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Materials and Nano Optics for Solid State Lighting

Helmut Bechtel, Philips Research Aachen

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Outline

- Status and promise of solid state lighting
- Luminous efficiency and color
- LED and OLED technology
- Light extraction and nano optics
- Phosphor conversion

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Market themes in Lighting

End user / Market Awareness

Health

Ambiance Lifestyle

Environmentally friendly

Total cost of ownership

See & be seen

latent awareness | emerging awareness | increasing awareness | high awareness | decreasing interest

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Retail: Examples of ambiance creation. Staging and sharing the shopping experience

The shop as a staged experience

Lighting to create a sense of experience that goes beyond shopping

The shop as a lighthouse in a sea of choices

Lighting that subtly directs the shopper while giving them the freedom to experience and choose

The shop as a centre of social activity

Lighting that focuses on different groups of people and their activities

Shops as interest zones

Customized to address different Communities

Experience Care Collective Empowerment

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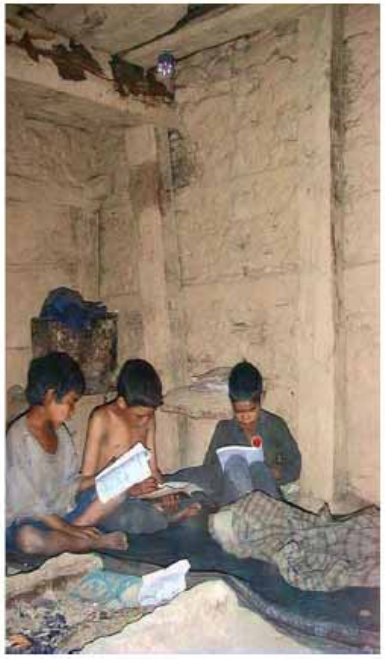
LED General Illumination for Off Grid Homes



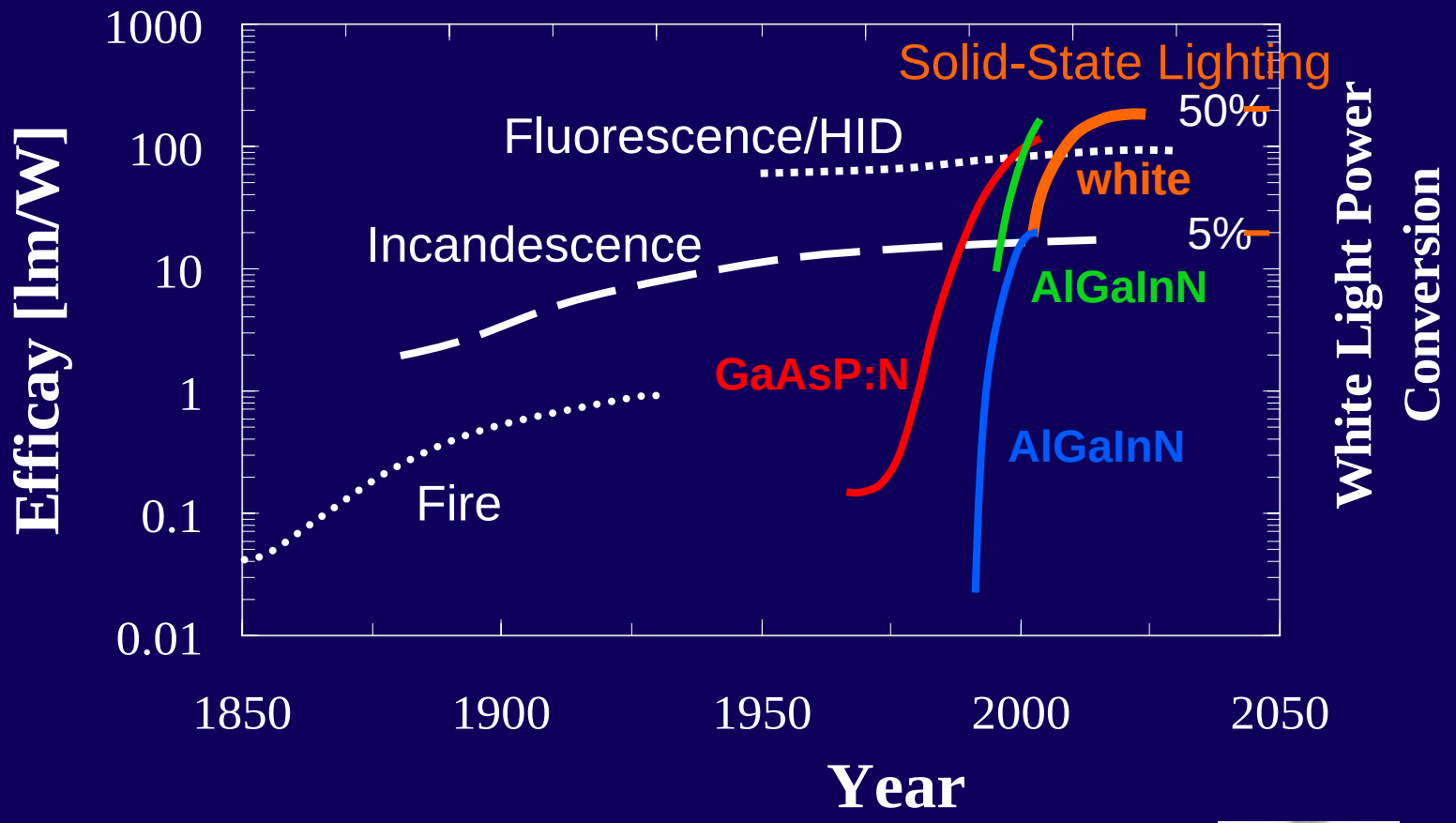
Nepal 2000*

India 2001*

Sri Lanka 2003*

* Photos Courtesy of Light Up the World and PICO Power

Efficacy of Light Sources



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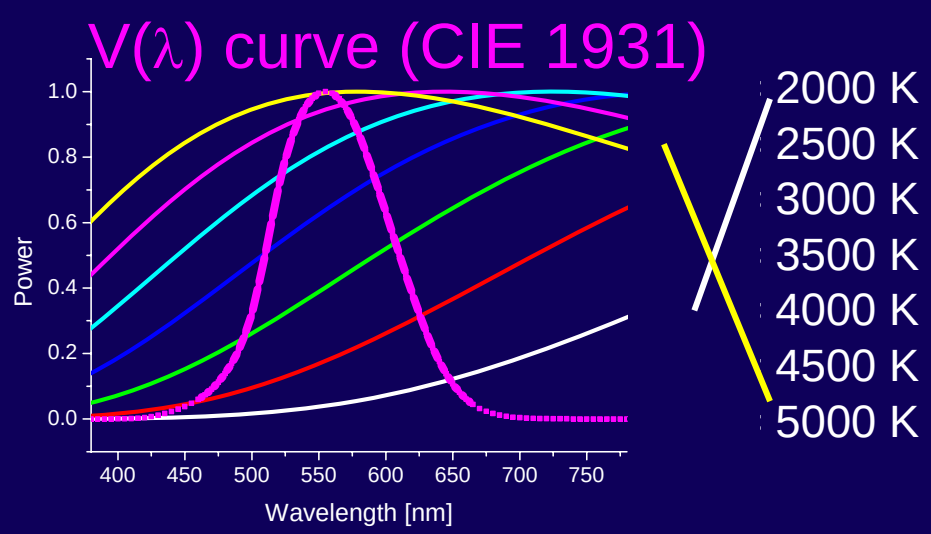
News from ***SolidStateLighting.net:***
June 15, 2006... Helsinki, Finland–

- **Shuji Nakamura winner of the 2006 Millennium Technology Prize**
  - Development of new, revolutionary source of light - bright-blue, green and white LEDs and a blue laser.
  - improvement of the quality of human life.
  - opportunities for significant energy-saving LED light.

Luminous Efficacy of Lightsources [lm/W]

$$\frac{\text{Luminous flux [lm]}}{\text{Power input [W]}} = \underbrace{\frac{\text{Optical Power [W]}}{\text{Power input [W]}}}_{\textbf{Radiant Efficiency}} \times \underbrace{\frac{\text{Luminous flux [lm]}}{\text{Radiant flux [W]}}}_{\textbf{Lumen Equivalent}}$$



$$LE = \frac{683 \int_{380}^{780} S(\lambda)V(\lambda)d\lambda}{\int S(\lambda)d\lambda} [lm/W]$$

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Color Rendering Index (CIE Pub 13.3)

Ra = 90

Ra = 70

Ra = 50

Reference colors to be compared to Planckian (<5000K) or Standard Daylight (>5000K)

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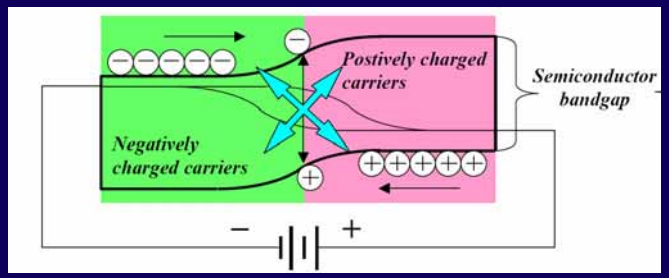
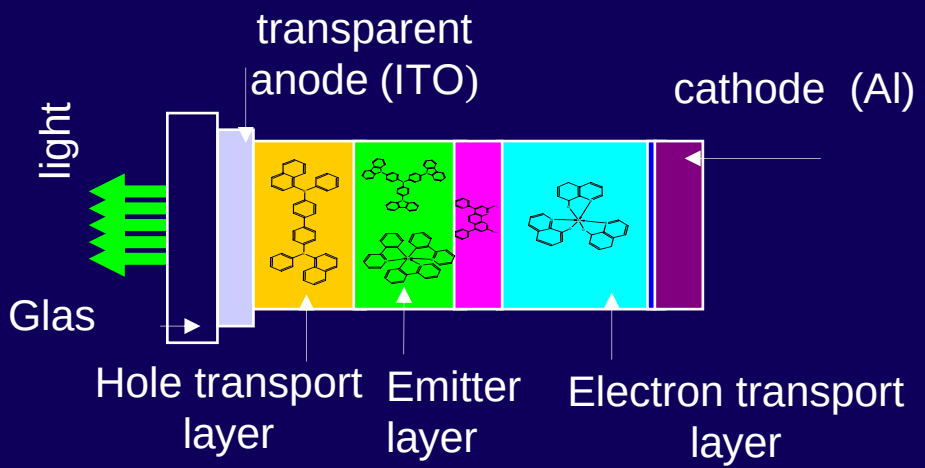
Solid State Lighting Technology

LEDs



OLEDs



Positive and negative charge carriers recombine to release energy as light or heat – fundamentally non destructive

Light generation process unlimited in efficiency and life

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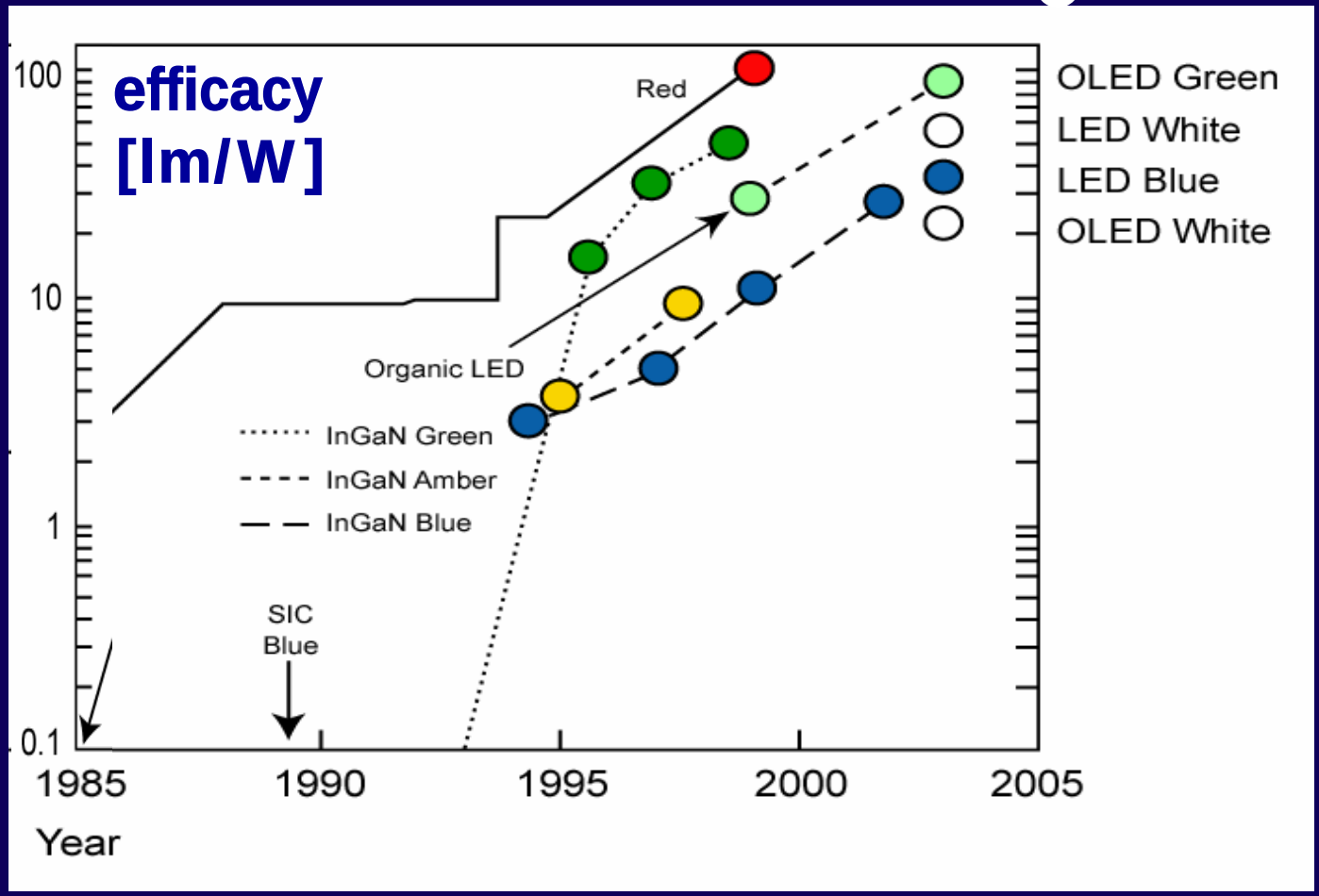
OLED and LED efficiency

CREE, June 20
131 lm/W



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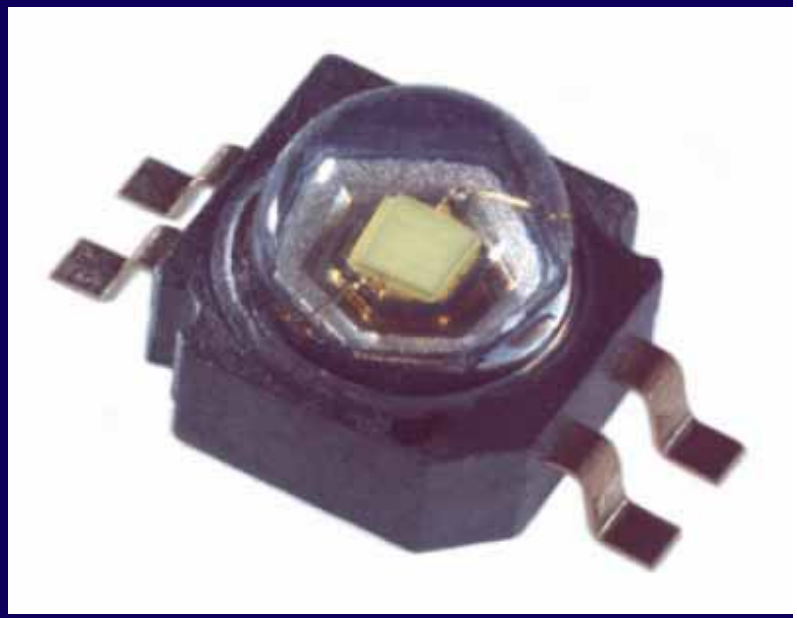
LUXEON® K2 LEDs from Philips Lumileds Win New Product Showcase Award, June 6, 2006

at Lightfair International in Las Vegas

- Honored by lighting professionals for a series of technology breakthroughs
- 140 lm output (1mm^2)
- 185°C maximum junction temperature
- a maximum 1500mA drive current,



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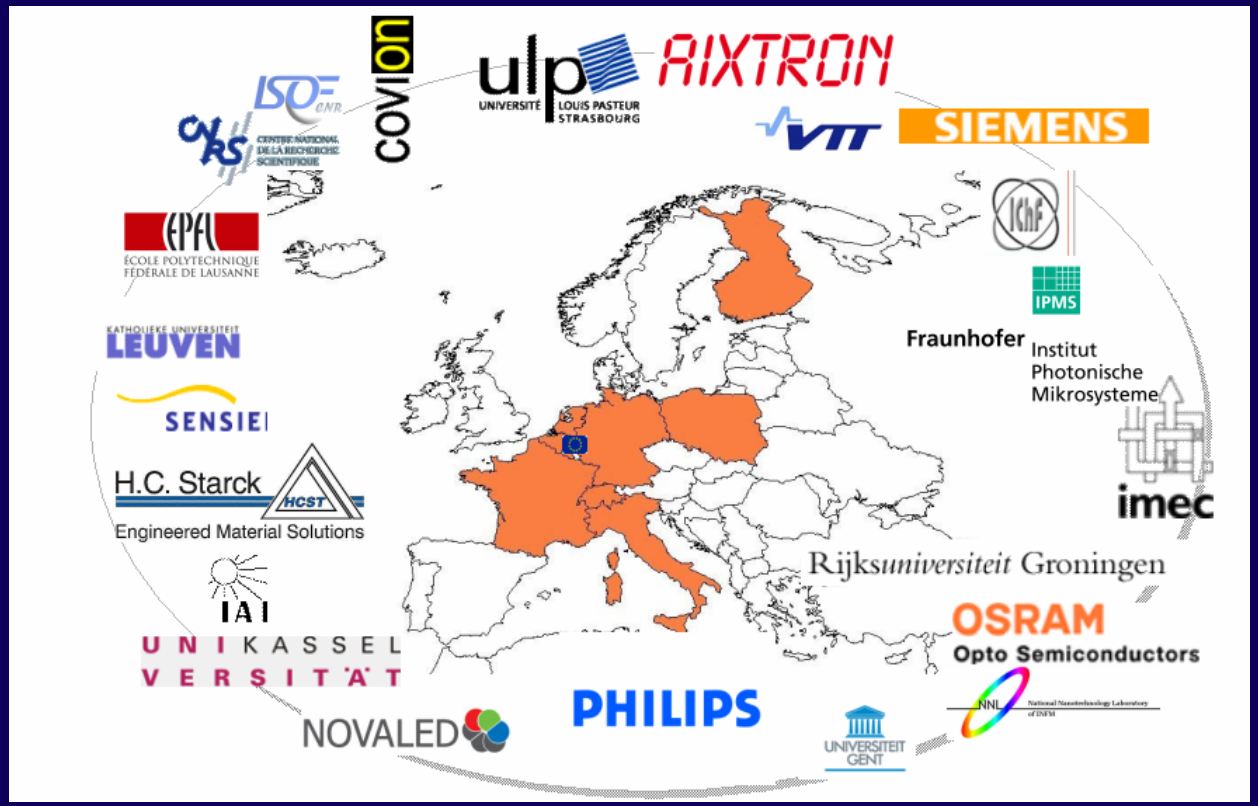
LED Technology: Philips Lumileds

- Leader in high power LEDs
  - Luxeon® - based light sources
  - Reference designs and IP (optical, mechanical, thermal and drivers) Phosphors (for white LEDs)

OLED Technology Development



24 partners from 8 European countries

European project OLLA (Organic LEDs for LightingApplications)
(see also: www.olla-project.org)

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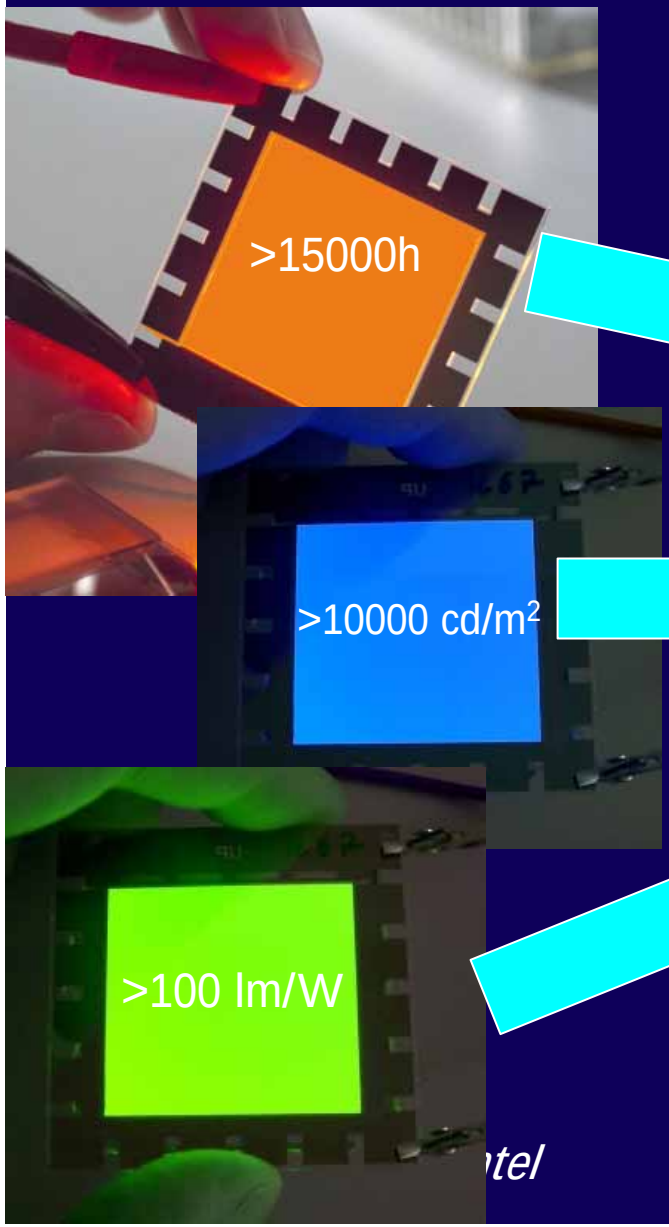
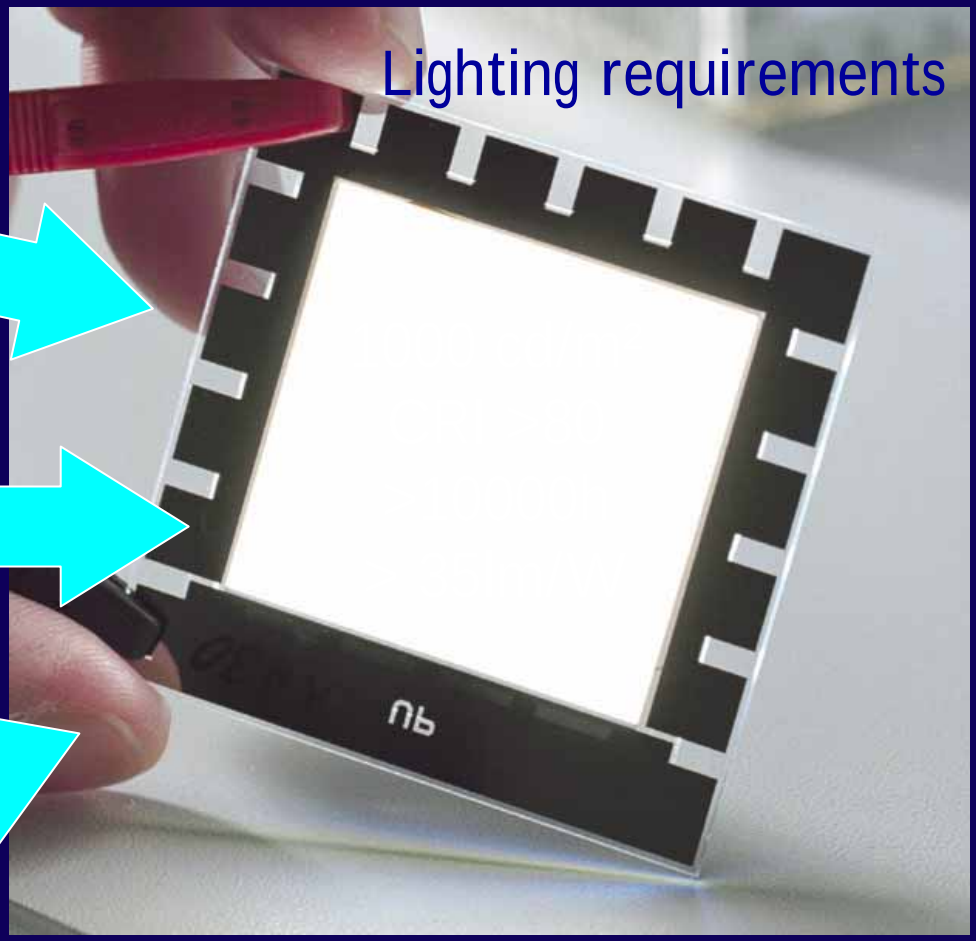
Already achieved



The lighting challenge



ntel

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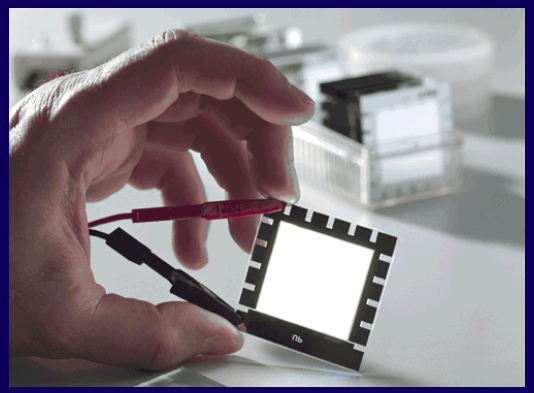
Philips and Novaled announced new records for lifetime and efficiency of high-brightness white OLEDs

06/07/2006

Combination for efficiency and lifetime of high-brightness white OLEDs has been established.

- Brightness: 1000 cd/m^2
- Efficiency: 32 lm/W
- CRI of 88.
- Lifetime 20000 hours



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OLED Lighting outside Europe

Japan

JUNJI **KIDO**

USA, GE

Anil Duggal 2 ft x 2 ft (60cm)

15 lm/W, 1200 lumens

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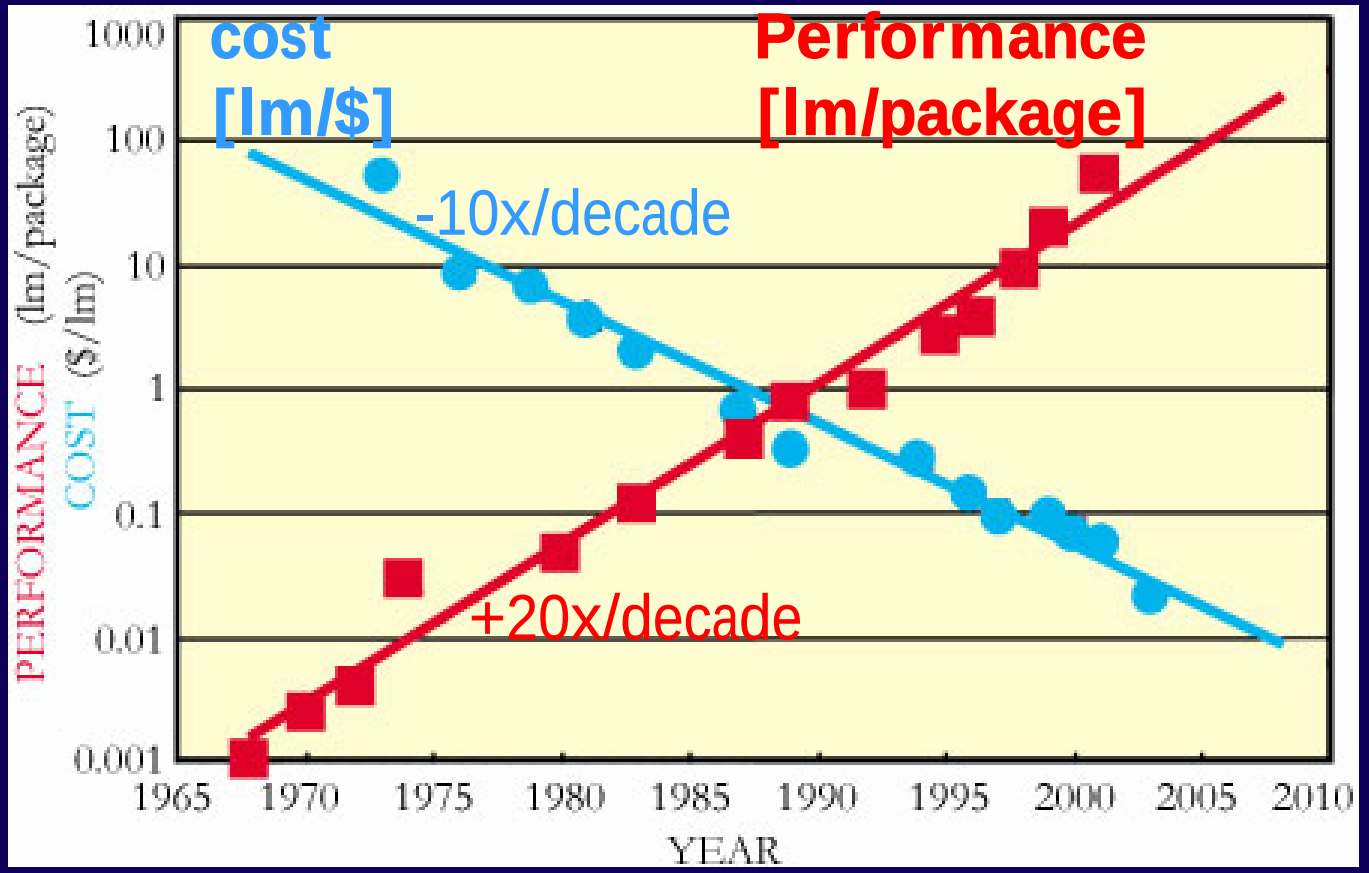
Challenges

- Cost down – lumen per $ up:
  - LEDs: 250 – 1000 lumen from 1 mm^2 chip for 2$
    M. G. Craford, December 13, 2005
- Improve light extraction and surface brightness
  - Application of photonic crystals
- White light generation
  - Phosphors for blue LEDs

Cost – Performance Development



Arpad Bergh, George Craford, Anil Duggal, and Roland Haitz
Physics Today Dec2001

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A challenge for SSL: Light Extraction

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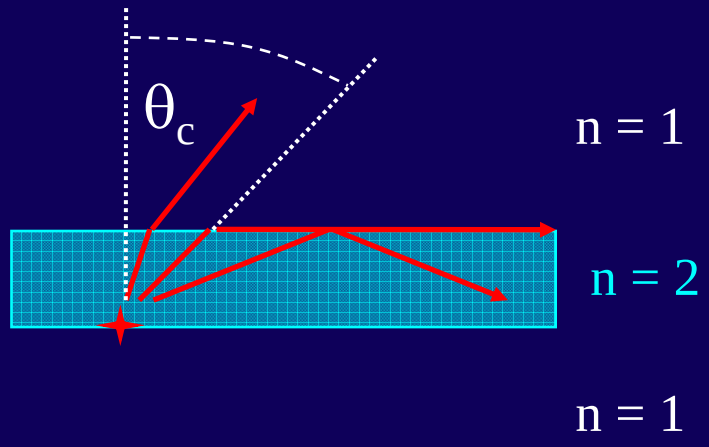
Total internal reflection



The fraction of emitted light from a luminescent film is:

(classical ray optics)

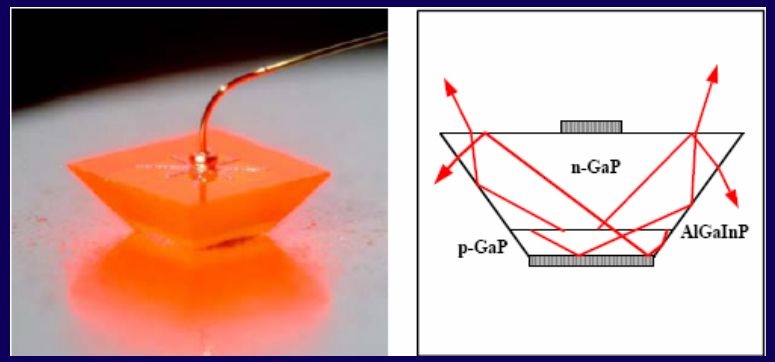
$$\eta = 1 - \sqrt{(1-(1/n^2))}$$

$$\eta = \frac{1}{2n^2} \text{ (for n} > 1.5)$$

η = 19 % for n = 1.7

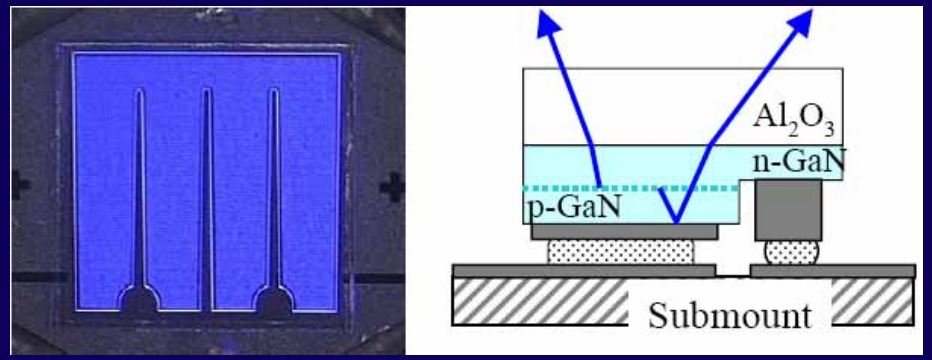
Light extraction from LEDs

Truncated-Inverted-Pyramid LED

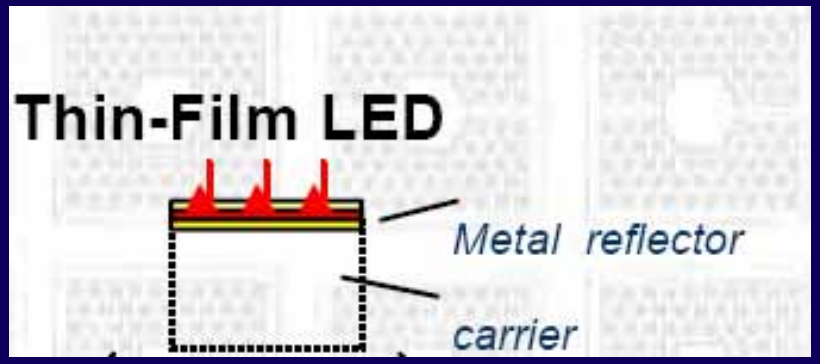


Osram Micro-mirror LED

AlInGaN Flip-Chip LED



Osram Thin-Film LED



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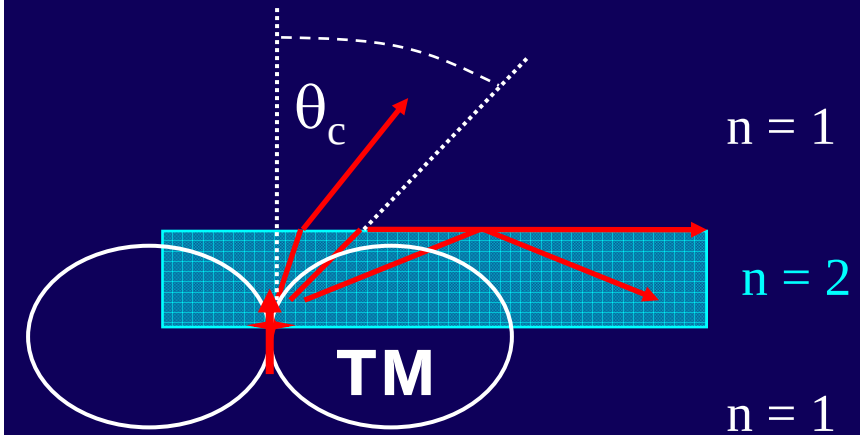
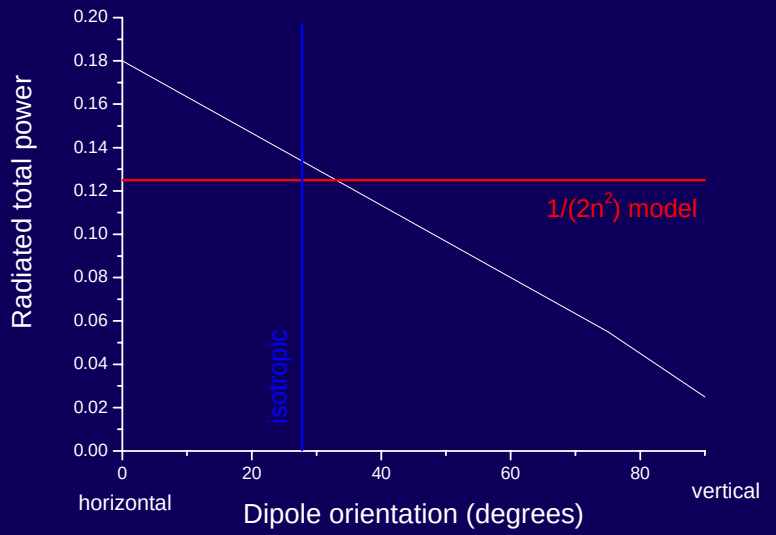
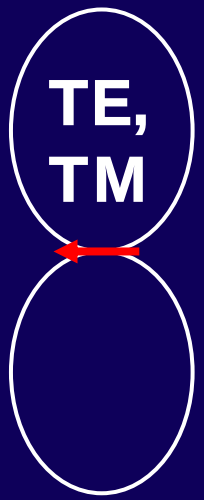
Light Extraction for radiating dipole





Electric dipole in front of a mirror

+ interference



J.A.E. Wasey and W.L. Barnes, Journal of modern optics, 2000, 47, 4, 725

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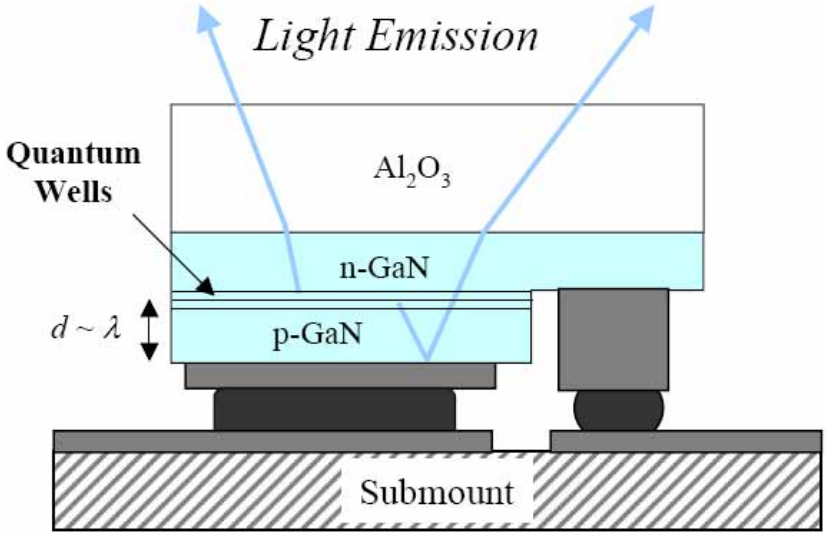
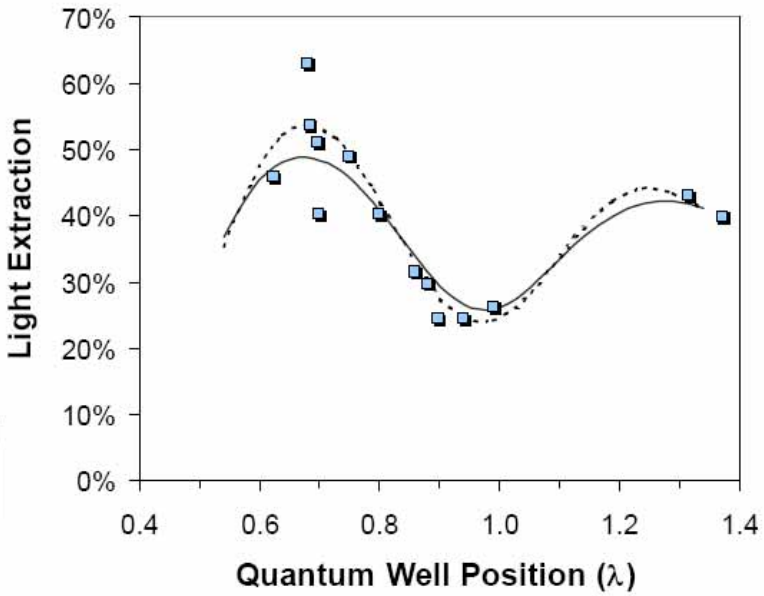
Flip-chip micro-cavity LED

Extraction efficiency > 50%

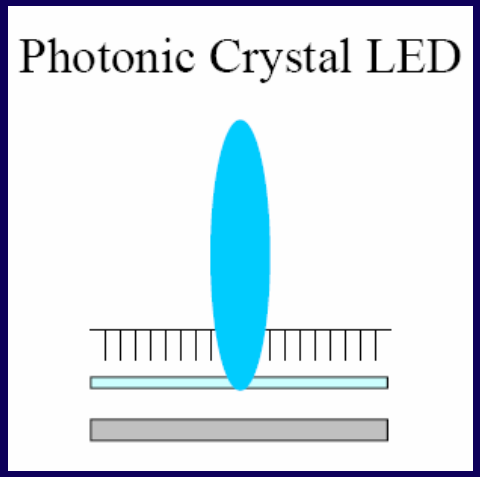
p-layer thickness control required

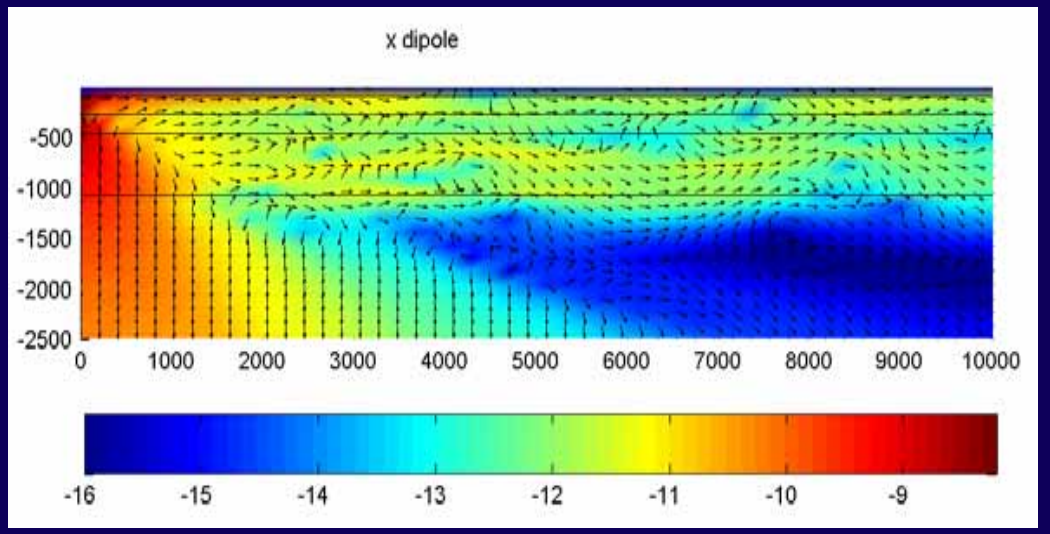




Shen et. al., *Appl. Phys. Lett.* **82**, 2221 (2003).

Application of (2D) photonic crystal structures

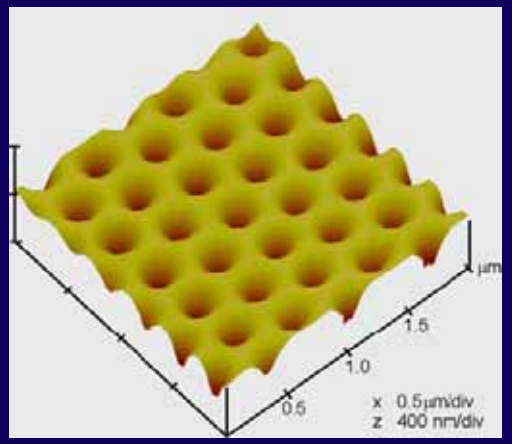


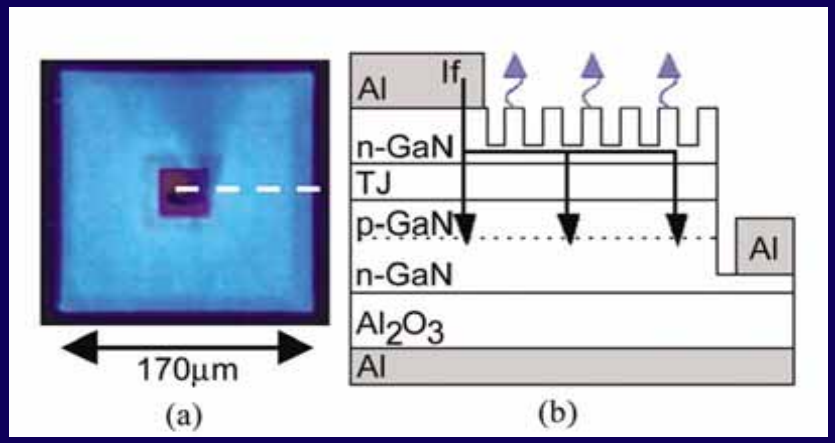


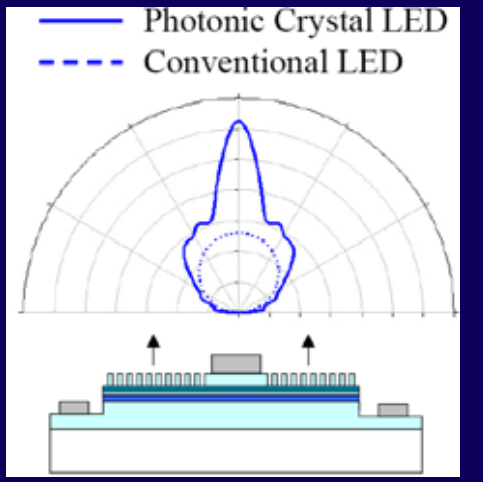
Log magnitude Poynting vector

Design with Finite Difference Time Domain software (FDTD solutions from Lumerical Inc. www.lumerical.com) which runs on a distributed cluster of 16 workstations

Improving efficacy and surface brightness







250 nm diameter holes in GaN.

Patterning by e-beam lithography

(Sandia National Laboratories)

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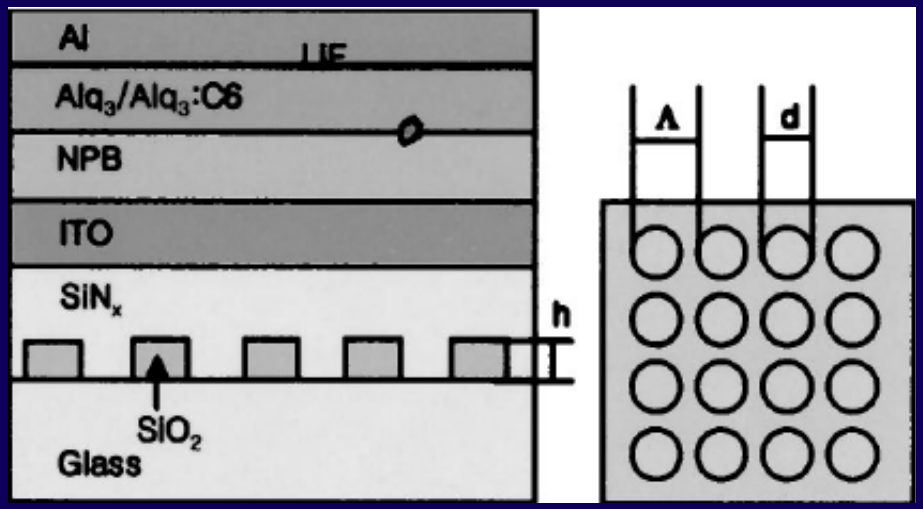
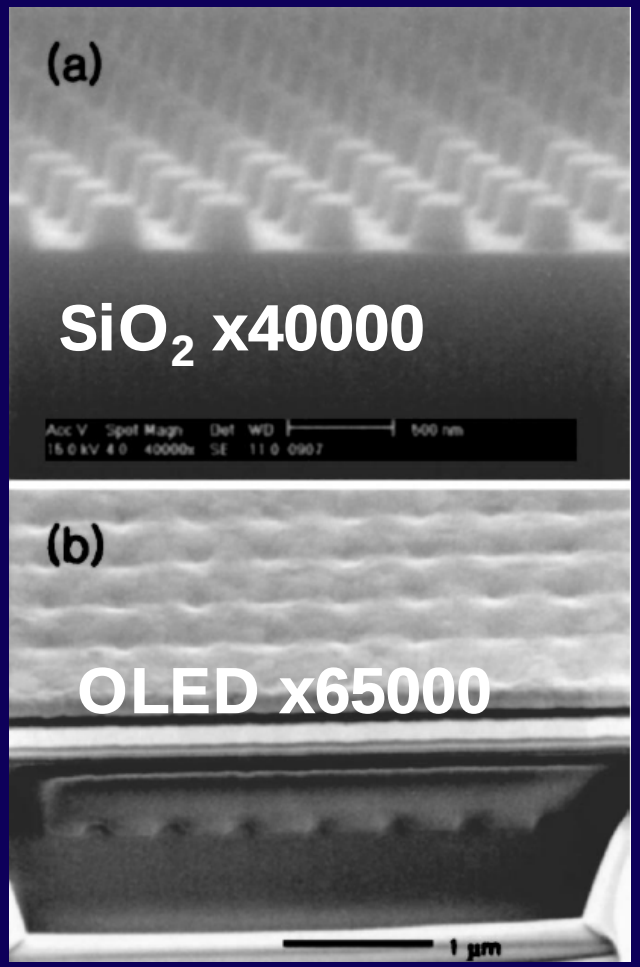
Wierer et. Al., Appl. Phys. Lett., Vol. 84 (19), 3885 (2004)

OLEDs with photonic crystal substrate

Young Rag Do et al., J. Appl. Phys 96 (2004) 7629





Issues:

Egalization of structure before OLED deposition

Costs on large substrates

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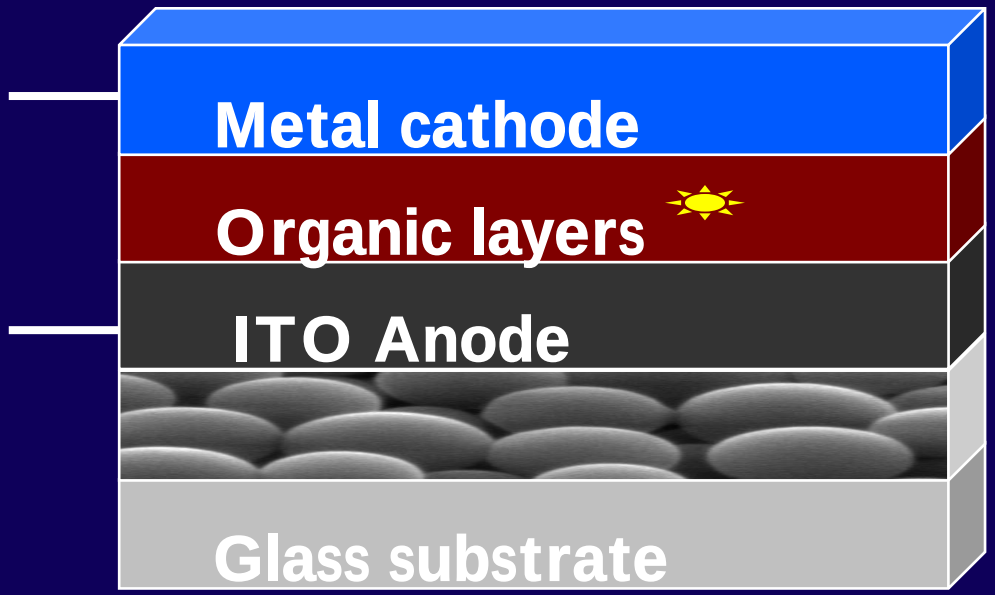
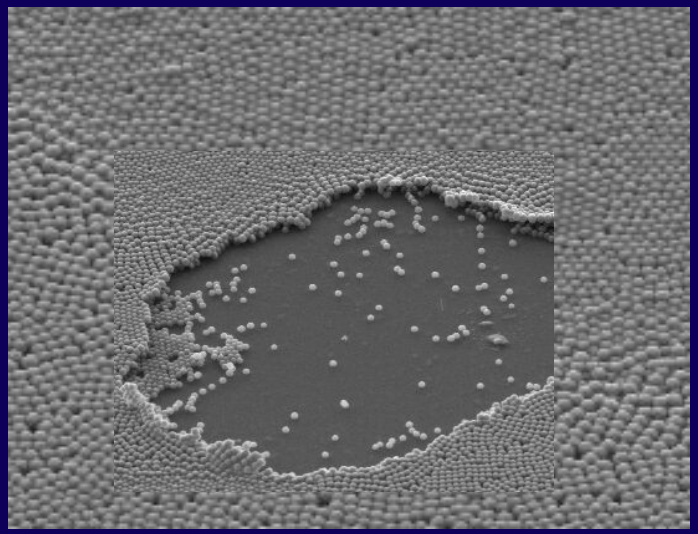
Monospher Particle layer between ITO and Glass



Monospher® (Merck) M100, M150 and M200 silica particles

Coating of 6" substrates realized



Particle distribution essential

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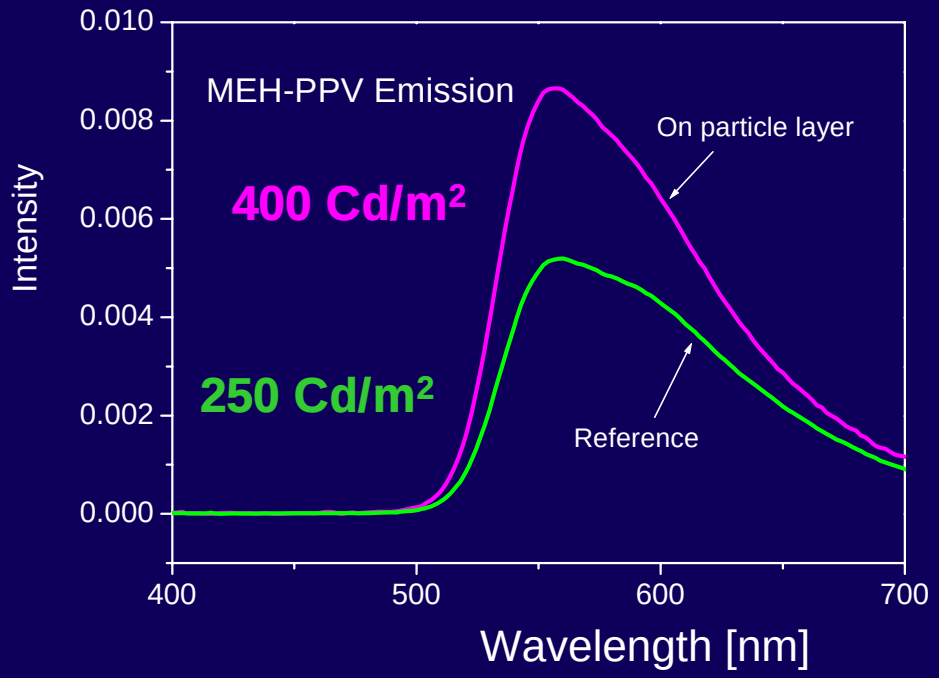
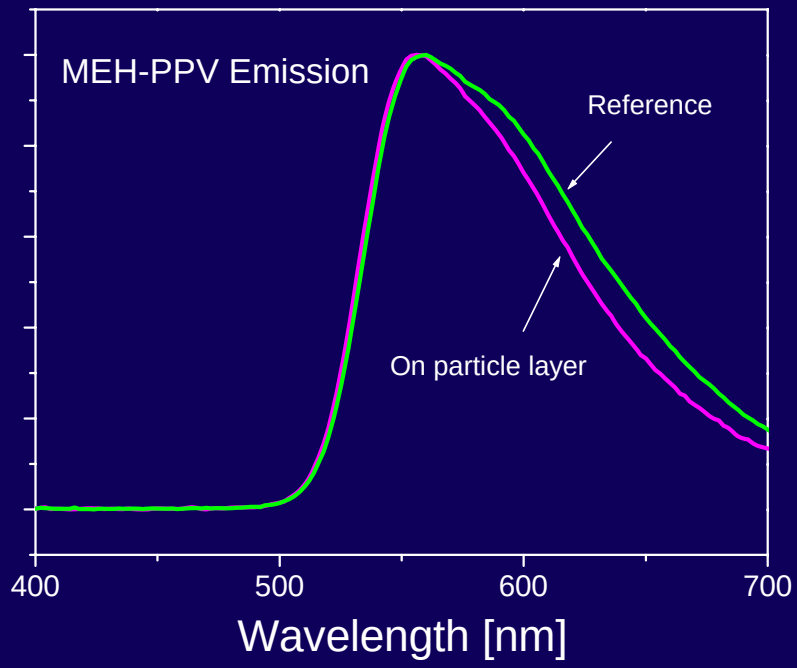
DC EL: 6V, same current





Gain: 60 percent

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Phosphor Conversion for White Light Generation

Blue polymer emitting polymer OLED with yellow phosphor

- Phosphor layer enhances light extraction
- Perfect color mixing
- But: What is the lifetime of the blue emitter?

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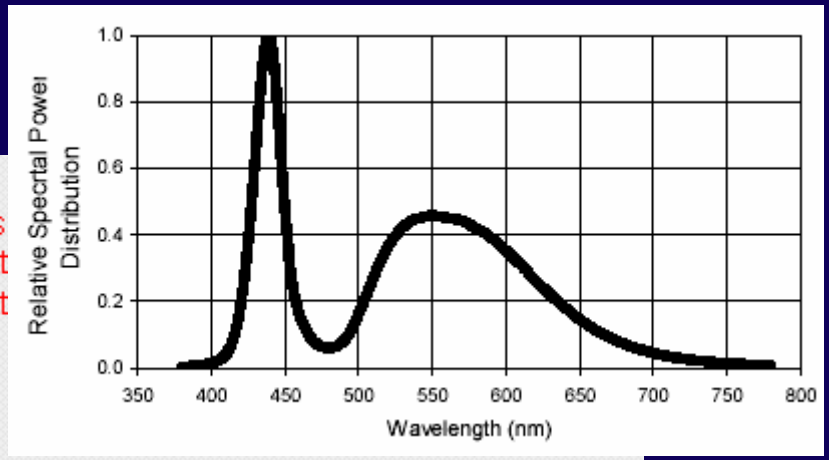
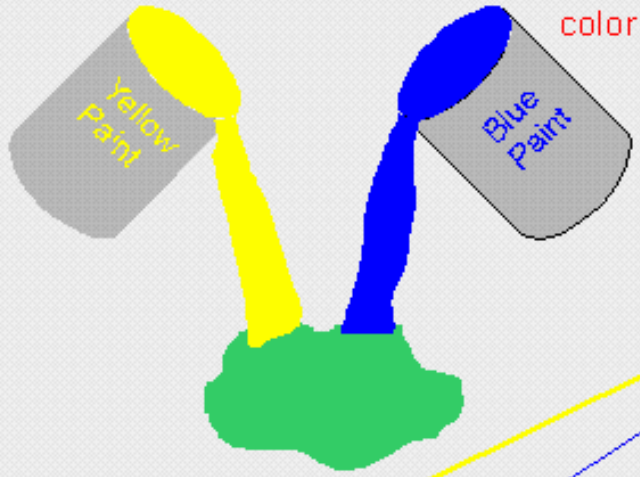
Additive Color Mixing



Pigments
color mixt
color mixt



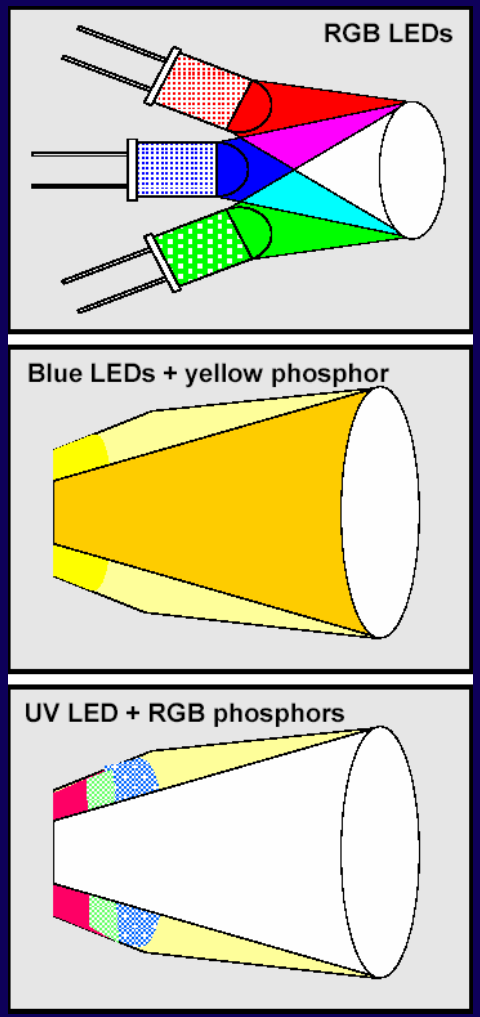
Consequently, yellow paint mixed with blue paint yields green paint. Yellow light mixed with blue light yields white light.

Applications for White Phosphor Coated LEDS

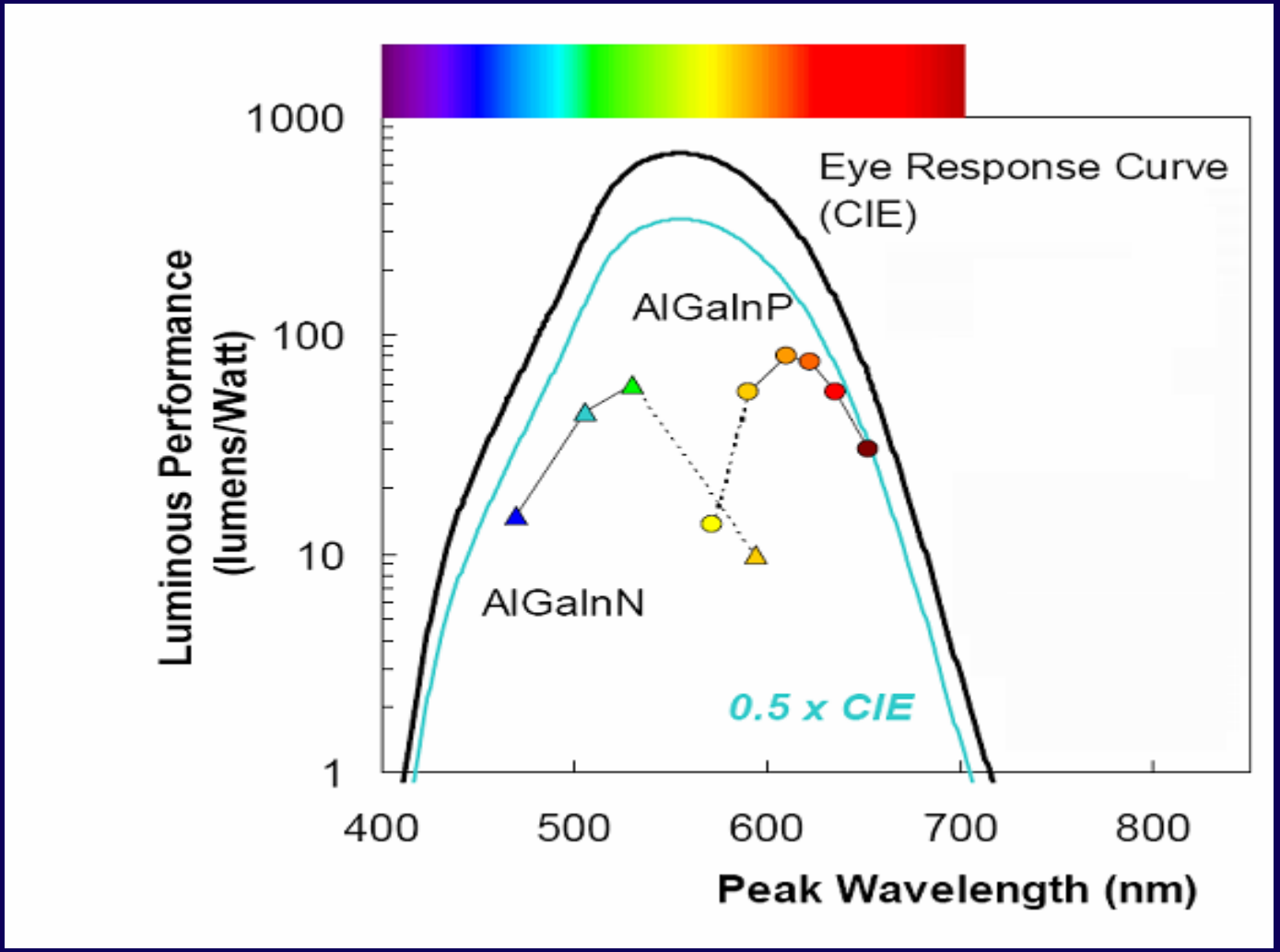
Lamps based on Luxeon White

Options for white light generation with LEDs

- RGB – LEDs
  - Potentially optimal
- Blue LED + Phosphor
  - Many advantages for Illumination
- UV – LED + Phosphor
  - Efficiency?
  - Stability?



LED efficiency for different colors



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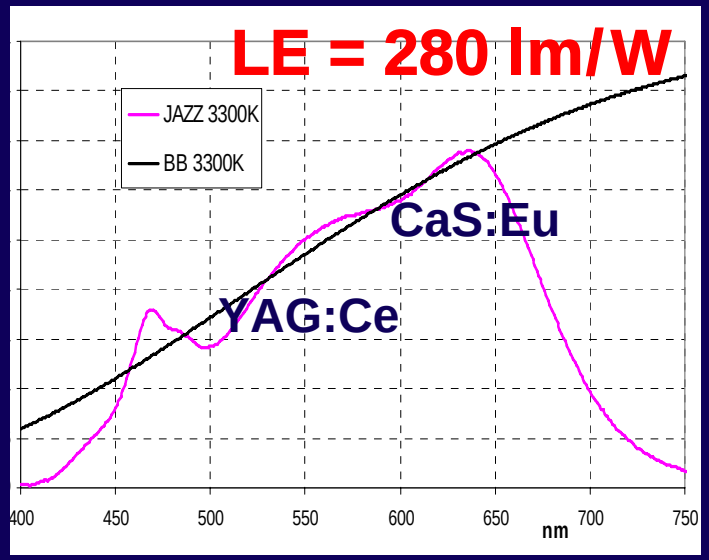
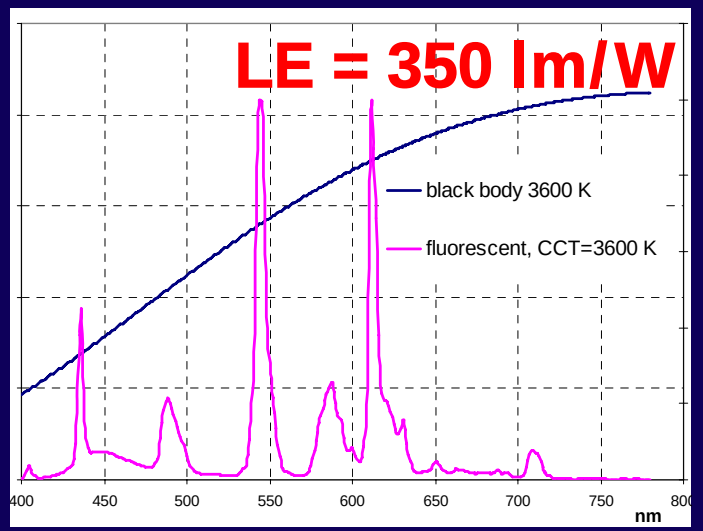
Luxeon Warm White (Jazz LED)

- **'Incandescent-like" White**
- YAG:Ce + CaS:Eu
- CRI 85+ (to 95)
- 2800 to 4000K
- 20-25 lm @ 350 mA

- Sulfide phosphors not process compatible
- Saturation issue
- Alternative for red needed





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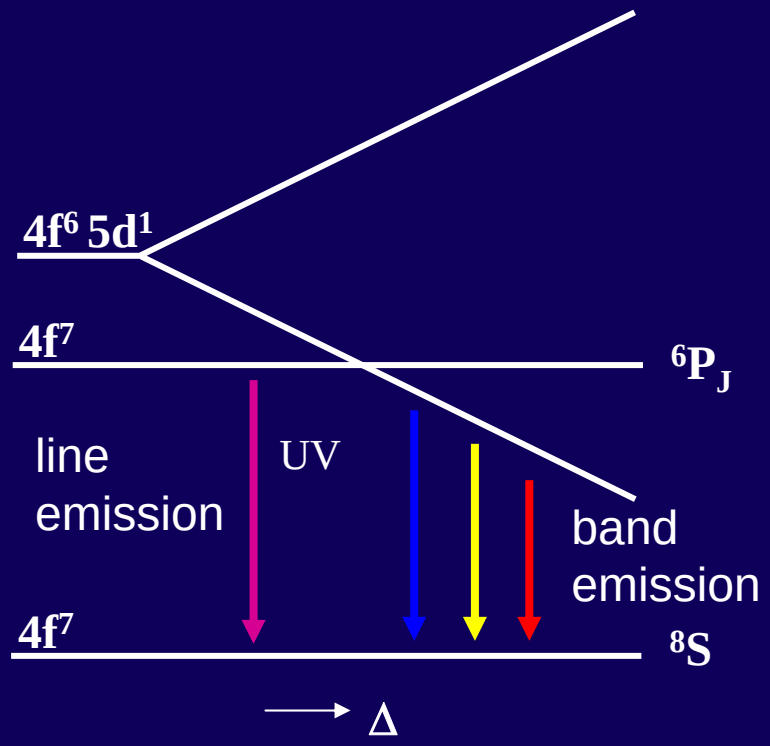
Eu^{2+} Phosphors

Energy level scheme Eu^{2+} ion



Emission spectra

- weak crystal field:
  line emission in the UV
- strong crystal field and/or
  high co-valency:
  band emission in the visible

SrB_4O_7:Eu	368 nm
$Sr_2P_2O_7$:Eu	420 nm
$BaMgAl_{10}O_{17}$:Eu	453 nm
$SrGa_2S_4$:Eu	535 nm
$(Sr,Ca)_2SiO_4$:Eu	575 nm
CaS:Eu	655 nm

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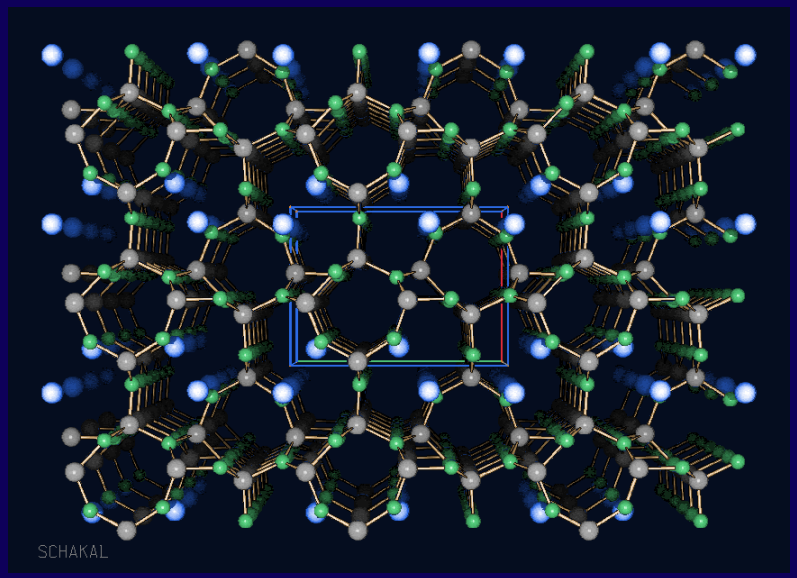
Development of $M_2Si_{5-x}Al_xN_{8-x}O_x:Eu$

EP 02102752.9, US 20030006702

Quantum efficiency > 90%, Absorption (450 nm) > 80%

Current research focused on morphology and adjustment of color point



highly condensed anionic network

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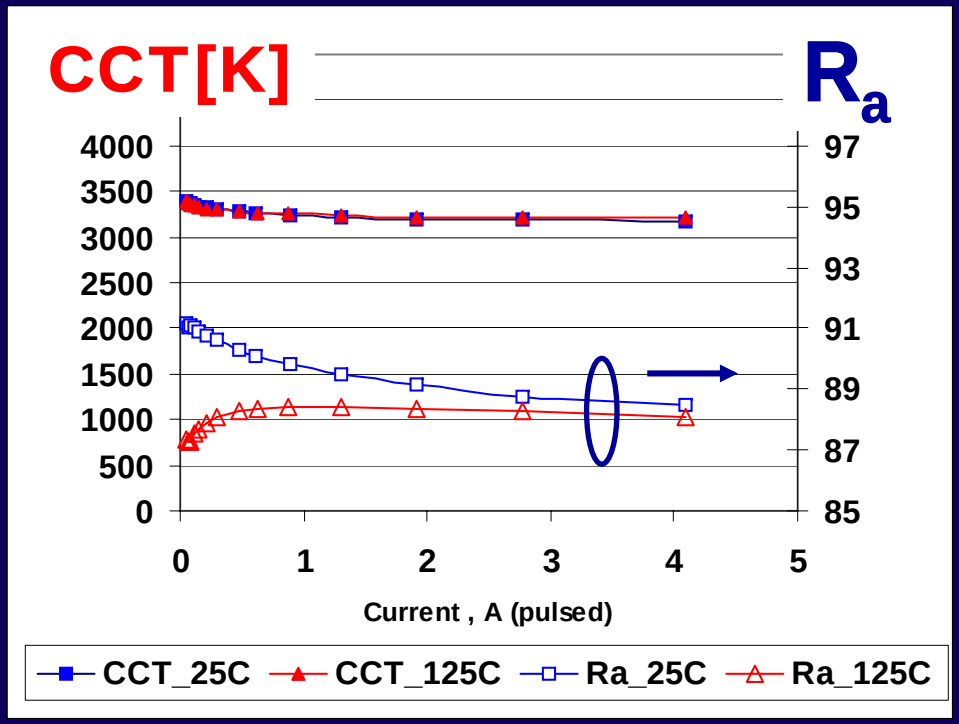
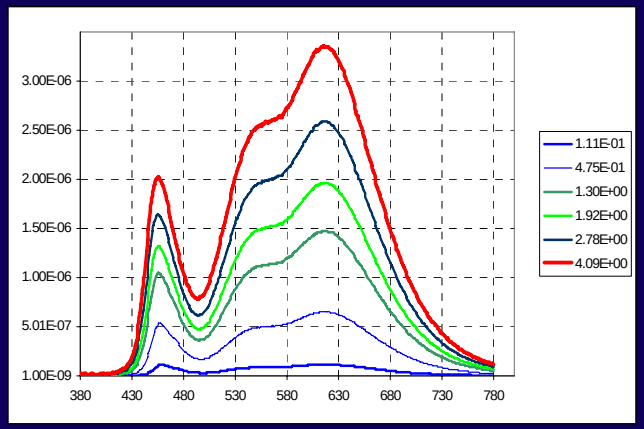
An All-Nitride White LED

LL Demo LED combining Philips green SiON and red SiAlON phosphors (QE > 0.9, QE_{rel}(200°C) > 0.95)



excellent stability of color quality is achieved.



R. Mueller-Mach, G. Mueller, M.R. Krames, H.A. Höppe, F. Stadler, W. Schnick, T. Juestel, P. Schmidt, Highly efficient all-nitride white light emitting diode, phys. stat. sol. (a) 202, 1727, 2005

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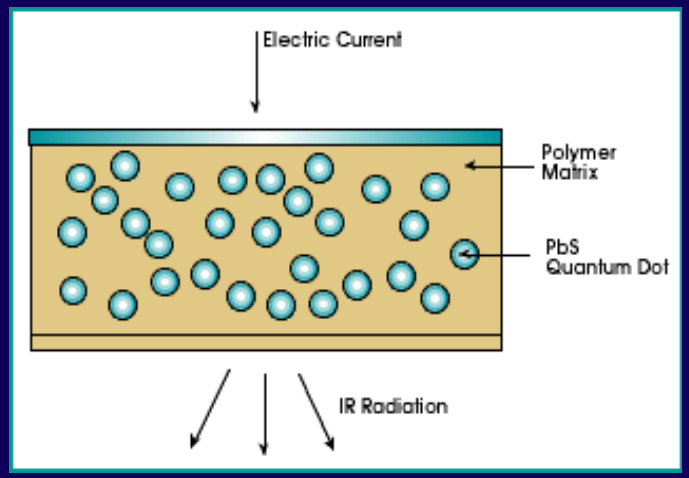
Nano Solutions

- Nano phosphors
  - 40 to 80 nm
  - QE < 70% (NDT YAG)
- Quantum dots
  - 2 to 20 nm (< $L_{Exciton}$)
  - QE < 70%

White directly possible



http://www.physlink.com/News/071403QuantumDotLED.cfm

Summary and Conclusions

- SSL: a disruptive innovation for lighting
  - Inorganic LEDs
  - Organic LEDs in the future
- Opportunities for nano-optical structures
  - Improve efficiency and brightness
  - Challenge in production and design
- LEDs profit from combination with phosphors
  - nitridosilicates and oxonitridosilicates
    New materials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