High Power White LED Technology for Solid State Lighting

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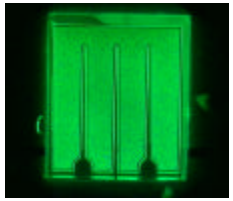
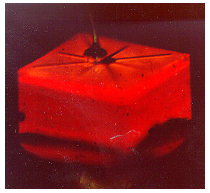
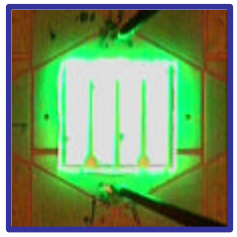
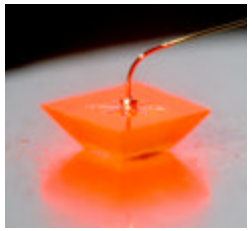
High Power White LEDs

Who is Lumileds

- **Fully integrated light source supplier that co-develops optimized system solutions!**
  - **LED dice**

  - **Luxeon ä Power Light Sources**
    - Arrays of High Flux LEDs on a metal core PCB

  - **Automotive, Traffic Signals, Signage & Contour Solutions**



High Power White LEDs

Outline

- **Competition in the market for Illumination, Incandescent & Fluorescent Bulbs.**
- **LED Metrics**
- **Options for making white light from LEDs**
- **Lumileds power white LED performance**
- **Some interesting demos**

Illumination Markets

How Much Energy is Used for Lighting

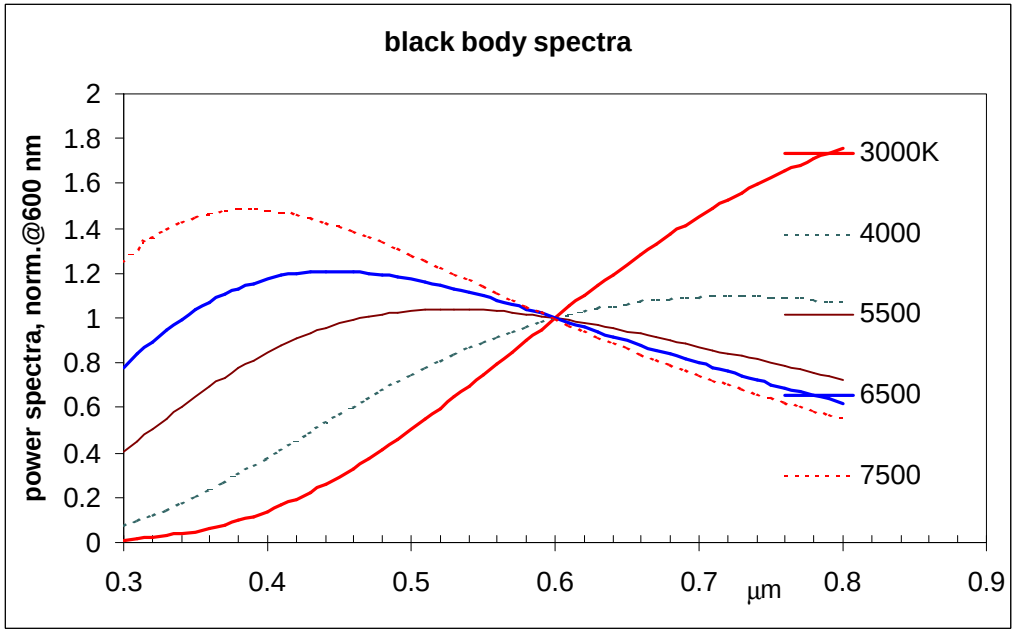
- **In 1999 the US used 3 Trillion kWhr of Electricity!**
- **20% or 600 Billion kWhr of Electicity generated was used in Lighting!**
- **Incandescent/Hal. lamps burn 40% of electricity to produce 15% of light!**
- **Fluorescent/HID lamps use 60% to produce 85% of light!**
- **Illumination market is $60Billion/yr and growing slowly, ~2%/yr**

Illumination Markets

Incandescent Bulbs

- **Incandescent = hot light, emitted from a (tungsten) filament at around 2800ºK**
  - Disadvantages:
    - mostly infra-red
    - glass vacuum envelope & filament both break easily
    - <15 lm/W luminous (<5% power) efficiency
    - fire hazard, burnt fingers, maintenance
  - Advantages:
    - Radiant cooling
    - Cheap 0.0005$/lumen
    - klm per package!

Basic disadvantage:
no chance to come close
to DAYLIGHT = 6500ºK



Courtesy Gerd Mueller LL

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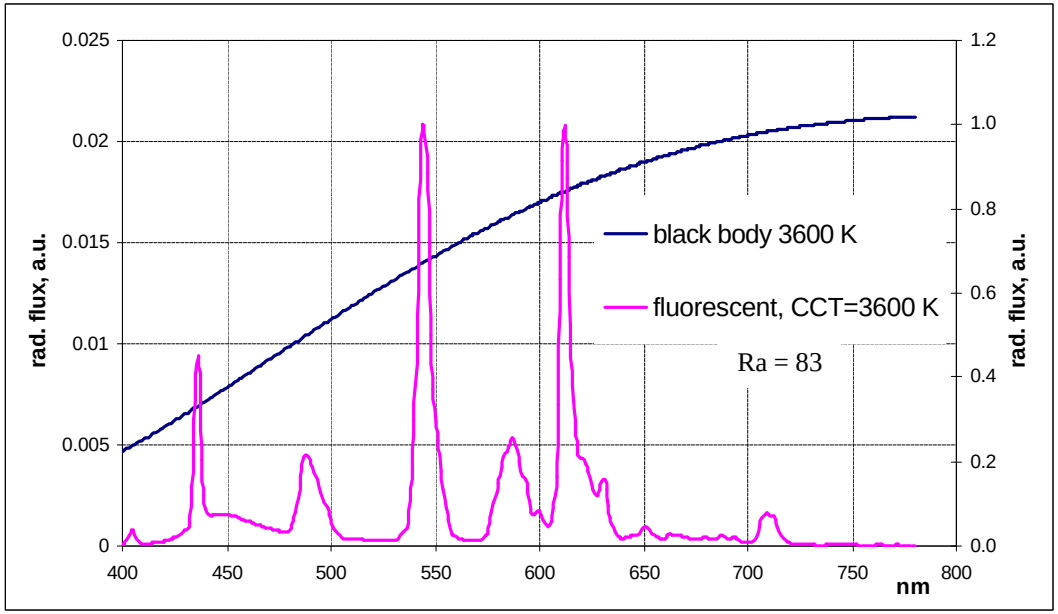
Illumination Markets

Fluorescent Bulbs

- **Fluorescent = cold light, emitted by phosphors excited by gas discharge.**
  - Advantages:
    - High efficiency 80+lm/W & High Flux klm/lamp
    - Moderate cost for large lamps 0.002$/lm
  - Disadvantages:
    - Lifetime short <10,000 hrs resulting in high maintenance.
    - Glass vacuum envelope leaks/breaks, ballast noisy.
    - Mercury!!

Basic Advantage:
any color temperature
possible by tri-color mixing



Courtesy Gerd Mueller LL

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Illumination Markets

Assumptions for using LEDs in lighting

- **LED lamps will be far more expensive than incandescent, halogen or fluorescent lamps for at least a decade.**
- **The expensive LED lamp must pay for itself through lifetime energy and maintenance savings.**
- **The lighting industry has spoiled the users with superb color rendering and color control.**
- **Near term LEDs must dominate monochrome and penetrate white niches!**

High Power White LEDs

Outline

- **Competition in the market for Illumination, Incandescent & Fluorescent Bulbs.**
- **LED Technology & metrics**
- **Options for making white light from LEDs**
- **Lumileds power white LED performance**
- **Some interesting demos**

LED Metrics

Tower of Babble?

optical power out / electric power in = Wall-Plug-Efficiency, **WPE**, (%,W/W)

photons out / electrons in = External Quantum Efficiency, **EQE**, %

photons internally generated / electrons in = Internal Quantum Efficiency , IQE, %

photons out / photons generated = extraction efficiency, %, η_{ext}

photon energy / applied voltage (times electron charge) = electrical efficiency, %, η_{el}

lumens out / electric power in = luminous efficiency [**lm/W**]

luminous efficacy, **LE** [lm/W] = luminous equivalent of the emission spectrum

$$\text{luminous efficiency} = IQE*\eta_{ext}*\eta_{el}*LE$$

$$IQE*\eta_{ext} = EQE$$

$$EQE*\eta_{el} = WPE$$

$$WPE*LE = \textbf{\textit{lm/W}}$$

LED Metrics

LED Skulduggery

"A Devious device or trick!"

Paul's Top 5 Sins

1) Quoting EQE without Vf or WPE

2) Quoting low duty factor results

3) Quoting WPE without current or current density & total power out.

4) Quoting WPE without temperature

5) Quoting Cd without Flux

What am I hiding?

1) Vf, power efficiency

2) Thermal resistance, heating

3) GaN in particular has strong dependence of WPE on current not much light comes out of a device at very low currents!

4) WPE is strongly dependent on junction temperature for AlInGaP, less so for AlInGaN.

5) Radiation pattern

LED Metrics

Tower of Babble take 2 for white LEDs

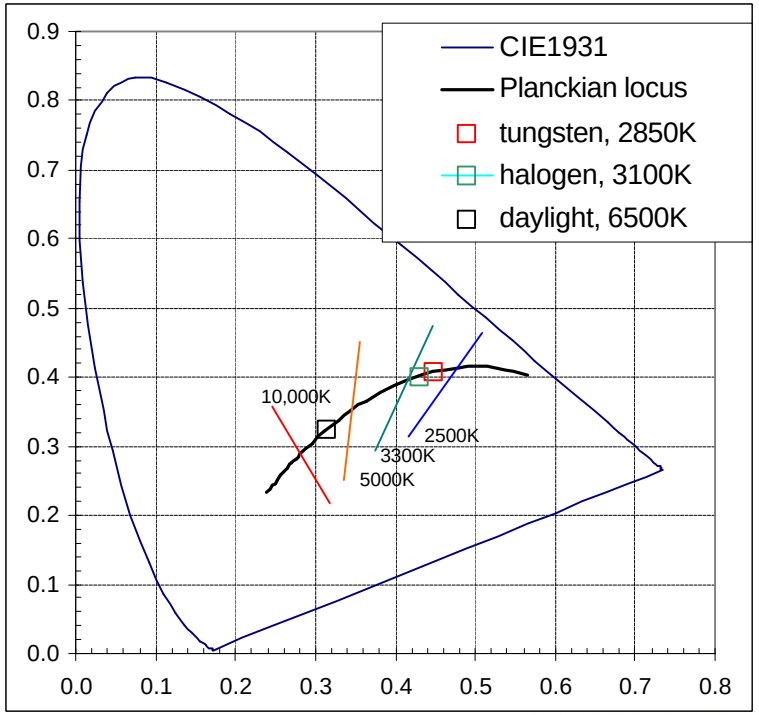
How well can a source reproduce "natural" colors = Color-Rendering-Index, **Ra**, %
(100 = sunlight, 85 = office, 60 = cabinet/lantern light)

Color Correlated Temperature = CCT, Kelvin
(x,y coordinates normal to black body curve)

Phosphor Converted LED = PCLED

LED photons pump phosphor which emits secondary, and longer, wavelength of light.

Stoke's shift = Difference in wavelength between absorbed and emitted photons. Emitted photons always have longer wavelength, i.e. lower energy!



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High Power White LEDs

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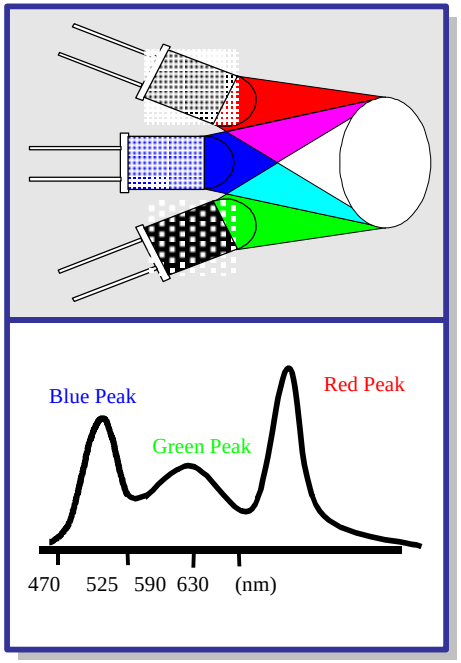
White Light from LEDs

Three methods of Generating LED White Light

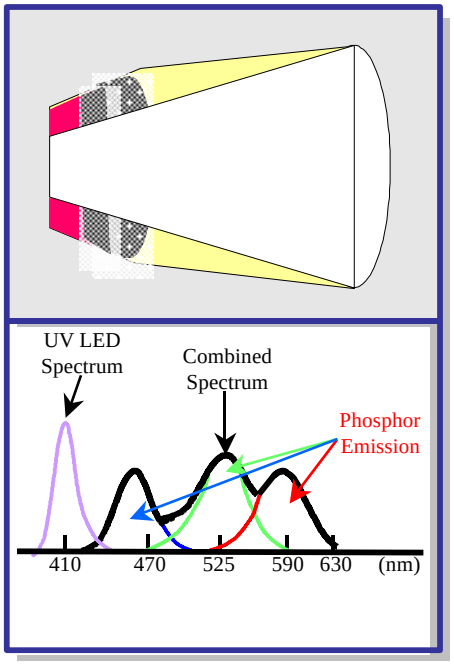
- **Each method has potential strengths!**

Red + Green + Blue LEDs



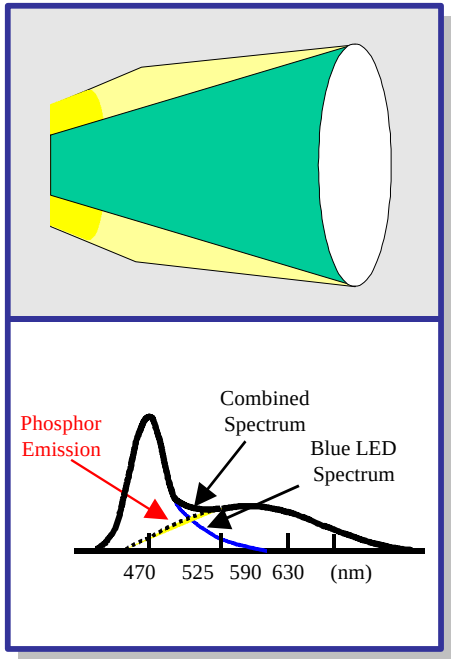
RGB LEDs

UV LED + RGB Phosphor



UV LED + RGB phosphor

Binary Complimentary



Blue LED + Yellow phosphor

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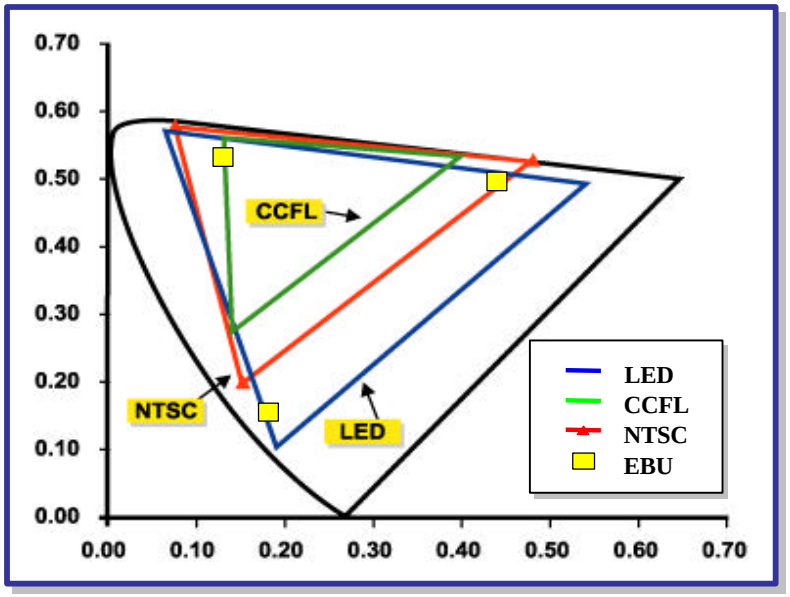
White Light from LEDs

Combining Red, Green and Blue LEDs

- **Advantages:**
  - Long term likely the most efficient!
  - Dynamic tuning of color temperature possible!
  - Excellent color rendering!
  - Very large color Gamut available!
- **Challenges**
  - Color Feedback required today to account for LED degradation with T & t!
  - Color mixing tricky!
  - Yellow-Green Gap!



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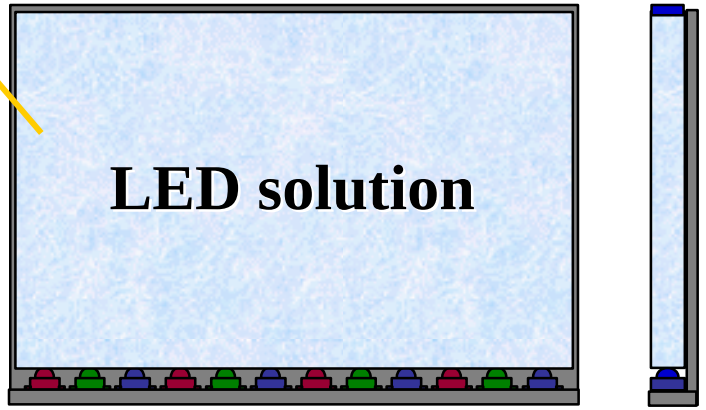
Combining Red, Green and Blue LEDs

Lumileds LCD Backlight!

- **20 Green, 10 Red, 10 Blue Luxeon's, ~ 1000 lumens!**
- **Today LED Solution has 140% Color Gamut and 120% CCFL power!**

Both displays showing the same slide *(red only background)* via a splitter

CCFL solution



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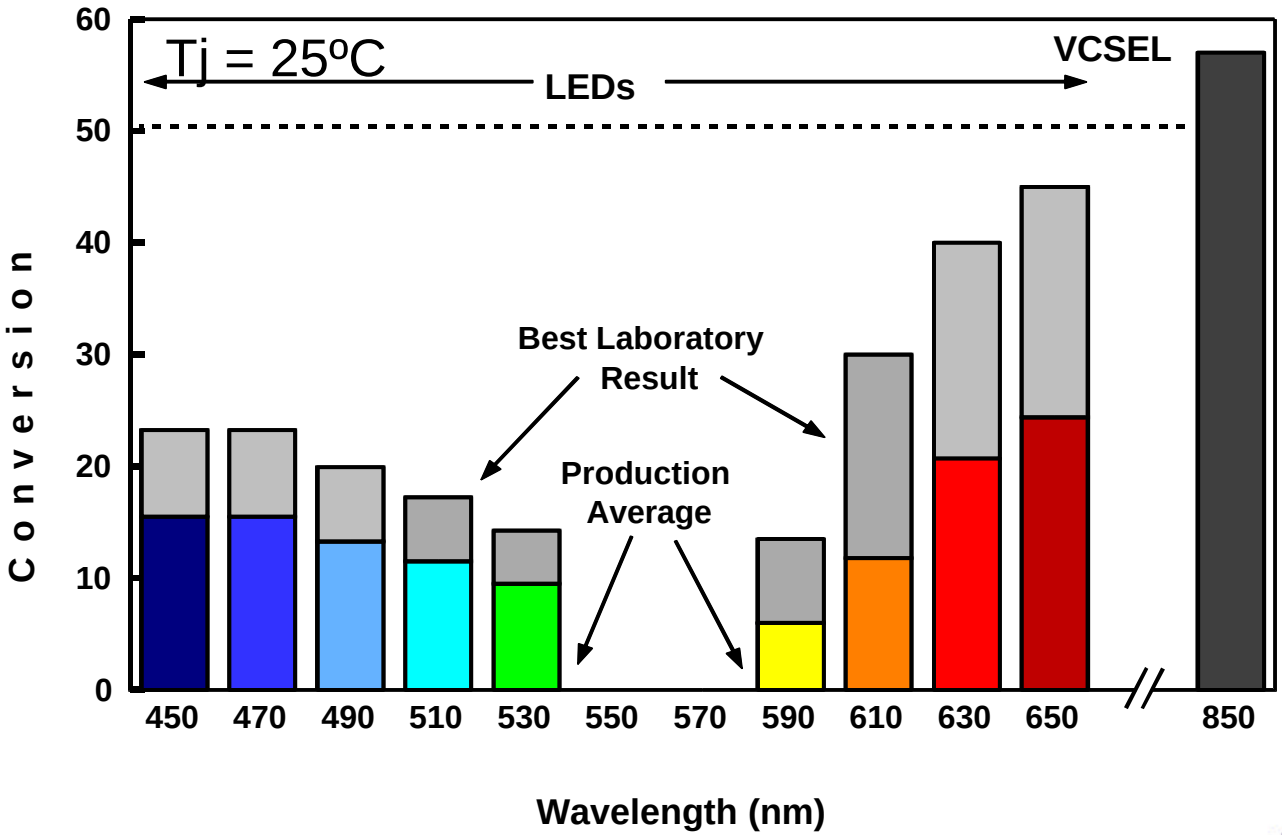
White from RGB LEDs

The Yellow-Green Gap!

- **Eye Sensitivity Peaks right in the middle of the Yellow-Green GaP!**



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White Light from LEDs

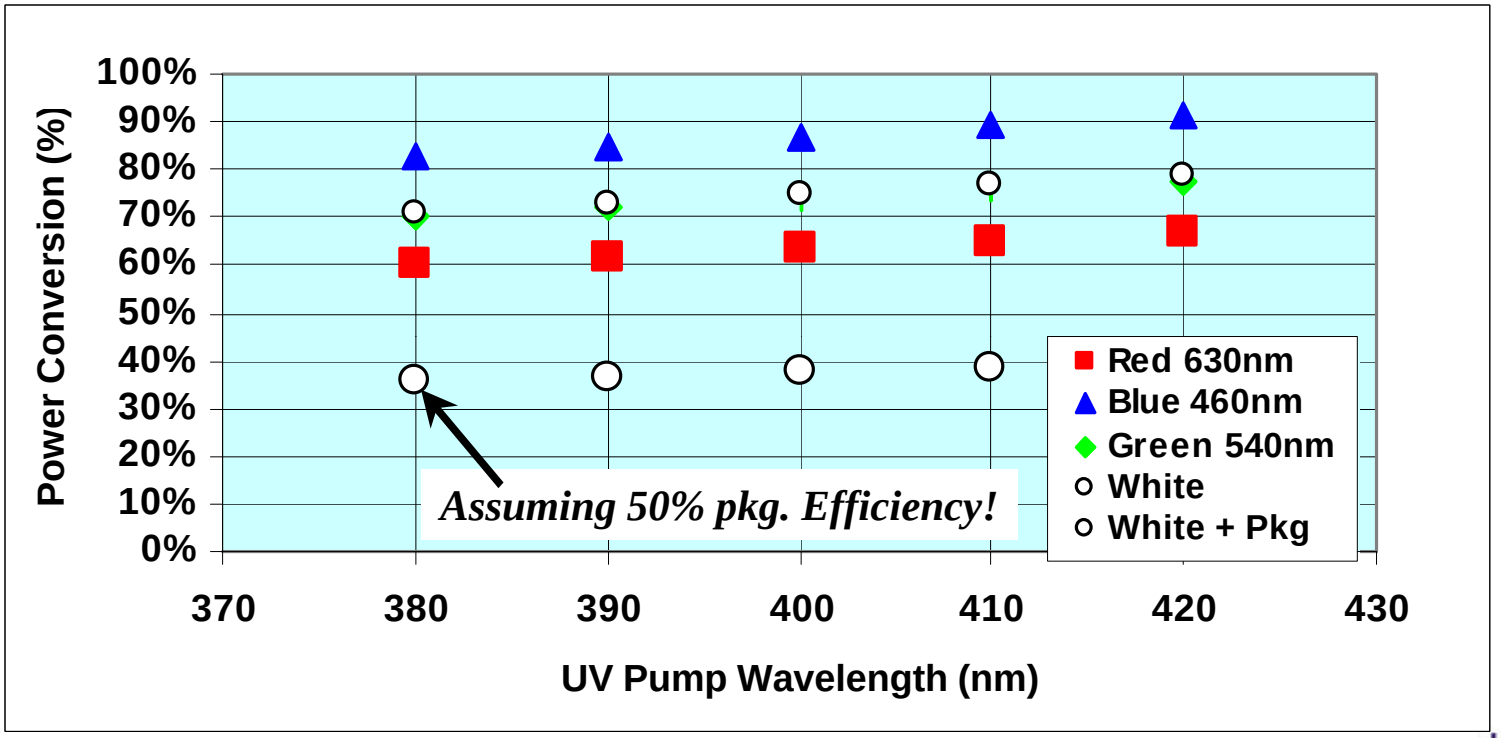
UV LED pumped RGB Phosphors

- **Advantages:**
  - White point determined by phosphors ONLY! (i.e. tolerant to LED variation)
  - Excellent color rendering possible!
  - Theoretically “Simple to manufacture!” (Looks like TV or Fluorescent lamp except for pump is now UV LED rather than electrons.)
  - Temperature stability of phosphors. (Can be great!)
- **Disadvantages**
  - Potential for damaging UV light leakage.
  - Fundamental limits on efficiency due to phosphor conversion efficiency, Stokes shift, self absorption,…
- **Challenges**
  - None available yet!?
  - Efficient Blue LED pumped phosphor not available yet?!
  - Color uniformity with angle!
  - Packaging must be robust to UV exposure.
  - Temperature stability of phosphors. (Great phosphors not available in all colors!)

UV LED pumped RGB Phosphors

UV LED must be >2x Green LED WPE for same lm/W!

- **Downshift in color causes fundamental energy loss.**
- **Scattering in phosphor + absorption in package (inc. phosphor) reduces extraction efficiency! Today's best package efficiency is ~50% for Blue + Yellow phosphor, UV + RGB phosphor likely to be even worse!**



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White Light from LEDs

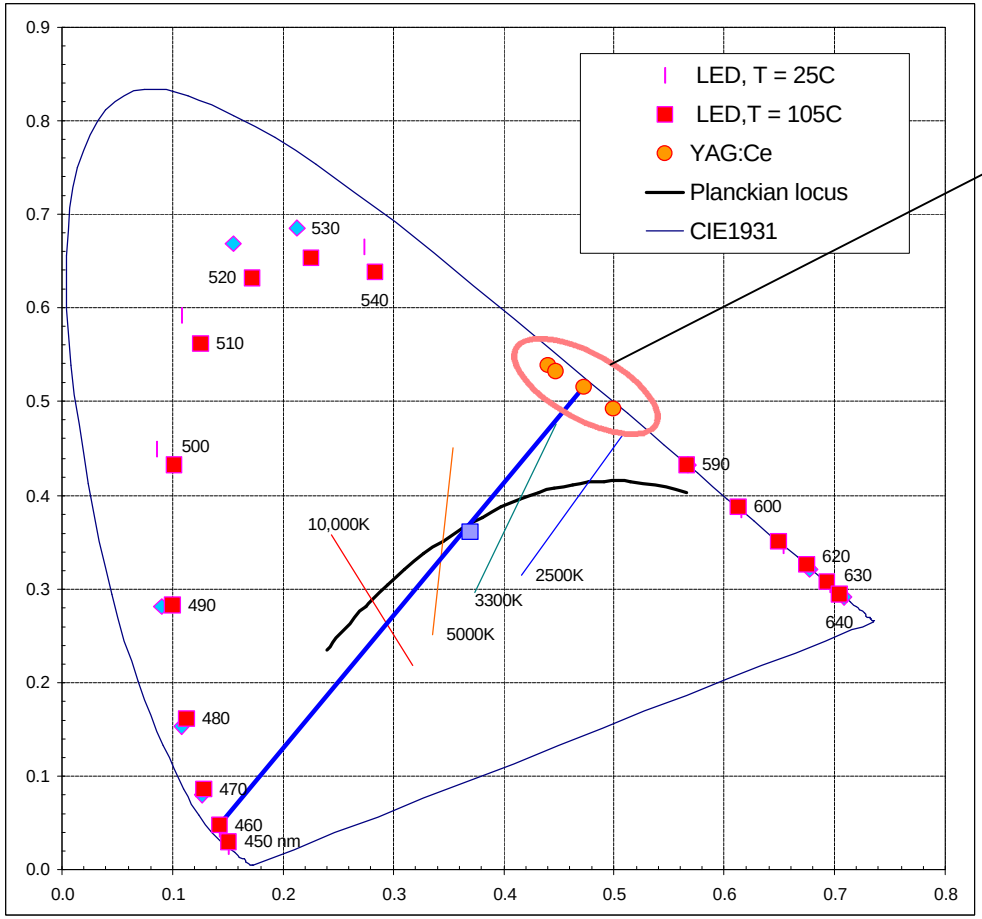
White from Blue LED + Phosphor(s)

- **Advantages:**
  - Simple and single Yellow phosphor versions available today!
  - Decent color rendering (Ra = 75 for Blue LED + Yellow Phosphor)
  - Temperature stability of phosphors. (Can be great!)
- **Disadvantages**
  - Limits on efficiency due to phosphor conversion efficiency, Stokes shift, self absorption,…
  - Better color rendering (i.e. multi phosphor comes at cost of efficiency)
- **Challenges**
  - Temperature stability of phosphors. (Great phosphors not available in all colors)
  - Color uniformity vs. angle
  - Multi phosphor versions to improve color rendering

White from Blue LED + Phosphor(s)

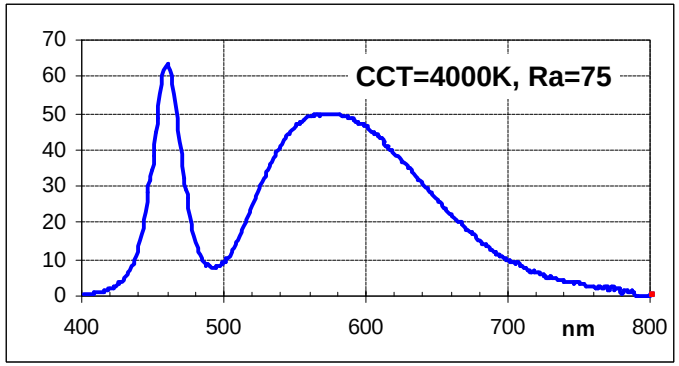
Today, PC LEDs are in the 20-30lm/W range!

- **Todays white LEDs are in the ~20-30lm/W range!**



Ce^{3+} doped garnet family, e.g.$(Y,Gd)_3Al_5O_{12}$

Combined with the same LED, Ce^{3+} phosphors hit the Planckian at different color temperatures:



Ra = 75 is not great (good FL has 83) but it is OK for some applications.

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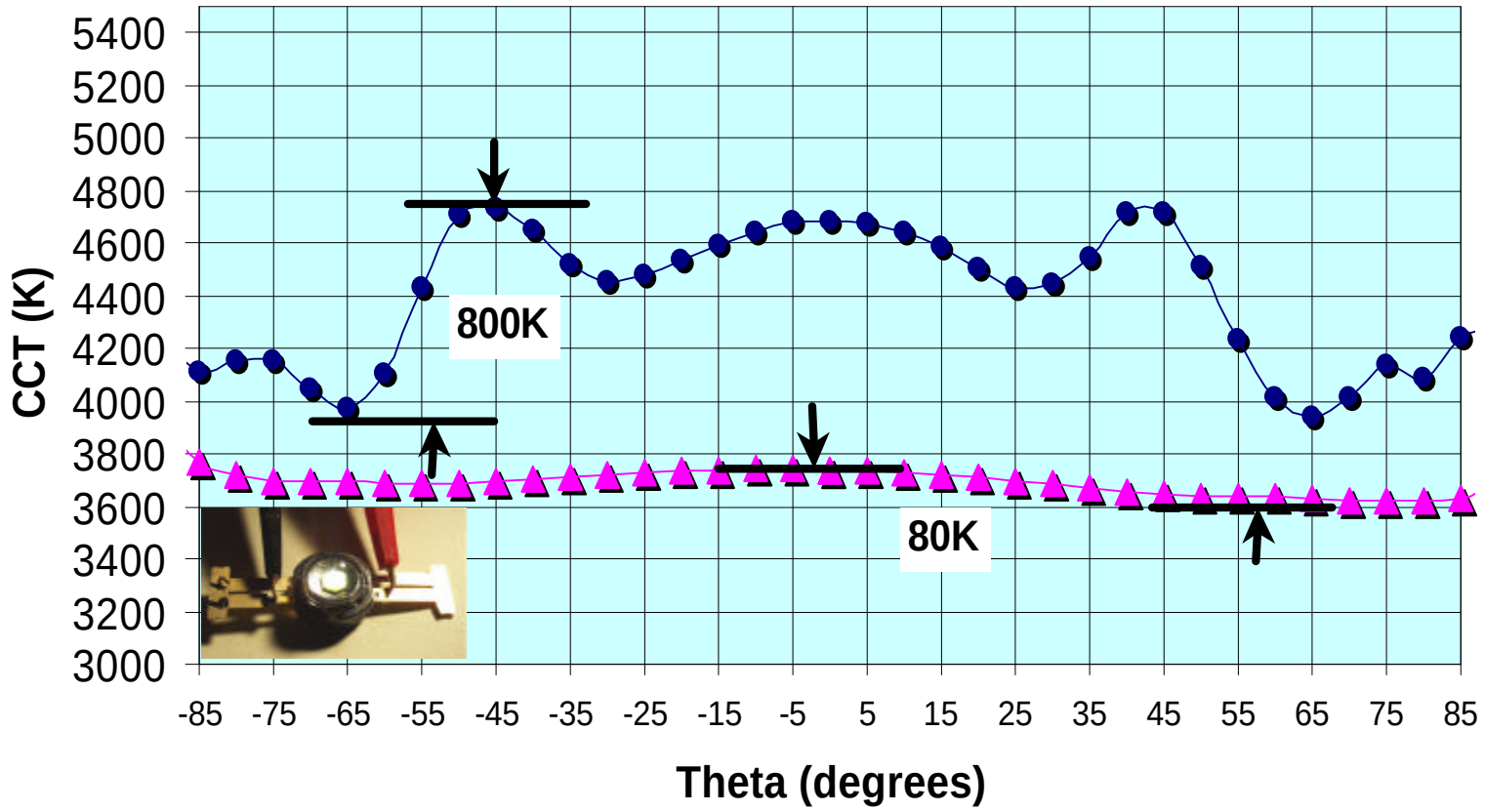
White from Blue LED + Phosphor(s)

Color Uniformity can be good for PC White!

- **CCT uniformity of 50-100K is sufficient for high quality illumination.**



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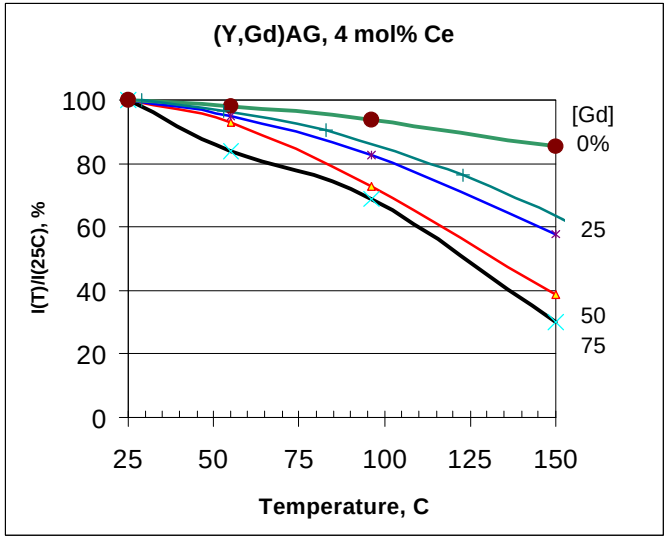
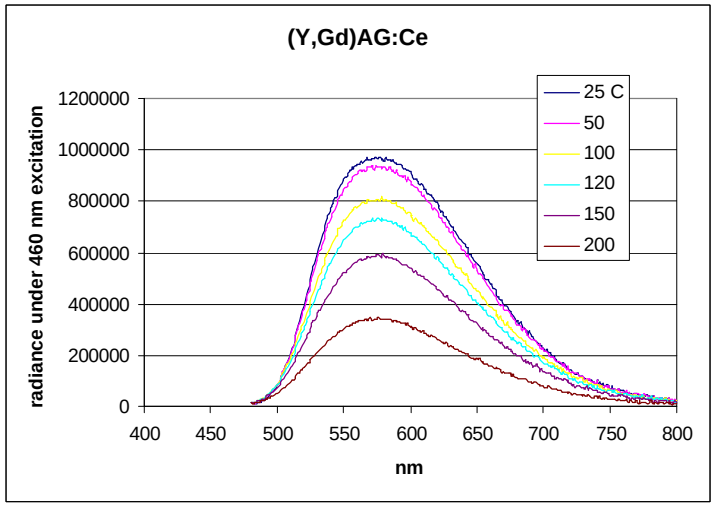
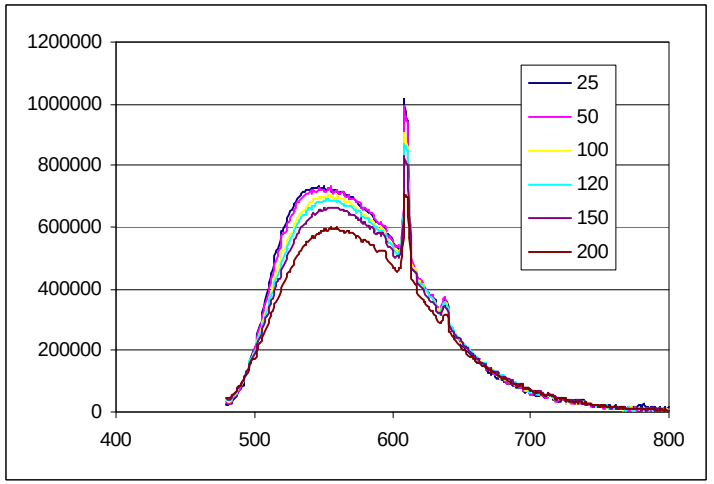
White from Blue LED + Phosphor(s)

Progress on Temperature stability of Phosphors

measured on powders







novel phosphors with improved color specs emerge; in this case using a Ce^{3+} - Pr^{3+} transfer of excitation energy and yielding more temperature stable behavior

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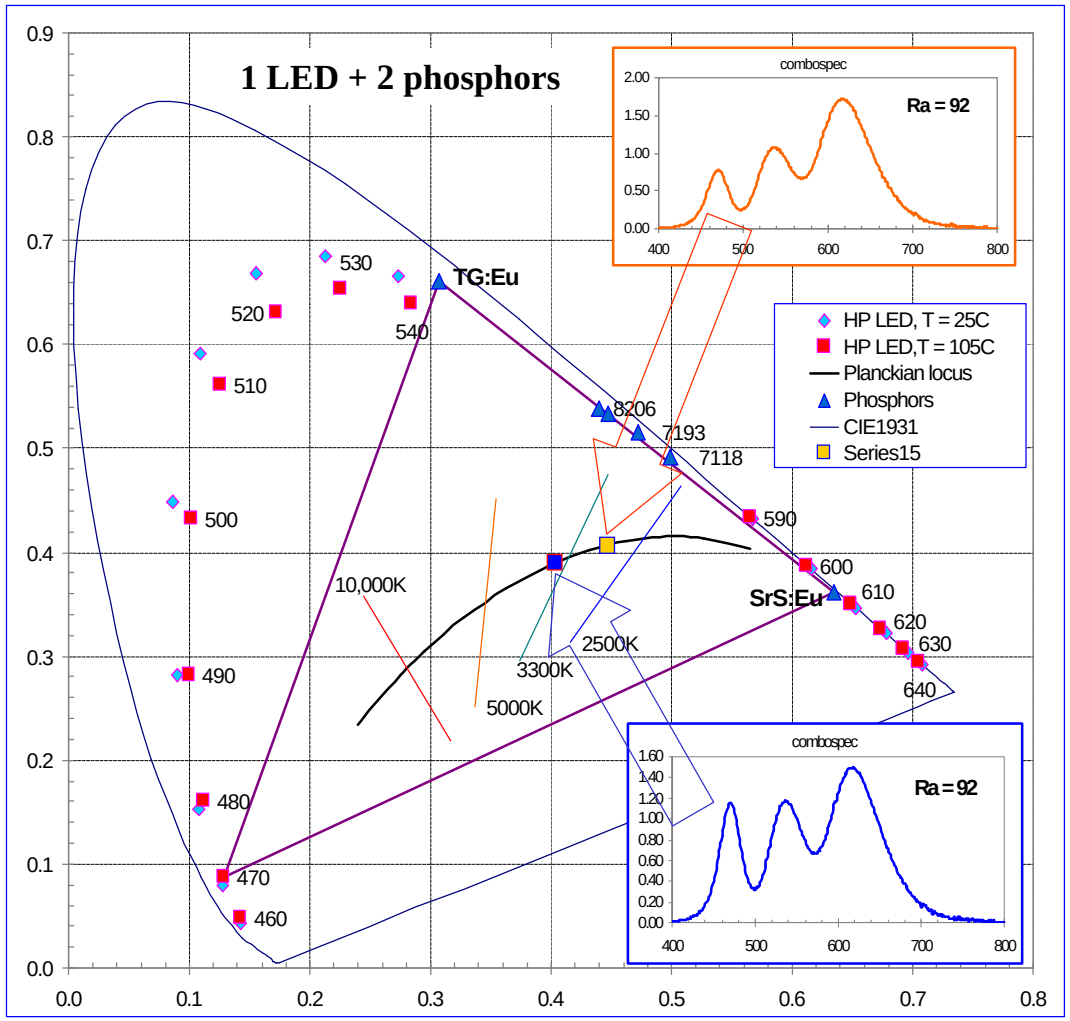
White from Blue LED + Phosphor(s)

The 2-phosphor-converted LED – 2pcLED



Adding green and red to the blue of the LED opens a huge color gamut and allows for *de-luxe* white of any color temperature – our best choice

- **$SrGa_2S_4:Eu^{2+}$ - green**
- **$SrS:Eu^{2+}$ - red**

The dipole-allowed 5d-4f transitions of Ce^{3+} and Eu^{2+} are uniquely suited for color converters:
high absorption, small Stoke's shift

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White Light from LEDs

All three white LED technologies share Three challenges!

1. **Maximize efficiency in lm/W**

90 lm/bulb
6 lm/W
0.005 $/lm

2. **Maximize flux density in lm/package**

3. **And of coarse reduce cost $/lm**

475 lm/bulb
10 lm/W
0.01 $/lm

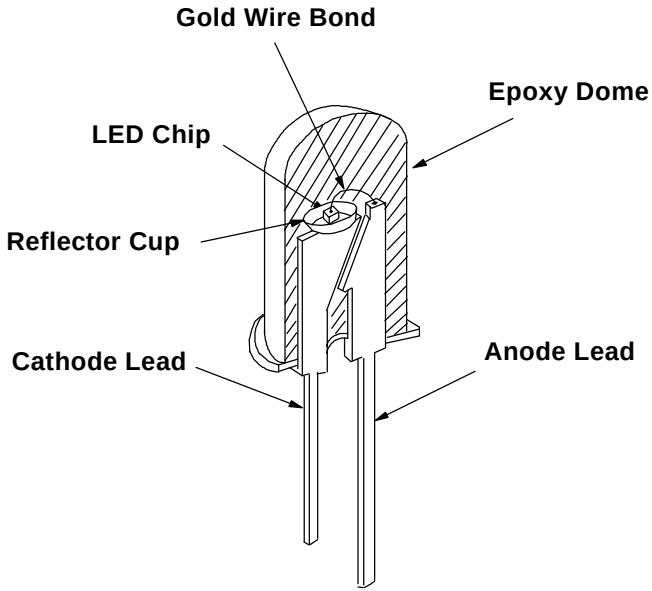
145 lm/bulb
50 lm/W
0.02 $/lm

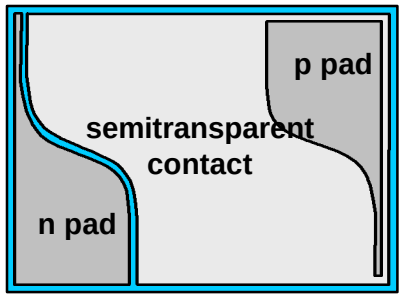
High Power White LEDs

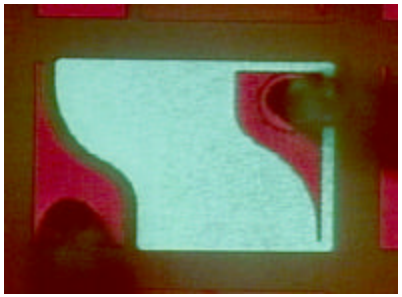
Outline

- **Competition in the market for Illumination, Incandescent & Fluorescent Bulbs.**
- **LED Technology & metrics**
- **Options for making white light from LEDs**
- **Lumileds power white LED performance**
- **Some interesting demos**

High Power White LEDs







Junction area ~ 0.06mm^2

Limitations of conventional 5mm Indicator LED lamps

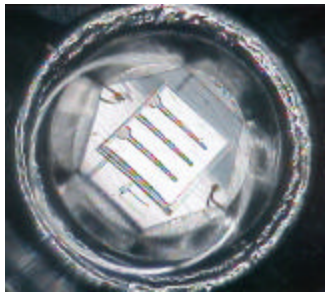
- **Very high thermal resistance, >200°C/W,**
- **Epoxy limited to <<120°C due to thermal yellowing,**
- **Light utilization efficiency is low.**

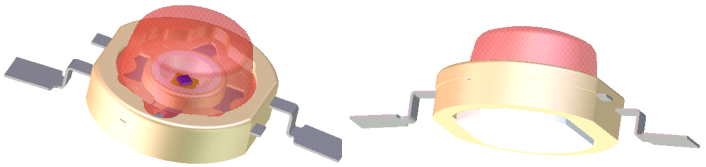
High Power White LEDs

Luxeon™ approach

Die design

- **Large area die for high power capability,**
- **Electrode design for low spreading resistance,**
- **Flip-chip configuration;**
  - high extraction efficiency,
  - low thermal resistance,
  - ability to integrate electronics.





Package design

- **Low thermal resistance package,**
- **Stable, soft gel inner encapsulant,**
- **Controlled radiation pattern and efficient optics.**

System design

- **Low thermal resistance board design,**
- **Efficient secondary optical elements.**

High Power White LEDs

Lumileds Luxeon™ Power LED Efficiency

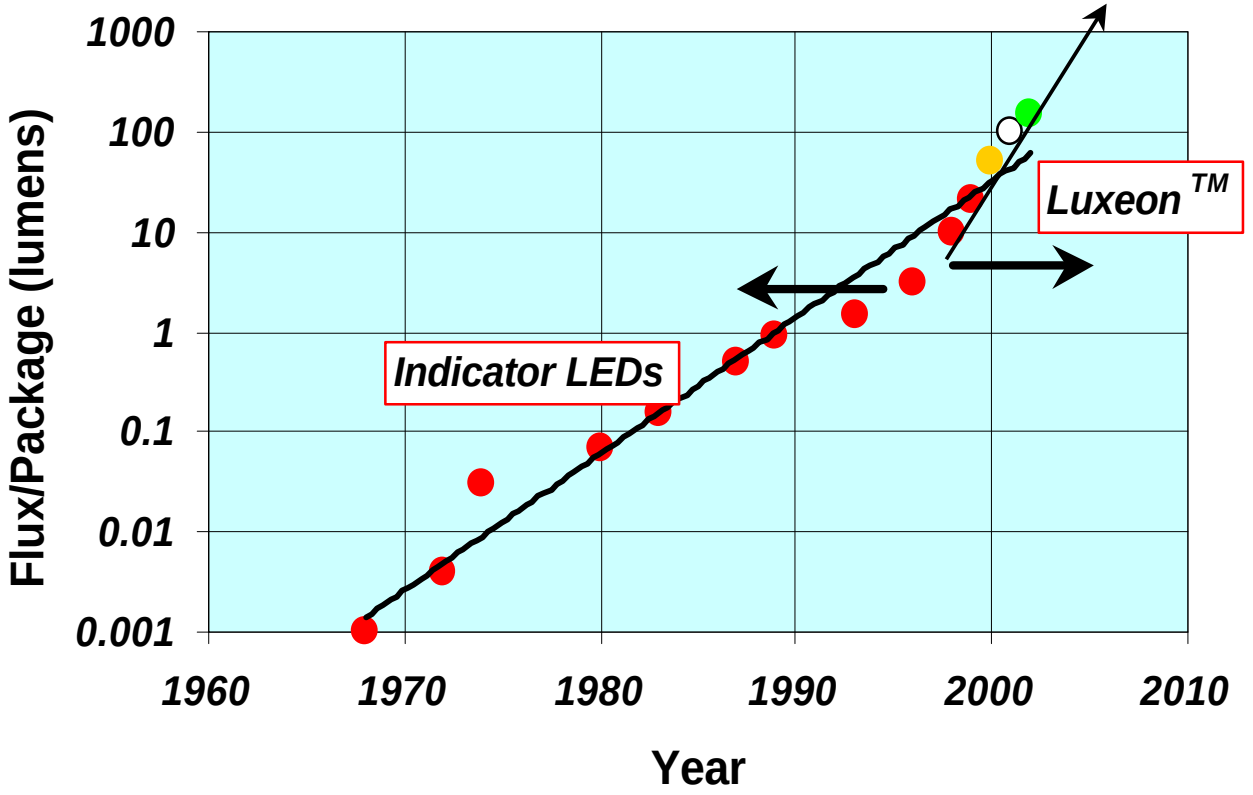
- **Leading the charge into Solid State Illumination**

	Production Typical		*R&D Demonstrations*	
350mA If	**lm/W**	**lm/LED**	***lm/W***	***lm/LED***
Red	44	43	50	50
Red-Orange	55	54	65	65
Amber	36	36	44	44
Green	25	30	50	55
Blue	11	14	15	20
White	18	22	30	36

LED Technology

Haitz's Law for LED Flux

- **LED Flux per package has doubled every 18-24 months for 30+ Years!!**
- **1965 Moore's Law "# of Transistors/chip will double every 18-24 months!"**



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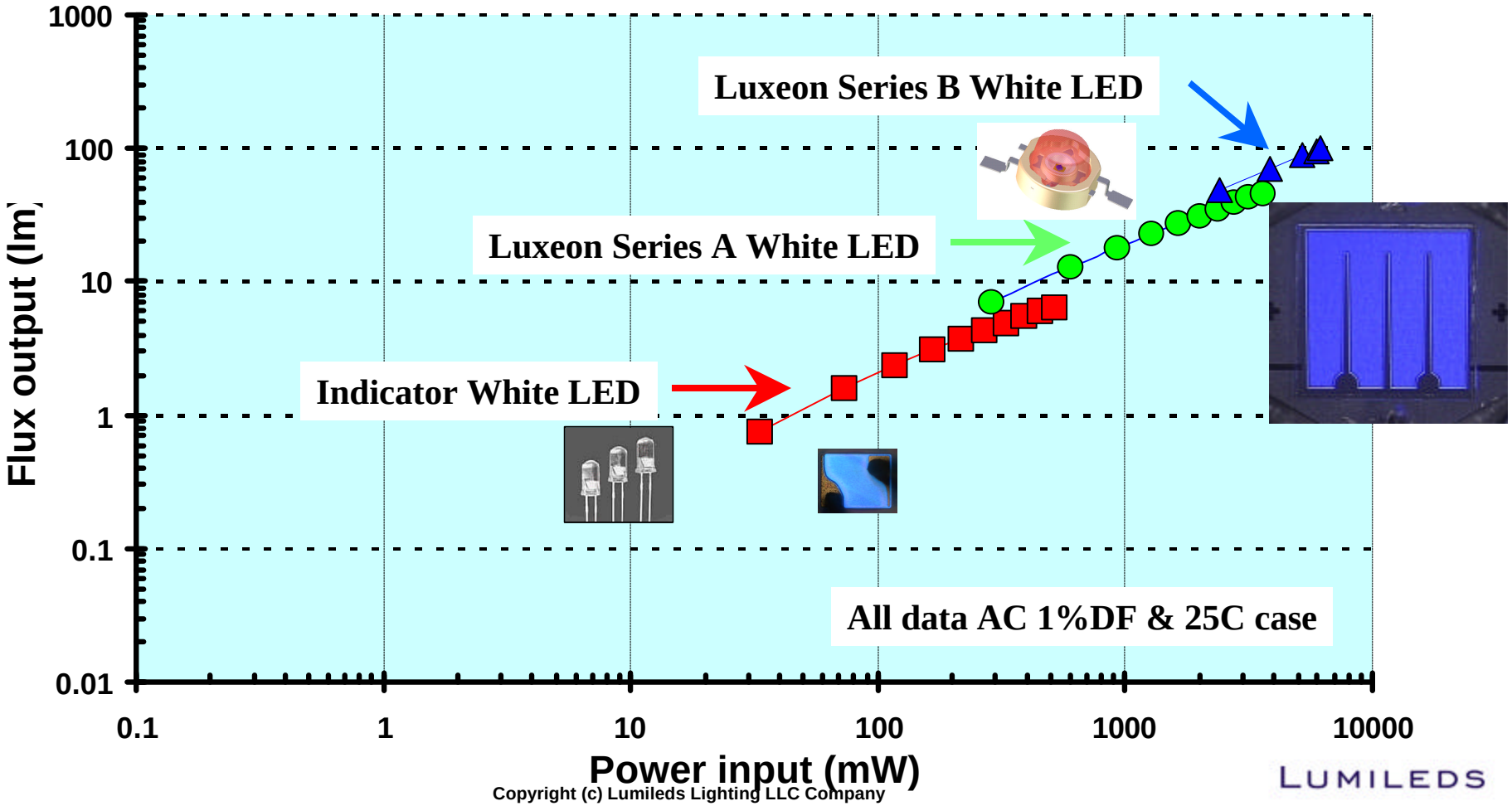
High Power White LEDs

Lumileds Luxeon™ Series A & B LEDs

- **First ever White LED > 100lm!! (100.2lm and 15lm/W to boot!!)**



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High Power White LEDs

Lumileds 100 lumen Club!

- **These are the only LEDs that approach "Illumination" flux!**

Red	1000	105	February-01
Amber	700	110	December-99
Green	700	108	March-01
White	1870	100.2	July-01
White	1400	>110	1-Sep

High Power White LEDs

What about Radiometric Power?!

- **State of the art 400nm indicator LEDs provide 15mW of power.**
- **How much power can a Luxeon part generate? :-)**

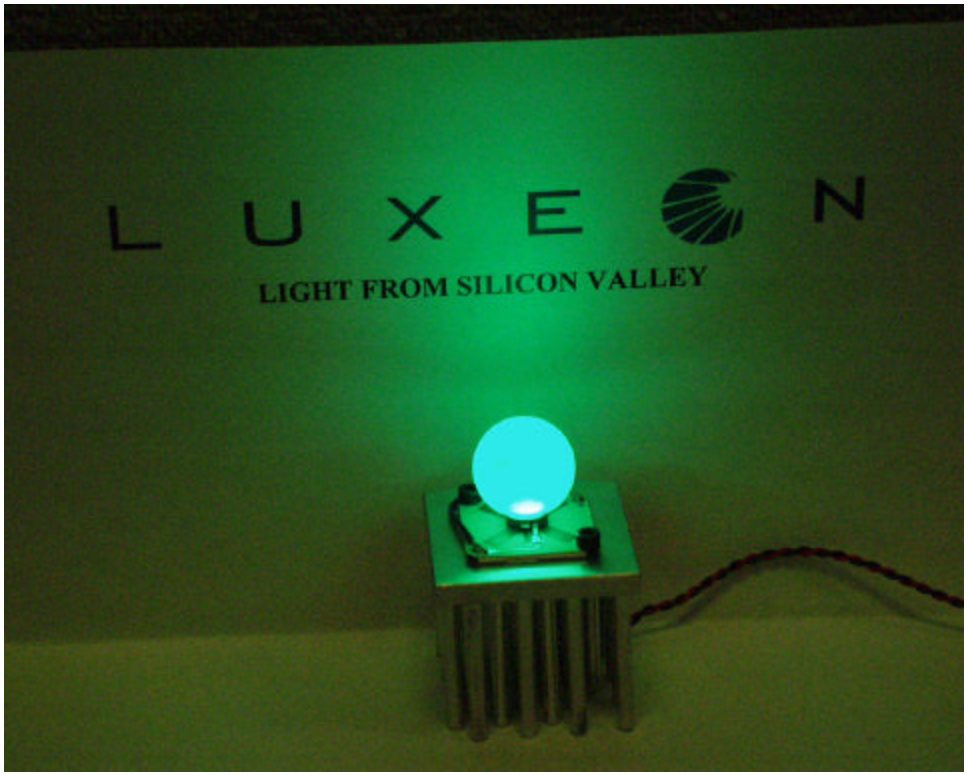
	If (mA)	*W/LED*	*Date*
Deep Blue 430nm	***Dan Steigerwald***		
	Talk 4445-19 08:30 8/1/2001		

High Power White LEDs

Lumileds Luxeon™ Series B Cyan LED

- **Single Series B Cyan LED can replace an 80W bulb in an 8” traffic ball!**

130 lm/bulb
30 lm/W
0.20? $/lm



High Power White LEDs

Lumileds Luxeon™ Ring

- **Fixture design by Philips Lighting and Lumileds.**
- **12 Luxeon's, ~240 lumens. Ring available *Now!***

High Power White LEDs

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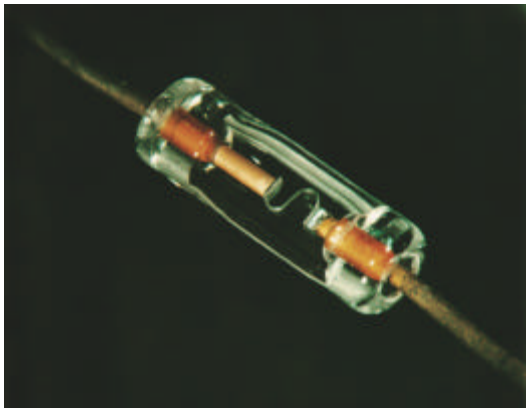
High Power White LEDs

Evolution of LED Package Technology

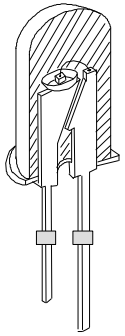
- **Power LEDs can handle ~50x power of an Indicator LED!**



1962

First Packaged LED

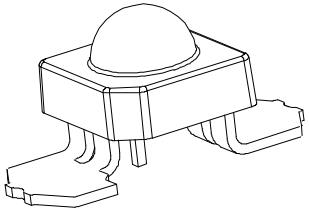
Indicator LED



P_{max}~0.1W
150-200 K/W
1970

Standard 5mm Lamp

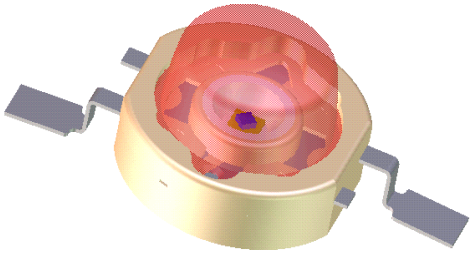
Indicator LED



P_{max}~0.2-0.4W
50 K/W
1994

LumiLeds SnapLED™

First Power LED



P_{max}~0.6-4.0W
9-14 K/W
1998

LumiLeds Luxeon™

Today's Power LED

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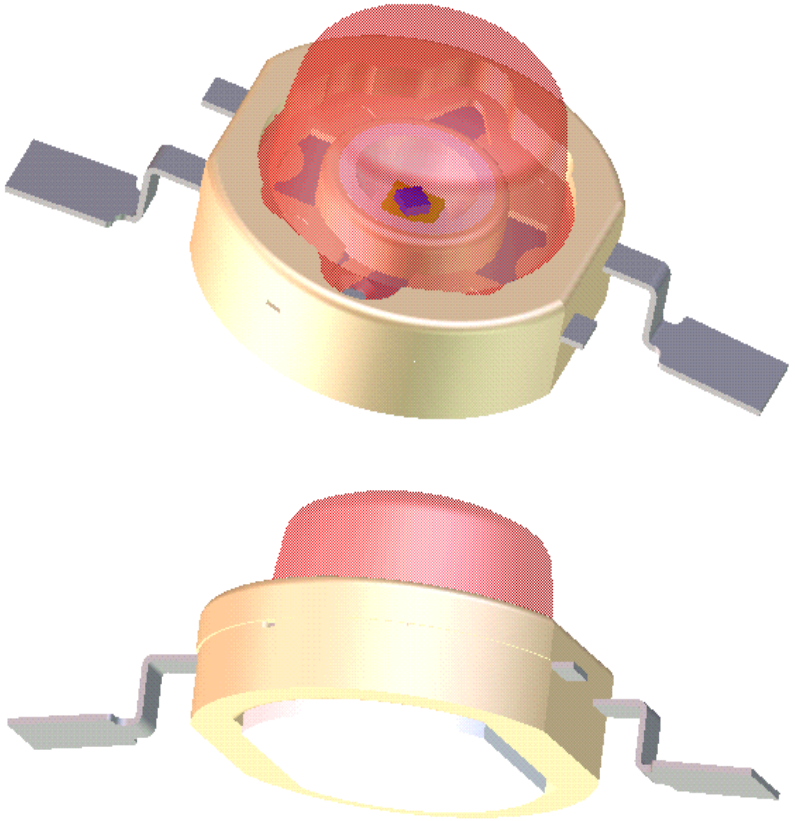
High Power White LEDs

Lumileds Luxeon™ Power LED

- **Packages designed to handle 1-5W!**



High-Power Package:

Improved thermal properties

Heat sink body with good thermal interface

Soft gel inner encapsulant

Including power AlInGaN or AlInGaP or Phosphor Converted AlInGaN Chip:

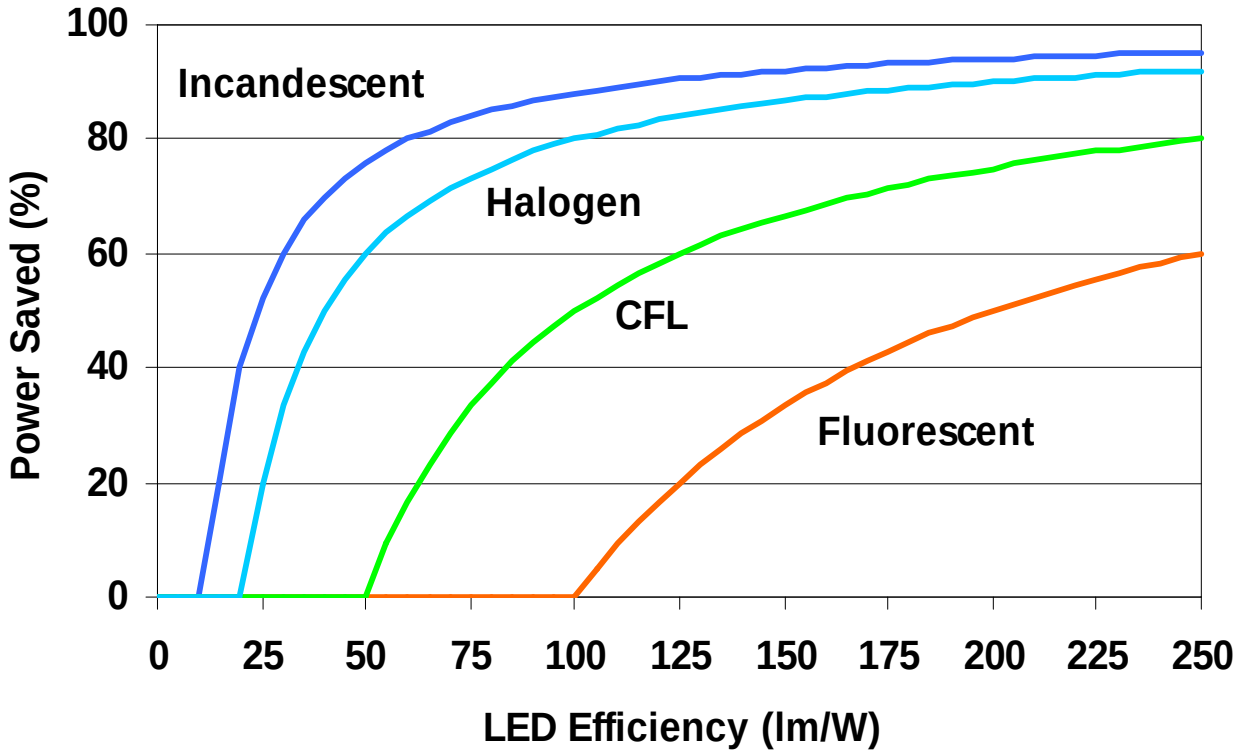
θ_{jc} *~ 12°C/W*

High optical efficiency > 95%

High Power White LEDs

Potential Power Savings vs. Traditional Lighting

- **Todays white LEDs are in the ~20-30lm/W range, but still low flux!**



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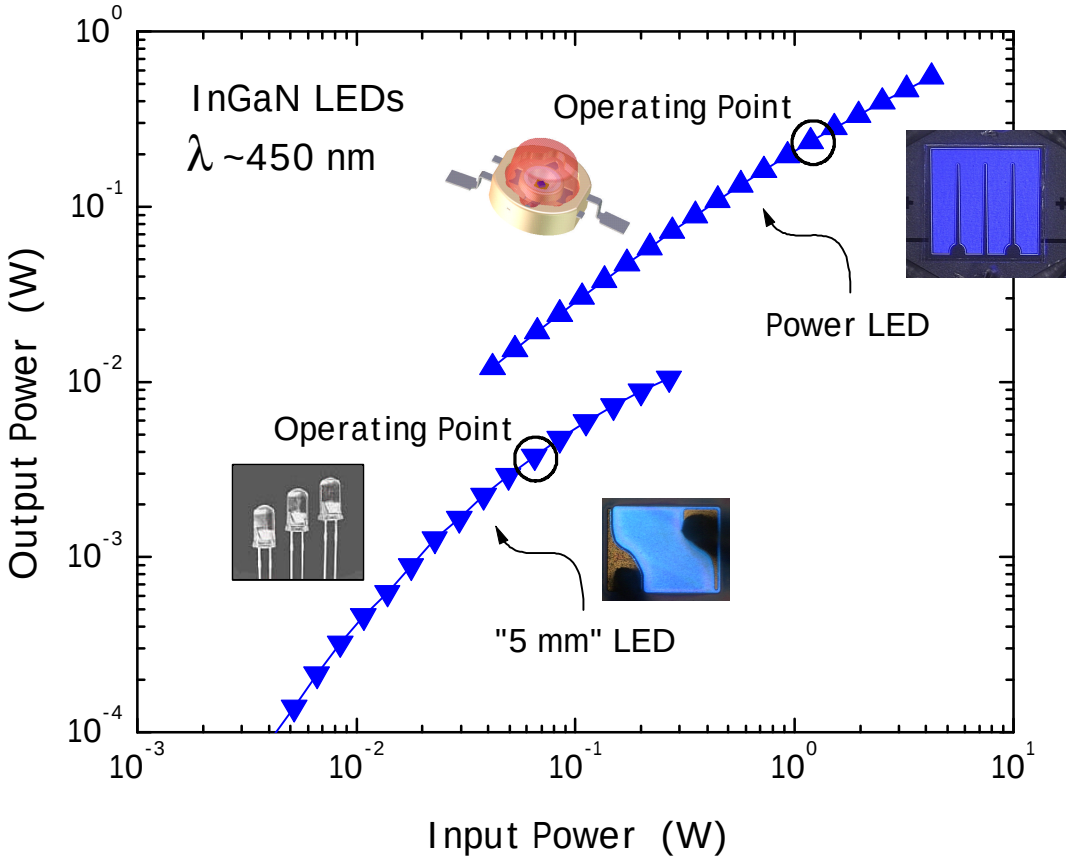
LED Technology

Indicator LEDs vs. Power LEDs

- **Indicator LEDs have output powers < ~50mW and Thermal resistances > 50K/W**



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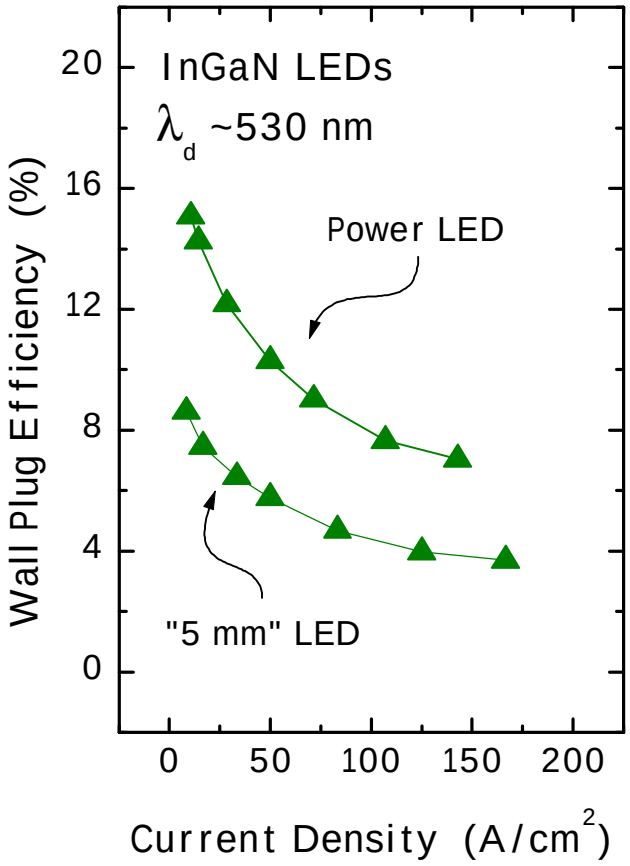
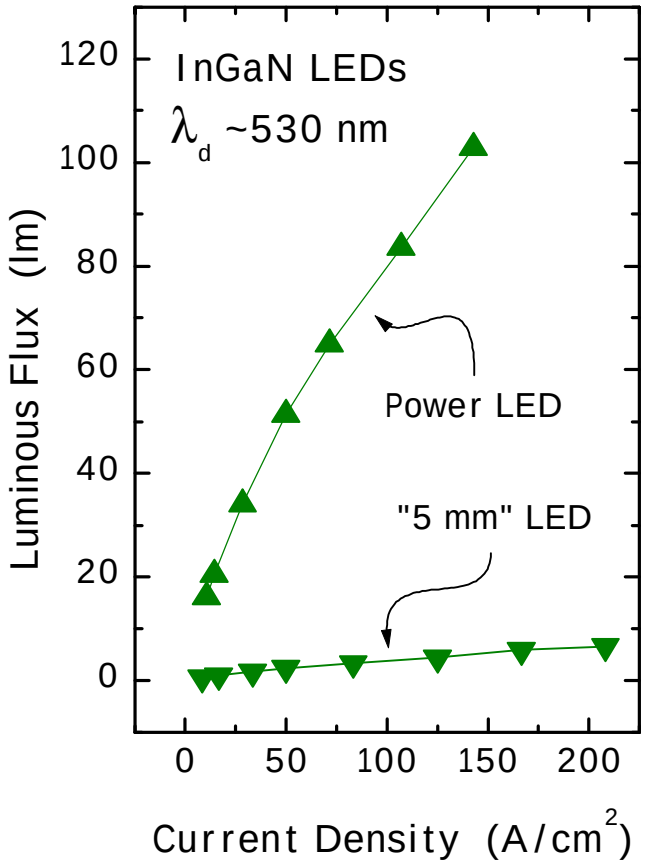
High Power White LEDs

Indicator LEDs vs. Power Luxeon™ LEDs!

- **Luxeon's are designed for low thermal resistance & high current density!**





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