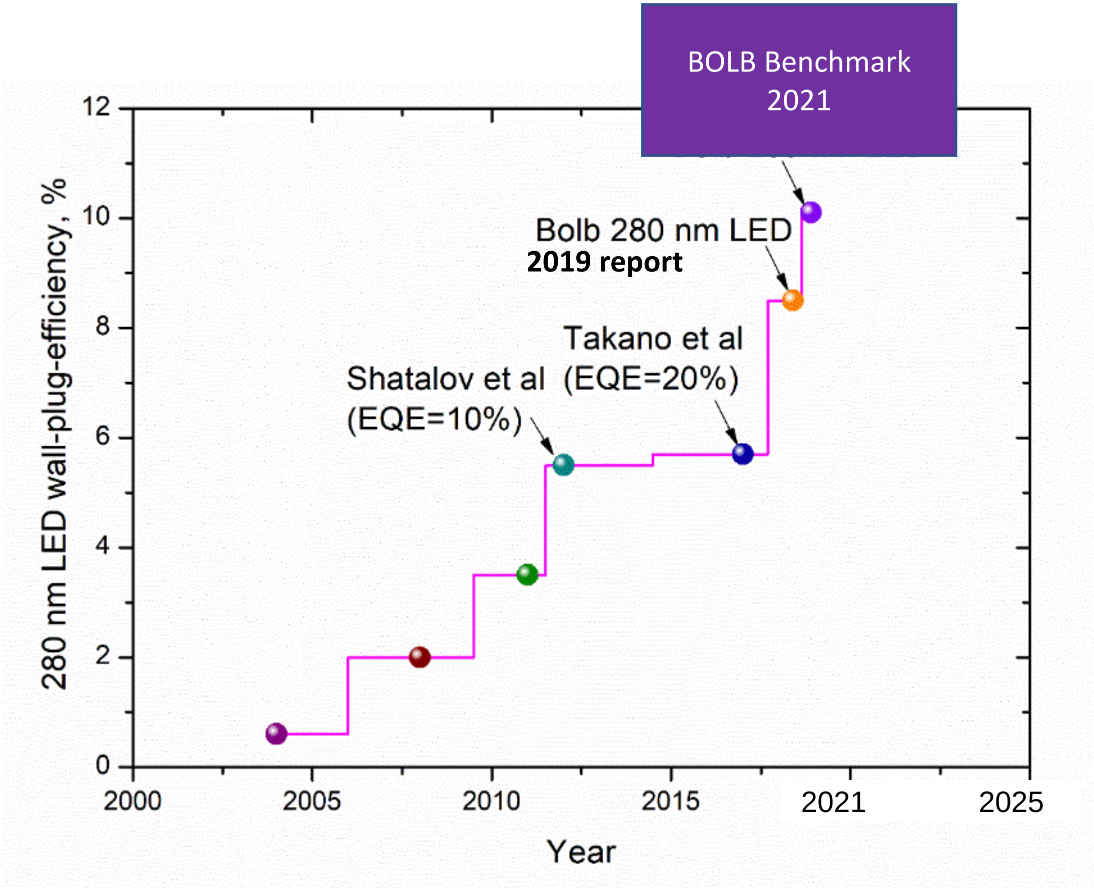


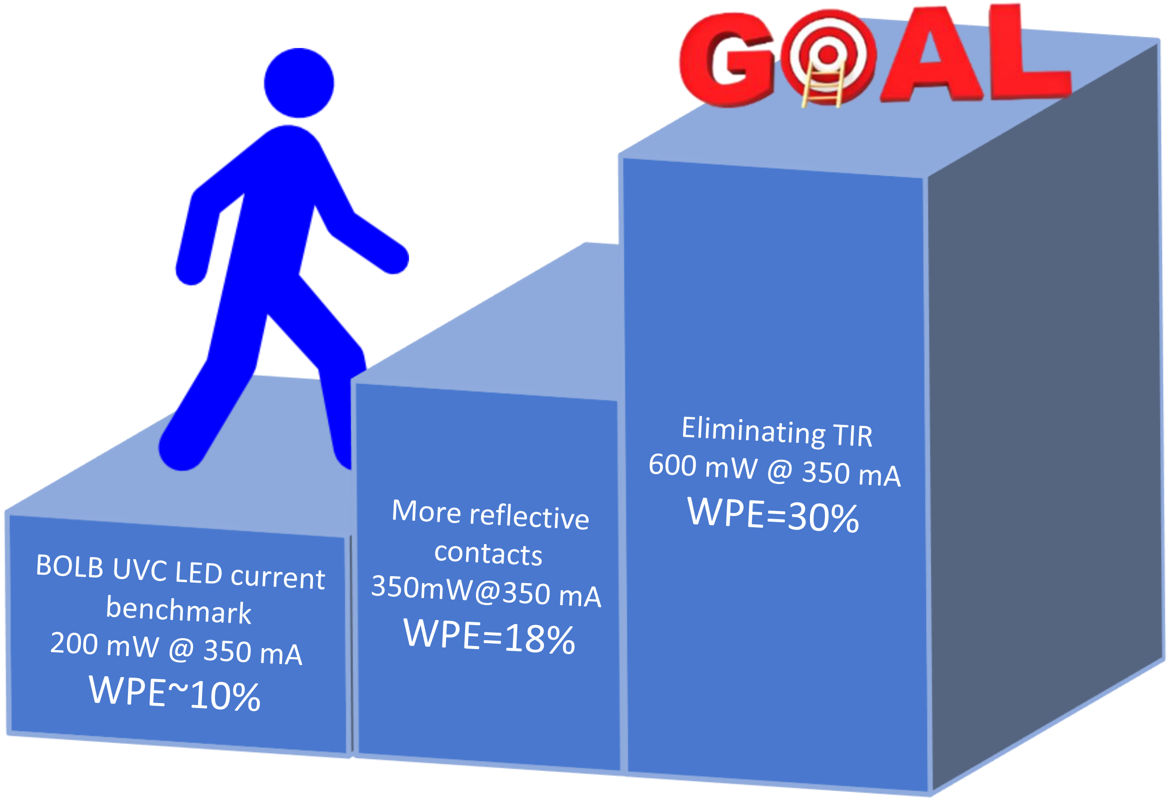




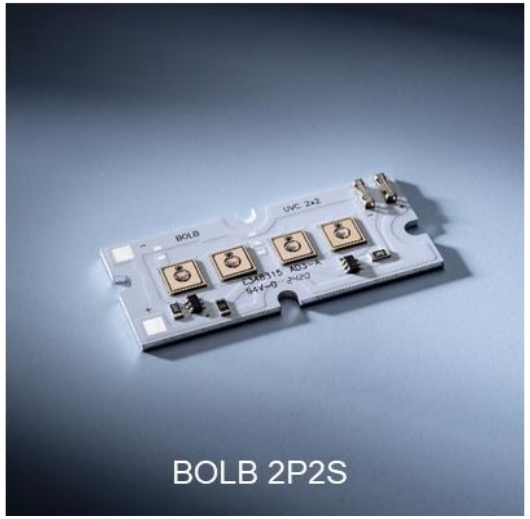


Future directions to improve UVC LED efficiency



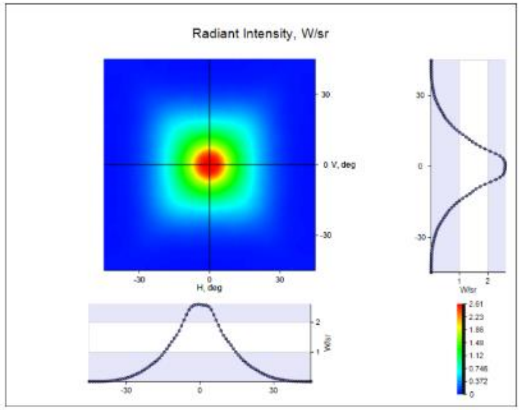


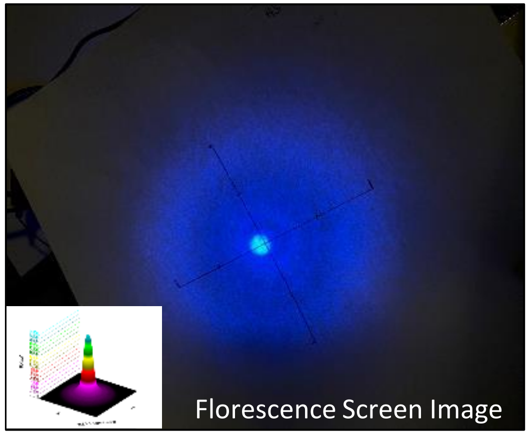
Packaging for UVC LEDs



- Common requirements
  - High UVC transparency or reflectivity
  - High thermal conductivity
    - Must handle 8~10x thermal load at the same current vs. visible LEDs
    - Severe derating at higher temperature due to poorer carrier confinement
    - Lifetime issues
  - Long term packaging degradation under UV (e.g. transparency, color and adhesive properties)
- Application specific:
  - Wide beam: wider coverage, reduce shadow;
  - Narrow beam: target specific area, reduce light escape

Harnessing UVC LED's high radiance with proper packaging




Florescence Screen Image

Type of Secondary Optics on SMD6060 274nm LED	Single LED Flux@350mA	Irradiance at Distance	
		1 mm	10 cm
	mW	mW/cm²	mW/cm²
Bare die	112.0	144.6	0.31
Bare die + SMD Reflector	96.5	228.5	2.43
Hemisphere	154.0	194.4	0.42
Hemisphere + SMD Reflector	123.7	265.0	3.20
Aspherical Lens	144.9	375.7	1.13
Compound Lens	136.1	676.5	1.23

- Requiring "Watt for watt replacement" of Hg lamps is ***WRONG***
- High irradiance achievable on target outclasses mercury lamp with 50x input power
- Huge implications for efficient water and air treatment applications
- For bio-sensing applications: >2W/cm^2 radiance possible with pulsed current drive

Application Examples: Surface treatment

BOLB's UVC LED 1x12 arrays and 5x5 arrays deployed during initial wave of the SARS2 pandemic for disinfecting high-touch surfaces for "refreshing" PPE

Test examples **Against HCov-229E ssRNA** human coronavirus on flat surfaces

- Single-emitter *99.995%* Kill in 15 seconds from 10 cm away
- 25-emitter *99.995%* kill in 2 seconds from 20 cm away; 60 seconds from 1 meter away (coverage 1 meter dia.)

Against **SARS-Cov-2 ssRNA** virus on porous surfaces
(courtesy UC Berkeley and others)

- *99.9~99.999%* Kill in 5~10 min for outer shell of N95 mask

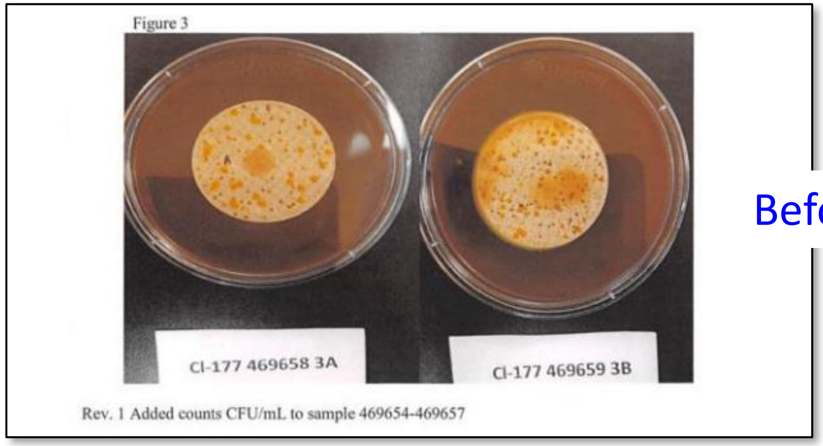
Application Examples: Aerosol Treatment



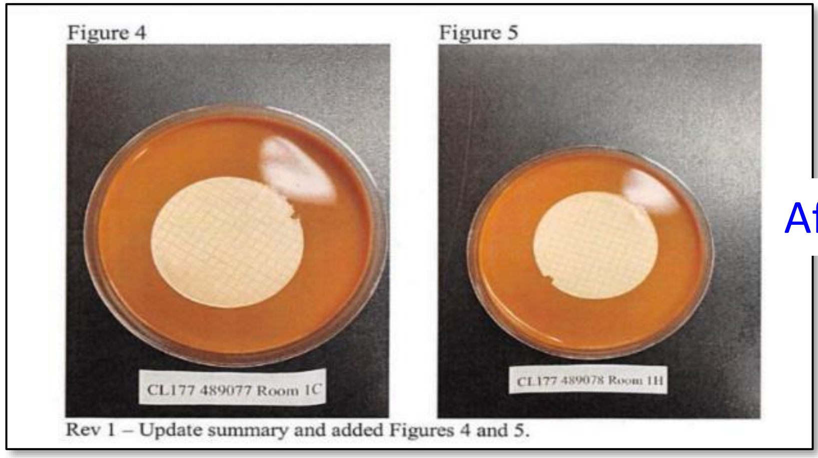

Model	LED Array 100+/-10 mW each @ 250mA	Air Flow L/min (CFM)	Single Pass Efficacy	30 m³ Volume Efficacy 60 min
Floor Unit (Cylinder)	25 LEDs	3000 (107 cfm)	99.96% *Staph aureus* ATCC-6538	99.94% HCoV-229E ssNRA Virus MRC-5 host
Ceiling-mount Unit	24 LEDs	8400 (300 cfm)	/	99.6% *Staph aureus* ATCC-8032

Potential Energy Savings by Reducing Mechanical Filtration Requirements

Application Examples: Water Treatment



Before



After

BOLB Single-emitter Reactor Water Treatment Tests

Flow Rate		E. coli Reduction Rate
LPM	GPM	
1.5	0.40	> 99.999%
5	1.32	99.999%
15	3.96	99.75%
20	5.28	97.52%

Summary

- WPE ceiling imposed by an optically absorbing cap layer has been broken
- Demonstrated output beyond 200mW@350mA per emitter
- Rapid progress in LED performance is expected through further light extraction enhancement
- High-power UVC LEDs are already practical in many applications
- Beam-shaping secondary optics at package level enables far more efficient air and water treatment reactor designs compared to Hg lamps, mitigating cost disadvantage and enables new applications

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