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# Lighting Your Path to the Future

M. George Craford, CTO
Philips Lumileds Lighting Company

LUMILEDS
LIGHT FROM SILICON VALLEY

IMAPS Global Business Council
November 14, 2007

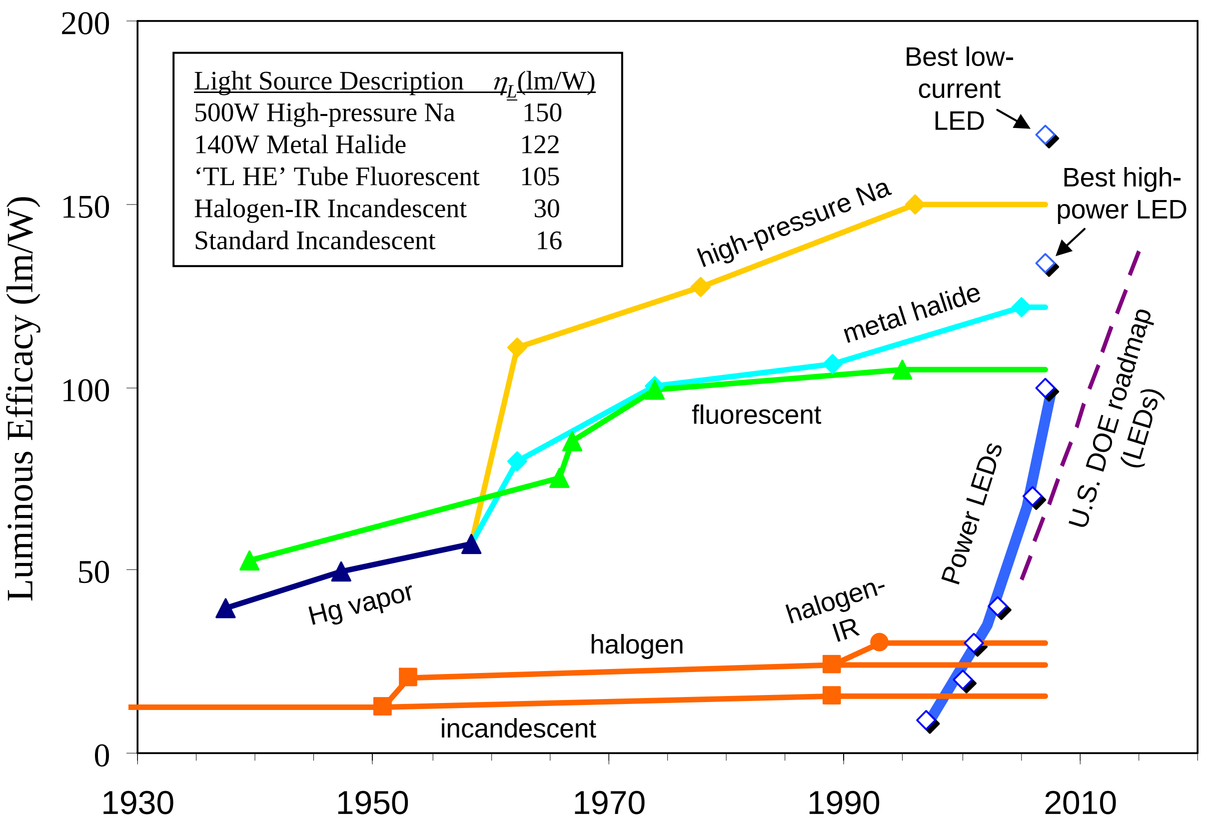
# Outline

- Power LED Technology Status and Trends
- Existing and Emerging Applications
- Challenges and Recent Developments for Solid State Lighting

Buckingham Palace, London, England

Lit by LUXEON LEDs

# Outlook: LEDs vs. Conventional Light Sources



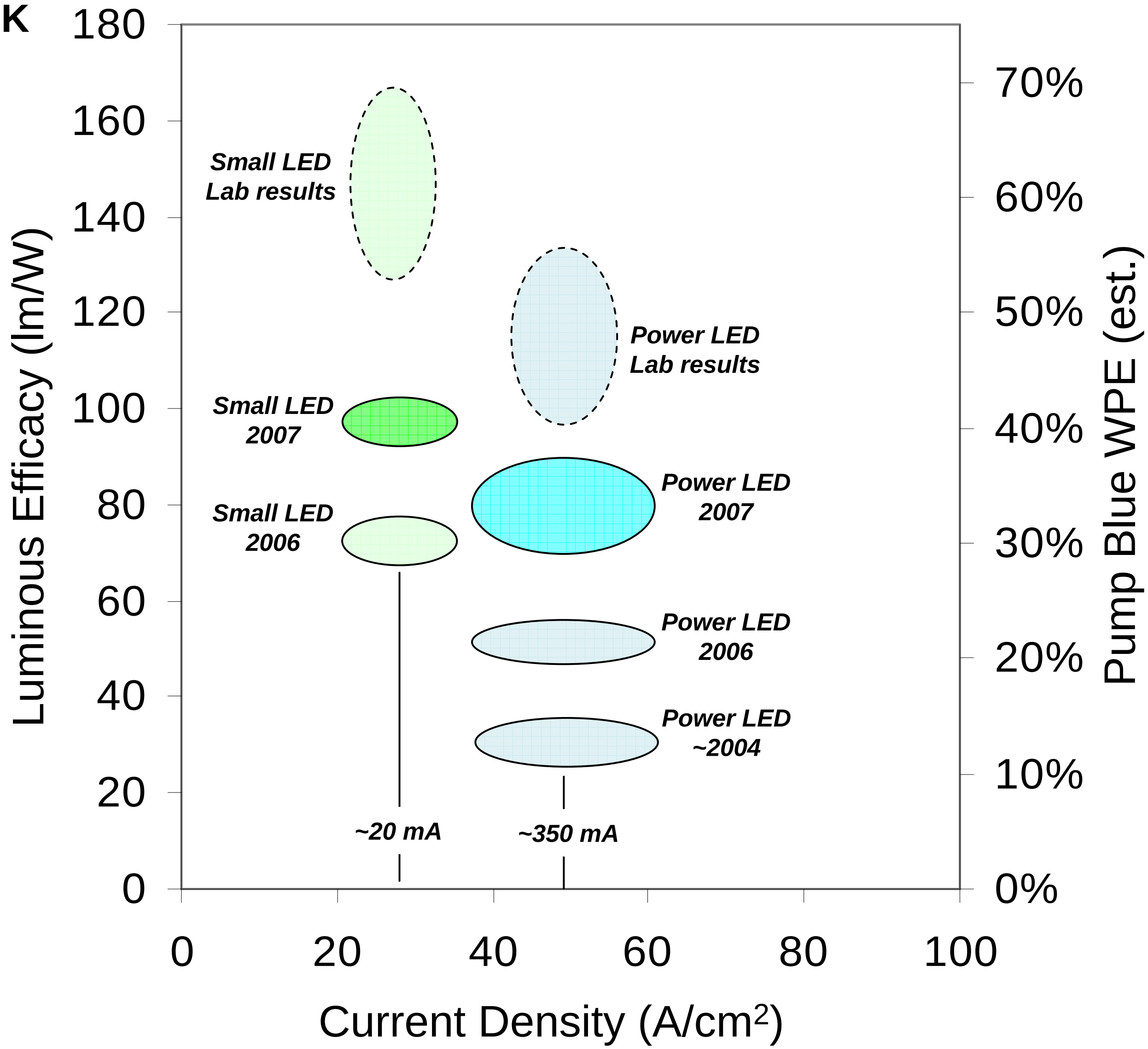

Krames et al., *IEEE J. Display Technol.* **3**, 160 (2007)

- Emerging ~ 100 lm/W phosphor white power LEDs
- Expect ~ 160 lm/W power LED performance within the next 5 years
- Multi-primary white could outperform (need breakthrough green, red)

# White LED Performance

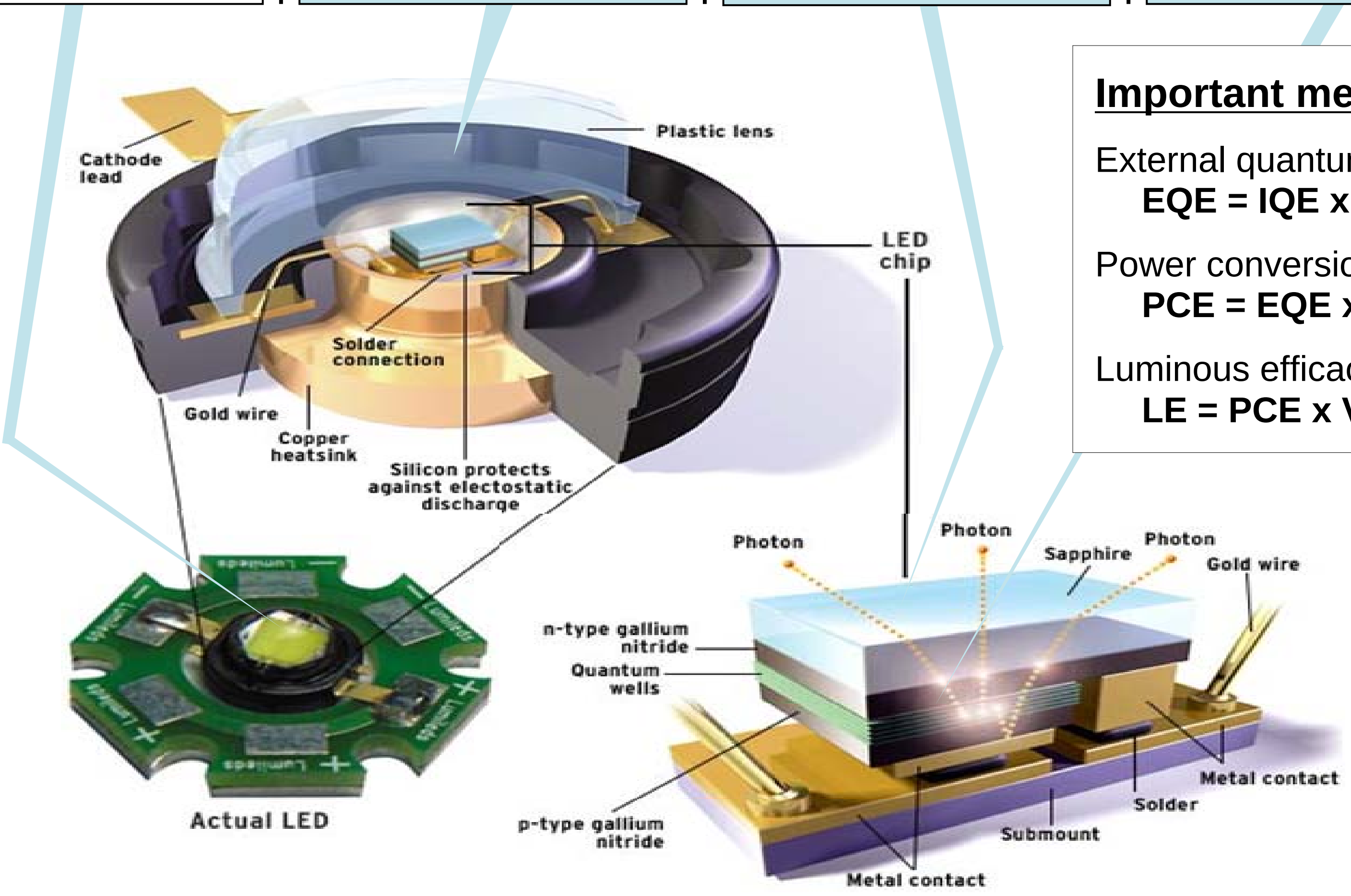
**"Cool" CCT ~ 4500 – 10,000K**

- Small 5mm LEDs
  - Lower current density
  - Lower forward voltage
- Power LEDs
  - More lumens/package
  - Lower cost per lumen



# The Four Elements of LED Technology

| Phosphors | Package | Device (chip) design | Epitaxy and Materials |
|---|---|---|---|



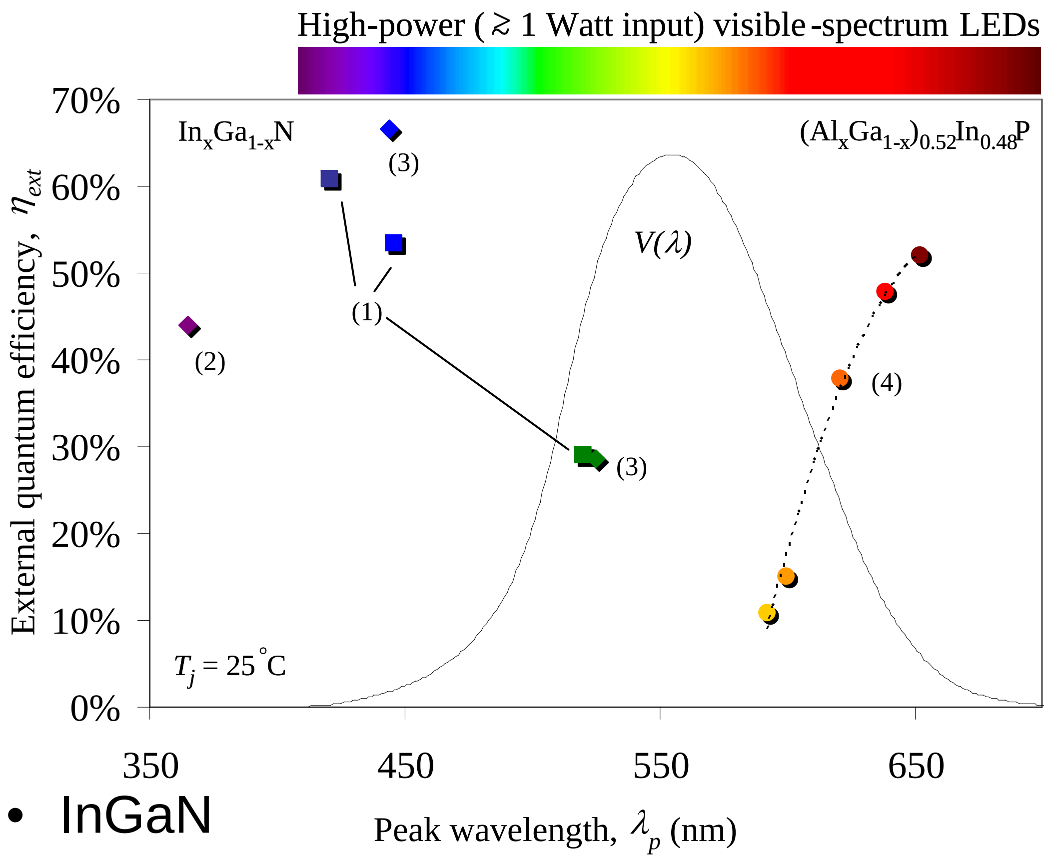

**Important metrics:**

External quantum efficiency:
**EQE = IQE x EXE**

Power conversion efficiency:
**PCE = EQE x $E_{ph}$ / Vf**

Luminous efficacy:
**LE = PCE x V($\lambda$)**

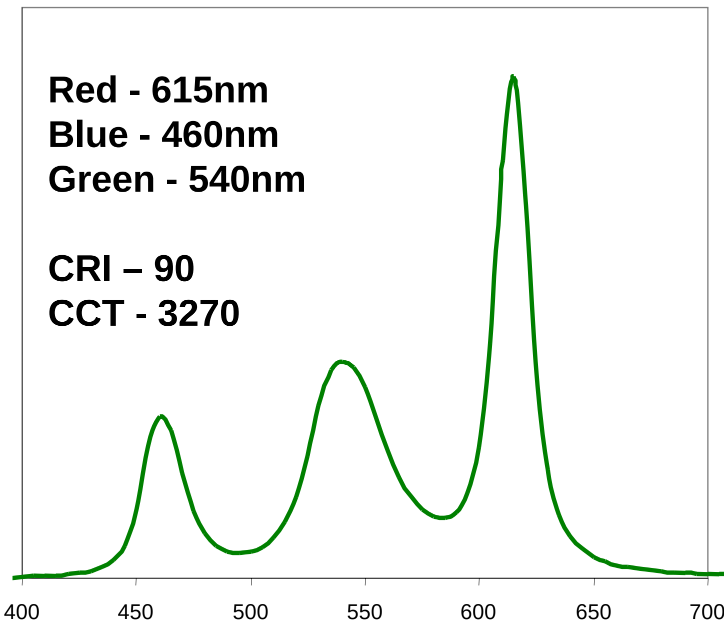
# High-Power (≥ Watt Input) LED Performance

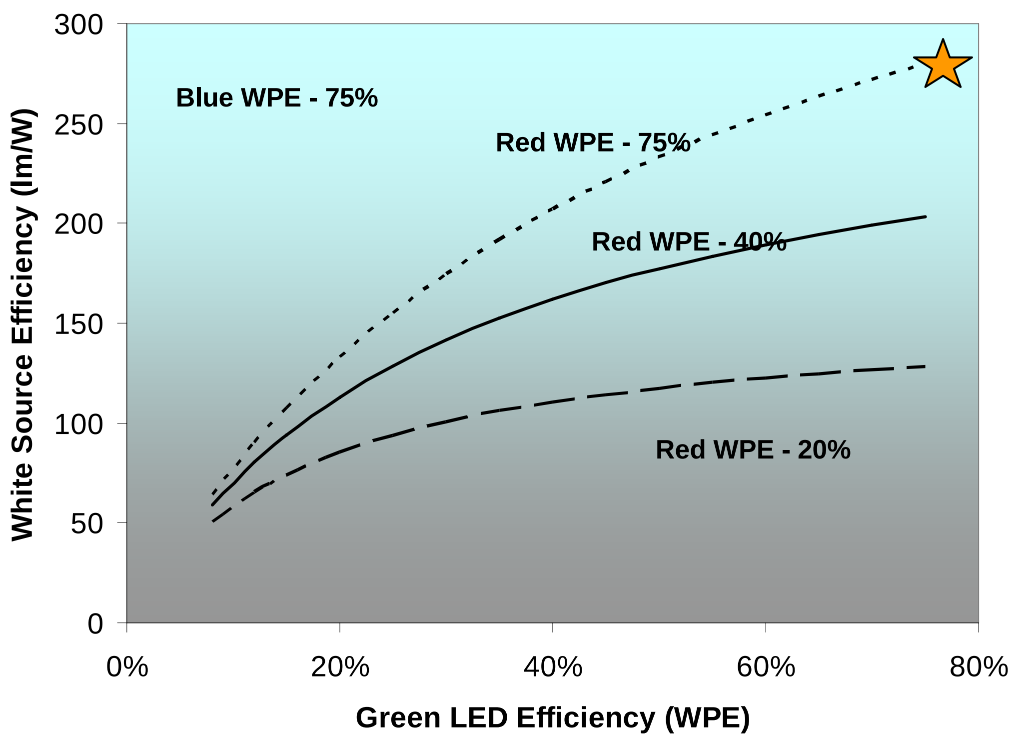



1) Philips Lumileds TFFC LEDs
2) Morita et al., Jpn. J. Appl. Phys. 43, 5945 (2004)
3) Nichia, ICNS-7
4) Philips Lumileds TIP LEDs

- InGaN
  - Maximum external quantum efficiencies in the blue
  - Lower efficiency with increasing InN % (~ 2x reduction green)
- AlGaInP
  - Fundamental bandstructure limitations at short wavelengths

# Red, Green, Blue Color Mixing for Warm White Illumination



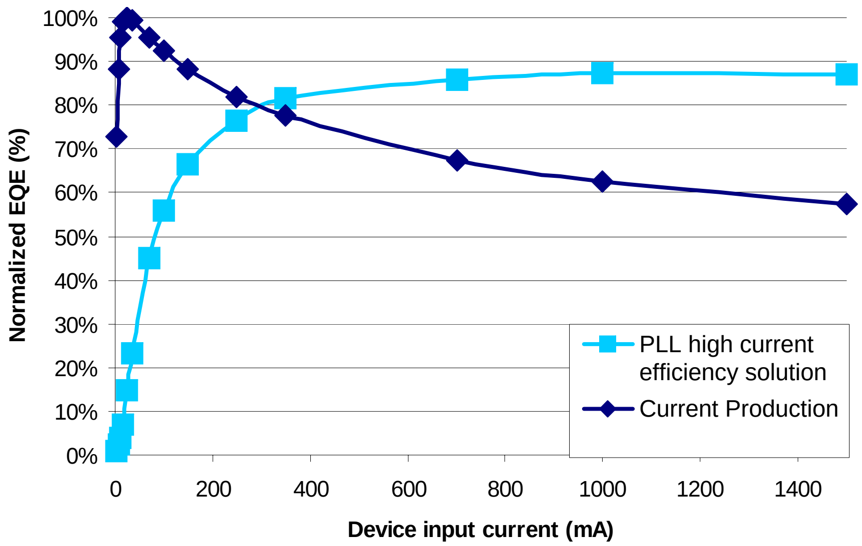



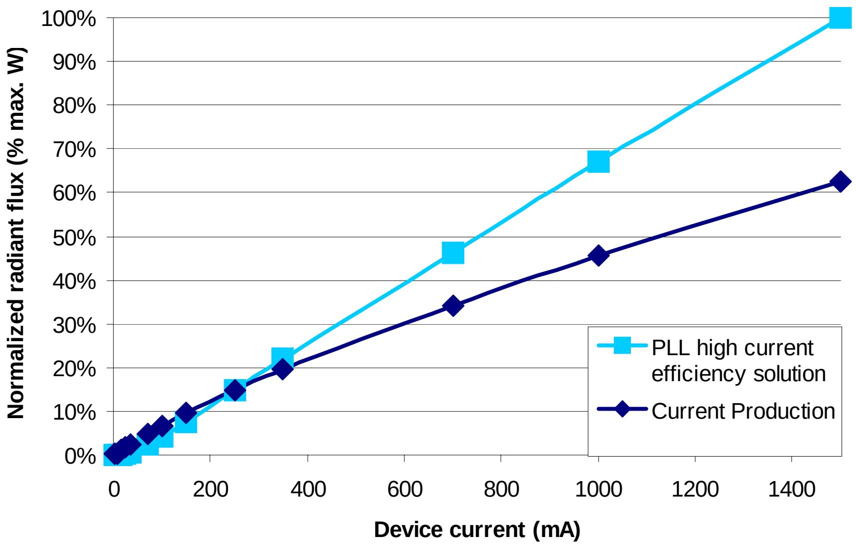

•If nitride RGB all reach ⩾ 75% WPE (very unlikely requiring three “miracles”) then the source efficacy would be ~280 lm/W before color mixing losses (possibly 15-30% which would imply about 200 lm/W → 240 lm/W)

•If RGB all reach >40% WPE (much more reasonable to expect) then ~150 lm/W source would be achieved which would be color tuneable

•Green is the key for enabling color tuneable white illumination to occur

# Recent Development: Improved Epitaxial Materials Process Reduces "Efficiency Droop" at High Current Densities *



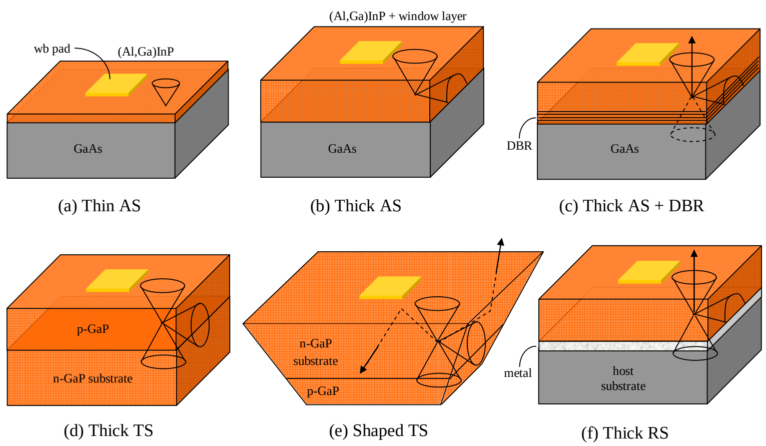

- High efficiency maintained to over 1.5A
- >20% flux gain at high current densities ($\geq$ 1.0A)
- Key step forward for achieving a high efficiency 1000lm emitter in a single 1mm$^2$ chip
- Auger effect is key issue.  Improvement is to use a thicker active layer. (DH vs QW's)

*Nate Gardner, et. al., presented at ICNS-7, Las Vegas, NV, September 16-21, 2007

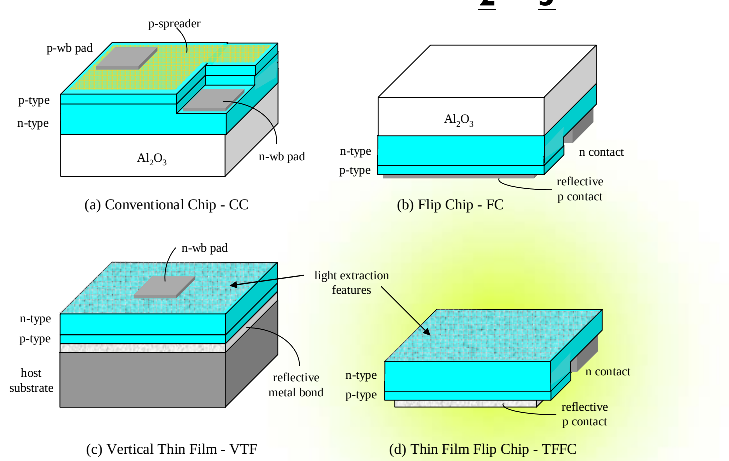
*Yu-Chen Shen, et. al.,  "Auger recombination in InGaN measured by photoluminescence," APL, (2007)

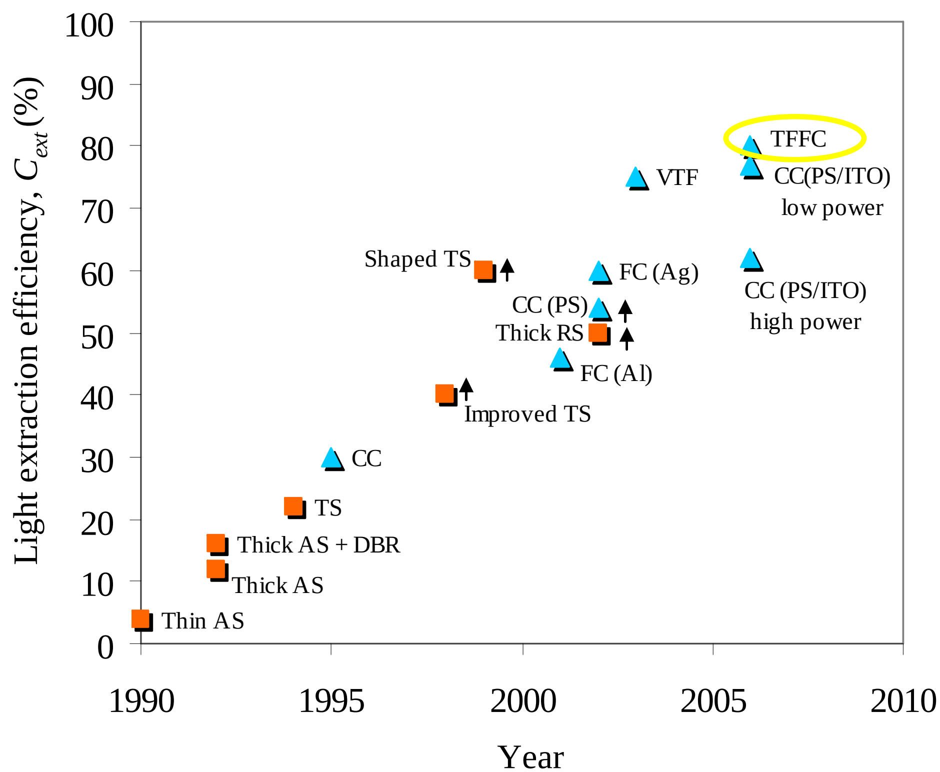
# LED Chip Design

## (Al,Ga)InP-GaAs or (Al,Ga)InP-GaP




## InGaN-GaN-$Al_2O_3$

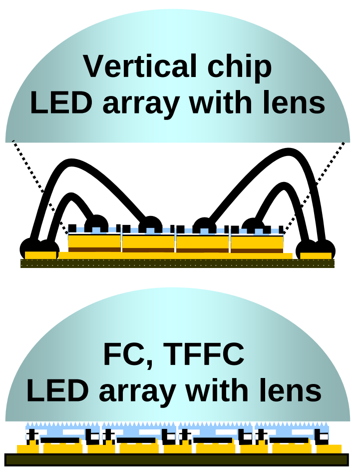


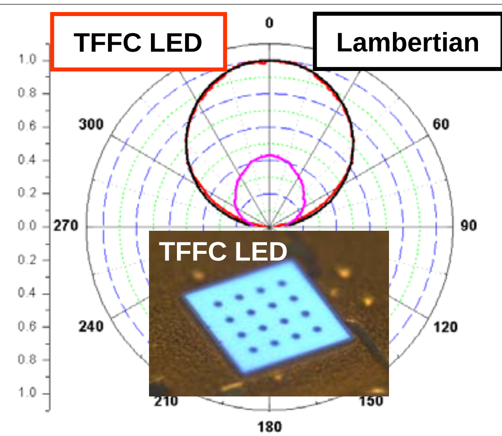




- Dramatic improvement last 15 years
- Light extraction efficiencies reach ~80% (InGaN) and 60%+ (AlGaInP)

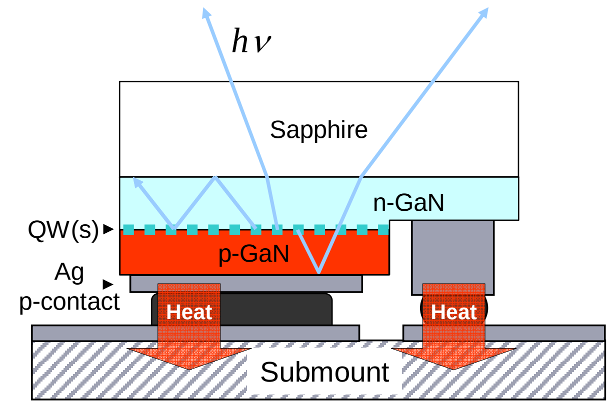
# State-of-Art Power LED Chip Design

- Flip Chip LED (FC)
  - Excellent heat extraction
  - No wire bonds
  - High extraction efficiency
- Thin Film Flip Chip LEDs (TFFC)
  - Highest extraction efficiency
  - Lambertian radiation pattern

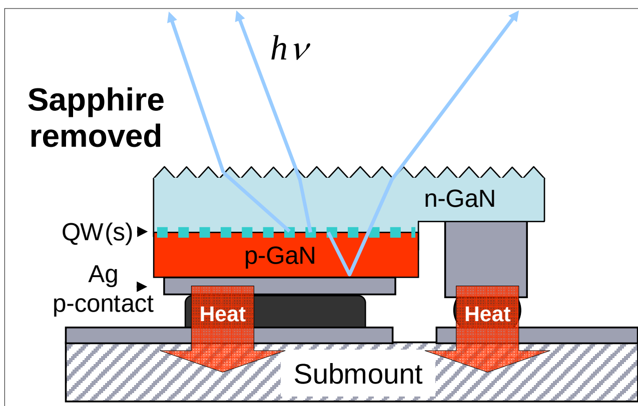



Lambertian radiation pattern of TFFC LED



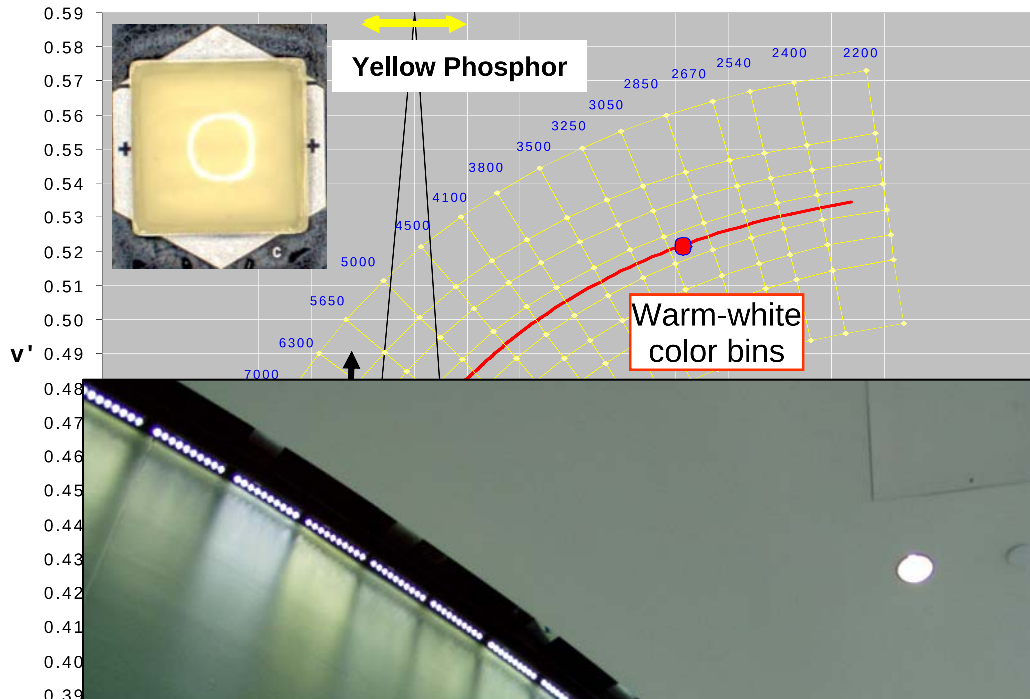

Flip Chip LED



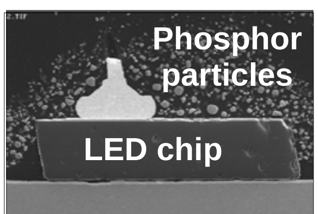

Thin Film Flip Chip LED

# <u>Key Challenge:</u> PC-White CCT Variation

- Imperceptible color variation for human eye:
  - 6500 K: ±200 K
  - 3000 K: ±50 K
- Manufacturing challenge
  - Blue wavelength range
  - Control of phosphor deposition process

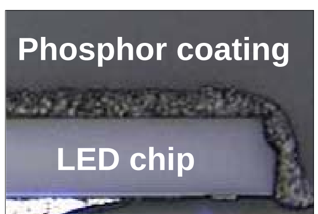







**<u>Conventional LED:</u>**

"Slurry deposited" phosphor particles




**<u>Luxeon LEDs:</u>**

Conformal phosphor coating

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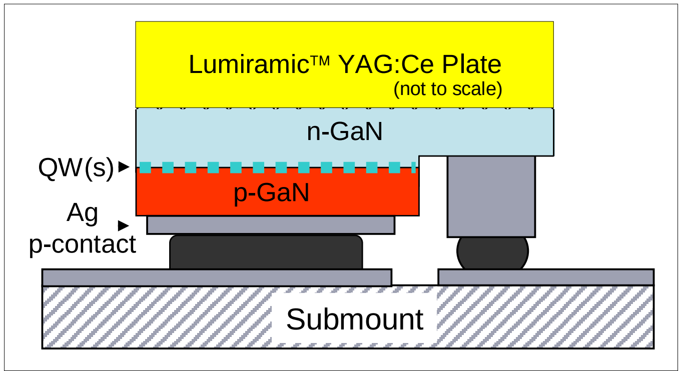
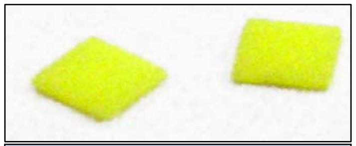
# Improvement: Solid-State Phosphor Element

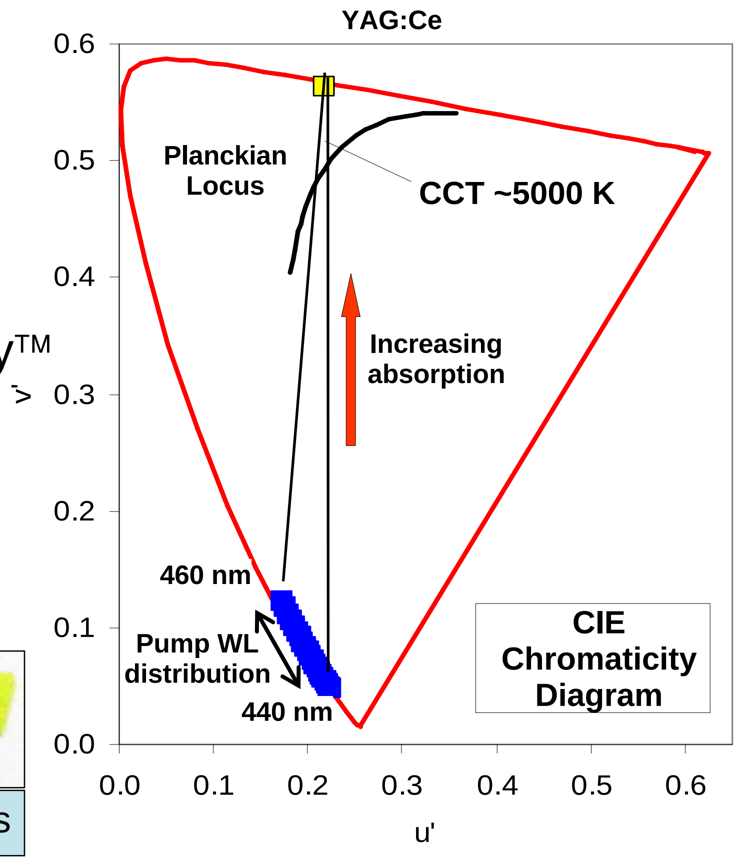
- Lumiramic phosphor technology™
  - Sintered YAG:Ce ceramic
  - Matches TFFC LED chips
  - Optically homogeneous solid-state material
- White LEDs with Lumiramic phosphor technology™
  - Precision in phosphor absorption via plate thickness control
  - 4x Reduction in number of color bins
  - High luminance and excellent color stability




TFFC LED with Lumiramic™

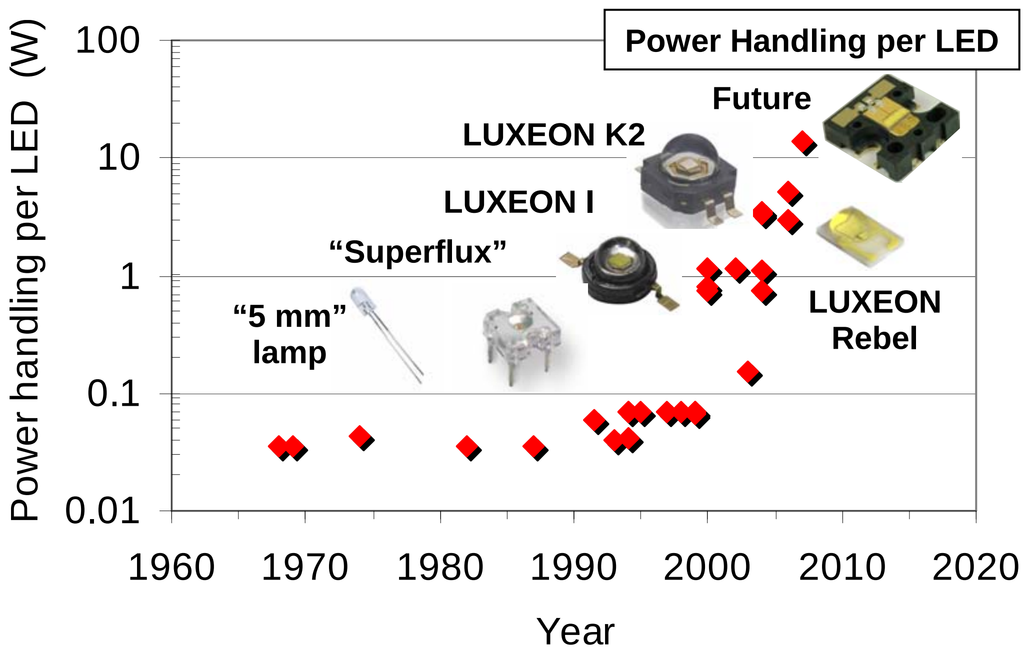


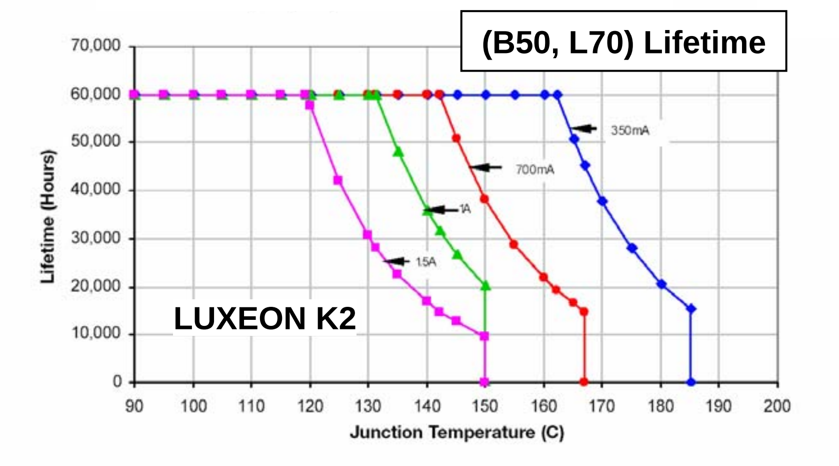
Lumiramic platelets



# State-of-Art LED Packages - Power Handling

- Power handling capability
  - LUXEON K2 >5 W
  - Luxeon Rebel ~3 W
  - Future >10 W
- Lumen maintenance
  - Strong function of
    - Junction temperature ($T_J$)
    - Drive Current ($I_f$)
  - Typical: 50,000 hour

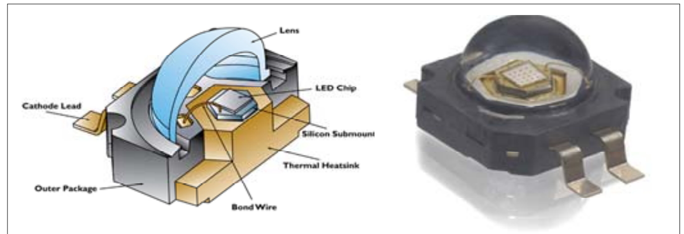


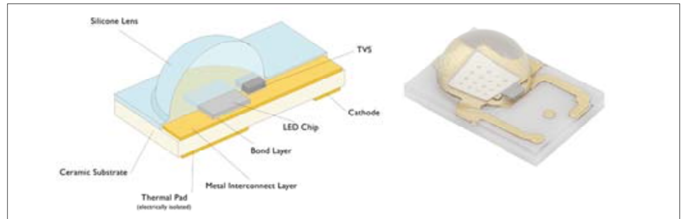

**Power handling increased >100 x in last decade**

# State-of-Art LED Packages

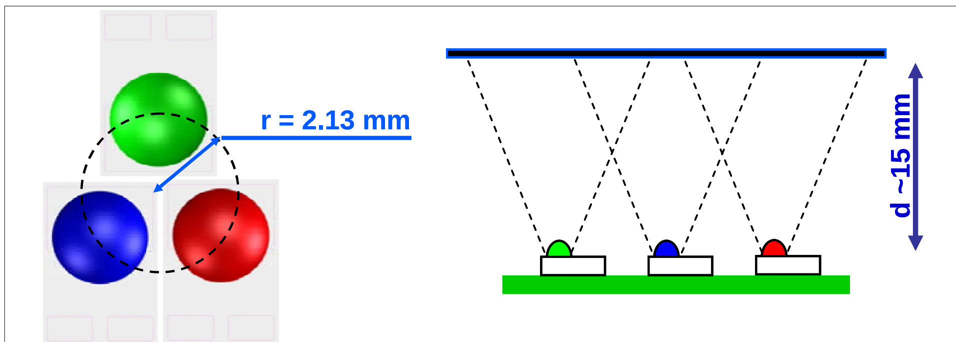
- LUXEON K2
  - Highest flux
  - Highest drive current ($I_f \leq 1.5$ A)
  - Highest operating temperature ($T_J \leq 185°C$)
  - Lowest cost of light
- LUXEON Rebel
  - Highest flux-density (footprint: 3 x 4.5 mm$^2$)
  - High operating temperature ($T_J \leq 150°C$)
  - High drive current ($I_f \leq 1$ A)
  - Highest flux/$ power LED




LUXEON K2




LUXEON Rebel

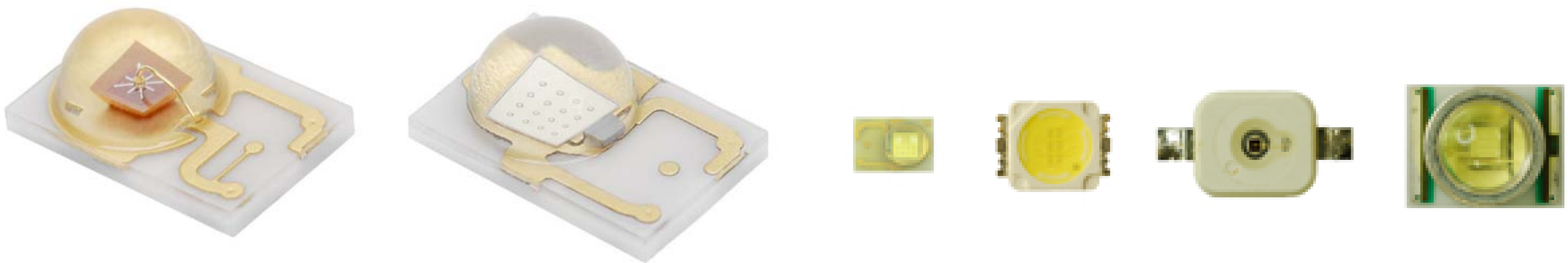



Example: Color mixing

LUXEON Rebel

- Small size reduces focal length
  - smaller optical systems
  - smoother mixing in small spaces
- First power LED “pixel solution”

# Ultra Small, Low Cost Power Packaging
# **LUXEON Rebel Platform**



**Performance**:

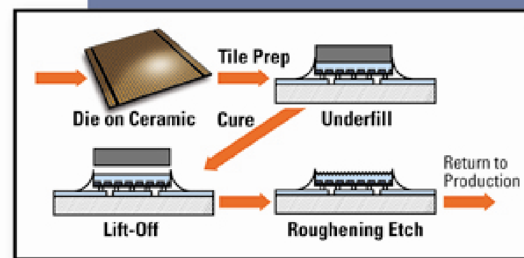
- Size: 3x4.5mm vs. 7.2 x 7.2mm
- Light output, efficiency, reliability leader in 350mA – 1A class
- Packing density: Up to 6x other power LEDs
- Lowest cost/improved Lumens/$
- Outperforms Chip-on-Board (performance, reliability)

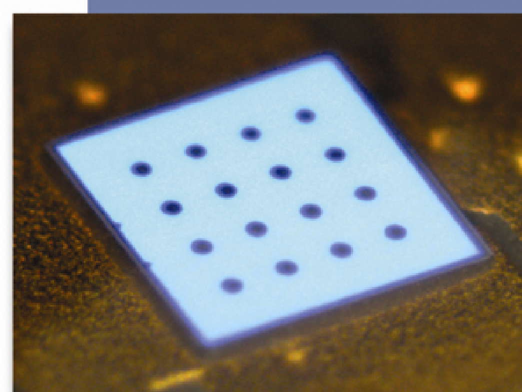
2007 LIGHTFAIR INTERNATIONAL

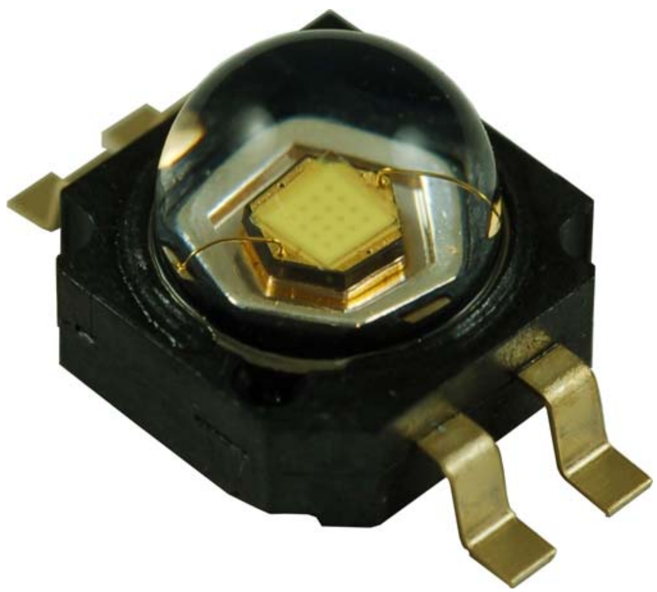
Winner: Technical Excellence Award

# Introducing LUXEON K2 with TFFC

- Utilizes the latest TFFC die for dramatically improved light output
  - Light output bins start at min 160 lumens in white
- Lowest Thermal Resistance: 5.5°C/W
- Highest Maximum Junction Temperatures:
  - 185°C for direct colors, 150°C for white
- Tested and binned exclusively at 1000mA
- Available first in cool-white to be followed by warm-white, neutral-white, blue and green
- Lead-free reflow solder JEDEC 020c compatible



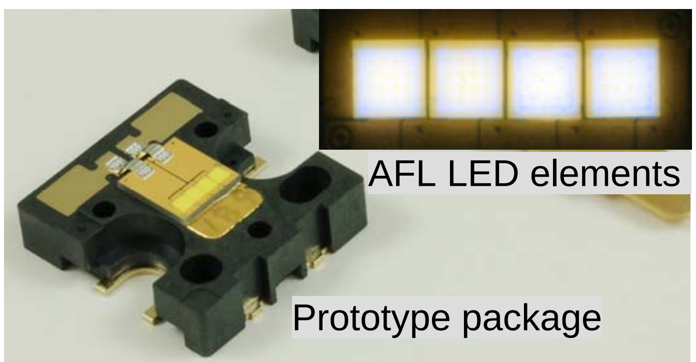


# LUXEON Automotive Forward Lighting Source

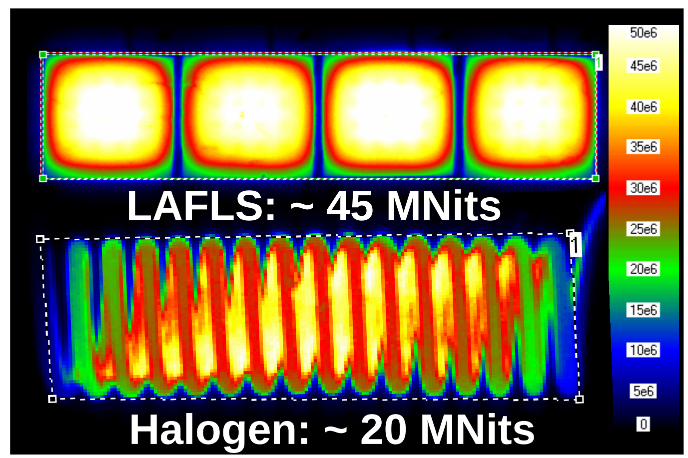
**Key Performance Attributes:**

- Automotive Reliability
- High Power Density (> 4 W/mm2)
- High Temperature Operation
- World class lumen output:
  - Today: 750 lumens @ 1A per 1x4
  - Future: >>1500 lm @ 2.3 A
- High luminance
  - Today: 45 MNits @ 1A per 1x4
  - Future: >90MNits

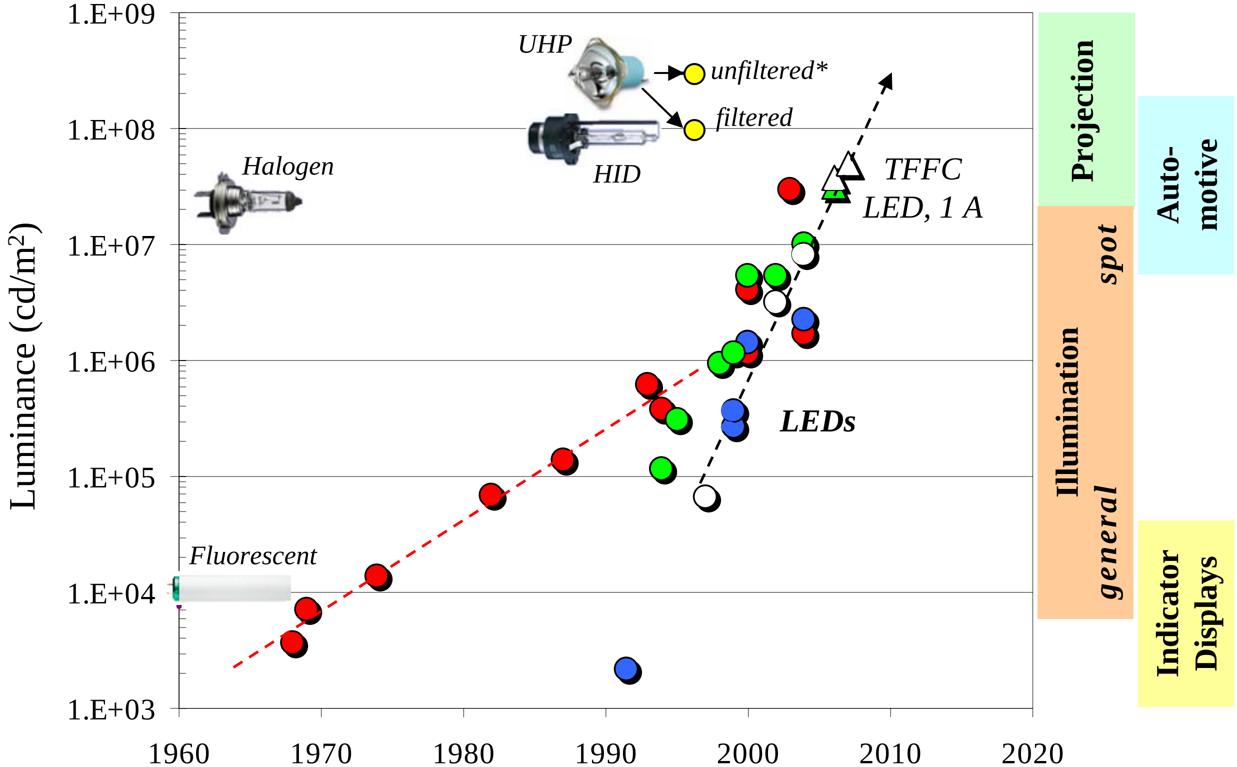
**2008 Audi R8**




Prototype AFL LED Package



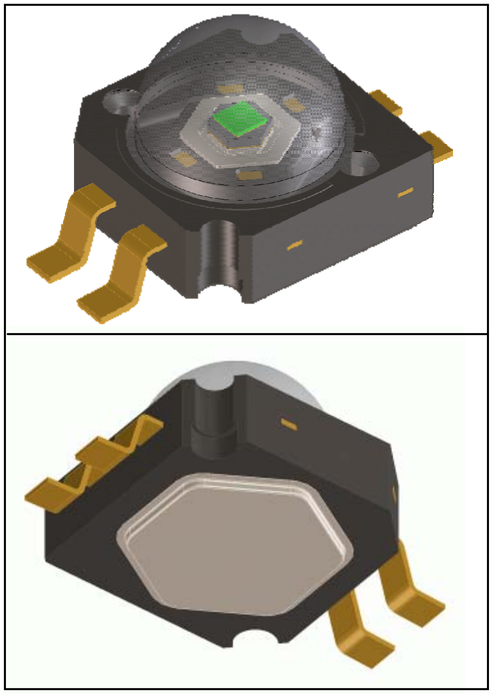
# Performance: Evolution of LED source brightness

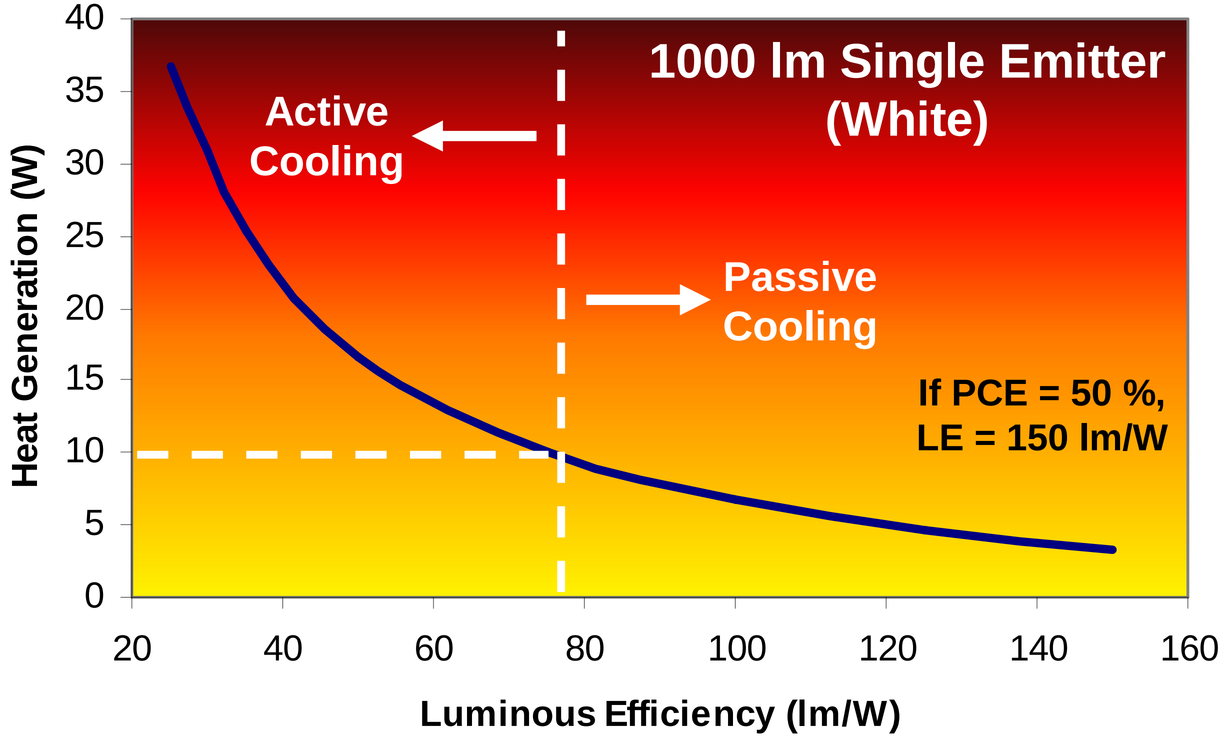



*collected flux of 4500 lm within 15 mm2-sr, an étendue typical for micro-display projection
(G. Derra, *J. Phys. D: Appl. Phys*. Vol. 38, pp. 1995-3110, 2005)

- Focus on power LEDs has accelerated luminance performance.
- LED brightness on target to match that of the UHP bulb.

# Heat Management: Easier in the Future

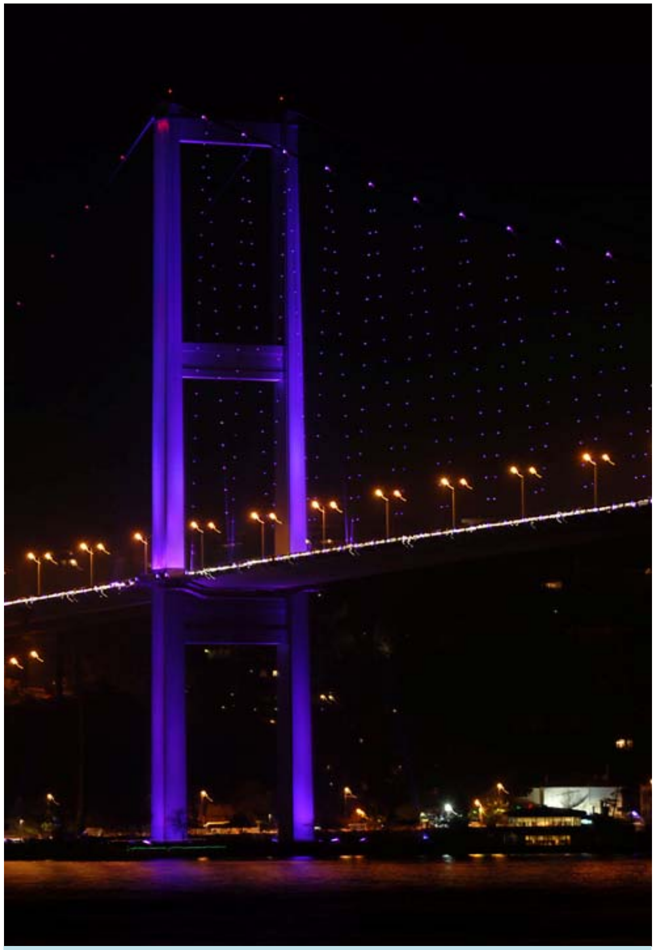




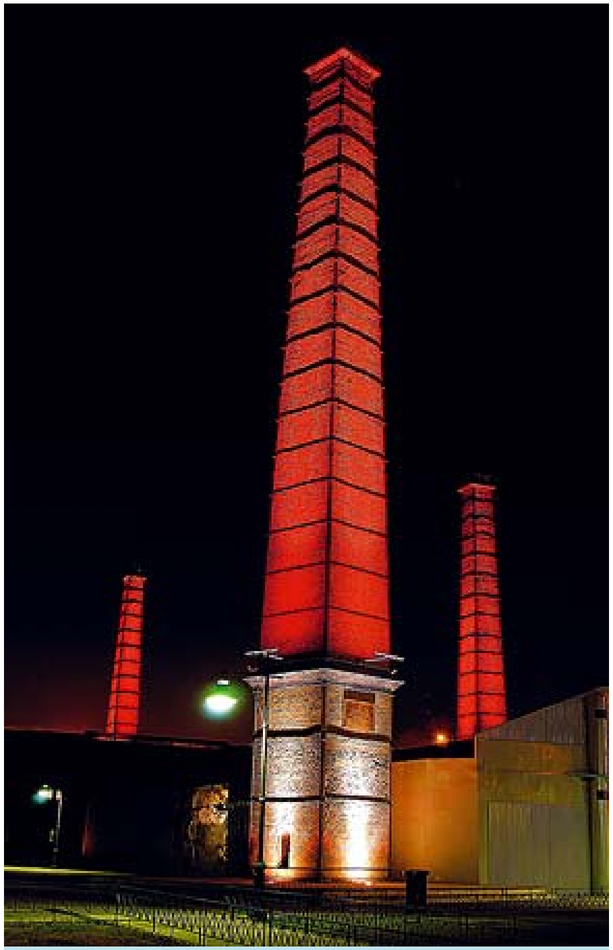

- LEDs pass all heat back to heat-sink and fixture
- Today's efficiency: Thermal management remains an issue and adds cost
- Future efficiency: Heat management should be straightforward
- Circuitry for driving LED is a large cost factor for replacement lamps. As LED efficiency goes up circuit cost will go down, but will likely remain a key issue

# LUXEON Applications Around the World

Mega Bridge, Bangkok, Thailand
*Philips*



Bosphorus Bridge, Istanbul, Turkey
*Philips*

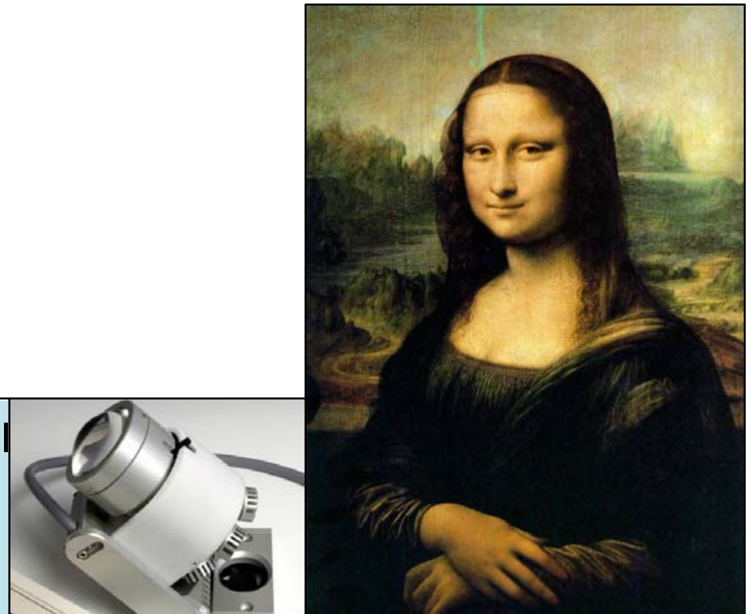


Technopolis, Athens, Greece
*Philips*

# High-power LED Applications: RGB White

- Illumination
- LCD Backlighting
- Projection

- LUXEON I and LUXEON III
- Replicates day-light without harmful ultra-violet or infra-red radiation
- Exact color rendition



**Mona Lisa Lighting by Fraen Corporation**

**SONY Qualia 005**

- Triluminos™ LED backlight for LCD panel
- Ultra-high color gamut (105 % NTSC)
- LEDs eliminate motion artifact
- Mercury free
- Long life

Pocket Projectors

- Flux: 12 – 100 lm
- Power: 10 – 25 W
- Weight: 1 – 1.5 lb
- Battery life: 2.5 h

**Toshiba TDP-FF1A**

**Mitsubishi PK-10**

**Samsung SP-P300M**

# High-power LED Applications: PC White

- Portable lighting
- Mobile phone camera flash
- Illumination
- Automotive forward lighting

- LUXEON V
- 2 – 80 variable lumens
- 1 - 40 variable hours
- Non imaging optics

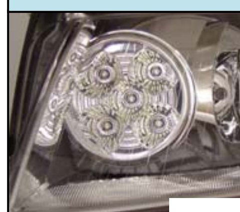
**Surefire DEF 1**

- Functional flash (<~3m)
- LUXEON Flash 
- LUXEON Module 


Casino Breda, Netherlands by Bocom

Daytime Running Light (DRL)

- Multiple LEDs per DRL
- 100° C ambient temperature




**S8** **S6**

# Why are LEDs Not Yet Widely Used for General Illumination?

- Cost has been too high
- Efficiency has been too low
- White "color" needs to be warmer and better controlled
- Engineering challenges: thermal, optical, electrical
- Other Issues: Standards, complimentary infrastructure, stable supply, etc.

# Key Challenge: Cost/lumen

- **The conventional technologies are much lower in cost**

| | $/1000 lm |
|---|---|
| Incandescents: | ~0.4 |
| Fluorescents: | ~0.6 |
| CFLs: | ~2.0 (and going lower) |
| White LEDs: | ~10.0 (best case-without driver!) |

**Need > 10x reduction!**

- **How do LEDs get closer?**

| | Gain Factor |
|---|---|
| Efficiency improvement (75 lm/W to 150 lm/W) | 2x |
| Higher drive currents (700 mA to 2A) | 3x |
| Lower chip and packaging costs | 2x |
| | Total 12x |

**LEDs are more competitive when total cost of ownership and environmental factors (no mercury) are considered**

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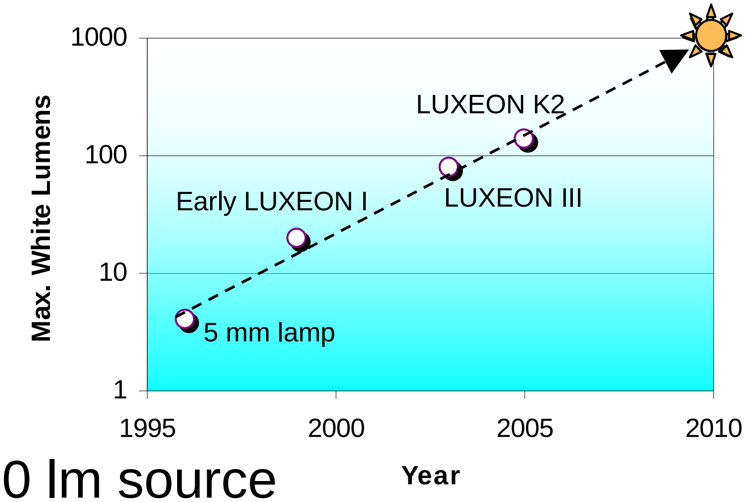
# Outlook: Goals for Phosphor White for Illumination




- Single-emitter Flux ("Power" LED)

  → **1000 lm target**

  – same as 60 W light bulb
  – today's LEDs: 100-200lm ea.

- Cost of Ownership (COO) Analysis – 1000 lm source

| | Input Power | Source cost | Energy cost/yr | COO (1 yr) | COO (5yrs) |
|---|---|---|---|---|---|
| 1 X 60 W incandescent | 60 W | $ <1 | $ 48 | $ 48 | $ 240 |
| 1 x 20 W Compact Fluor. | 20 W | ~ $ 2 | $ 18 | $ 20 | $ 90 |
| 10 x 1-W TFFC emitters | 14 W | $ 20 | $ 13 | $ 33 | $ 85 |
| 1 x 160 lm/W LED | ~ 6 W | ~ $ 1 | $ 5 | ~ $ 6 | ~ $ 26 |

at $0.10 per kWh

→ **Target: ~160 lm/W, 1000-lm LED**

# Outlook: How achievable is 160 lm/W, 1000-lm LED?

*For single 1000-lm emitter, 2 A drive current needed*

2000 mA : 1x1 mm$^2$

| | | PC White | |
|---|---|---|---|
| | | Today | **Future** |
| Light Extraction Eff. | $C_{ext}$ (%) | ~90 | **~90** |
| Internal Quantum Eff. | IQE (%) | ~40 | **~90** |
| | EQE (%) | ~36 | **~80** |
| Forward Voltage | $V_f$ (V) | ~4.2 | **~2.9** |
| | PCE (%) | ~25 | **~75** |
| Luminous Efficacy* | LE (lm/W) | ~61 | **~160** |

*assumes 250 lm/Wopt phosphor conversion for cool white CCT ~6000

- High-current-density (~ 250 A/cm$^2$) efficiency is critical
- Blue internal quantum efficiency (IQE) must increase by > 2x
- Must reduce forward voltage (ongoing programs)
- Warm white would be lower by (10 - 30%)

# Summary

- Power LEDs are improving rapidly.  Commercial performance in the 100 lm/W range is beginning, and ~150 lm/W should happen within five years
- Key issues for conversion to LEDs include: More lumens, lower cost, complementary infrastructure, standards, and consistent high volume supply
- Performance improvement for green devices is a key issue for RGB tuneable white
- It is clear that LEDs will dominate general illumination.  The only question is timing
- Full conversion at 150 lm/W will reduce electricity used for lighting by ~50% and “save” over 100 nuclear reactors worldwide