Progress in LED technology for solid state lighting

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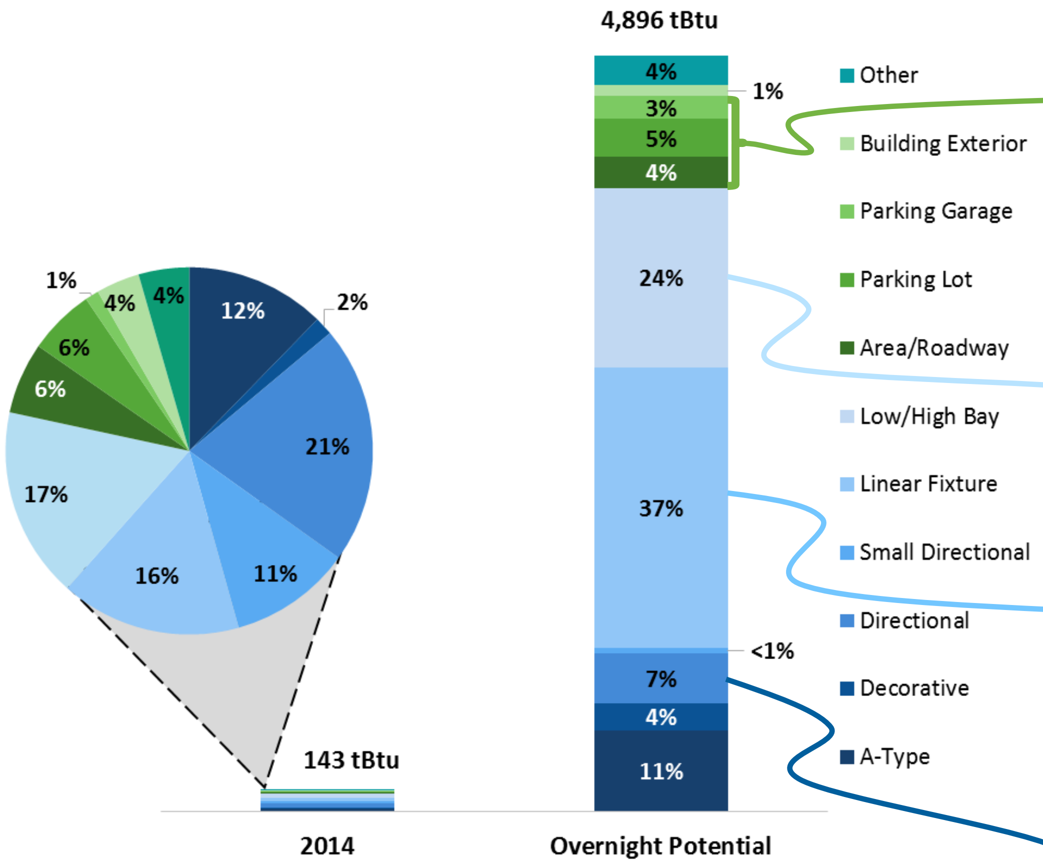
LUMILEDS

Four segments critical in driving LED energy savings



Outdoor

Low/High Bay

Linear Fixture

Professional Directional

From: DOE, Adoption of LEDs in Common Lighting Applications, 2015

Factors Impeding Adoption Rate

Outdoor

- TCO most important but initial cost still critical
- Often payback longer than local government budget control cycle
- Key to adoption: cost reduction
  - Cost reduction in components has reached limit
  - Further cost reduction by system integration
- Directional: High luminance can enable disruptive integration

Low/High Bay

Linear Fixture

- Green field (new construction) has high adoption rate
- Brown field (renovation or installation upgrade) lagging
- Energy savings potential of brown field >> green field
- How to increase adoption in brown field, using Office example:
  - T'LED remains lowest cost option to replace F-T8.
    - Continued efficacy improvements to >200 lm/W
    - Maintain long lifetime, 100khrs (savings replacement OH)
    - Maintain color and flux over lifetime
  - Intelligent controls with energy harvesting (daytime, proximity) offers potential beyond efficacy gains

Professional Directional

- Quality of light is a main driver for adoption in retail & hospitality
- Retail benchmark is CDM: efficacy, flux, cost, spectral performance
- LED enables smaller source, but not yet competitive vs CDM
- Adoption: CDM performance + intelligence and FF + cost

LED Technology development directions to speed adoption

Spectral engineering (Retail, Hospitality)

Major opportunity to improve efficacy as well as visual and non-visual responses

- Narrow band spectra continue to drive white efficacy improvement
- Need flexibility in color fidelity to broaden design space
- Direct colors: esp. UV / violet / blue for InGaN, and red / far red for AlInGaP
- Narrow-band down-converters: tunable material systems in central part of visible spectrum
- Need human factor studies to quantify visual and non-visual effects

High luminance combined with high efficacy (Directional Applications)

Enable form factors and designs with higher efficacy and lower system cost

- High-power epi and die architectures
- Low phosphor quenching
- Integration into high-power LED packages and LED light engines

Higher level of integration (All applications)

Optimized performance, FF reduction, system level cost reduction

- Driver on board
- Sensor and communications IC integration

Adoption barrier externalities: Recent confusion and negative press on human-light interactions related to LED street lighting

AMERICAN MEDICAL ASSOCIATION

June 14, 2016

AMA Adopts Community Guidance to Reduce the Harmful Human and Environmental Effects of High Intensity Street Lighting

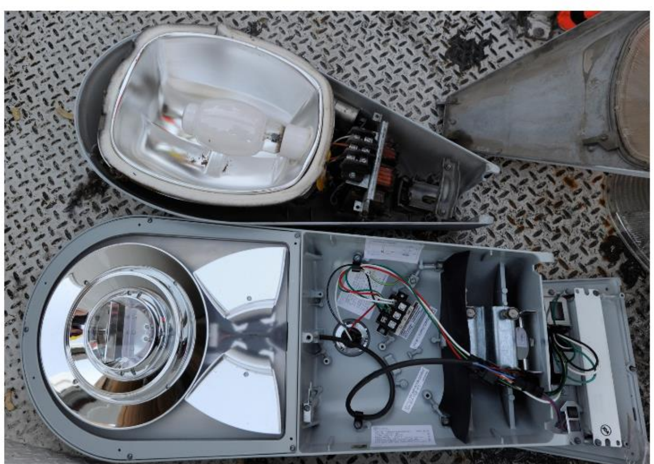
- AMA encourage the use of 3000K or lower lighting for outdoor installations such as roadways.
  - *blue-rich white LED street lighting five times more disruptive to our sleep cycle than conventional street lighting*
  - *brighter residential nighttime lighting is associated with reduced sleep, impaired daytime functioning and a greater incidence of obesity*

BAD NEWS!

The Washington Post

Health & Science

Some cities are taking another look at LED lighting after AMA warning



An LED fixture, bottom, is displayed next to an older streetlight, top, in Las Vegas, Nev. on Aug. 3, 2011. (Ethan Miller/Getty Images)

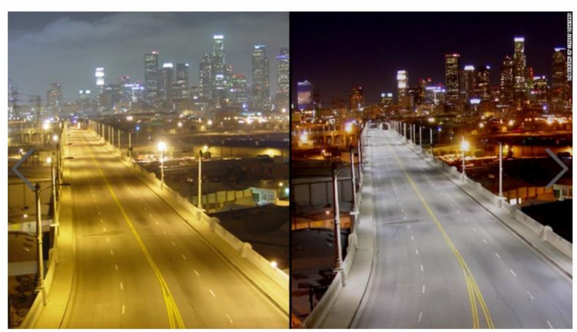
CNN Health » Doctors issue warning about LED streetlights

Doctors issue warning about LED streetlights

THE CONVERSATION

By Richard G. "Bugs" Stevens, The Conversation

Updated 2:00 PM ET, Tue June 21, 2016



Photos: Los Angeles LED streetlights

The Sixth Street bridge over the Los Angeles River looks a bit different with old, left, and new streetlights.

The Tragedy Of LED Streetlights: They Don't Need To Be Such A Nuisance

Seth Porges, CONTRIBUTOR

I write about the tech of culture and the culture of tech.

FULL BIO

Opinions expressed by Forbes Contributors are their own.

I can see the enemy advancing by the day. The sidewalks that crisscross my Brooklyn neighborhood have mostly changed over to newfangled LED streetlights, while my block—a quiet residential side street—remains bathed in the orange glow of classic sodium-vapor lights. At least for now. Every night I find myself walking home under this reassuring glow, I know it could be the last. The writing is on the wall (and well-publicized city plans): Even forgotten holdout blocks will eventually fall to the LED's promise of cheap, energy-efficient, and ever-so-bright white light.

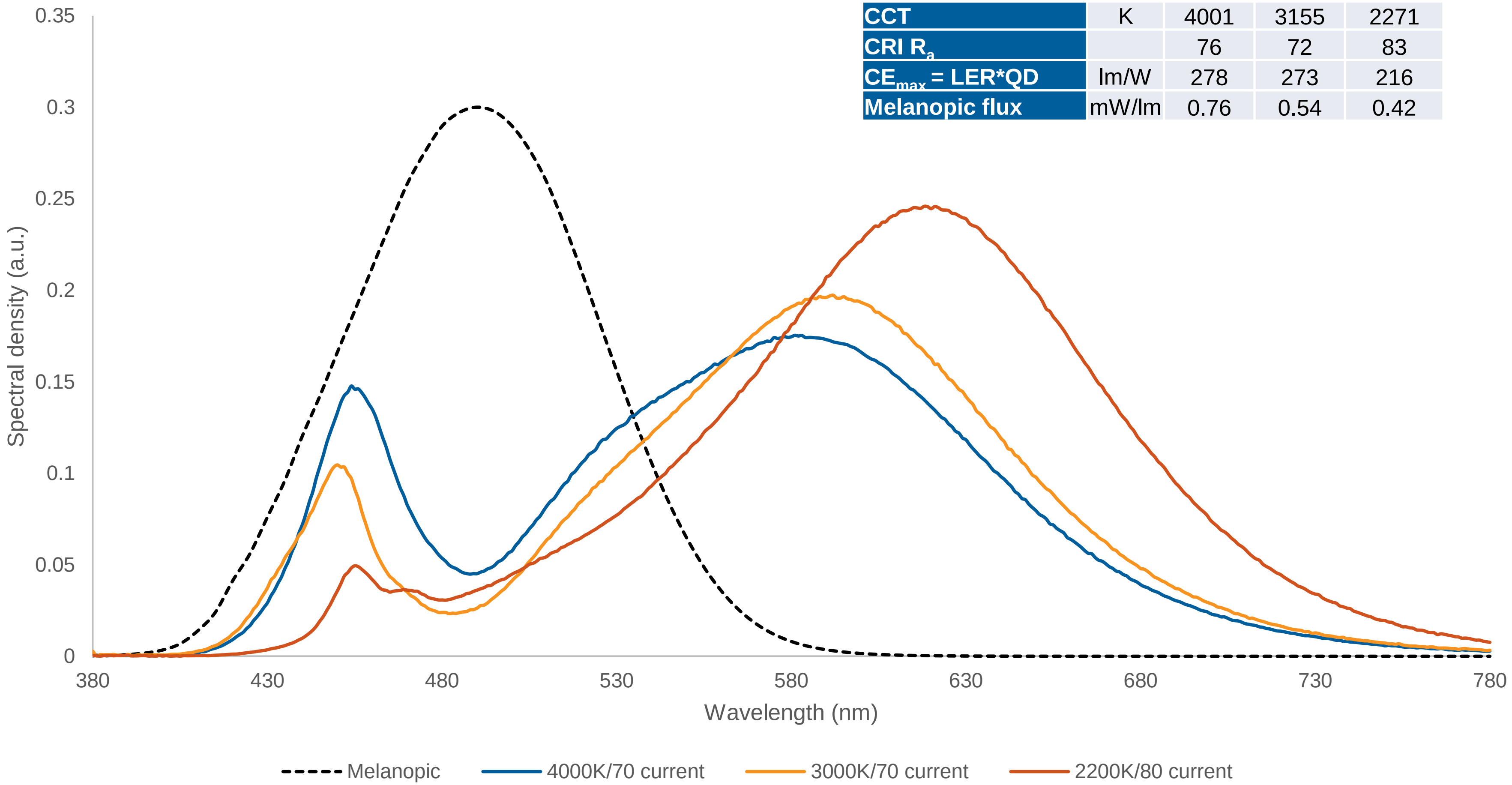
Now, you may know this change is fraught with issues. LED streetlights are decidedly less romantic, add to light pollution, totally mess with our circadian rhythms, and are flat-out ugly. What you may not know: This transition is all the more tragic because almost all of these drawbacks could be avoided.

LUMILEDS

Spectral engineering to reduce blue content

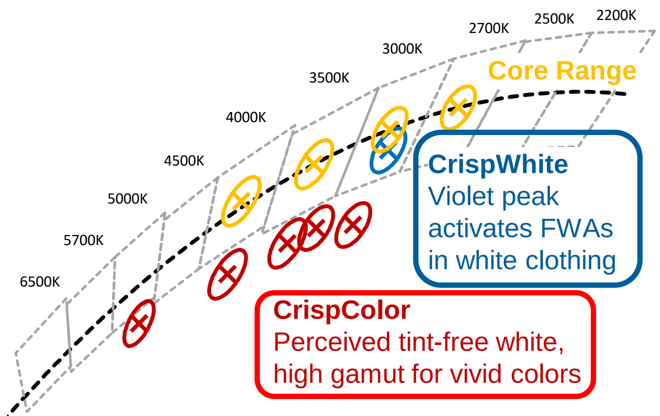
Flexible CRI specification enables spectra with significant efficacy gains and potentially reduced physiological impact

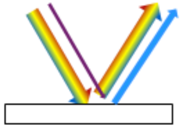
		4000K 70CRI	3000K 70CRI	2200K 80CRI
CCT	K	4001	3155	2271
CRI R_a		76	72	83
CE_{max} = LER*QD	lm/W	278	273	216
Melanopic flux	mW/lm	0.76	0.54	0.42

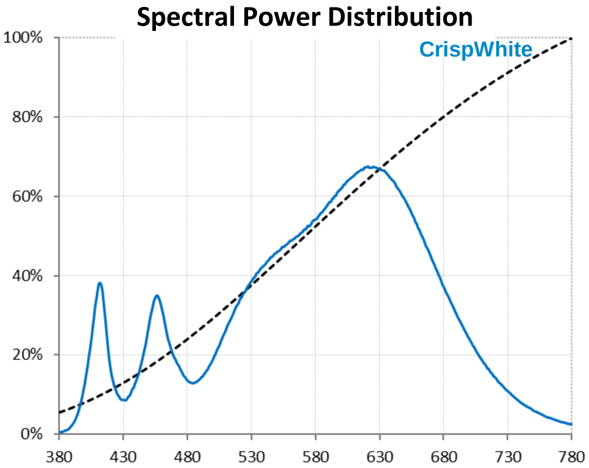


Spectral engineering for Retail: Beyond CDM @ CDM Cost

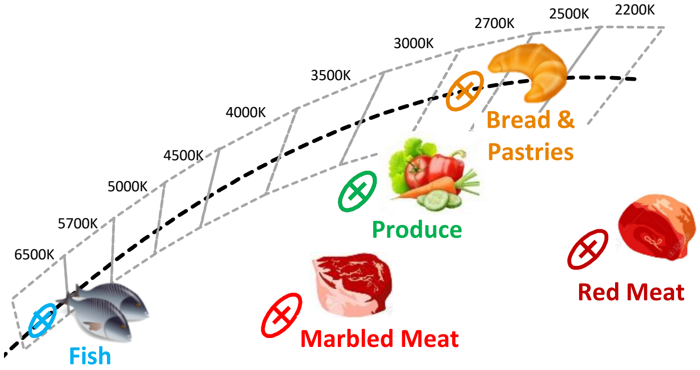
COB spectra for Fashion Retail

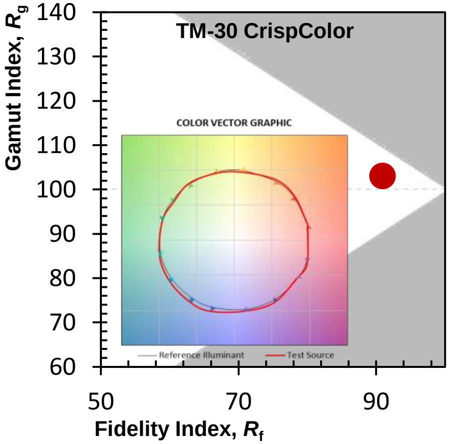


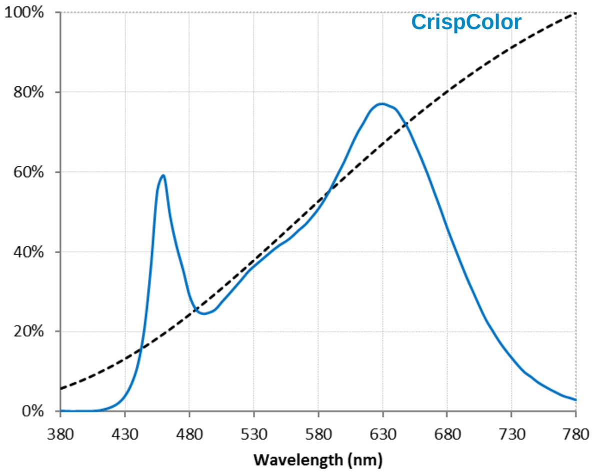




COB spectra for Fresh Food



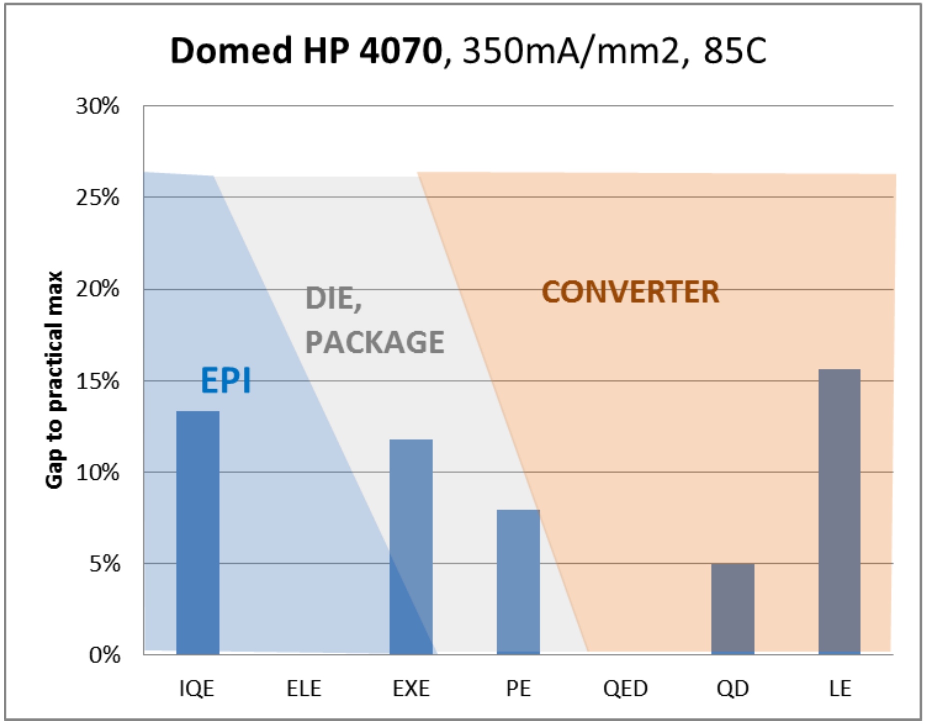


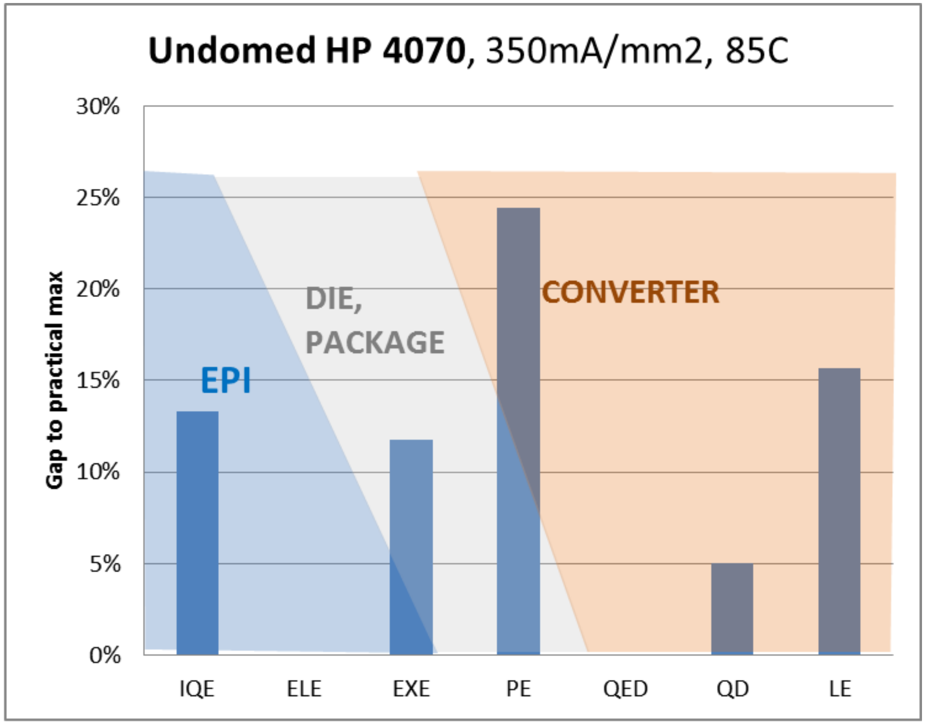


Retail applications:
Optimized spectrum, cost and now efficacy

Model	CCT	CRI	Rf	Rg	Efficacy (lm/W)
Core Gen3	3,000K	93	89	97	120
CrispWhite	3,000K	90	87	102	100
CrispColor	3,000K	90	91	103	110

Efficacy Improvement Focus Areas



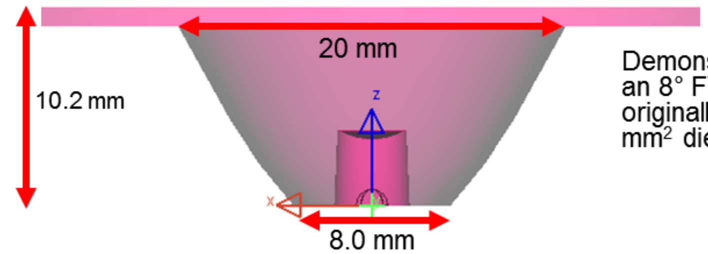


- Significant improvement opportunities remain in Epi, Die, Package and Converter/Phosphor
- Undomed LEDs reduce source size but have lower efficiency than domed LEDs
- Benefits of undomed LEDs: reduces source size, reduces solid angle and hence etendue

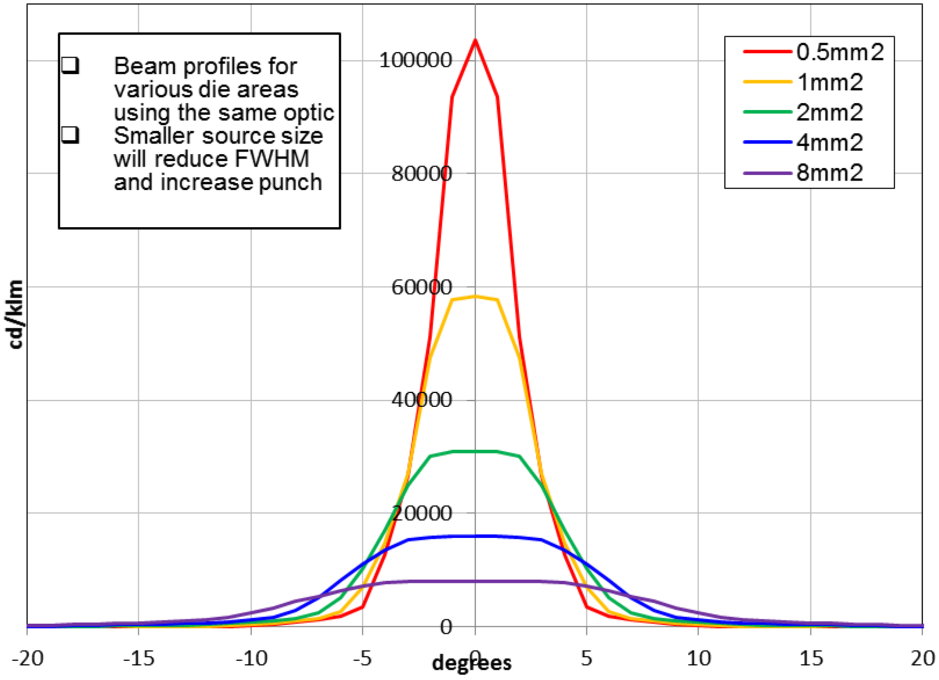
Impact Emitter Source Size on Beam Profile: Fixed Optics

- Decreasing the source size will increase the punch (cd/lm) and narrow the FWHM
  - The FWHM roughly scales with the linear dimension of the die.
  - The punch roughly scales with the inverse of die area.
  - For example, going from 2 mm^2 to 1 mm^2 will reduce the FWHM by $1/\sqrt{2}$ and increase punch by a factor of 2.

8° beam example	Die area (mm^2)				
	0.5	1	2	4	8
FWHM (°)	4.0	5.7	8.3	12.3	17.1
factor from 2mm²	0.5	0.7	1.0	1.5	2.1
Punch (cd/lm)	105.1	58.4	30.8	15.8	8.0
factor from 2mm²	3.4	1.9	1.0	0.5	0.3

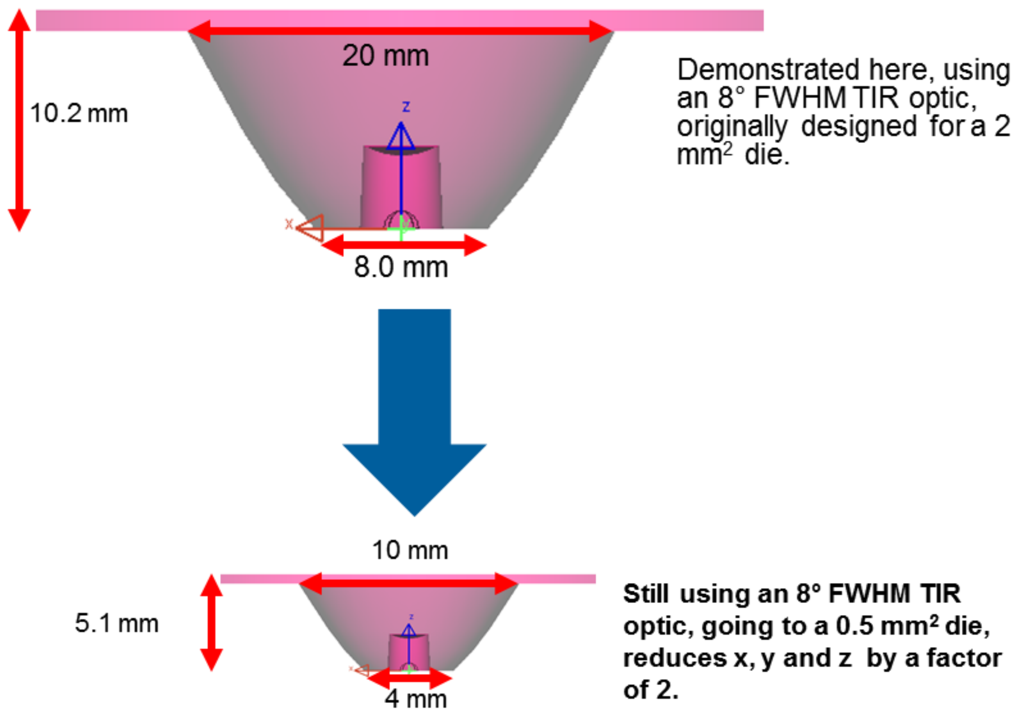


Demonstrated here, using an 8° FWHM TIR optic, originally designed for a 2 mm^2 die.

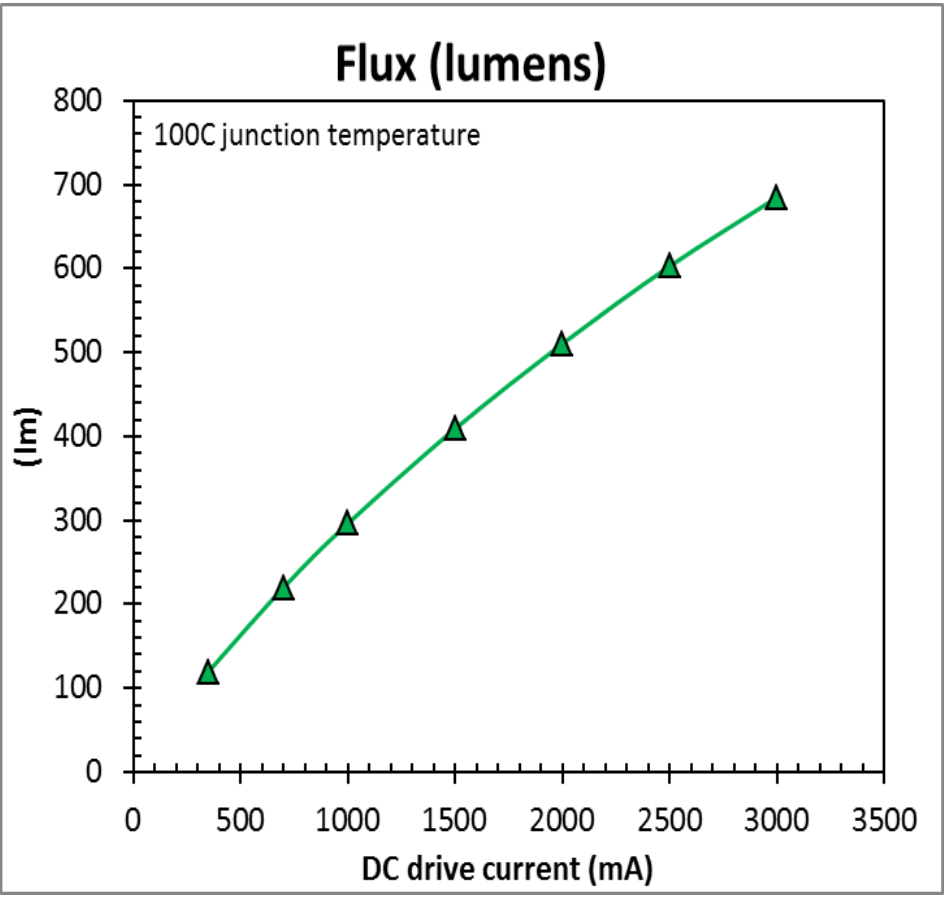


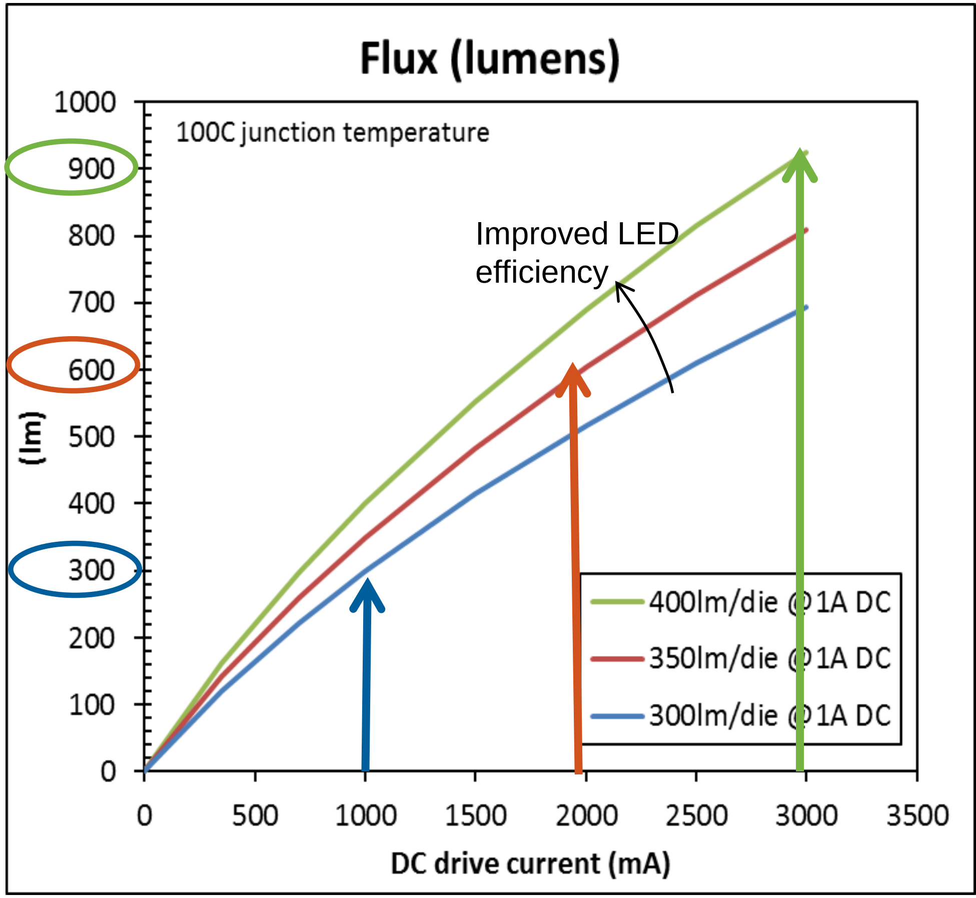
Impact of Emitter Source Size on System Optics

- Preserving beam performance (FWHM and punch): smaller source size reduces the optics size.
- Going from a $2mm^2$ to $0.5\ mm^2$ emitter enables the optics to be reduced by a factor of two, in x, y and z
- 8x volume decrease creates opportunity for significant form factor, weight and cost reduction; opportunity increases for larger luminaires
- So Low Etendue, High Luminance LEDs (highly directional) can create high value in a wide range of apps.



Increasing LED luminance = Increasing current density

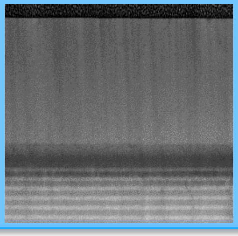




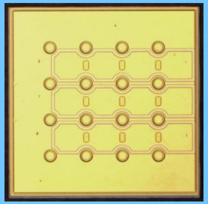
High Current Density impacts all elements of LED Design

EPI STRUCTURE

- Efficiency Droop
- Heat generation
- Reliability



DIE DESIGN



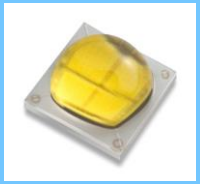
- Current spreading
- Thermal resistance
- High temperature reliability

PHOSPHOR

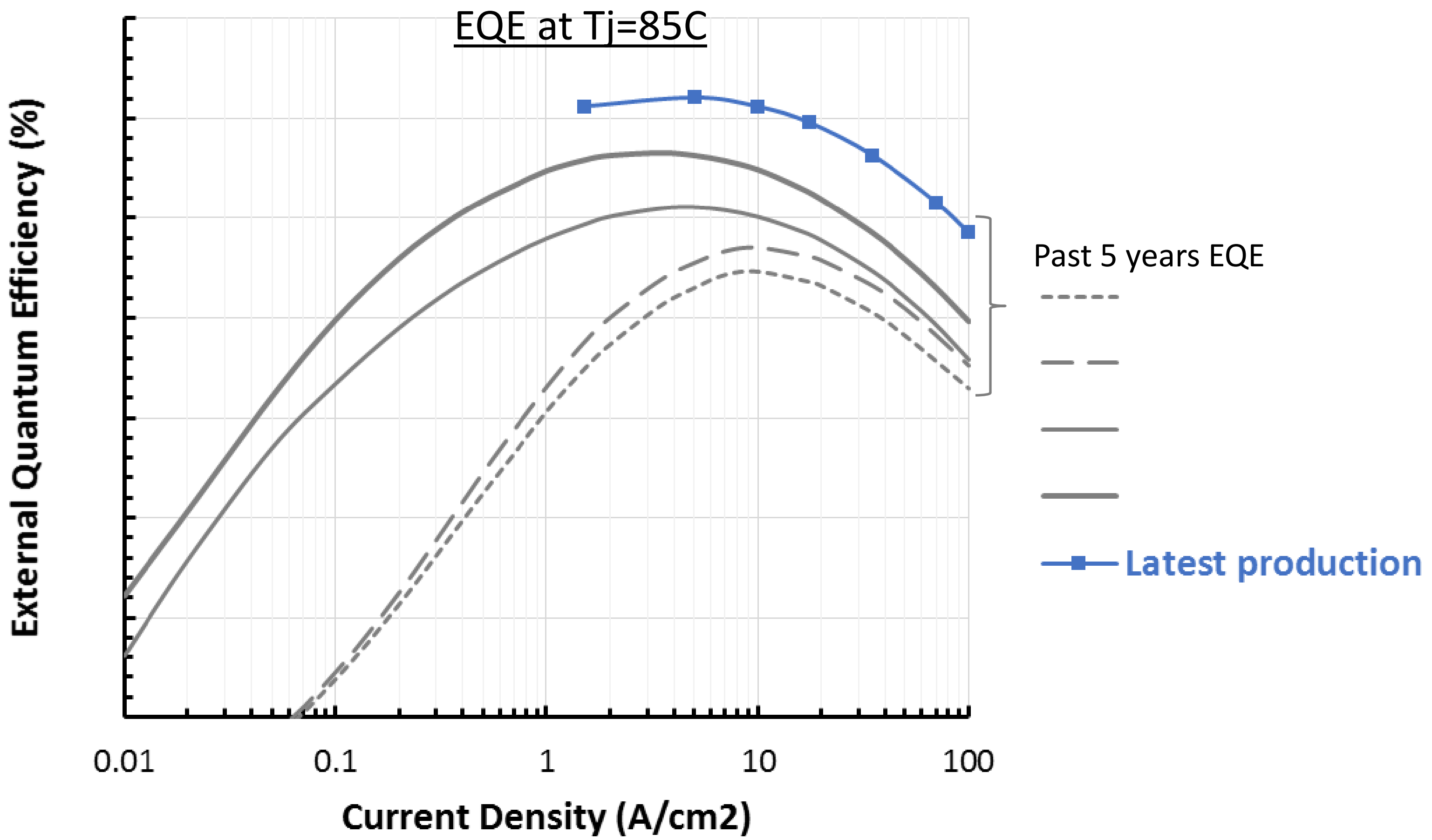
- Degradation at high temperature
- Photo-Thermal Saturation
- Reliability

PACKAGE AND ENCAPSULANT

- Browning under high optical flux
- Hardening/cracking
- Lifetime/reliability



Lumileds Epi improvement over the last 5 years



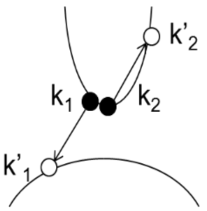
Continuous performance improvement focus remains on:

- Material quality improvement (low current density)
- Droop reduction (high current density)

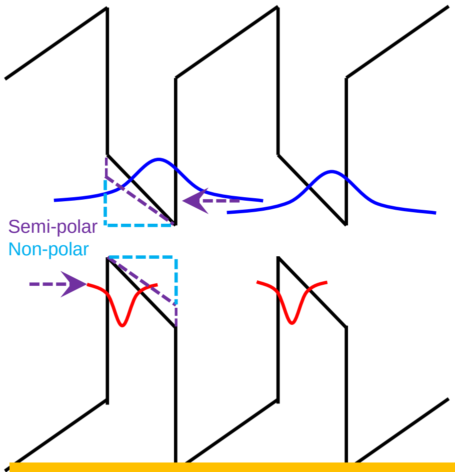
Routes to Improve Droop

Droop losses are due to Auger recombination and hot electron overflow – there are generally two approaches to circumvent this physical phenomenon:

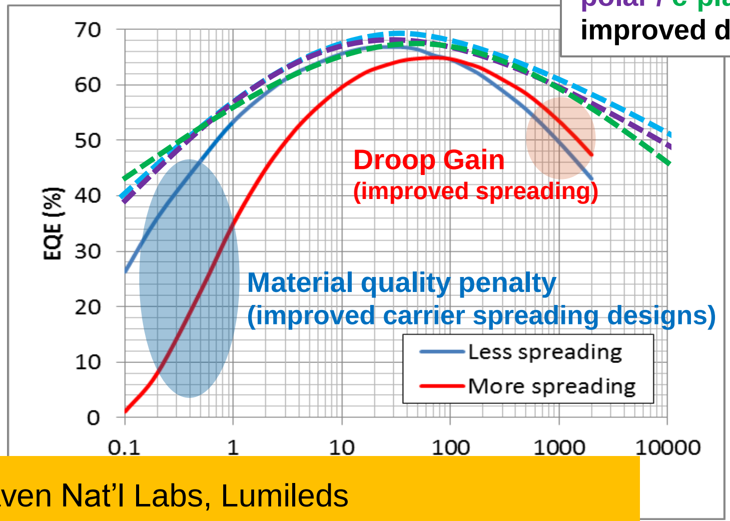
1. Improve carrier spreading to more quantum wells
2. Improve radiative recombination rate to reduce carrier density per QW at a given drive current



Active region design can improve carrier spreading and overlap but hurts material quality



Thin QWs improve e-h overlap but make Auger losses worse



DOE-funded project: MIT, Sandia & Brookhaven Nat'l Labs, Lumileds
Focus on fundamental understanding of defect origin in droop optimized LED structures

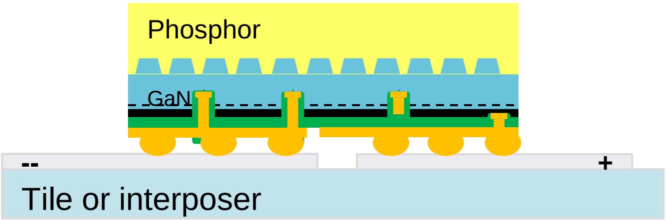
Solutions:

1. Improve droop by spreading to multiple QWs using well known c-plane growth
2. *Move to Semi/non polar GaN substrate, opens path to single thick QW to enable high radiative recombination rates and reduce Auger losses; solve large wafer cost/availability issue; improve crossover point versus c plane sapphire.

*** Ref: High-power blue-violet semipolar (20-2-1) InGaN/GaN LEDs with low efficiency droop at 200/Acm². Zhao, Y et al. Appl. Phys. Exp. 2011**

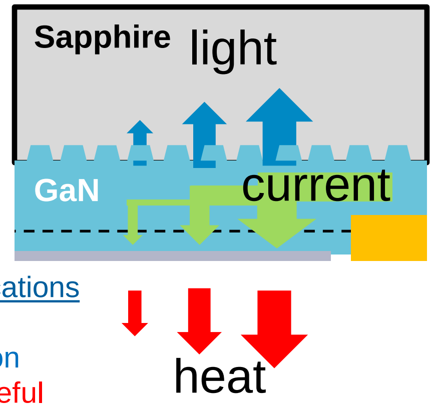
LED Device Architecture Comparison for High Luminance

Thin-film Flip-chip (TFFC)

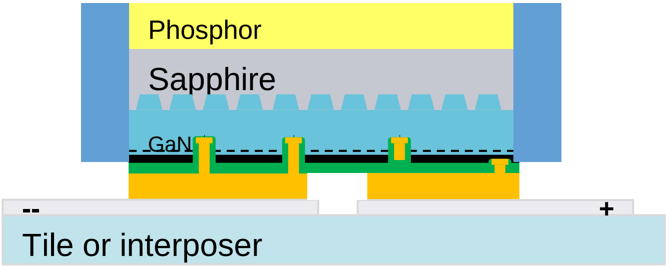


Pro: High luminance light source for directional applications
Supports high packing density
Contact/heat-sink does not interfere with light emission
Con: Thin-film structure adds complexity requires careful handling

"Flip-Chip"

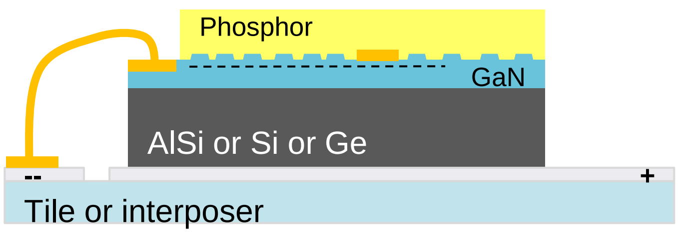


Chip-Scale Package (CSP)



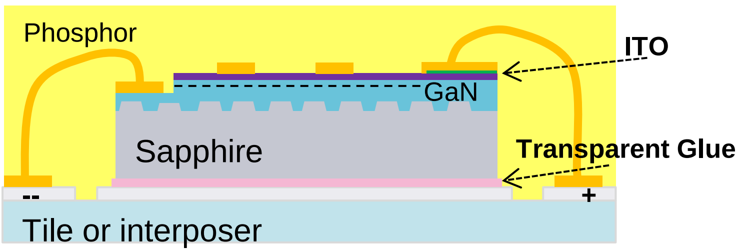
Pro: Sapphire gives robust structure for direct attach
Contact/heat-sink does not interfere with light emission
SMD compatible, enabling high packing density
Blocked side-light version enables high-luminance
Con: Cost higher than Lateral, lower than TFFC and VTF

Vertical Thin-Film (VTF)



Pro: High luminance light source for directional applications
Excellent heat sink for high power applications
Con: Thin-film structure adds complexity and requires careful handling
Wire-bond complicates phosphor integration and limits packing density

Lateral (Mid- & Low- Power)



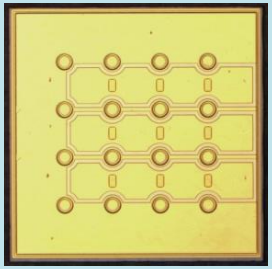
Pro: Lowest cost
Sapphire provides robust structure
Maximum extraction for non-directional applications
Con: Not compatible with high luminance:
Current crowding limits ability to drive at high current density
Poorer heat sinking due to the use of transparent glue
Wire-bonds complicate phosphor integration & limits packing density

High Luminance Array Compatible Device Architectures

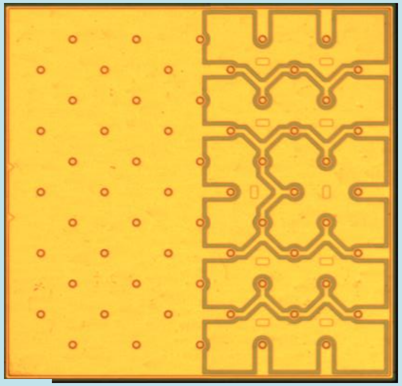
Designed for high current density, high thermal performance and high packing density

TFFC – Thin Film Flip Chip

1mm^2

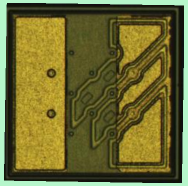


2mm^2

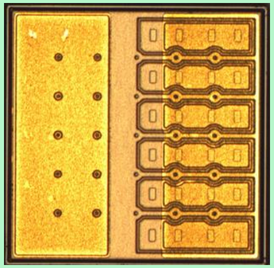


CSP - Chip Scale Package Examples

0.5mm^2

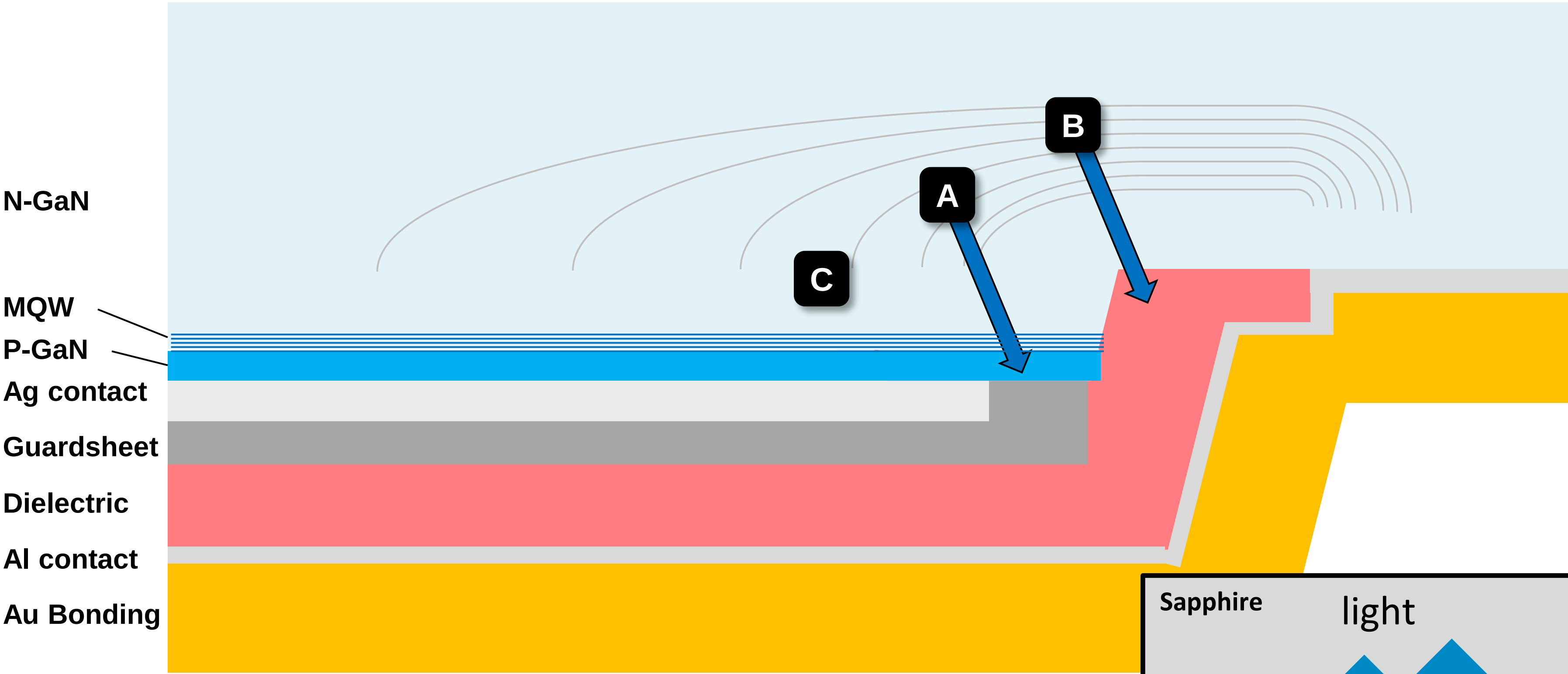


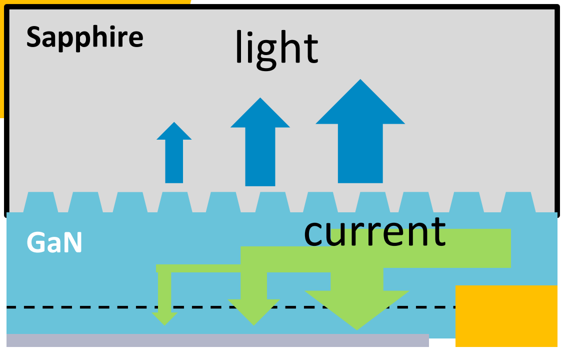
1mm^2



Extrinsic Droop in LED Die

Cross section of edge of contact via



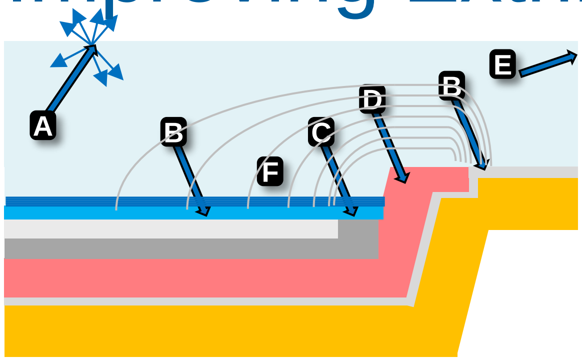


LOSS MECHANISMS

- **A** →***Absorption in guardsheet***
- **B** →***Photon trapping in dielectric***
- **C** →***Current crowding – exaggerates "extrinsic droop" <u>and</u> higher losses in A & B due to high local current density***

Losses increase with increasing current densities

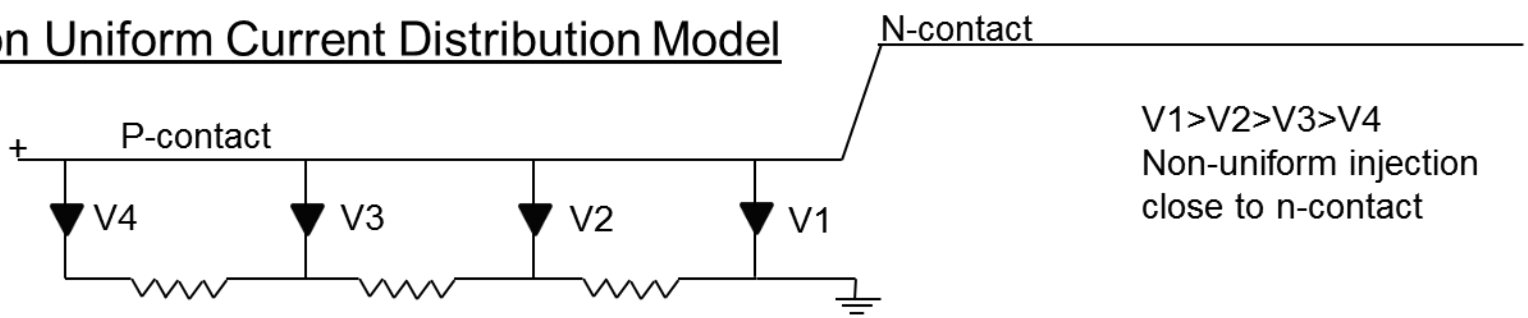
Improving Extrinsic Droop in LED Die



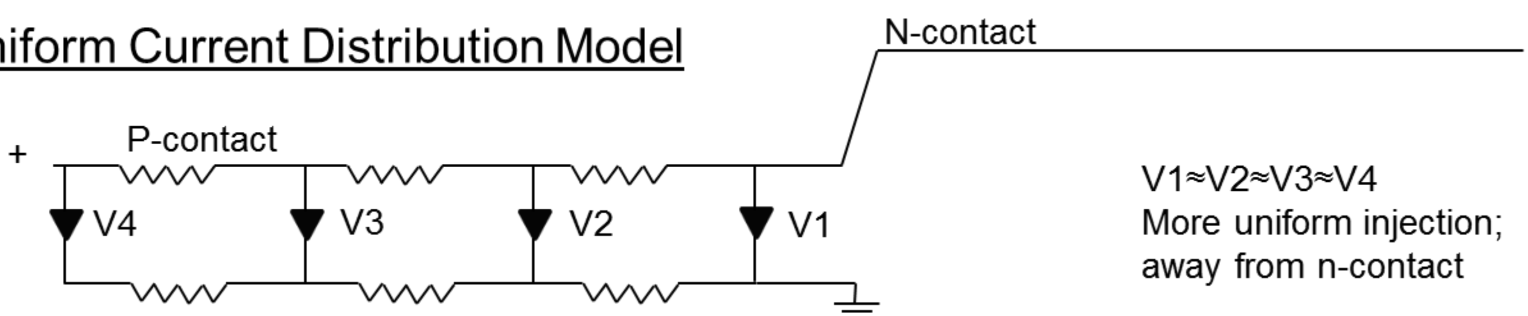
At high drive current density, extrinsic droop can be reduced by re-engineering the device architecture and materials to :

- reduce absorption losses; need to consider all of the device layers
- reduce current crowding at contact vias; establish uniform current distribution:

Non Uniform Current Distribution Model

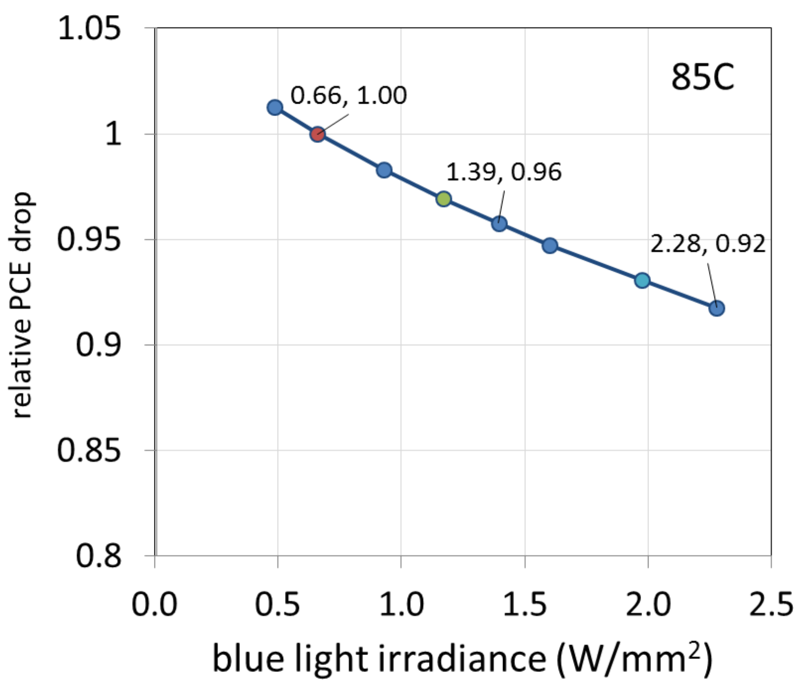


Uniform Current Distribution Model



Phosphor droop in LEDs

- Phosphor droop refers to decrease of Phosphor Conversion Efficiency (PCE) with increasing flux
- For this example of a typical warm white pcLED,
  - the PCE relative drop is ~4% for each doubling of blue light power density
  - This drop accounts for 20-25% of the total white LED efficiency droop with drive



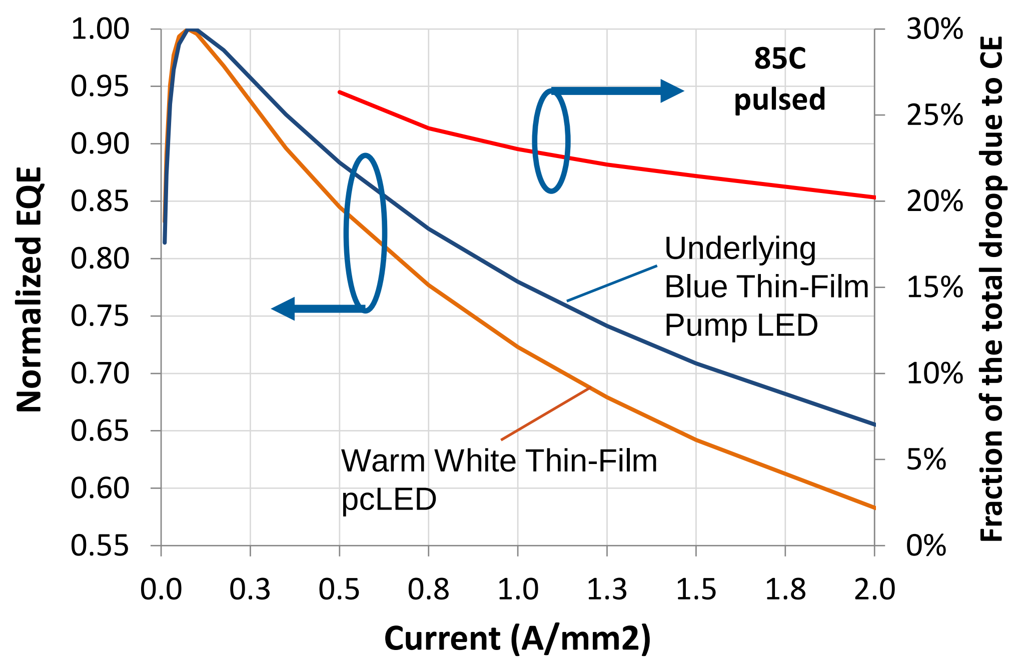
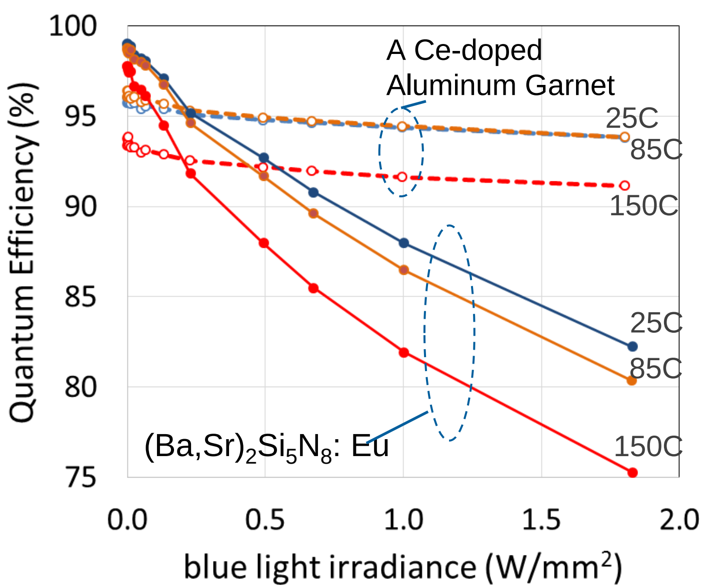


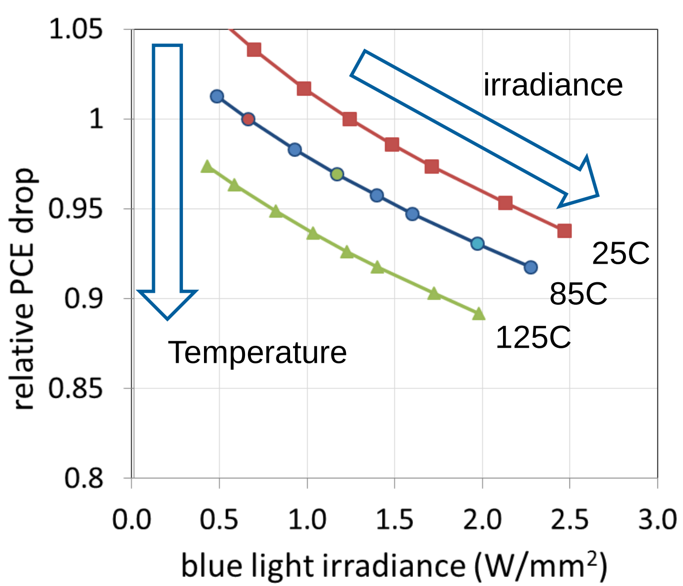
Photo-thermal quenching: impact on conversion efficiency

- Photo-quenching in Eu^{2+} red nitrides shows strong dependence on temperature
- Cerium-doped aluminum garnets show little dependence of photo-quenching on temperature, but, depending on composition, may exhibit considerable thermal quenching

- Photo-thermal quenching of phosphors readily translates into Conversion Efficiency (CE) quenching in pcLEDs
- At typical operating conditions of a HP LED irradiance 0.7 – 1.5 W/mm² and we easily get to the $T_{phosphor}$>100C



WW High-Power LED example



Status of Red phosphors for high luminance applications

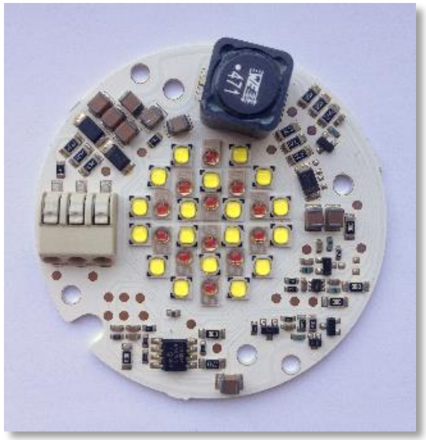
At high drive current density opportunities remain for major PCE improvement:

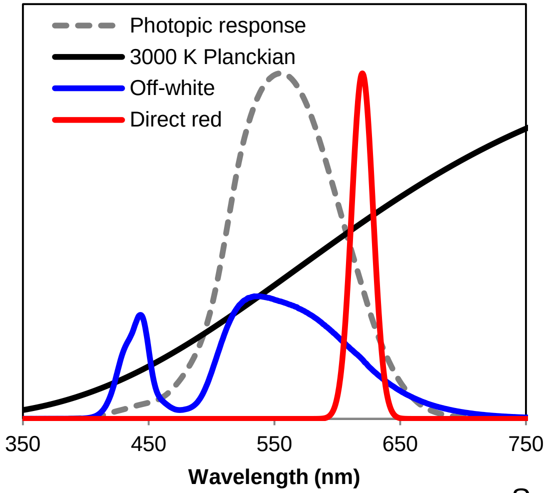
- ~30% from all effects
- ~10% (1/3 of above) from PTQ improvement, impacted by current density and temperature
- 20% (2/3 remaining) from optimizing FWHM and WL
- Fundamental materials development needed

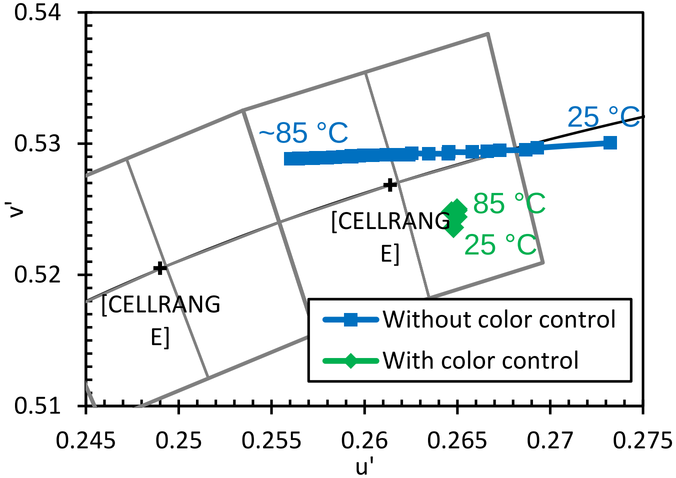
	FWHM	WL	QE low drive	QE high drive
Eu2+ 258 and SCASN nitrides				
SLA				
KSIF				
QDs				

Narrow-band solution using direct red

Hybrid light engines (phosphor-converted off-white + direct red)







Supported by DOE SSL program under award DE-EE0005099

High efficacy at CRI Ra>90 R9>50

- Need improvement in red to drive further efficacy improvement (H/C factor)
- Requires integrated control electronics to stabilize color point

Example: Office Troffer

LED Retrofit Lamp:

2’x4’; 4.5klm T8
Fluorescent tube

2’x4’; 4.5klm LED Tube

T8 tube replaced with T-LED + Driver.
Value proposition: TCO driven by LED lifetime; Quality of LED Light over Fluorescent Light

Level and Form Factor Collapse:

2x

2’x2’; 4.5klm troffer LED on L2

L2 boards + driver -> form factor reduction.
High performance + guaranteed consistency.
Technology Enabler: High performance LEDs, very tight binned color, flux and Vf
Value proposition: Consistency, TCO, cost (material, weight, space), vol. reduction 2x.

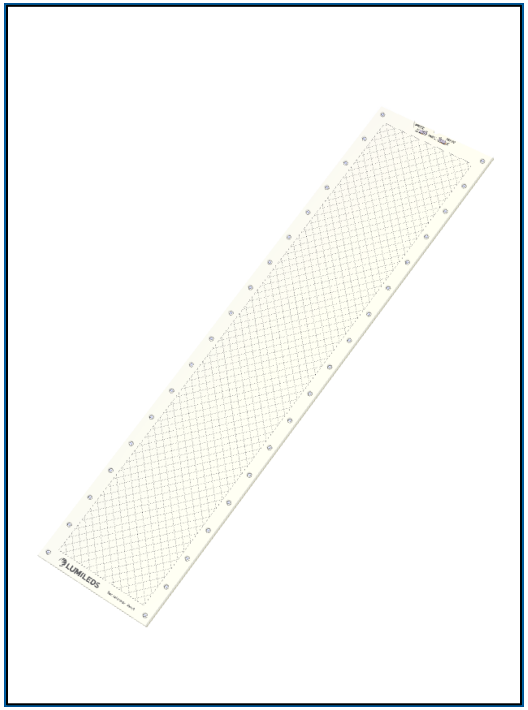
50x

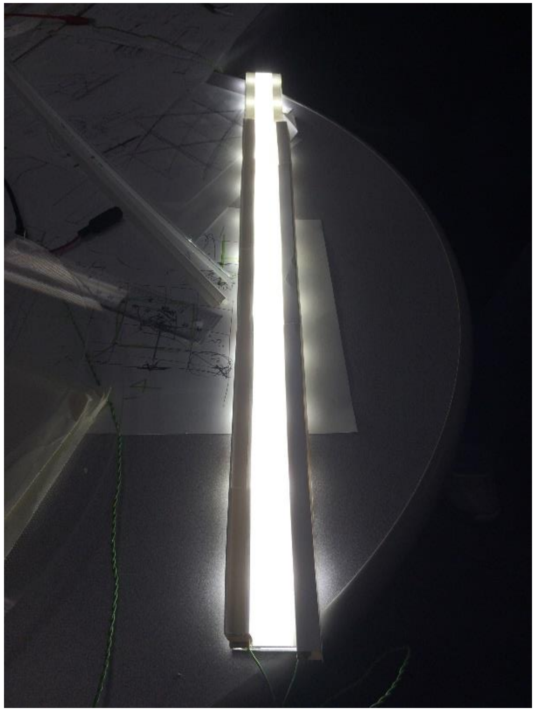
18” diameter, 4.5klm output
1cm thick; enabled by:
CSP LEDs + Lightguides

Further reduces troffer volume by over 50x (continued cost savings)
Value proposition: TCO (cost: material, weight, space) and Design
Technology enabler: L1 HP LEDs….still much more we can do here!

Linear fixture innovation

>50x Volume Reduction over 4'x2' troffer





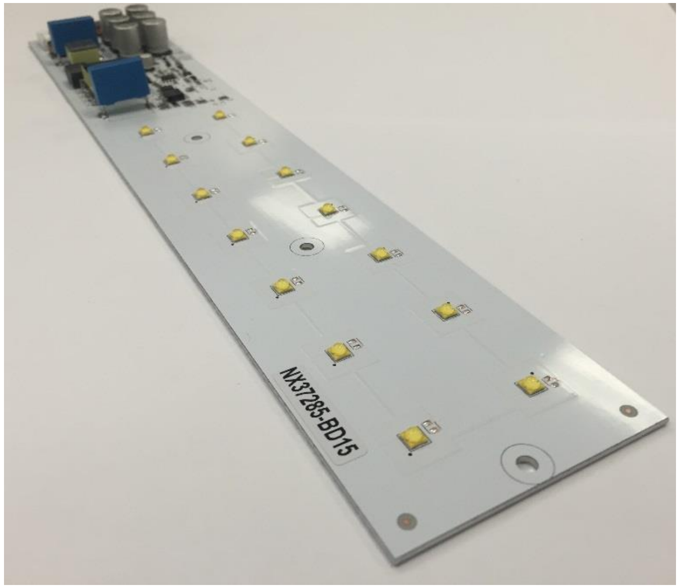
- 4.5 klm: 4' x 3"
- <1cm thick linear lighting
- Enabled by:
  CSP LEDs + Lightguides

New form factors for office applications.
Value proposition: Design with same TCO as 18" diameter (cost: material, weight, space)
Technology enabler: L1 CSP LEDs

Driver on board integration

First phase: system cost reduction
- Fewer connectors, brackets, wires
- Smaller luminaire → lighter infrastructure
- Driver and LEDs optimized together

Supported by DOE SSL program
under award DE-EE0006703



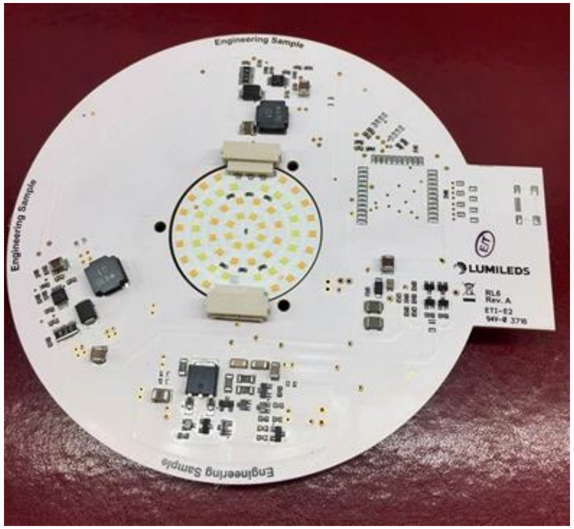
Second phase: disruptive form factors and long lifetime
- Miniaturization based on high-frequency switchers
- Improved lifetime by eliminating electrolytic capacitors

Intelligent Controls

- Meshed Wireless Controls
  - Fast and easy upgrade
  - Future proof (OTA updates)
  - No central controller/server/router
  - Self-healing communication

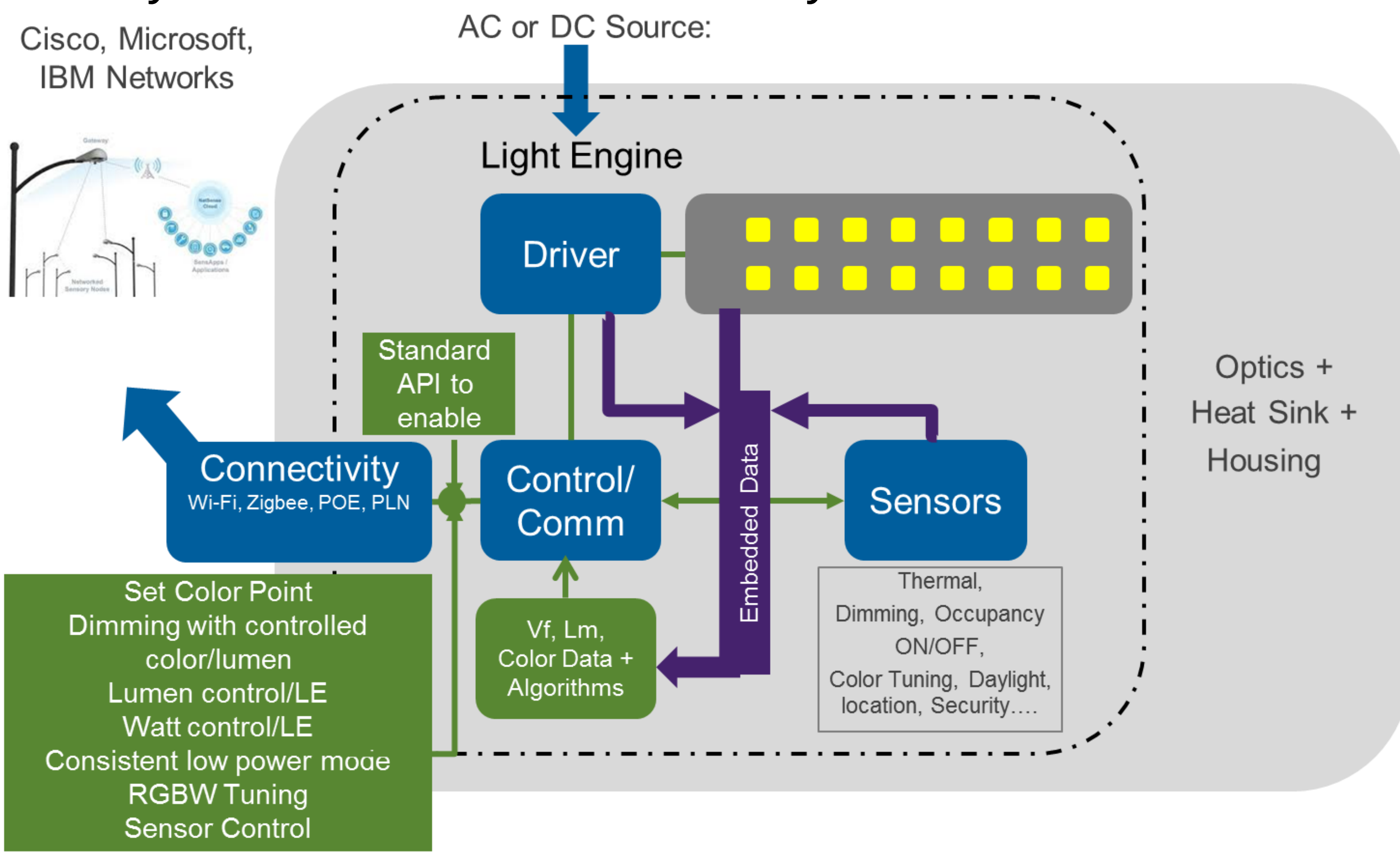
- When tied into LED array on board
  - Predictive analytics for Lumen Maintenance and color shift
  - Simplified power/connectivity structure
  - Use LED data for OTA synchronizing of luminaire settings

Bluetooth® SMART



Future of Connected Light Engines: APIs & Embedded Data

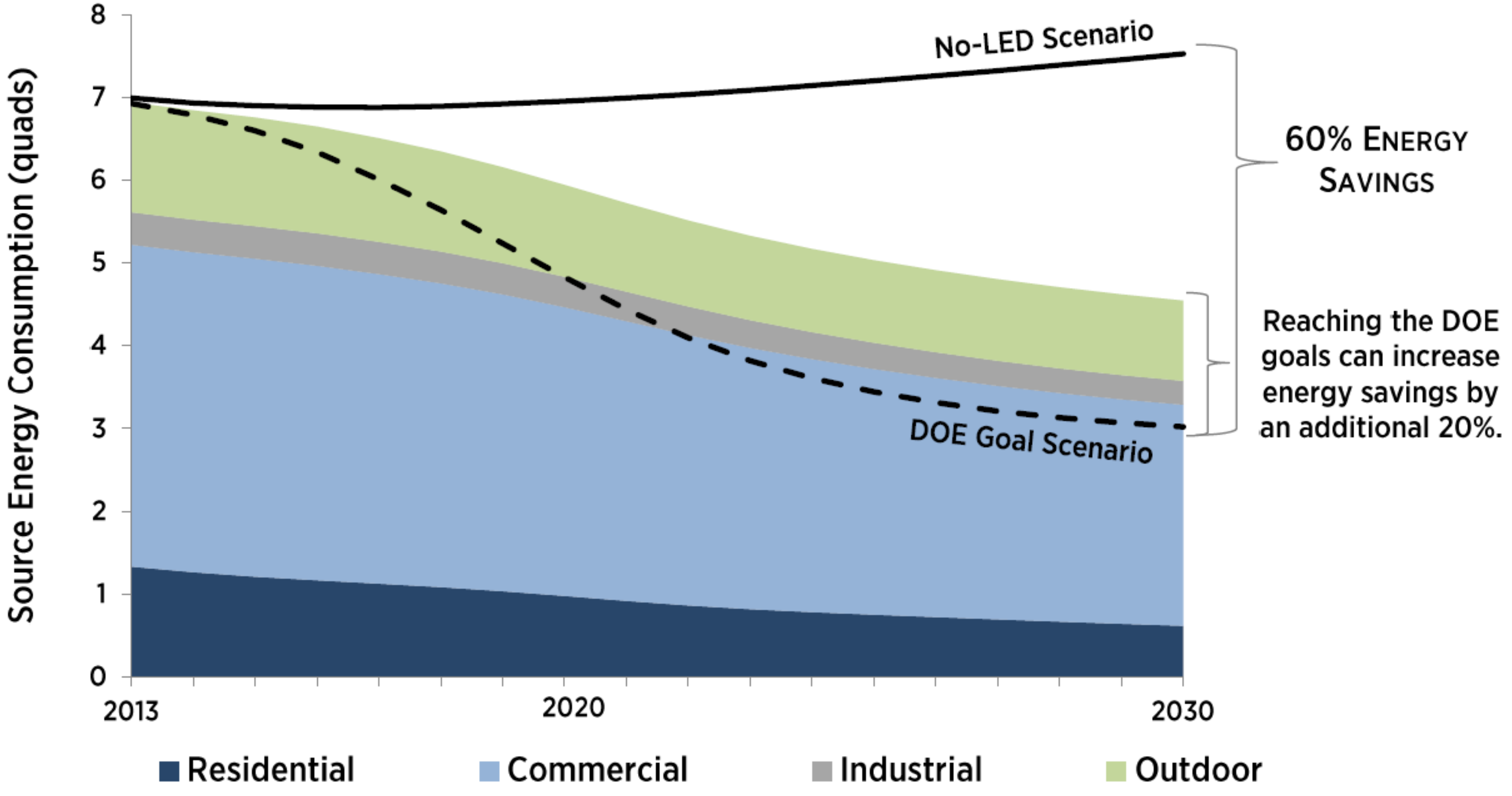
Resiliency and Robustness enabled by embedded data



Conclusions

- We have tremendous opportunities to accelerate the LED adoption
- Retail/Hospitality: With new capability of highly customized spectrum for specific applications, now positioned to displace CDM. Work continues with LED color customization and continuous performance improvement.
- Directional Lighting: Huge opportunities for disruption through high luminance LEDs focusing on system level performance & integration; opening the gateway to cost effective dynamic beam steering.
- Intelligence; daylight and dimming sensing already demonstrated tremendous potential, the next step is robust, resilient and connected networks, which opens the door to an API architecture and embedded LED data applications.
- In each of the above areas we have highlighted key developments needed in core LED technology, without diving into the electronics, FW and SW challenges for next generation system level integration and intelligence.

Benefit of accelerating adoption: measured in quads!!



From: DOE, Energy Savings Forecast of SSL in General Illumination Applications, 2014

LUMILEDS