# LED technology considerations for high luminance sources

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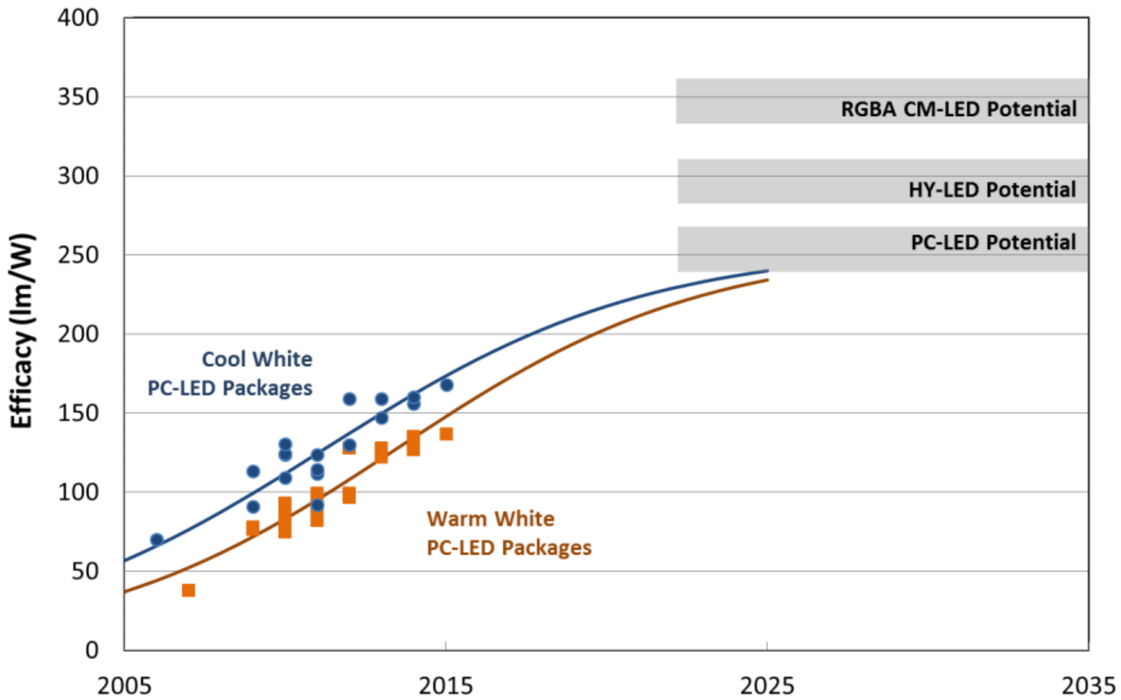
# Tremendous progress in LED efficiency



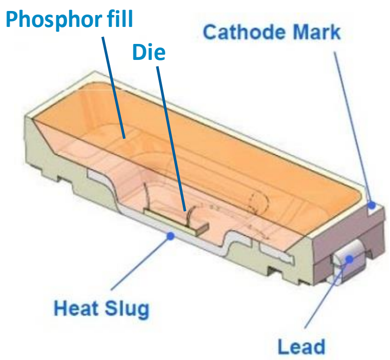

*Note: Blue = cool white (5700K) data (circles) and logistic fit (line); orange = warm white (3000K) data (squares) and logistic fit (line). Late-2015 measured commercial products reach approximately 160 lm/W for cool white and approximately 140 lm/W for warm white. Approximate long-term-future potential efficacies of three white-light architectures (pc-LED, hy-LED, RGBA cm-LED) are shown as grey bars.*

**Figure 5.4: Efficacies of Commercial LED Packages Measured at 25°C and 35 A/cm$^2$ Input Current Density**

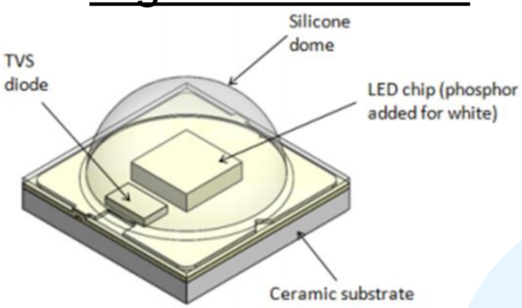
# Dominant high efficiency architectures

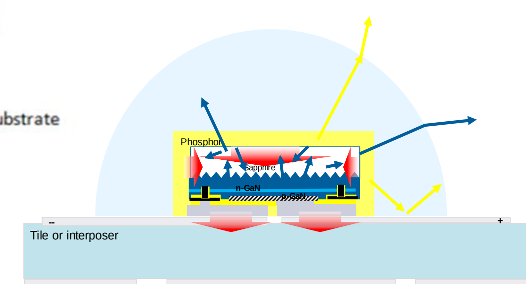
## Mid-Power LEDs




- High extraction efficiency die
- Low operating power densities allow for high epi IQE
- Large highly reflective cup reduces optical losses
- Large volume of phosphor relative to die area reduces irradiance levels: lower photoquenching and high package efficiency

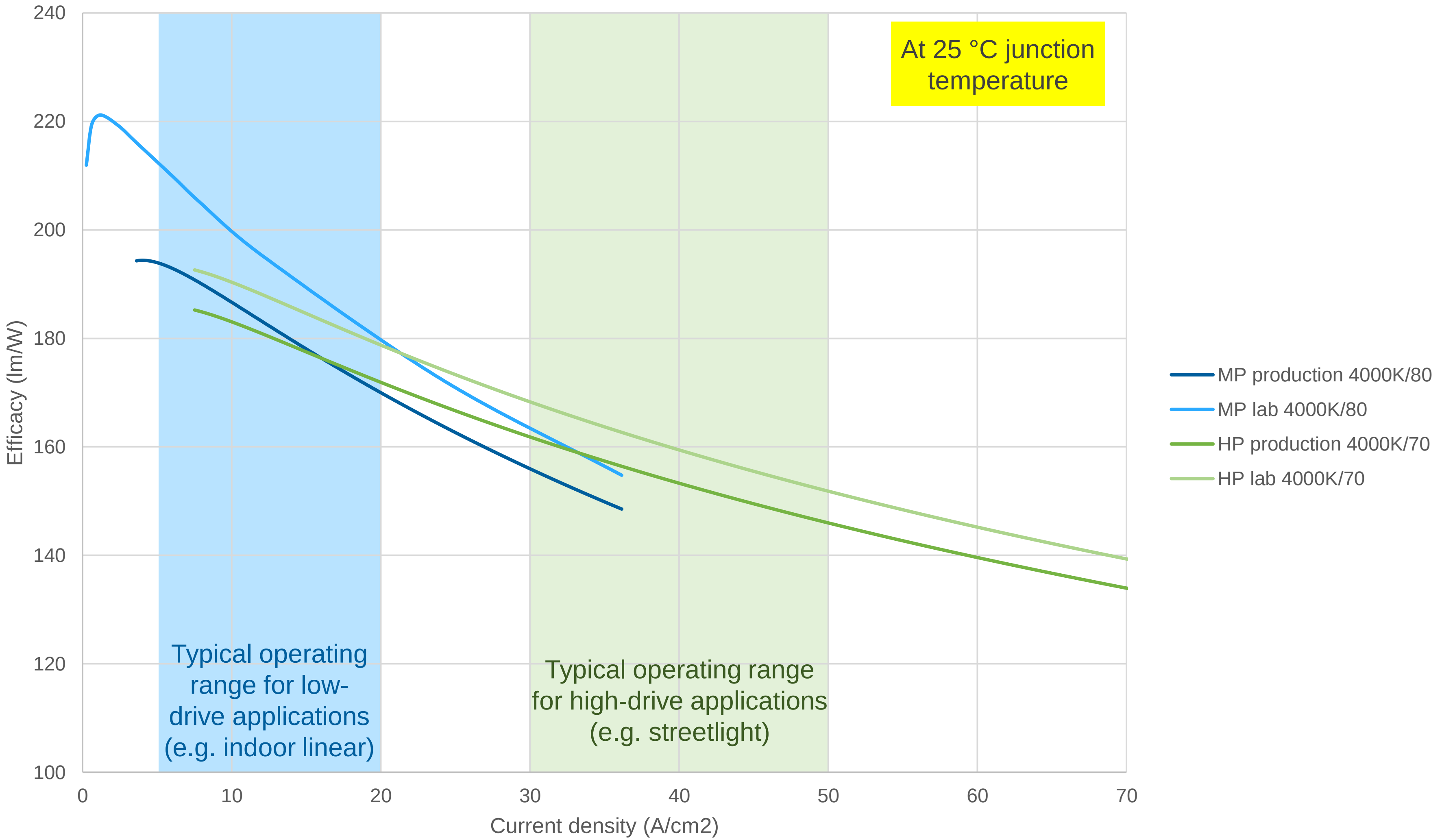
## High-Power LEDs




- High extraction Thin-Film or Flip-Chip die
- Highly reflective and thermally conductive submount
- Flip-Chip die allows for reduction in photo-thermal quenching of phosphors
- Die footprint  2mm$^2$ or larger to keep epi IQE high
- Large silicone dome to aid photon extraction

# LEDs for low-drive vs. high-drive applications



# Etendue and brightness limitations of dominant high efficiency architectures

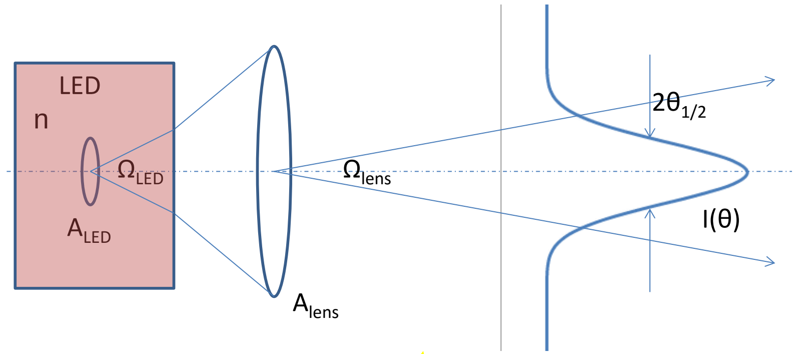
Etendue $G = n^2 \cdot A \cdot \Omega$,

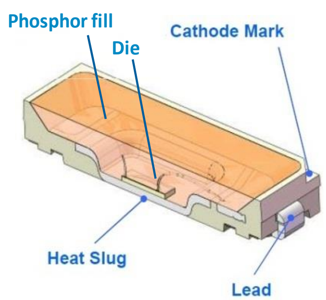
Where A is the area of the emitting source

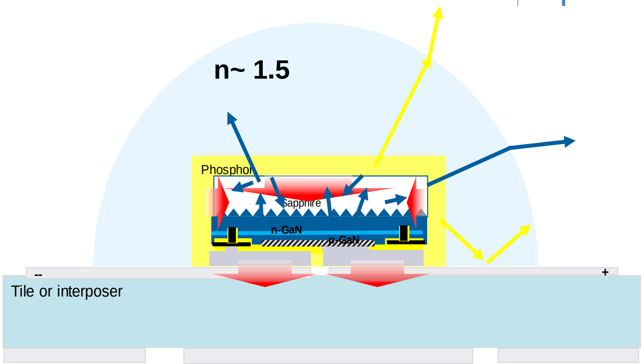
Ω is the emission solid angle

n is the index of refraction

Etendue can only increase in an optical system (optical equivalent of Entropy)



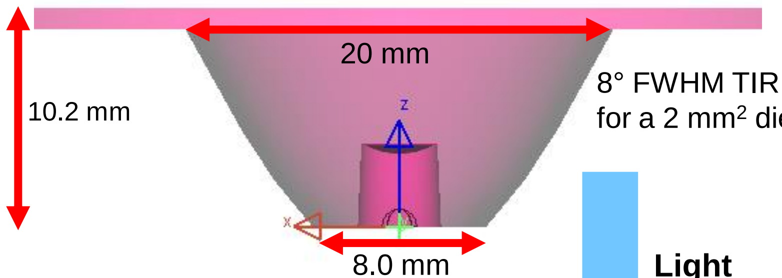




- Large source area
  - increases etendue
- Input power limited by:
  - die design
  - die attach

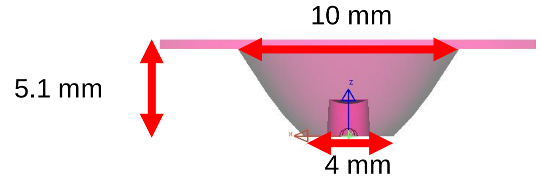
- Common die footprint 1-2mm$^2$ or larger
  - increases etendue
- Silicone dome
  - increases etendue
- Multi-side emitters: larger solid angle
  - increases etendue

# Versatility of low etendue, high brightness sources




8° FWHM TIR optic for a 2 mm² die

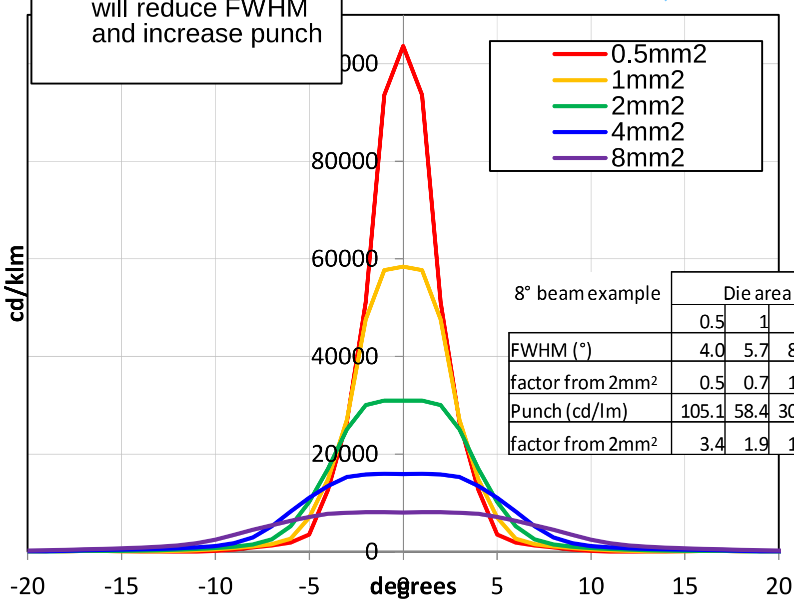
**System size**




**Still using an 8° FWHM TIR optic, going to a 0.5 mm² die, reduces x, y and z by a factor of 2: 8x system volume reduction**

**Light utilization**

- Beam profiles for various die areas using the same optic
- Smaller source size will reduce FWHM and increase punch



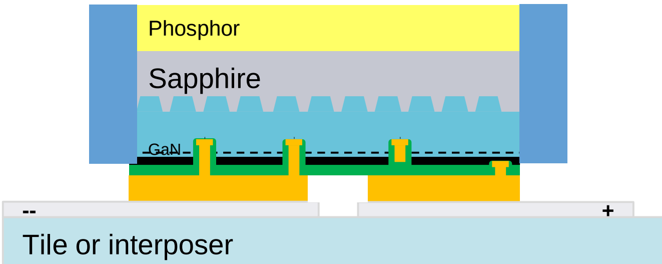

| 8° beam example | Die area (mm²) | | | | |
|---|---|---|---|---|---|
| | 0.5 | 1 | 2 | 4 | 8 |
| FWHM (°) | 4.0 | 5.7 | 8.3 | 12.3 | 17.1 |
| factor from 2mm² | 0.5 | 0.7 | 1.0 | 1.5 | 2.1 |
| Punch (cd/lm) | 105.1 | 58.4 | 30.8 | 15.8 | 8.0 |
| factor from 2mm² | 3.4 | 1.9 | 1.0 | 0.5 | 0.3 |

-We illustrate system level impact of source etendue by varying source area

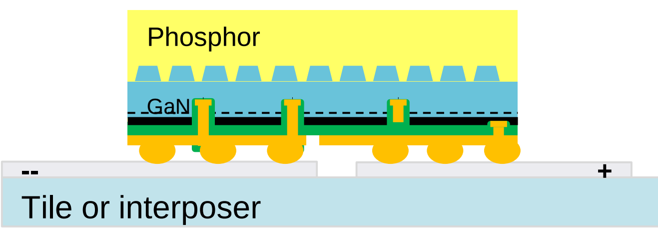
-Lower source etendue allows greater freedom to optimize for light utilization and system size

# High-luminance LED architectures

### Chip-Scale Package (CSP)




### Thin-Film Flip-chip (TFFC)



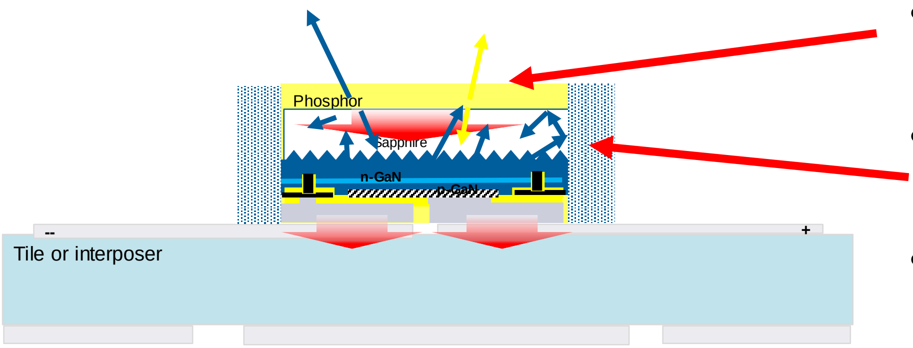

### Vertical Thin-Film (VTF)

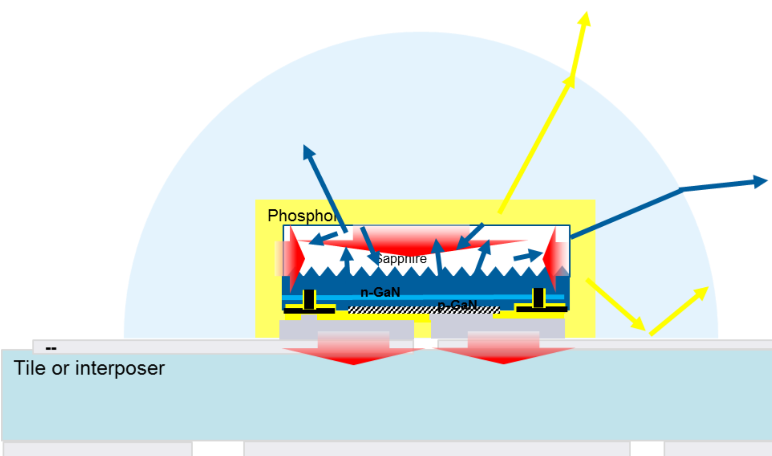

- **Key features of low-etendue, high-luminance architectures:**
  - **Small source size**
  - **High current density die**
  - **Low thermal resistance**
  - **Proximity “on-chip” phosphor**
  - **Single-sided emitter (side-coated phosphor and die as needed)**
  - **No dome**

- **Challenges:**
  - **Lower optical Package Efficiency due to absence of dome and the addition of side-coat**
  - **With current densities above 35A/cm2 need to consider:**
    - **impact of EPI IQE droop**
    - **impact phosphor photo-thermal quenching**

# Package efficiency penalty for high luminance architectures



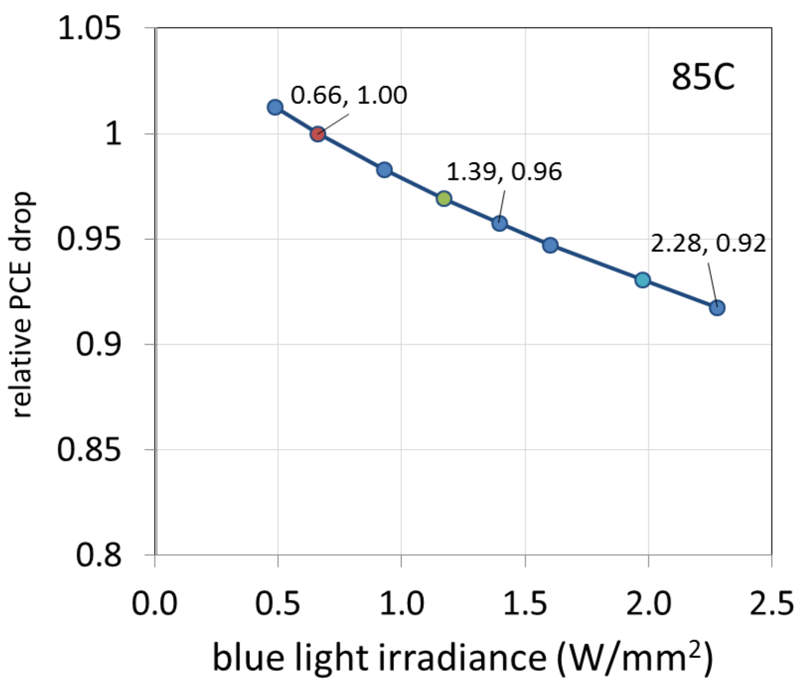

- Reduced extraction with removal of domes
- Reduced extraction of photons with side-coat
- Due to finite thickness of converters need side-coat even with Thin-Film architectures
- Reduced phosphor heat dissipation and higher photo-quenching compared to multi-side emitters

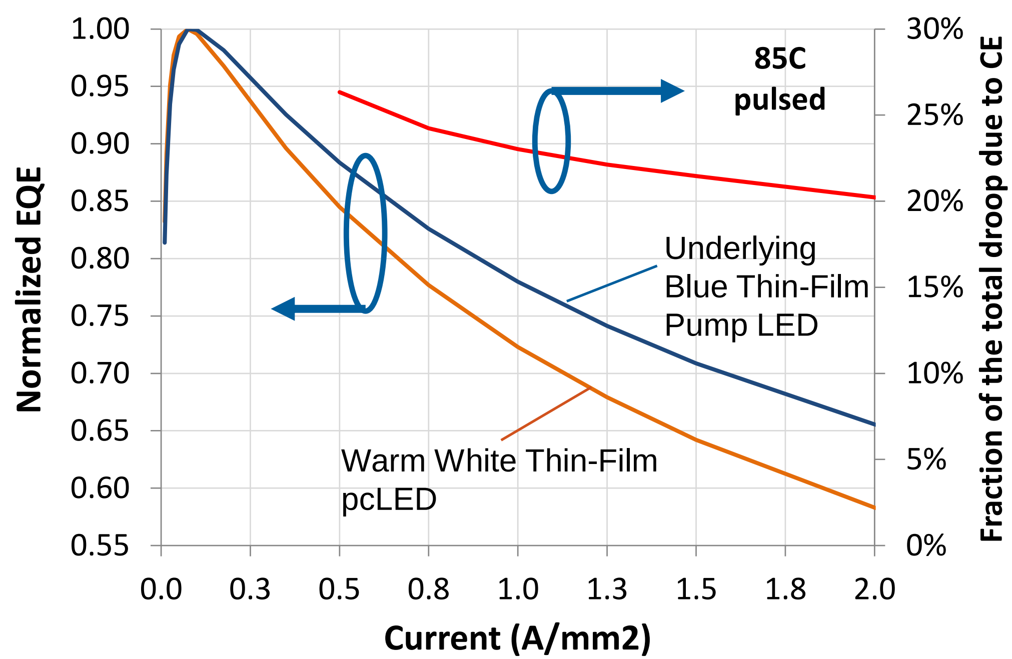
**Key focus area: optical absorption in the pump chip**

# Phosphor droop in LEDs

- 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

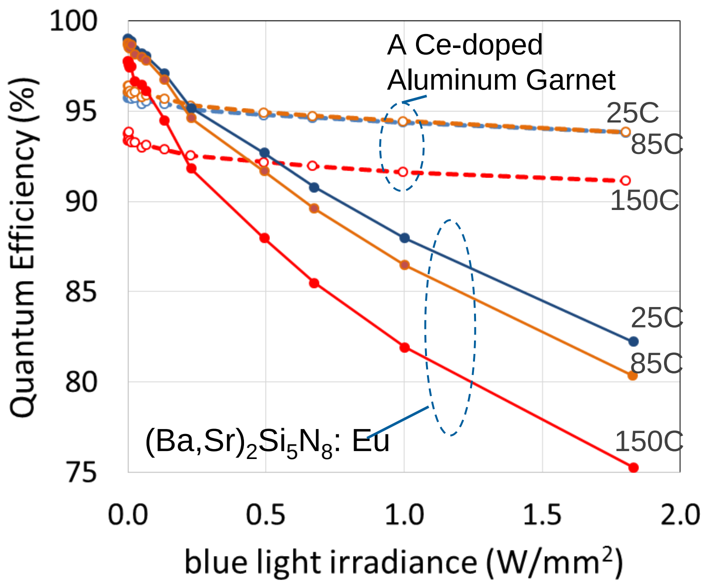


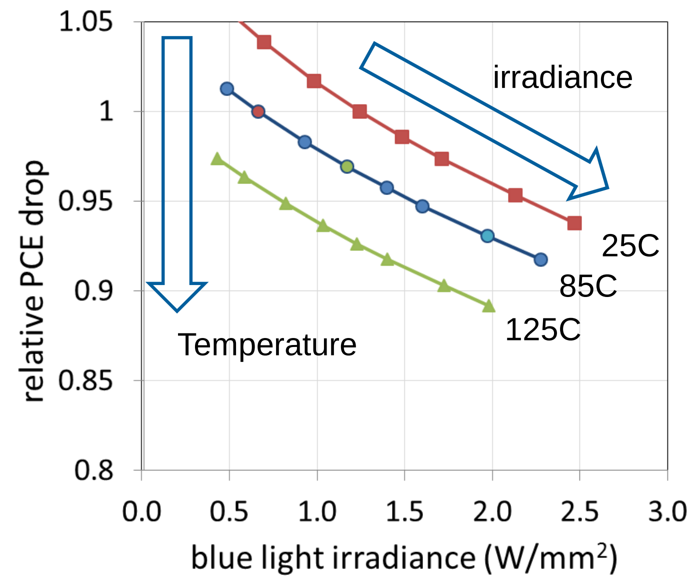
# Photo-thermal quenching of phosphors in LEDs: impact on conversion efficiency

- 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

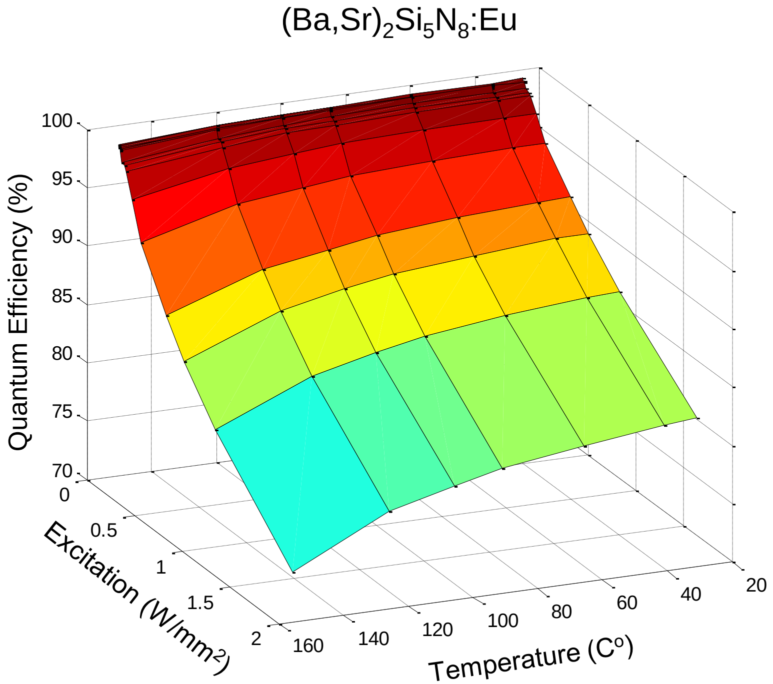
- Photo-thermal quenching of phosphors readily translates into Conversion Efficiency (CE) quenching in pcLEDs
- At typical operating conditions of a HP LED T*phosphor*>100C, irradiance 0.7 – 1.5 W/mm$^2$




WW High-Power LED example



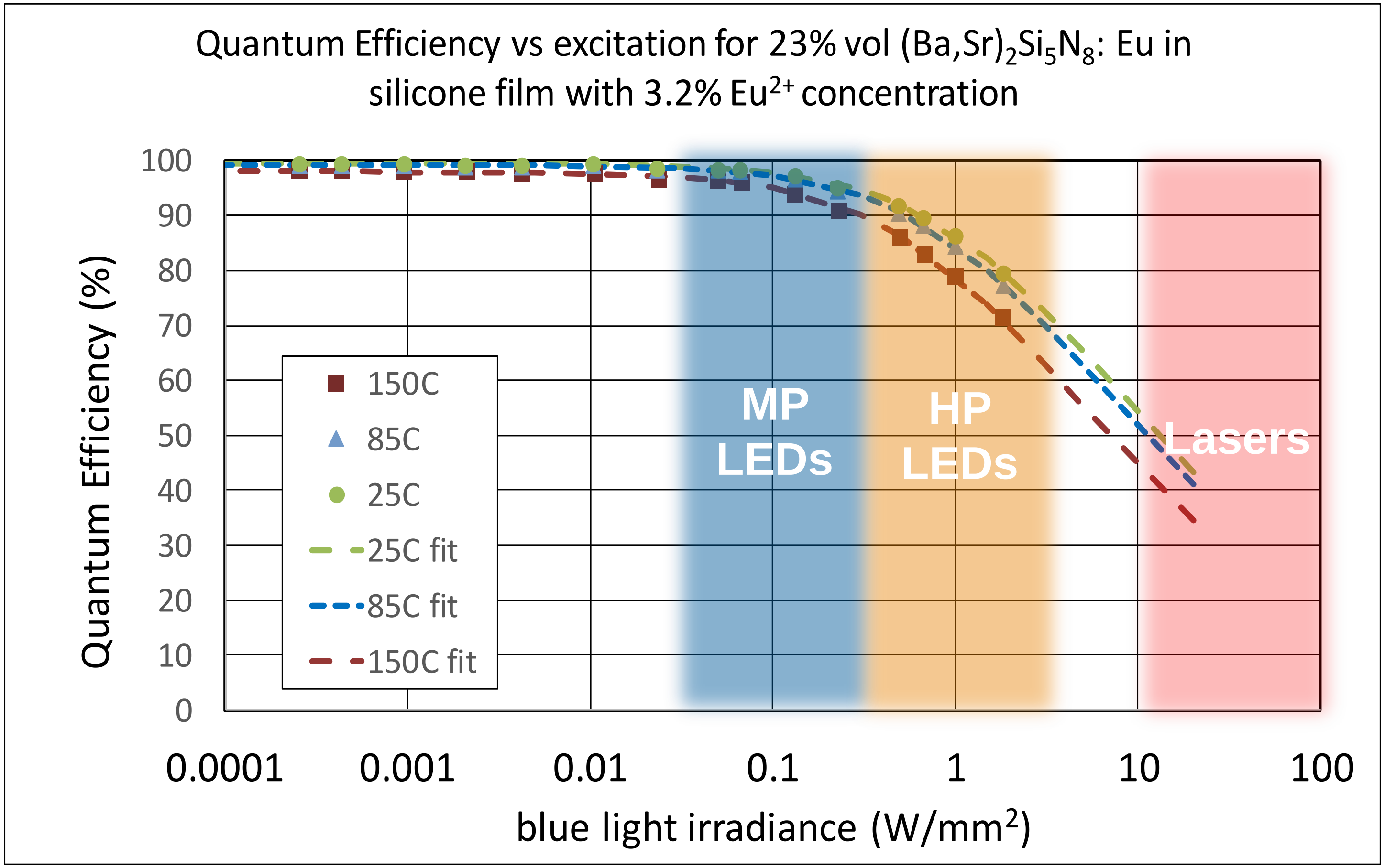
# Dependence of phosphor droop on temperature: Photo-Thermal Quenching




(Ba,Sr)$_2$Si$_5$N$_8$: Eu powder phosphor doped with 2.5% Eu$^{2+}$ in a film of silicone

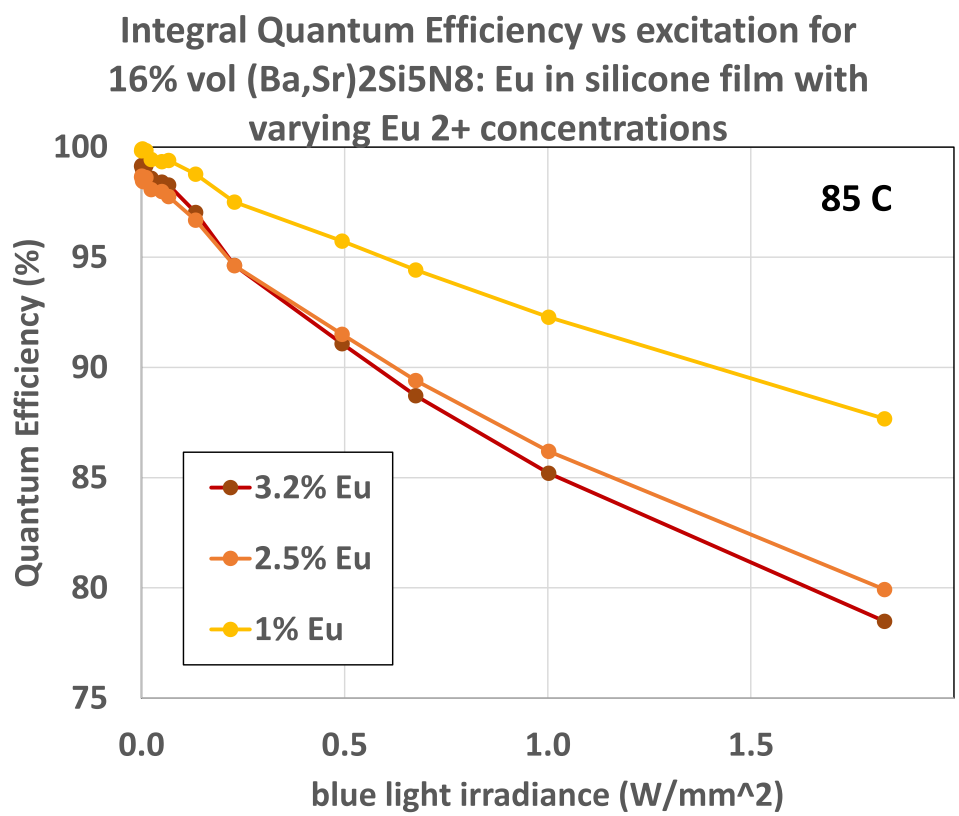
- Photo-quenching in Eu$^{2+}$ red nitrides shows strong dependence on temperature
- Thermal quenching is rather low at low excitation where QE measurements are usually done and quoted
- Thermal and photo effects on QE need to be considered in LEDs

# Example of phosphor QE in different applications



# Droop dependence on activator concentration

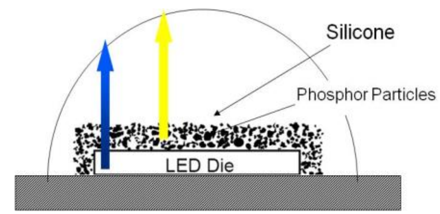
- Photo-quenching in $Eu^{2+}$ red nitrides shows strong dependence on activator concentration
- Red nitride phosphors with higher $Eu^{2+}$ concentration are used for high CRI applications
- Conversion efficiency droop due to PTQ is most pronounced for warm white, high Ra emitters

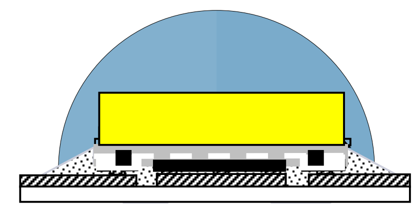



Adapted from: Oleg B. Shchekin et al, Phys. Status Solidi RRL, 1–5 (2016) / DOI 10.1002/pssr.201600006

# Converter materials for high-power density operation

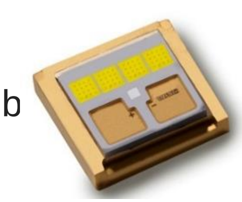
- Keep activator concentration in the phosphor low to minimize PTQ
- Maximize heat conductivity through the converting layer and out
- Low activator concentration in powder phosphors leads to increased phosphor layer thickness or loading to achieve a target color point. This results in:
  - Efficiency penalty due to excessive scattering
  - Efficiency penalty due to poor thermals of the thicker layer
- In a ceramic phosphor, scattering can be tightly controlled to allow for thicker layers enabling lower activator concentration
- High thermal conductivity of ceramic allows for flexibility in phosphor thickness
- Ceramic phosphors are well suited for high power density applications



Lumileds Lumiramic (ceramic phosphor) technology examples in high power density applications

LUXEON F PC Amb



LUXEON Altilon H1K

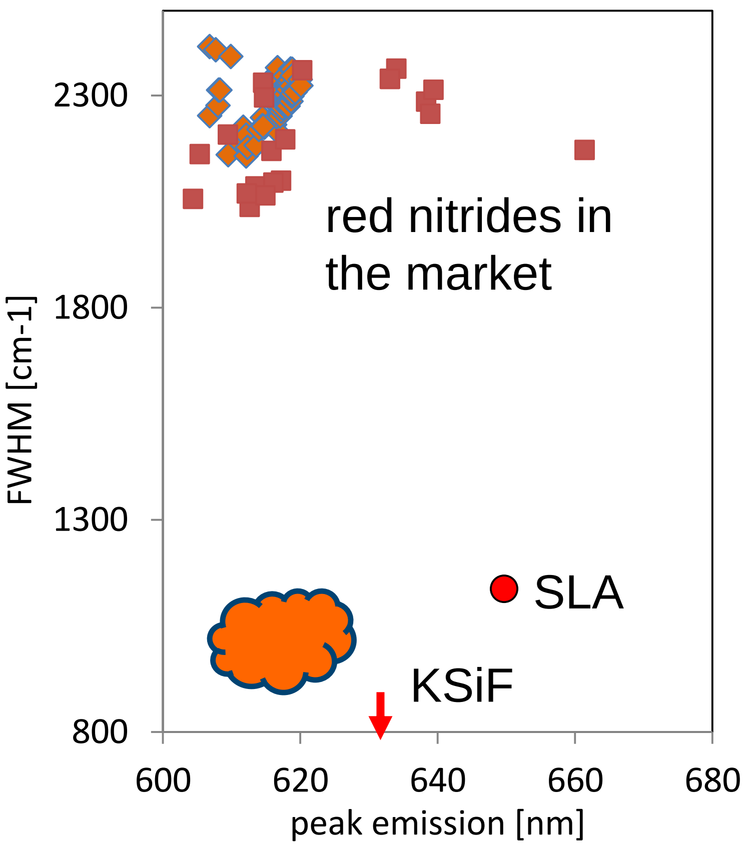
 

# Gains in conversion efficiency from phosphor emission linewidth

## CE vs phosphor FWHM with optimum peak wavelength;  3000K, 80 CRI

| | | Green FWHM | | | | | |
|---|---|---|---|---|---|---|---|
| CE | | 30 | 50 | 70 | 90 | 110 | 130 |
| Red FWHM | 30 | 24% | | | | | |
| | 50 | | | | | | |
| | 70 | | | | | | |
| | 90 | | | | 0% | 0% | |
| | 110 | | | | | -7% | |

- Other than QDs, don't yet have a phosphor material allowing full freedom in spectral engineering



# Status of red phosphors for high luminance applications

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

- Don’t have materials fulfilling all the requirements; fundamental materials development needed
- Focus needed on PTQ and QE at operating conditions in addition to spectral characteristics

# Summary

- High luminance LEDs can enable significant value add from system form factor, weight and cost reductions.

- Developing efficient high-luminance LEDs requires improvement in
  - epi droop
  - die design for high power densities
  - Die and package technologies for high photon extraction
  - Low droop phosphors  for WW and high Ra

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