Outline

• Introduction
  - LED applications
  - Dominant LED architectures
  - Key LED metrics and progress
  - Remaining technology challenges

• Update on technology advancements
  - Droop in InGaN based LEDs
  - Green gap
  - Amber and red LEDs
  - Quantum Dots

• Technology impact on LED products (examples)
  - 90 CRI LEDs with QDs
  - High Luminance LEDs
  - Integrated, compact spot module

• Conclusions
Application Focus

Breadth of SSL applications requires a range of LED capabilities

High Efficacy

Indoor Area Lighting
- Mid/Low Power
- COB
- Mid Power

Outdoor/Stadium
- High Power
- CSP

Spotlights
- HD CoB
- High Power
- CSP

High Luminance

Downlights
- COB
- Mid Power

High Bay & Low Bay
- High Power
- MP

Specialty
- High Power
- CSP

Colors

Architectural
- Color
- High Power

Horticulture
- Color
- MP Color
- High Power
## Relevant LED Architectures

Fundamental LED architectures and key characteristics

<table>
<thead>
<tr>
<th>Emitter Type</th>
<th>Emitter image</th>
<th>Luminance</th>
<th>Efficacy</th>
<th>Directionality</th>
<th>Luminance</th>
<th>Source Size</th>
<th>Luminance Uniformity</th>
<th>Color over Angle</th>
<th>Color over Source</th>
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<tbody>
<tr>
<td>Domed High Power</td>
<td></td>
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<td>Directional CSP</td>
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<tr>
<td>Chip on Board</td>
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<td>+++</td>
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LED Metrics

Critical LED metrics: Luminous efficacy and Luminance

Luminous efficacy: $\eta_L (\text{lm/W})$

$\eta_L = \text{WPE} \times \text{CE}$

- **WPE** = $\text{IQE} \times \text{EXE}_n \times \text{ELE}$
  - IQE: Internal Quantum Efficiency
  - EXE$_n$: Extraction Efficiency
  - ELE: Electrical Efficiency

- **CE** = $\text{LE} \times \text{QED} \times \text{QD} \times \text{PE}$
  - LE: Lumen Equivalent
  - QED: Quantum Efficiency in Down Conversion
  - QD: Quantum Deficit
  - PE: Package Efficiency

The efficiency of a “white” LED converting electrical power to light perceptible by the human eye (lm/W)

Luminance: $L_V (\text{cd/m}^2 = \text{nit})$

$L_V = d^2 \frac{\Phi_V}{(dS \times d\Omega \times \cos \Theta)}$

The luminous power per unit solid angle per unit projected area (cd/m$^2$)

Increasing Luminance

- Higher drive current: Reduction of IQE and QED
- Smaller source size: Reduction of PE
LED Progress

Substantial efficacy improvements

In addition, improvements in:

- “Quality of light”
  - High CRI available
  - Uniform CoS and CoA
  - Controlled radiation patterns
  - Glare control
- Lumen maintenance
- Color stability
- Cost reduction ($/lm)
Key Focus Areas for LED Technology Development

There is still a lot to do...

Further efficacy improvement
- Epi and die development
- Narrow band phosphors and QDs

Efficacy at high drive current for high luminance applications
- Droop reduction
- Converter saturation
- Efficient packages with small source size

Efficacy across the visible spectrum
- Improve InGaN green and AlInGaP amber and red
Droop
“Droop” in InGaN based LEDs
Decrease in LED efficacy with increasing drive current

Typical operating range:

MP LEDs

HP LEDs

Epi droop: non-radiative recombination in active layers at high current density

Phosphor droop: photothermal saturation of quantum efficiency of phosphor materials (esp. red)
Origin of “Epi Droop”

Dominant mechanism: Auger recombination

Key processes to consider:

- Carrier density in the QWs
  - Auger recombination increases with increasing carrier density
  - Reduce carrier density by improving electron and hole transport to spread carriers more evenly

- Radiative vs Auger recombination in QWs
  - Auger recombination increases as QW width decreases
  - Design of active region structure to improve radiative recombination rate

- Materials quality
  - The number and type of defects in the material has significant impact on performance (peak efficiency)
  - If thick QWs can be grown with good materials quality, the onset of efficiency droop can be pushed out
Green Gap
Green Gap

InGaN LED efficiency drops approaching green WL

- EQE vs WL peaks at 425 nm (>70%)
- Royal blue (440nm) >65%
- EQE ~2x lower for green

AlInGaP
- Band structure fundamentally limits EQE at shorter WL
- Inherent temperature dependency worse than InGaN

Data from various manufacturers included
Efficacy of Direct Green Emitting LEDs

Green LEDs in “droop” regime at lower current densities

Contributing factors for lower efficiency in “Green Gap”:

• Lower IQE (or peak EQE):
  - Worse carrier overlap (larger polarization induced electric fields, which increase with increasing bias in c-plane)
  - Material quality challenges with higher indium in QW (lattice mismatch, miscibility gap, etc....)

• Worse efficiency Droop:
  - Greater energy barriers to carrier transport, which increases carrier density on p-side QWs → higher Auger
  - Worse electron-hole overlap reduces radiative rate, which increases carrier density in QWs → higher Auger

Order of magnitude difference in peak efficiency current density
Amber and red AlInGaP LEDs
Efficiency of Direct Emitting AlInGaP LEDs

Reduced efficiency for amber LEDs and limited hot/cold factor

IQE is flux limiting for amber

- IQE drops steeply when the Al% approaches 53%, because the bandgap transitions from direct to indirect
- IQE and H/C factor is ~ 30%

Light extraction is flux limiting for red

- IQE is ~80-90%, thus the light extraction efficiency is the limiting factor for flux
- Phosphide refractive index is high, resulting in light trapping inside the LED die
AlInGaP Epi Structure

Key issues facing AlInGaP Technology

- Point defects originating from the growth substrate degrade active region
- Small Band offsets
- Carrier overflow significant for short WL devices
- Indirect band gap nature when wavelength gets close to amber
Quantum Dots
Quantifying the Benefits of Narrow Band Phosphors

Simulated FWHM Dependence for LE at 3000K and 90CRI

<table>
<thead>
<tr>
<th>Gaussian Green FWHM (nm)</th>
<th>30</th>
<th>50</th>
<th>70</th>
<th>90</th>
<th>110</th>
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<tr>
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<td>90</td>
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LE gains normalized to 90nm Red and 110nm Green FWHM
Technology impact on LED products (examples)
QD LEDs
CRI 90 MP LEDs with QDs narrow gap to CRI 80

- Efficacy gap to comparable CRI 80 LED reduced to ~7% (2700K, CRI 80)
- Red QDs in on-chip configuration released in LUXEON 3535L HE Plus mid-power LED
- LED meets required reliability criteria
High-Luminance LEDs
High-drive CSP technology enables “bright” sources for highly directional applications

- Luminance of >75 Mnit from compact, Lambertian light source
- Enable small form factor luminaires with narrow beam angle and high punch
- Precise delivery of light where it is needed to drive energy savings

<table>
<thead>
<tr>
<th>Metric</th>
<th>Typical value</th>
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<tr>
<td>Viewing angle</td>
<td>118°</td>
</tr>
<tr>
<td>Total included angle</td>
<td>140°</td>
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<tr>
<td>Forward emission</td>
<td>99.9%</td>
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</table>

![Graph showing luminance vs current with >200% increase at higher currents.](image)

![Graph showing luminance vs polar angle with Lambertian distribution.](image)
Compact Modular Light engine
High luminance LEDs enable small form-factor light engine

Enable upgrade-ability of light engine by:

- Tightly packing CSPs to allow for flexible high étendue sources
- Choosing power and control partitioning to allow for standard interfaces
- Placing minimal electronics and intelligence on board with CSP array
Conclusions

LED technology advancements have resulted in substantial improvements

• **LED efficacy:** MP LEDs achieve ~200 lm/W and HP LEDs achieve 150 lm/W at their respective typical operating conditions

• **High drive current density operation:** Compact sources with high luminance are becoming available delivering up to 100Mnits with controlled forward directed beams

• **Quality of light:** Narrow band red phosphors and QDs enable CRI 90+ LEDs with efficacy close to CRI 80 LEDs (~7% gap with QDs)

• **Direct color LEDs:** Quantum efficiency of direct emitting green and amber LEDs continues to improve. Green InGaN LEDs with EQE >35% at operating conditions are now commercially available and have the potential for significant further advancement