# Innovations in LEDs

**George Craford**
Philips Solid Sate Lighting Fellow

2015 DOE Solid State Lighting
R&D Workshop
January 27, 2015

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# Outline

- **PAST - What Happened and What Can We Learn**
- **PRESENT – Where Are We and What are the Emerging Trends**
- **FUTURE – How Do We Get to 250l/w and What is Next in SSL Innovation?**

## Congratulations!!

The Nobel Prize in Physics 2014

Photo: A. Mahmoud
Isamu Akasaki

Photo: A. Mahmoud
Hiroshi Amano

Photo: A. Mahmoud
Shuji Nakamura



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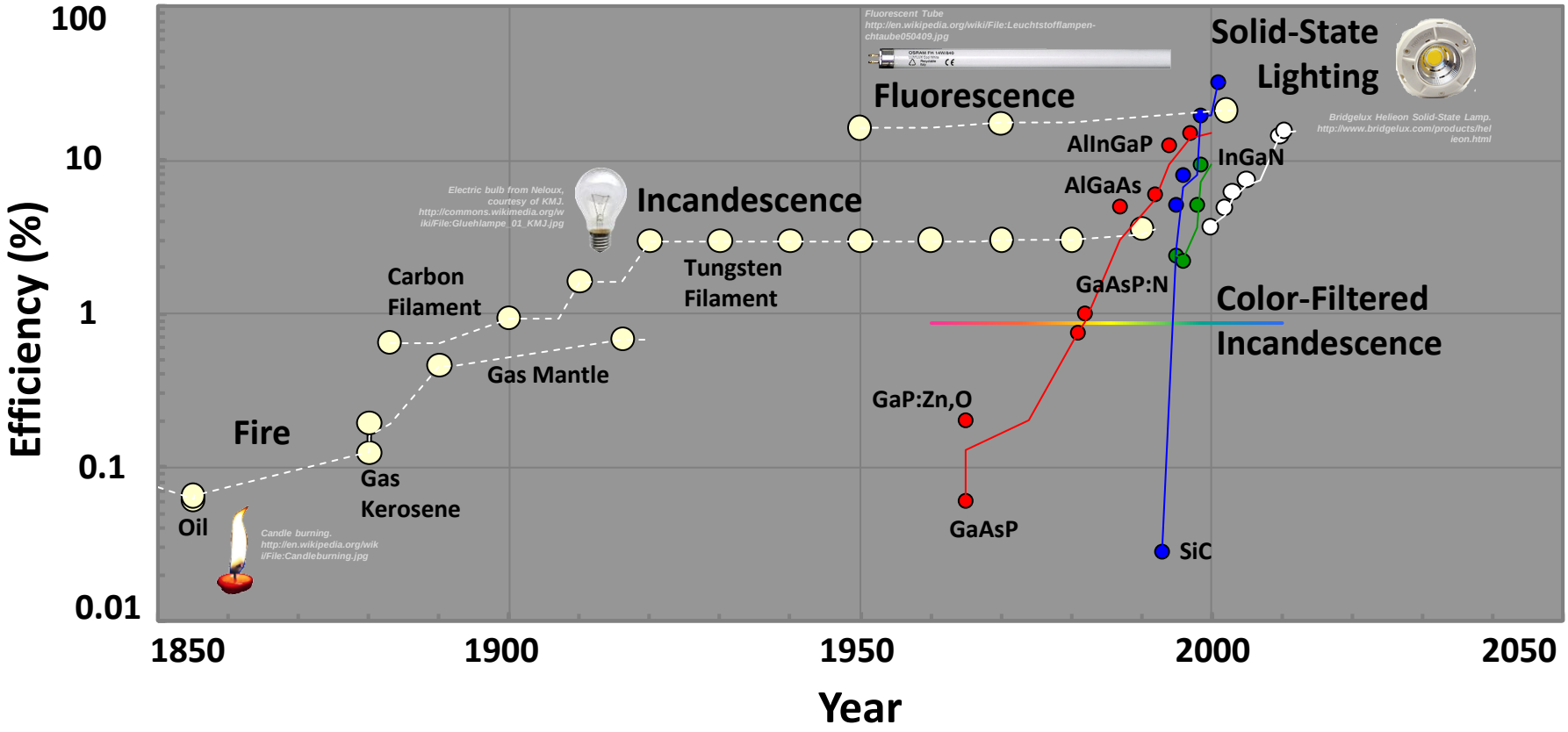
# 200 Years of Lighting Technology Efficiency




- Courtesy of J. Tsao and J.A. Simmons, Sandia National Laboratories



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# Evolution of Visible LEDs

## Selected events

- **1907** Electroluminescence observed in Carborundum (SiC) – *H.J. Round*
- **1923-1930** Comprehensive study of SiC electroluminescence and discussion of application for communications - *O.V. Losev*
- **1947** Discovery of transistor – *Bardeen and Brattain*
- **1951** Explanation of SiC electroluminescence as carrier injection across a p/n junction – *K. Lechovec, et al*.
- **1955** Visible electroluminescence in GaP – *G.A. Wolff, et al*.
- **1962 Demonstration of coherent visible light emission from direct bandgap GaAsP alloy semiconductors – *N. Holonyak and S.F. Bevacgua***
- **1962-Present** Continuing development and optimization of various direct bandgap ternary (GaAsP, AlGaAs) and quarternary (AlInGaP, AlInGaN) material systems for high performance LEDs – *RCA Monsanto, Hewlett Packard, Stanley, Osram, Toshiba, Toyoda Gosei, Nichia, Cree and others*

Craford Presenting Holonyak with LED Headlight at Symposium at the University of Illinois celebrating the 50th Anniversary of the LED October 2012



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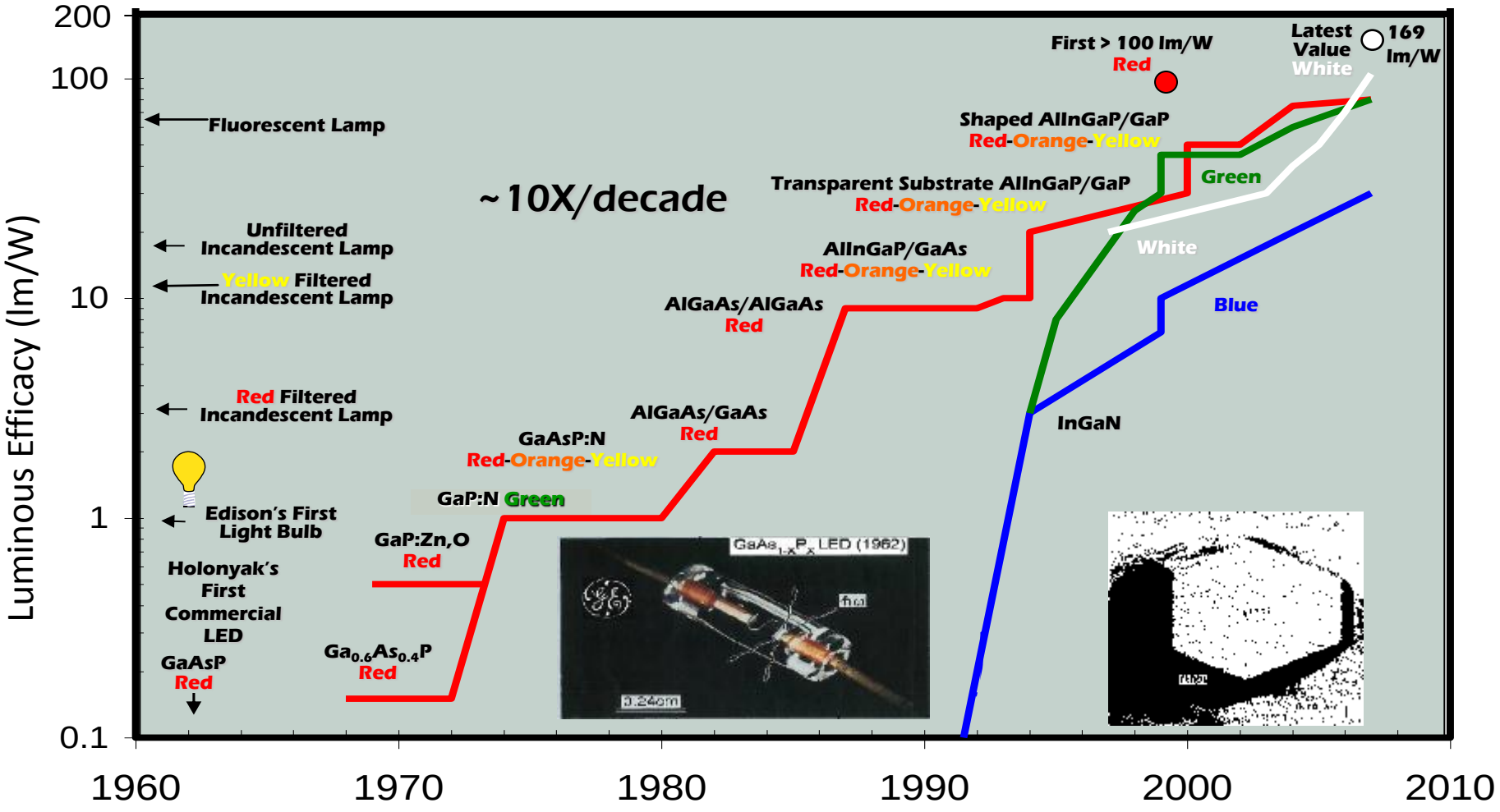
# Evolution of LED Performance



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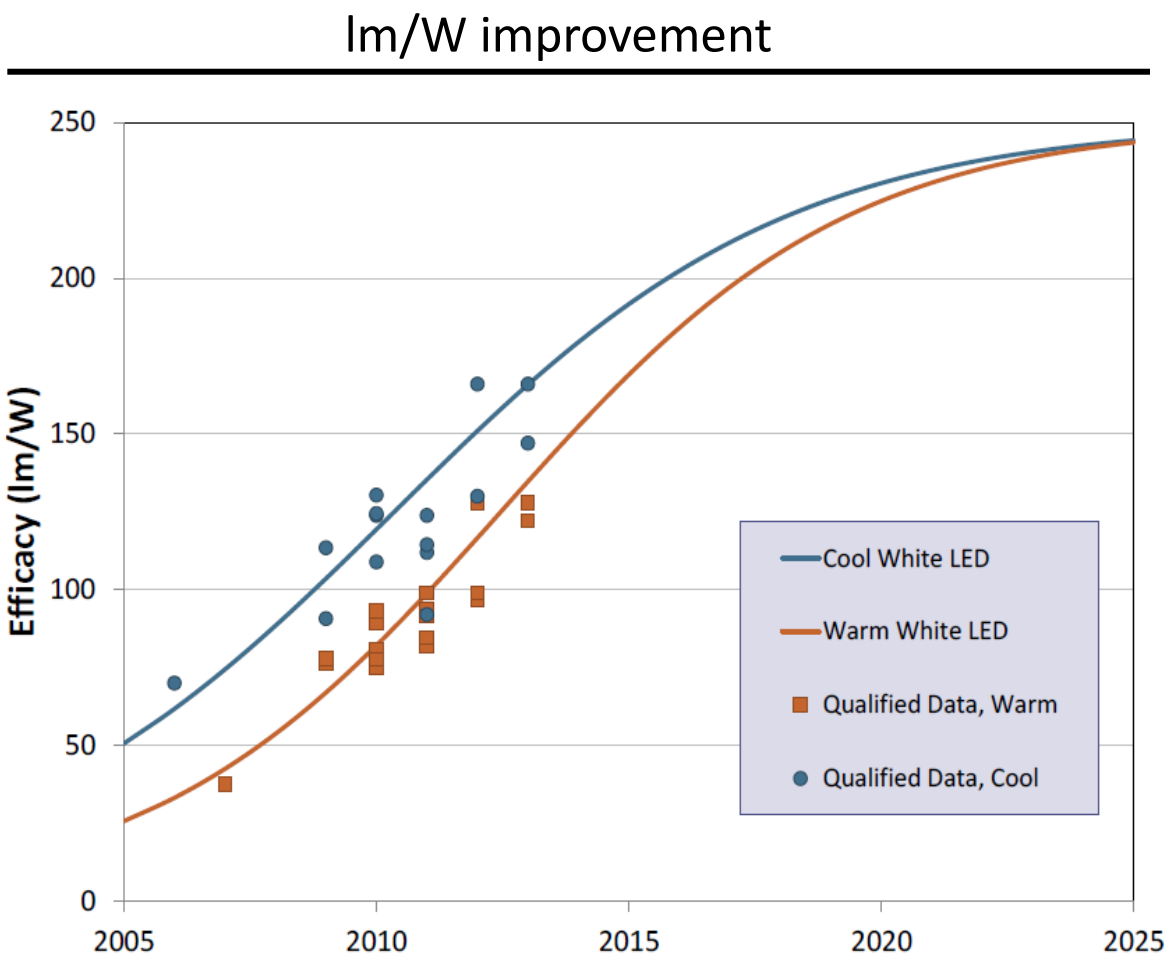
# lm/W improvement is still going…




Source: DOE 2014 SSL Roadmap



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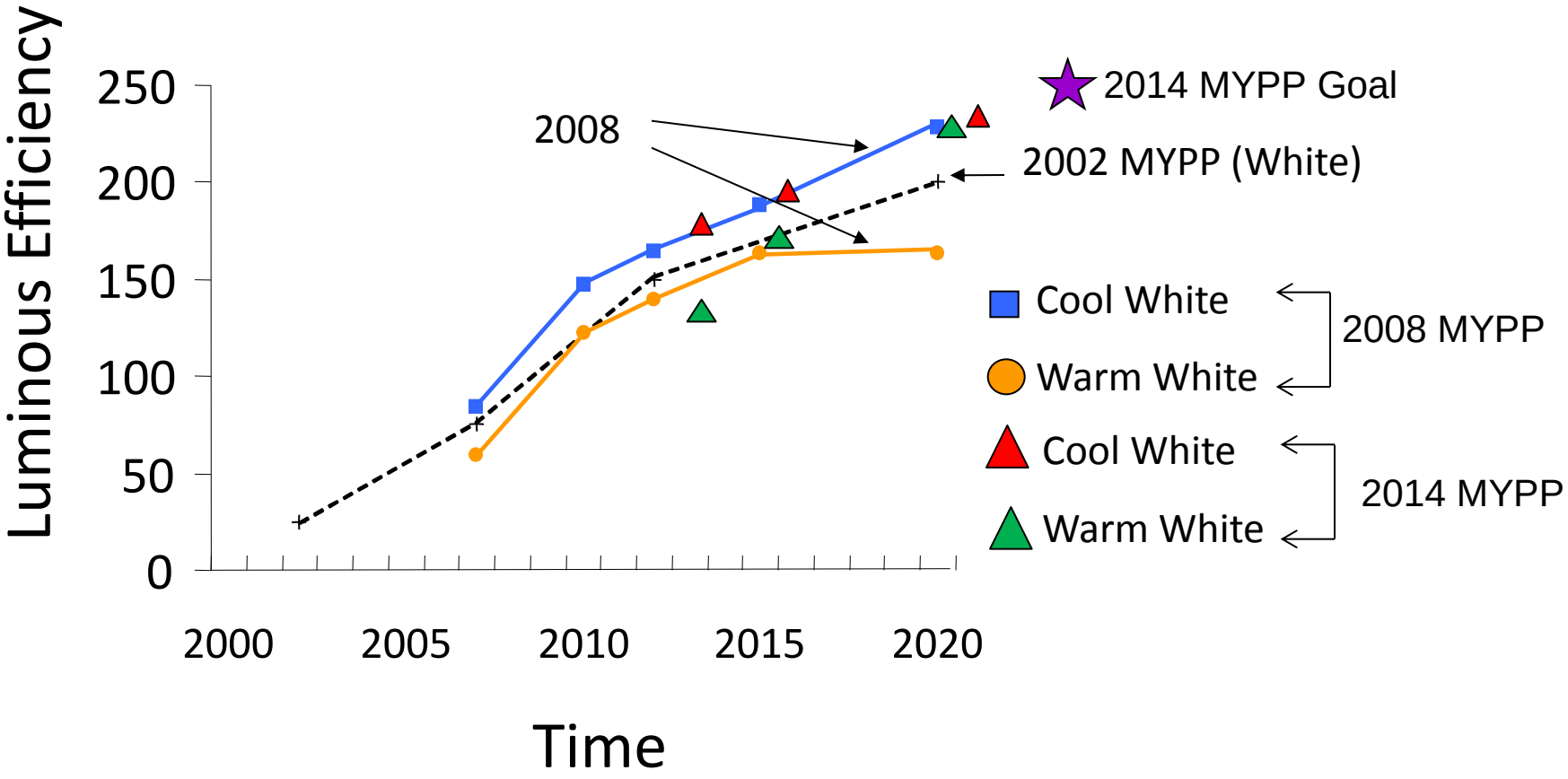
# Historical Perspective on Department of Energy Performance Projections



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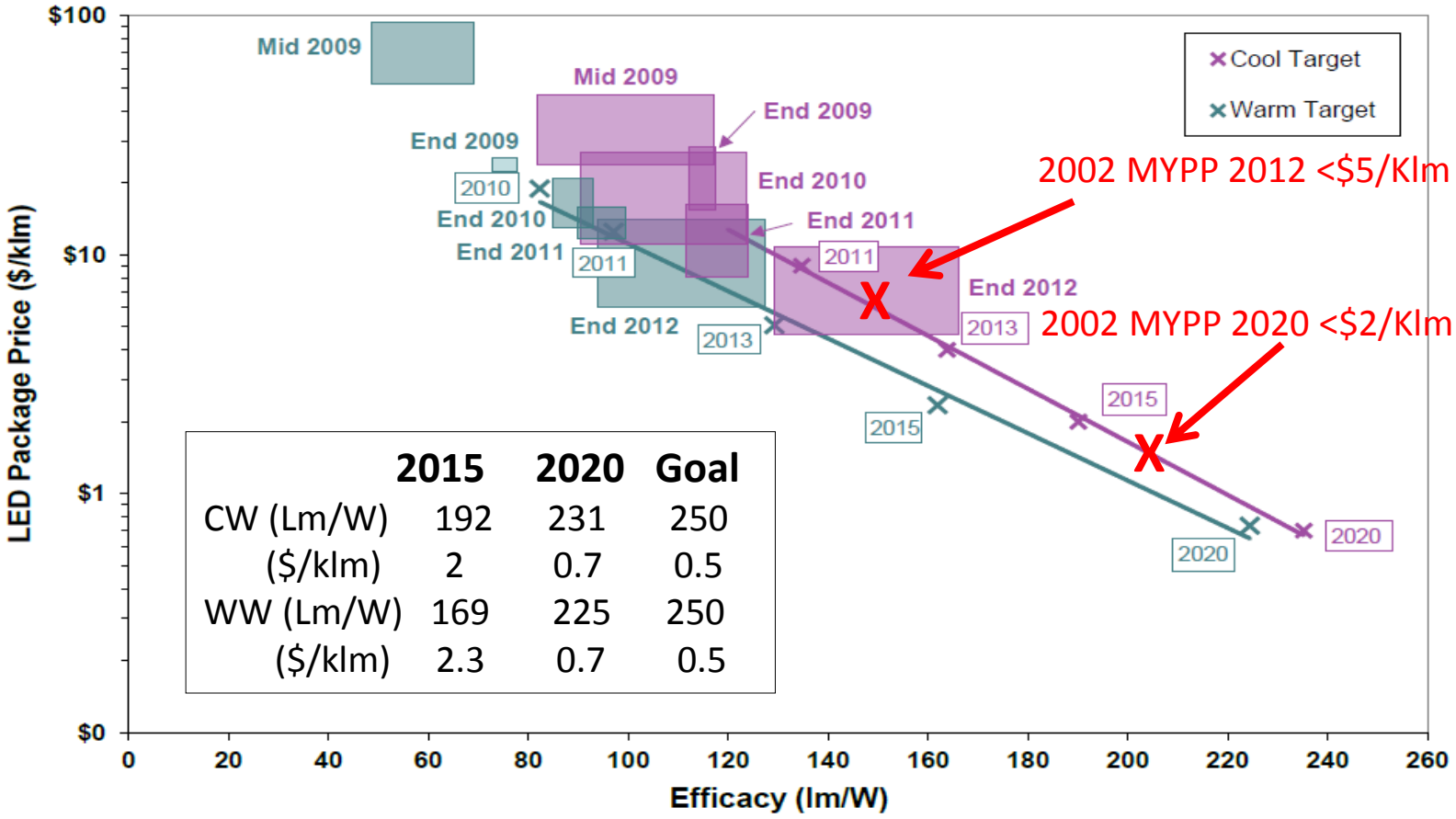
# Price-Efficacy Tradeoff for LED Packages




| | 2015 | 2020 | Goal |
|---|---|---|---|
| CW (Lm/W) | 192 | 231 | 250 |
| ($/klm) | 2 | 0.7 | 0.5 |
| WW (Lm/W) | 169 | 225 | 250 |
| ($/klm) | 2.3 | 0.7 | 0.5 |



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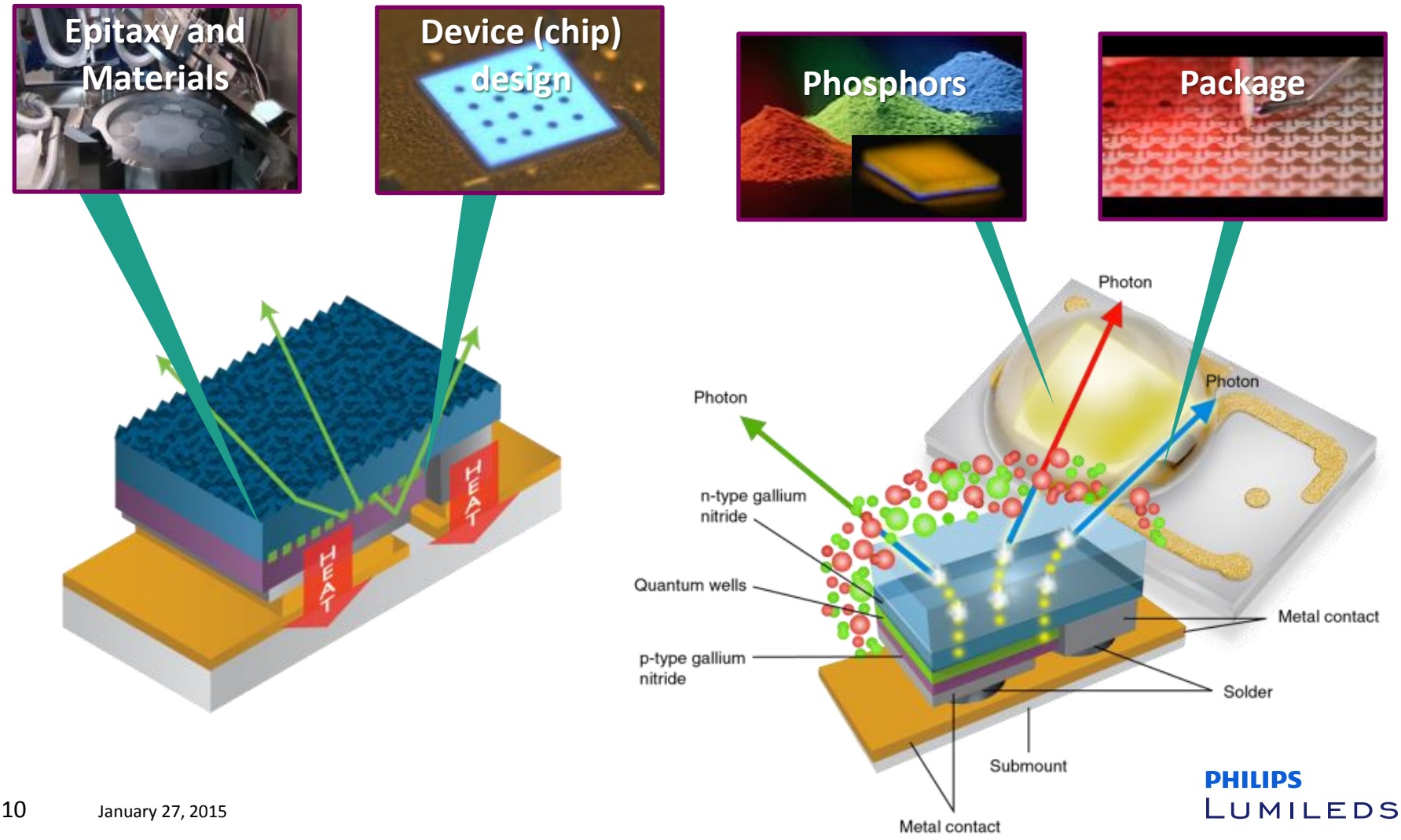
# LED Building Blocks



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# LED Building Blocks and Their Impact on Efficacy

The cells with “X” indicates a component of luminous efficiency affected by a particular LED building block.

| LED Building Blocks | IQE | ELE | EXE | CE | | | |
|---|---|---|---|---|---|---|---|
| | | | | PE | LE | QD | QE |
| epi (substrate, emission wavelength, heterostructure) | X | X | X | | X | X | |
| die (type, p-, n- contacts, interconnects) | X | X | X | X | | | |
| package (type, encapsulants, interconnects) | X | X | X | X | | | X |
| converter (phosphors, encapsulants) | | | X | X | X | X | X |



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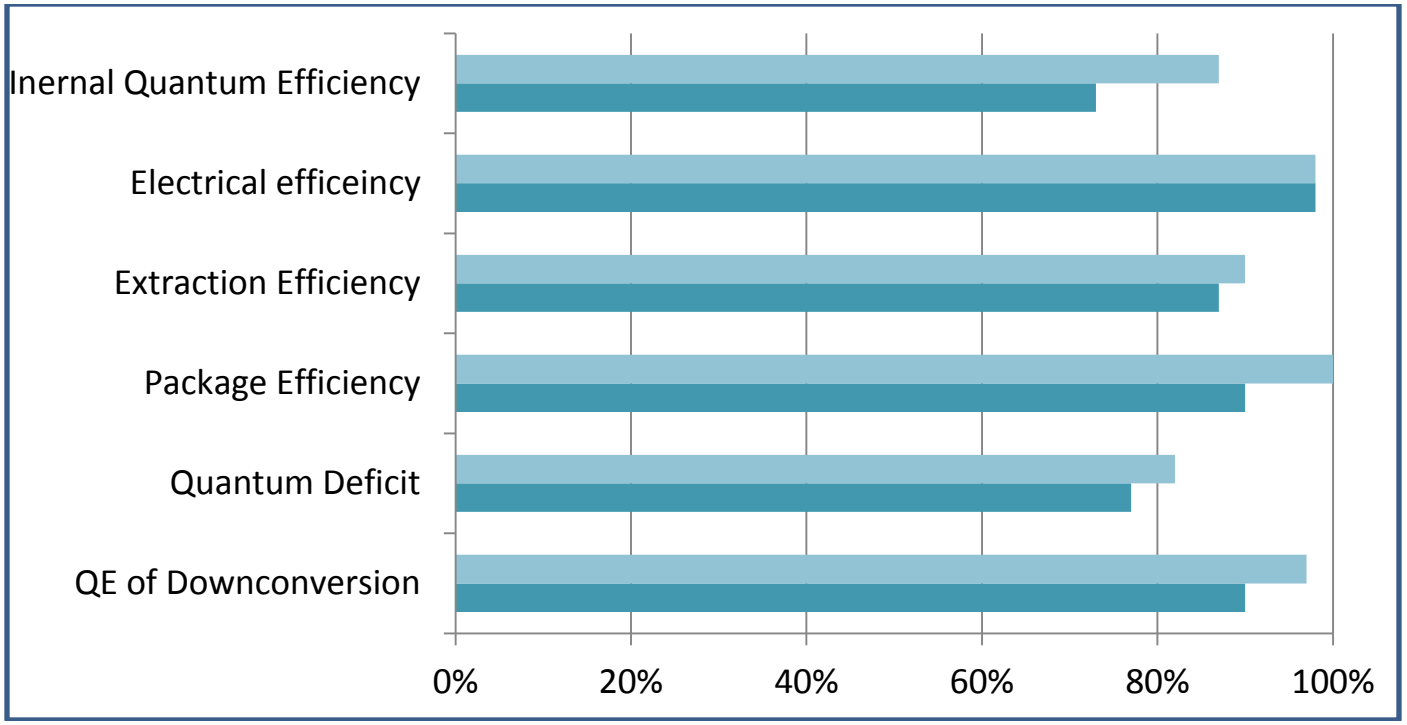
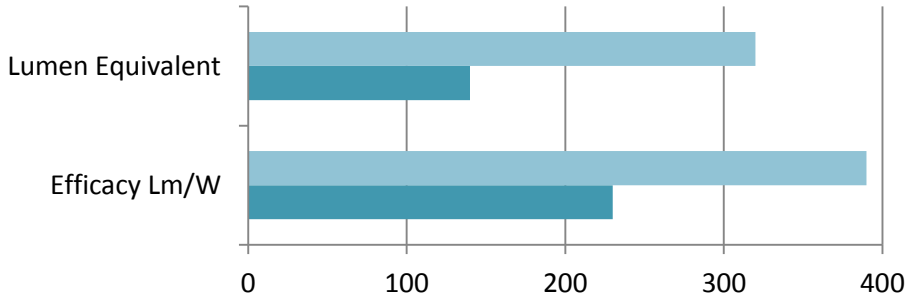
# Efficacy breakdown for a typical warm white phosphor converted LED

J=350mA/mm2 and Tj=85oC




**values listed for 3000K 80CRI phosphor converted LEDs at J=30mA/mm2 and Tj=85C**



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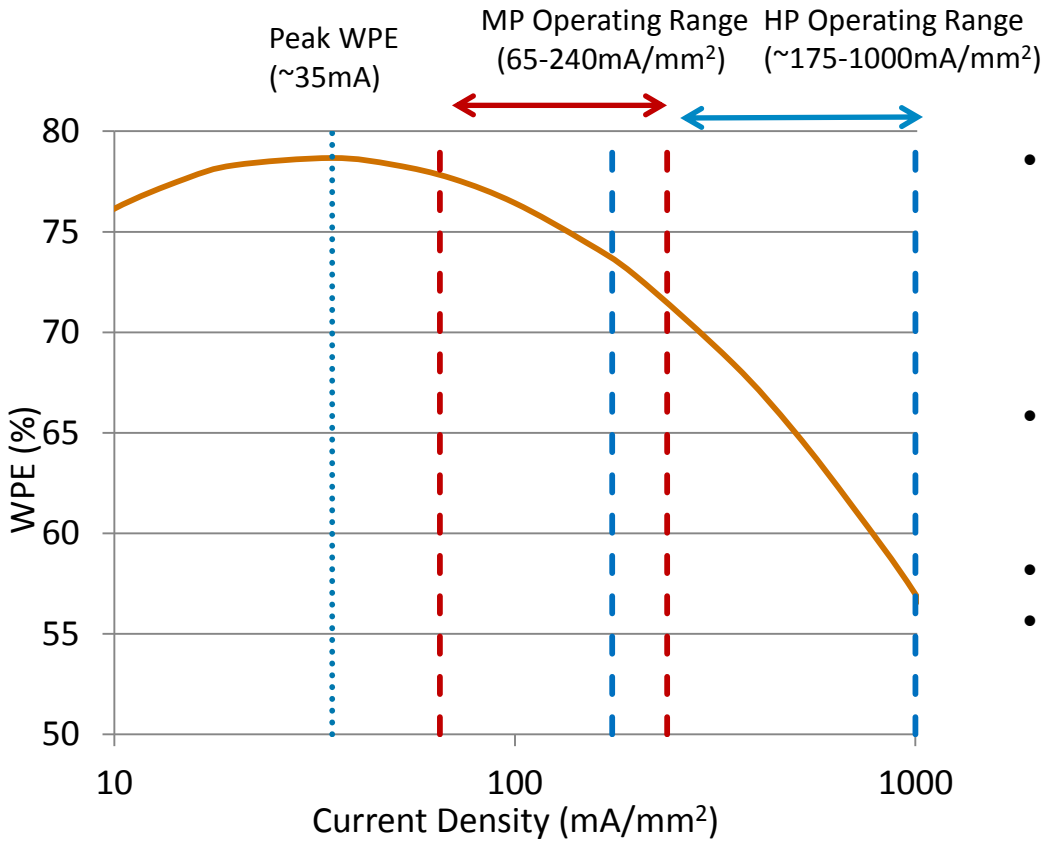
# Droop Impact for Mid-Power and High-Power LEDs




- Droop results in reducing efficacy above ~35mA/mm², so impacts <u>both</u> MP and HP, with greater impact at increasing drive currents
- For lm/$, LEDs are driven harder and harder once the system level efficacy has been reached
- Droop impacts MP
- Droop impacts HP

**Conclusion:** Droop is important for both MP and HP LEDs.



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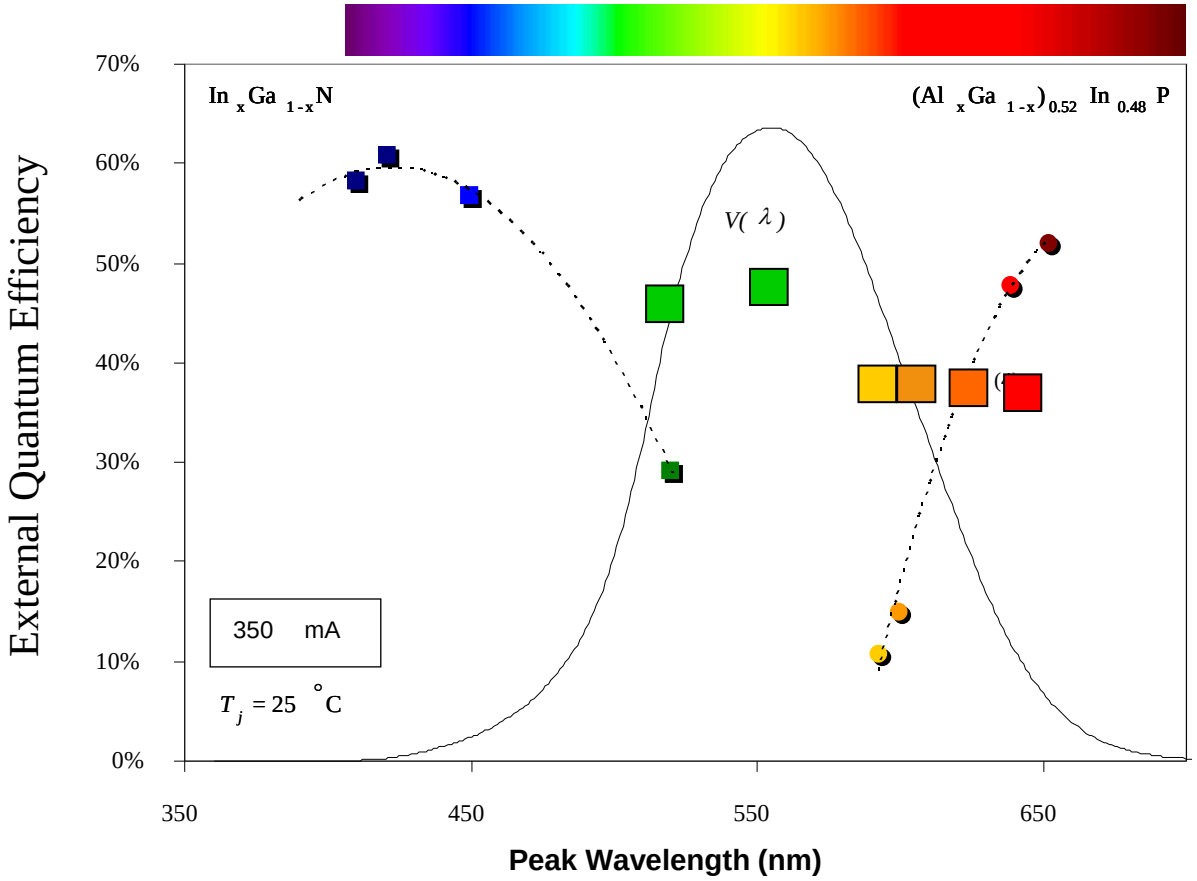
# Direct Emitting Green is Still Needed



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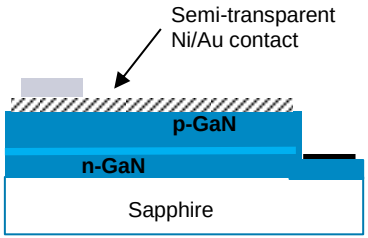
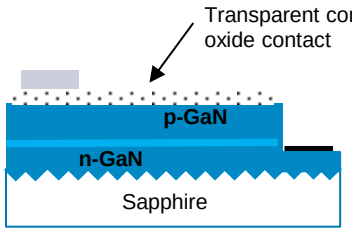
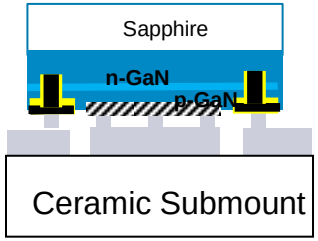
# Evolution of GaN Blue Die



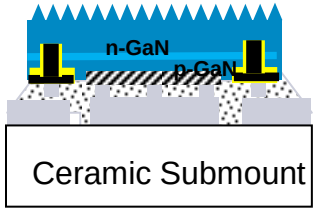

Conventional chip



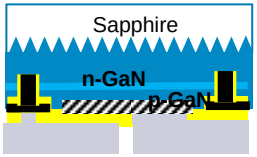

Lateral die



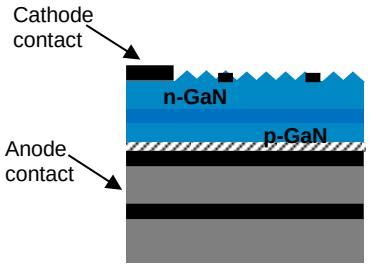

Flip Chip



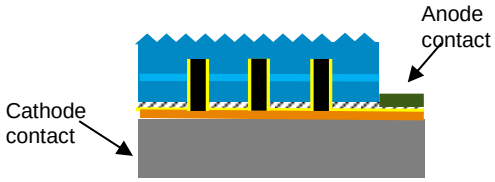

Thin Film Flip Chip (TFFC)




Chip Scale Package (CSP)




Vertical Thin Film (VTF)




Embedded-Contact VTF (EC-VTF)



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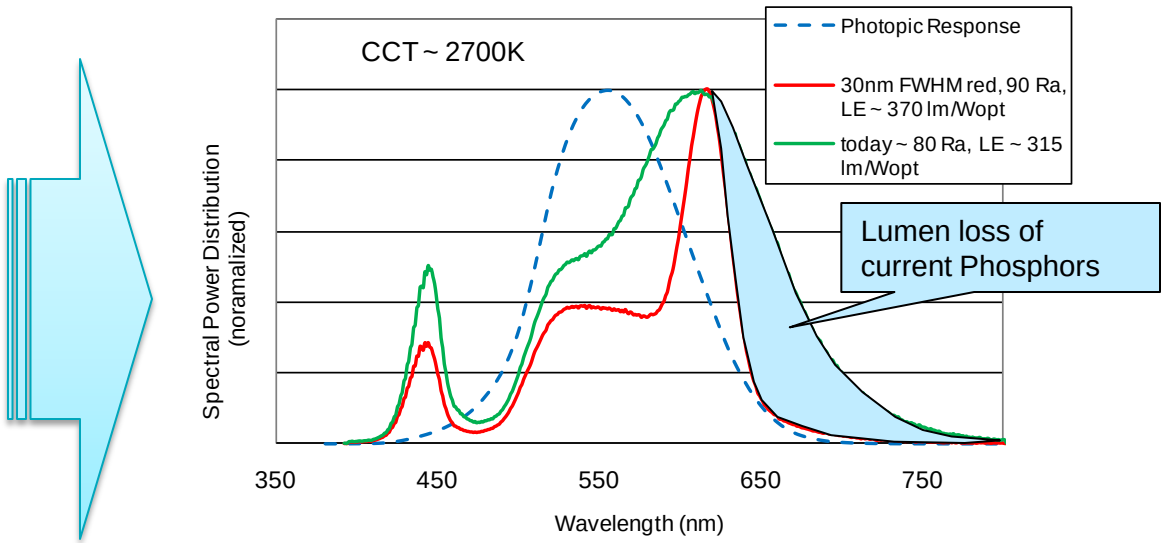
# Narrow Red Phosphor to boost CE for High CRI WW LEDs

- Current red phosphors have broad emission (90-100nm)
- Substantial amount light emitted in far-red reducing lumen output with limited benefit for color rendering
- Reduced width of red phosphor emission could increase efficacy of warm white LEDs by 20%



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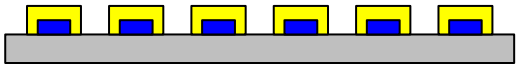
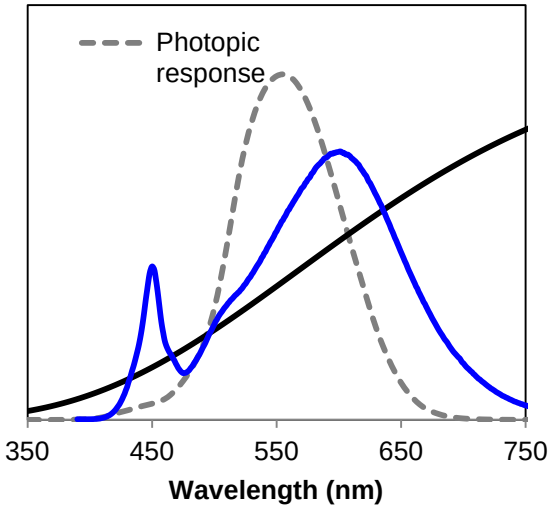
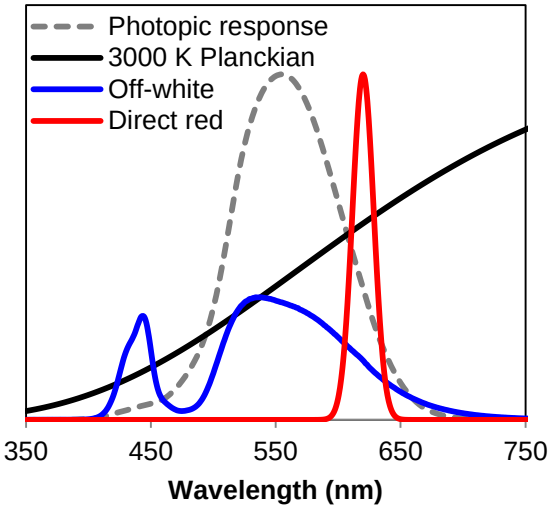
# Different Approaches for White LEDs

**Phosphor-converted LEDs**
Blue pump LED + phosphor

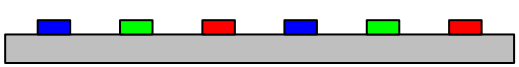


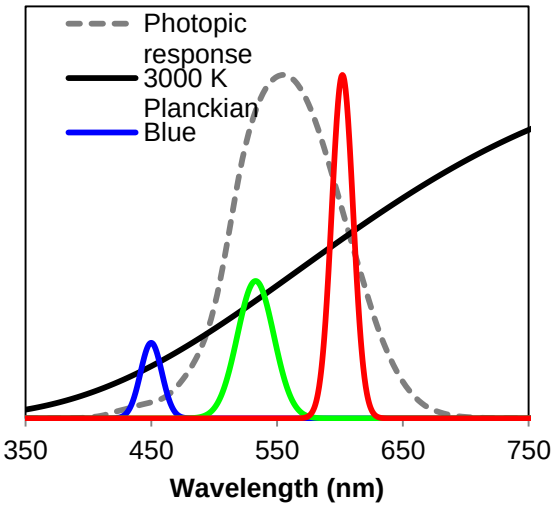



**Hybrid LEDs**
Combining phosphor-converted and direct-emitting LEDs




**Direct-emitting LEDs**
3 or 4 colors





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# Key Technical Challenges

| | PHOSPHOR-CONVERTED | HYBRID | DIRECT EMITTING |
|---|---|---|---|
| Improved (Narrow) **Red** Phosphor | X | | |
| Improved **Green/Yellow** Phosphor | X | X | |
| Fix Droop | X | X | X |
| Improved **Blue** LED | X | X | X |
| Improved **Red** LED | | X | X |
| Improved **Green** LED | | | X |



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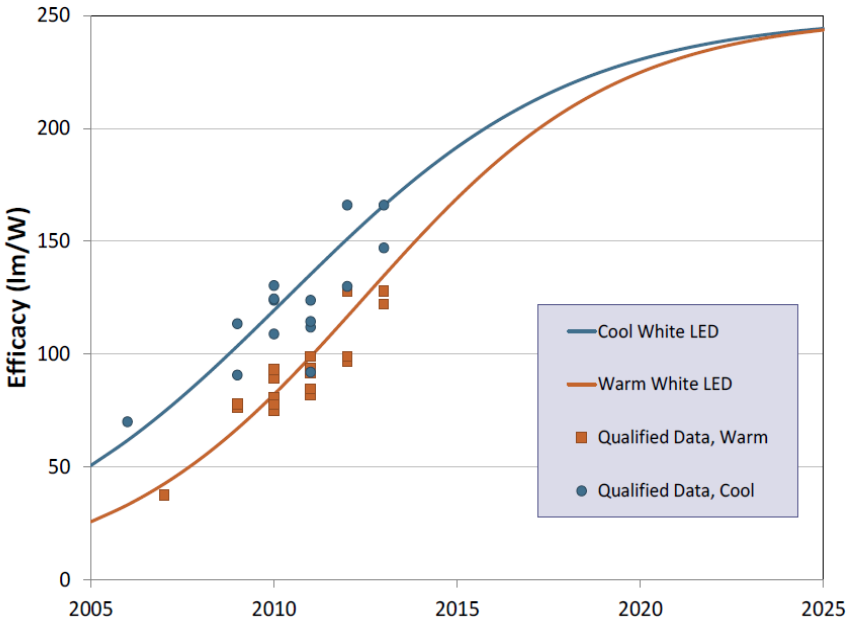
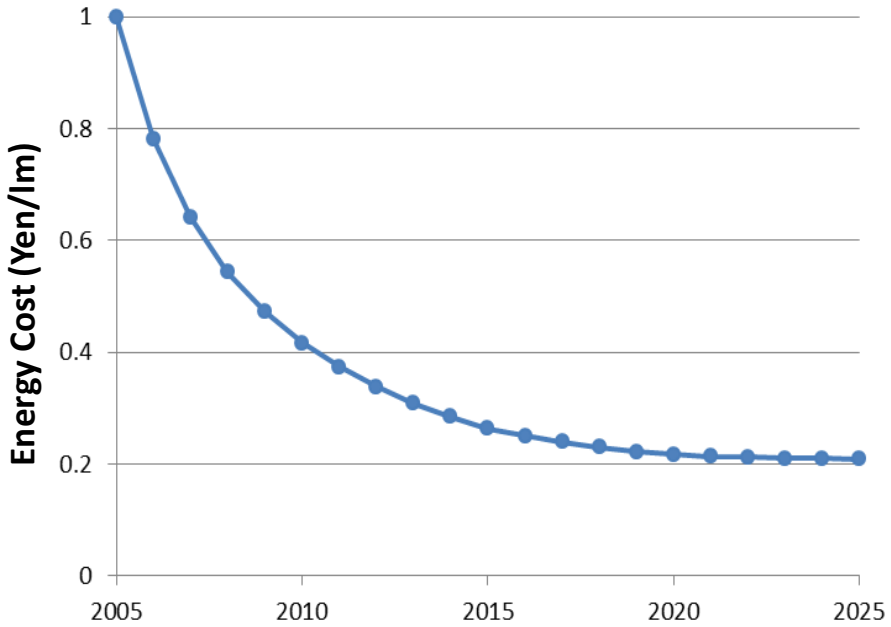
# ROI Energy Saving vs. Effort to Improve Lm/W is Getting Less Attractive

Lm/W improvement




Energy saving effect




Source: DOE 2014 SSL Roadmap



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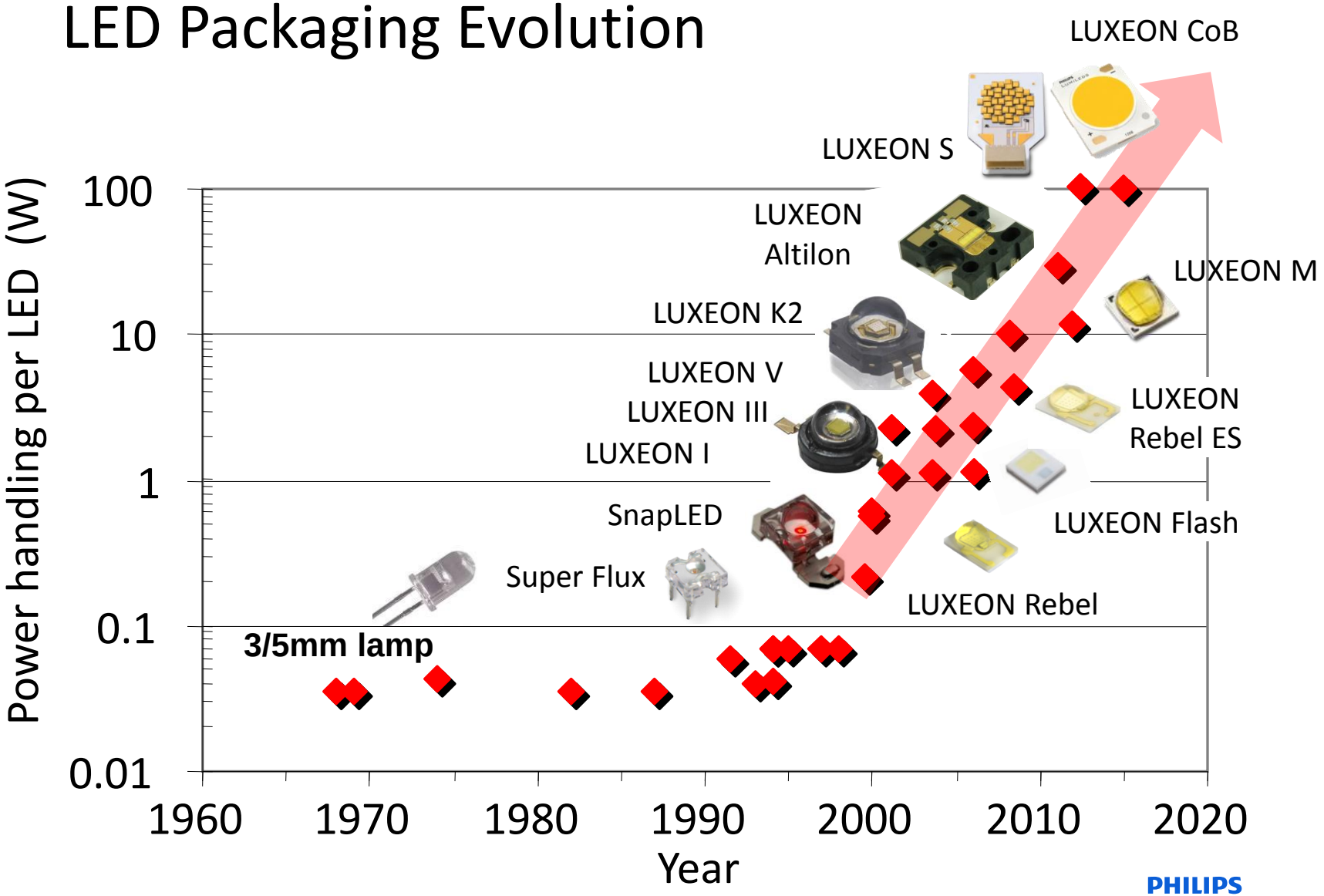
# LED Packaging Evolution



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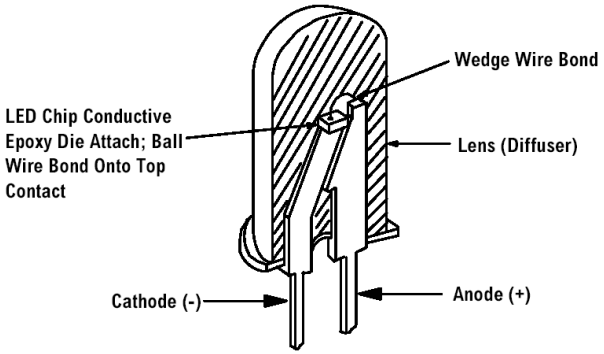
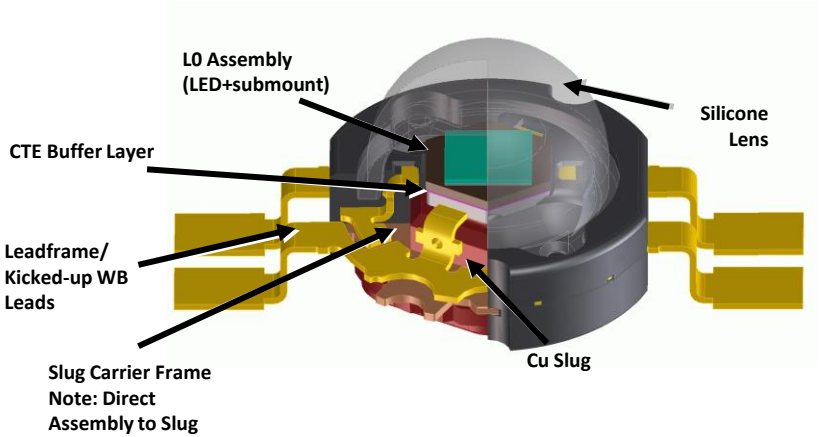
# LED Packaging: Reducing Costs & Improving Customer Flexibility

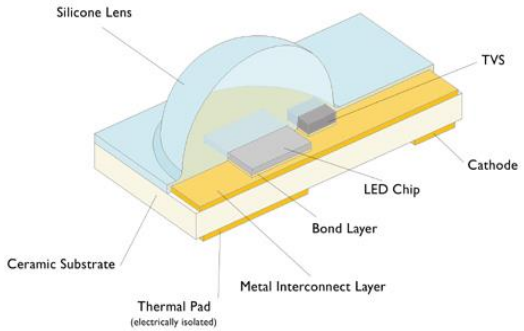
## 5mm Indicator Package Example



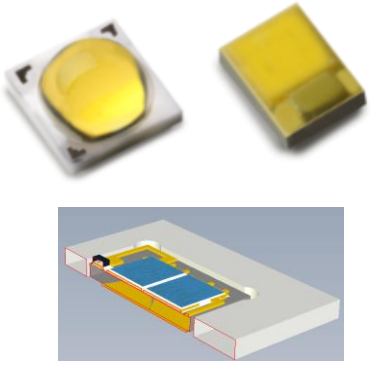

## LUXEON High-Power Package Example




## LUXEON Die on Ceramic Package

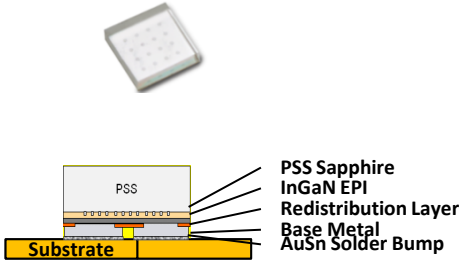



## Chip in a Frame Package



## LUXEON Flip-Chip

High Performance Chip-Scale Package



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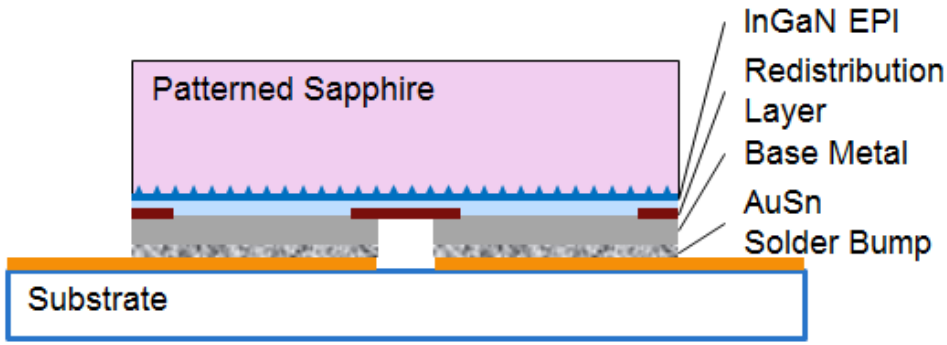
# Chip Scale Packages: Flexible & Reliable

LUXEON
FlipChip

## Flip Chip Architecture



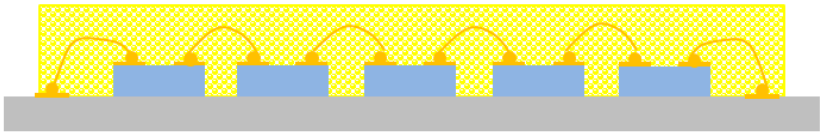

- No wire bonding
- Failure is short mode

## High lumen compact COB solutions

Flip chip + Remote Phosphor Film

vs.

CoB by conventional structure die





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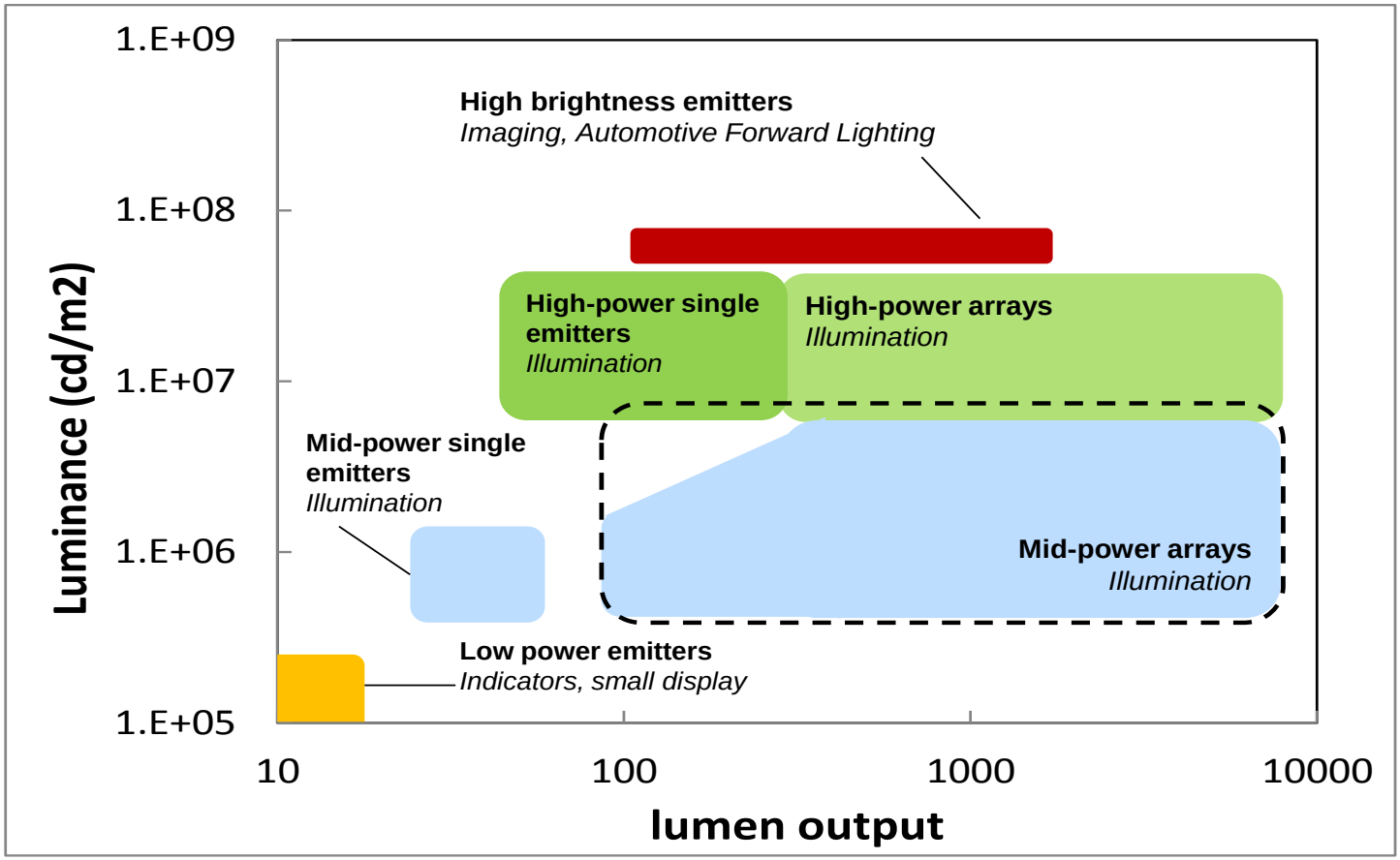
# Applications by Luminance and Lumen output



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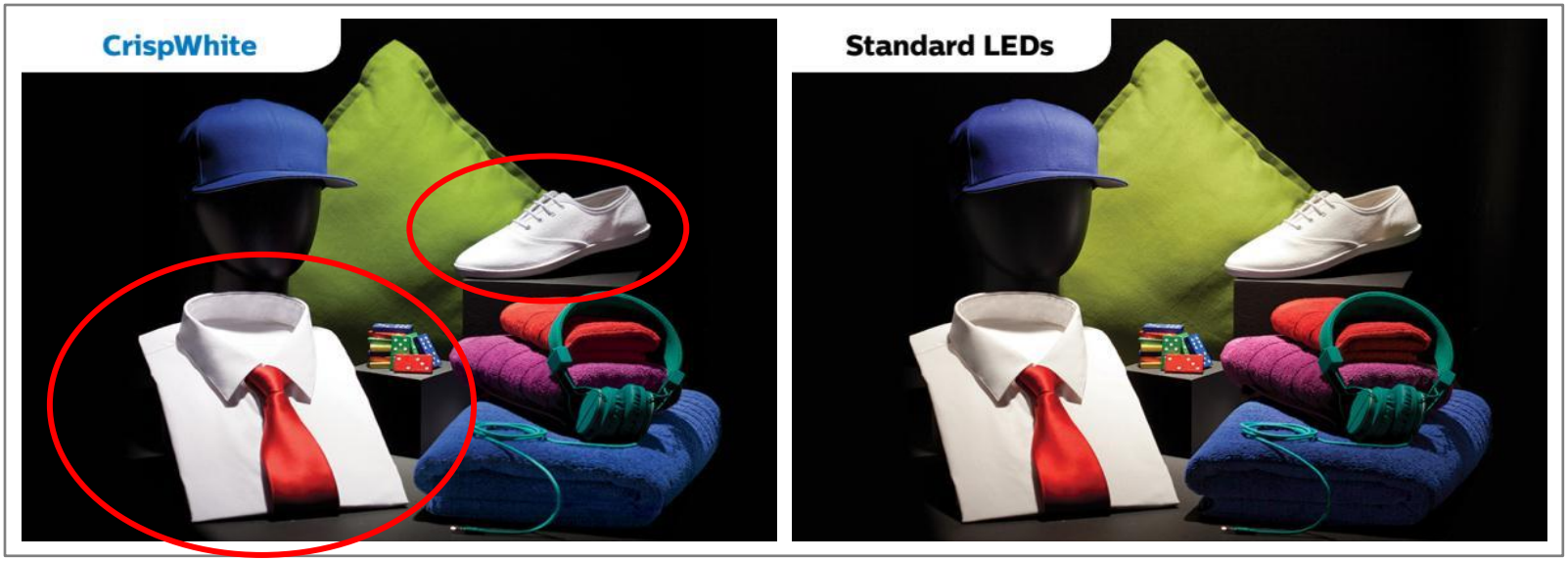
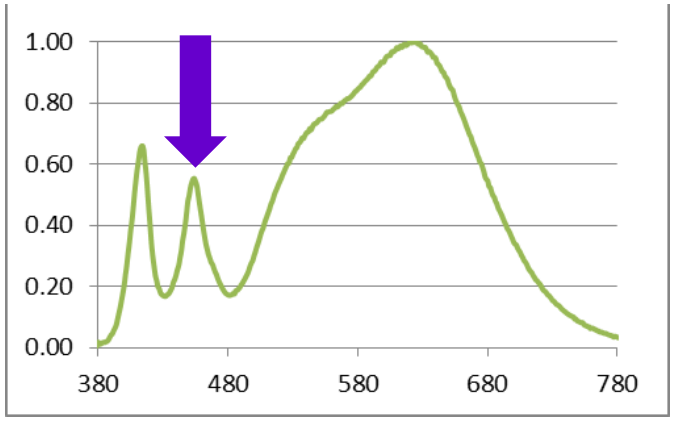
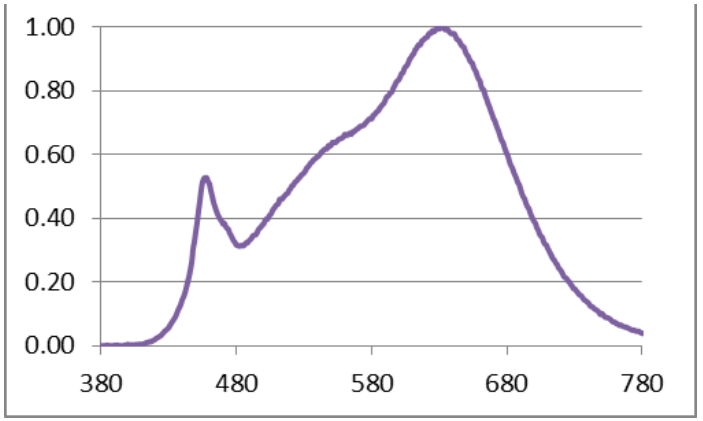
# Technology for Crisp Whites

## …by LEDs with application specific spectra



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# What's Next in Lighting After the "Replacement Transient"??

What would lighting look like if we had gone straight from fire to LEDs??

- How widely will the "digital lighting revolution" extend with color tuning, motion sensing, communication, etc?
- Will ceiling lighting move from troffers and spots to large area "skylight" ceilings made up of programmable color changeable LED panels?
- What lighting will be developed that will help us to be healthier and more productive?
- Will the solar / LED "marriage" expand from off-grid lamps and streetlights to solar powered homes?
- Will structures, clothes, furniture, body art, etc. with embedded LEDs become widely utilized?
- What completely new design concepts will emerge?

# Smart Lighting Applications

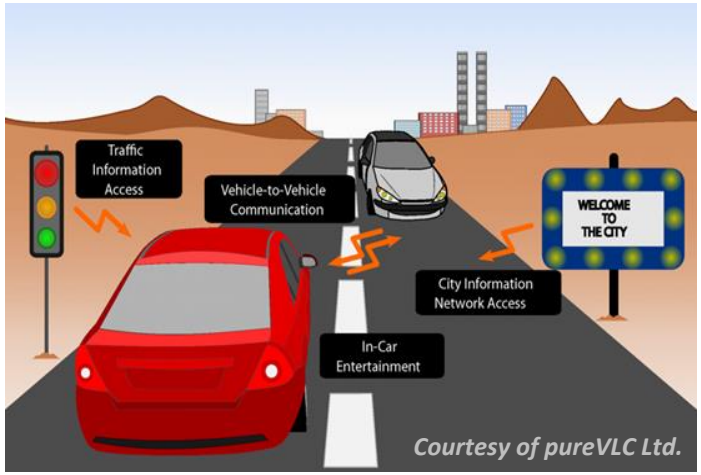
***"2nd Wave Lighting: Smart and Feature Rich***


***Integrated Illumination and Displays***

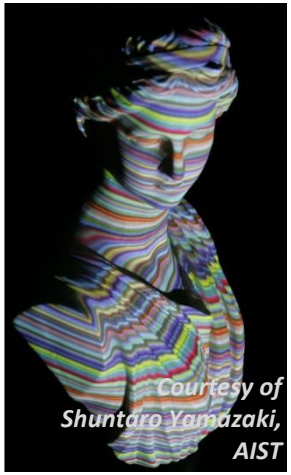

***Human Health, Well Being and Productivity***



***Agriculture***




***Communication***




***Light-Field Mapping***

M.H. Crawford, J.J. Wierer, A.J. Fischer, G.T. Wang, D.D. Koleske, G.S. Subramania, M.E. Coltrin, J.Y. Tsao, R.F. Karlicek, Jr., "Solid-State Lighting: Toward Smart and Ultra-Efficient Materials, Devices, Lamps and Systems," in D.L. Andrews, Ed., "Photonics Volume 3: Photonics Technology and Instrumentation" (Wiley, 2014).

Courtesy Jeff Tsao UCSB Presentation Feb 22, 2014



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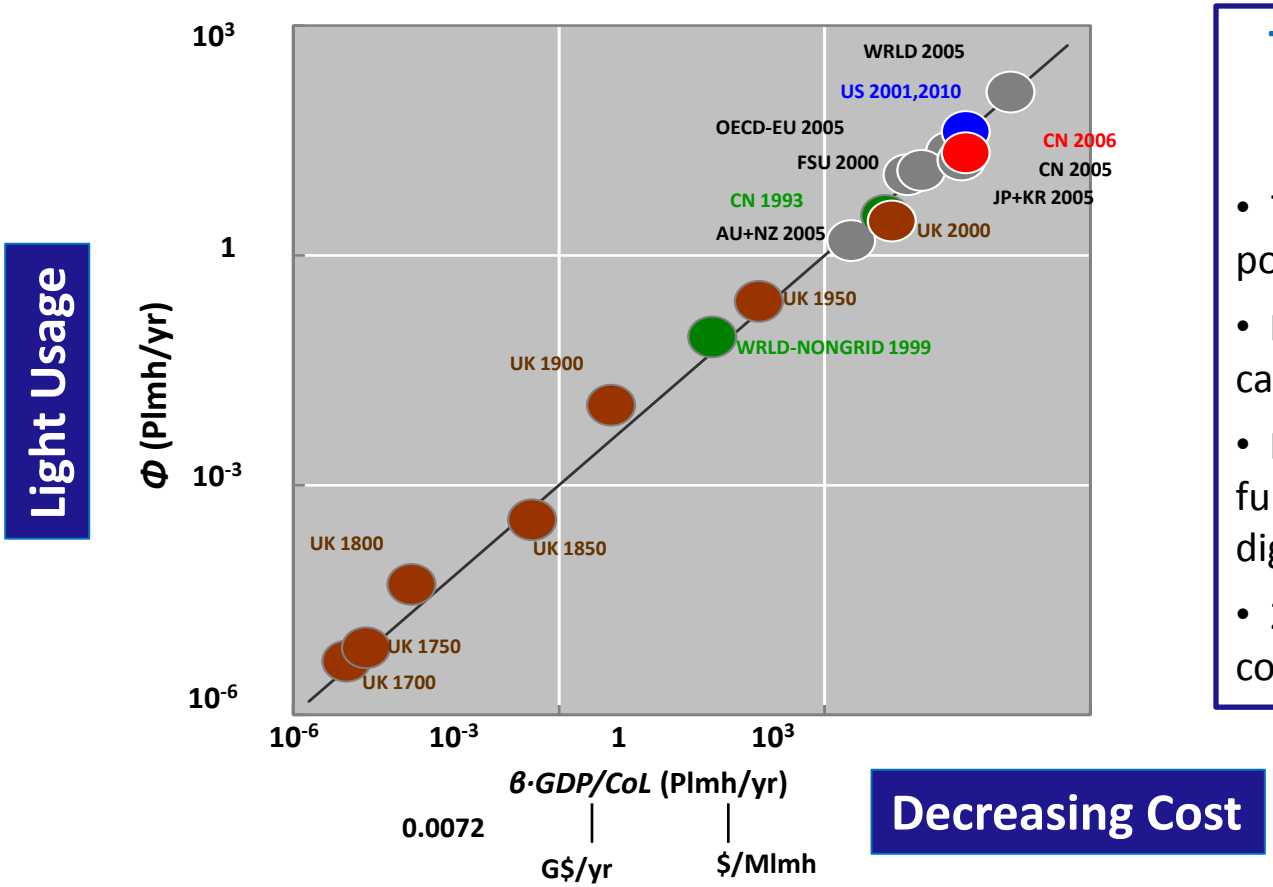
# Historic per Capita Light Consumption Increased with Sinking Cost of Light




**Trend to "More light" continues**

- 70% of world wide population in cities by 2050
- Developing regions catching up
- New applications and functionalities enabled by digital light
- 20% of world wide power consumption for Light

J.Y. Tsao and P. Waide, "The World's Appetite for Light: Empirical Data and Trends Spanning Three Centuries and Six Continents," LEUKOS **6**, 259-281 (2010).



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# Summary

- LED performance appears to be moving from revolutionary to evolutionary improvement
- After decades of focus primarily on lumens/watt and lumens/dollar application specific packaging has become a third innovation focus area
- Future design concepts and applications often including “smart” lighting will revolutionize lighting in ways impossible to predict


# Thank you