Materials Challenges for Solid-State Lighting

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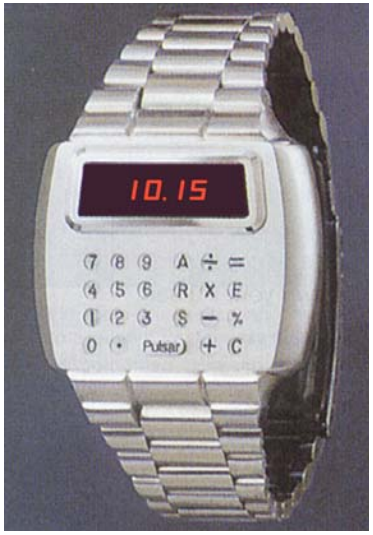
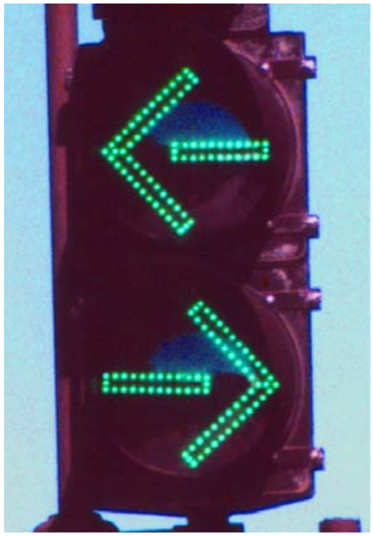
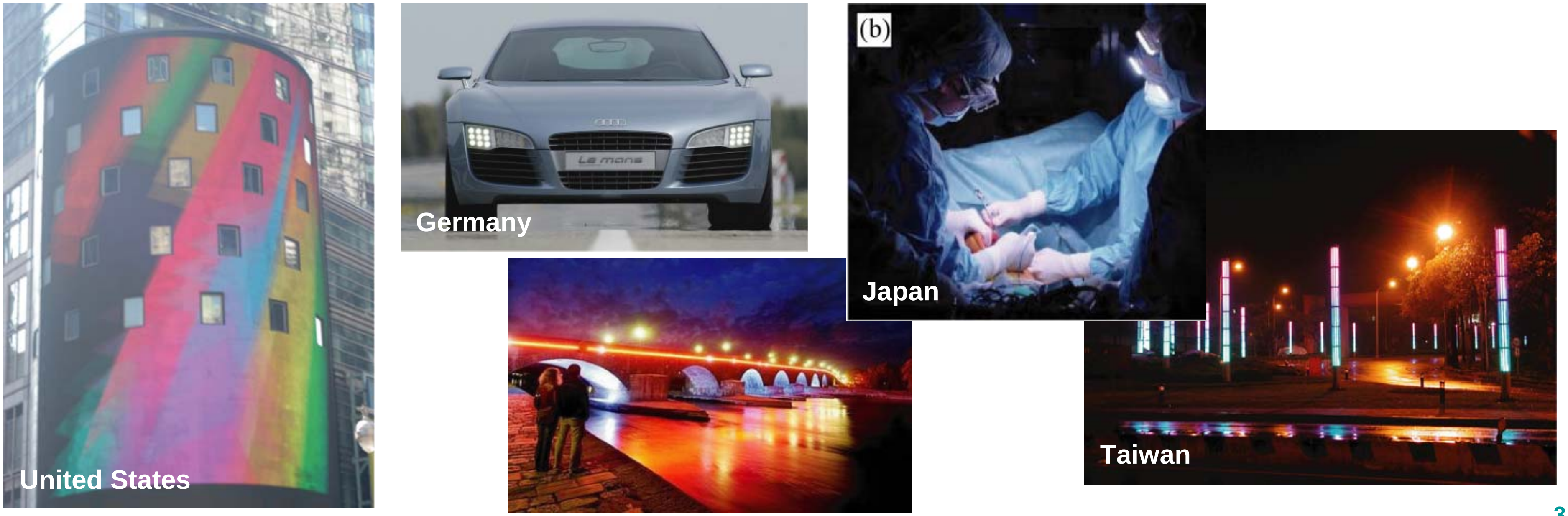
Outline

- Introduction
- Materials:
  - **Reflectors**
  - **New materials with extreme refractive index**
- Devices:
  - **White LEDs with remote phosphors**
- Systems:
  - **Solid-state lighting – Figures of merit**
- Future:
  - **Smart Lighting Systems**

Traditional and new applications

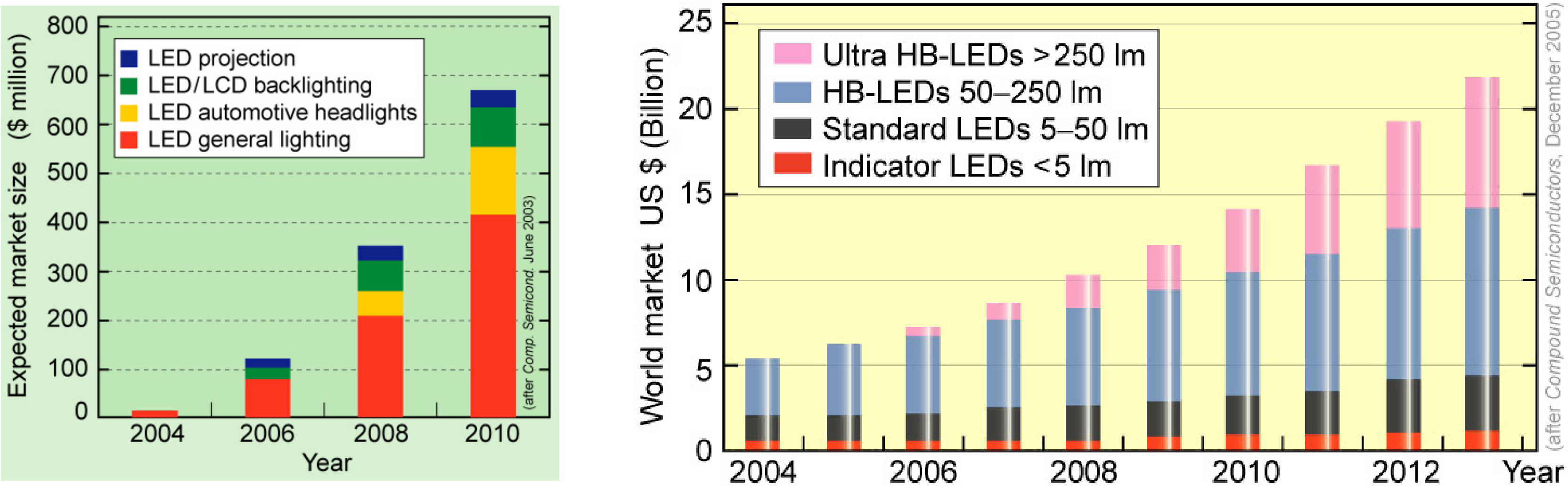






Solid-state lighting

- **Inorganic devices:**
  - Semiconductor plus phosphor illumination devices
  - All-semiconductor-based illumination devices
- **Organic devices:**
  - Remarkable successes in low-power devices (Active matrix OLED monitors, thin-film transistors, TFT-LCD monitors)
  - Substantial effort is underway to demonstrate high-power devices

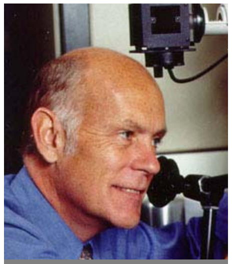


Predicted growth of LED market

Energy Conservation – A Singular Opportunity

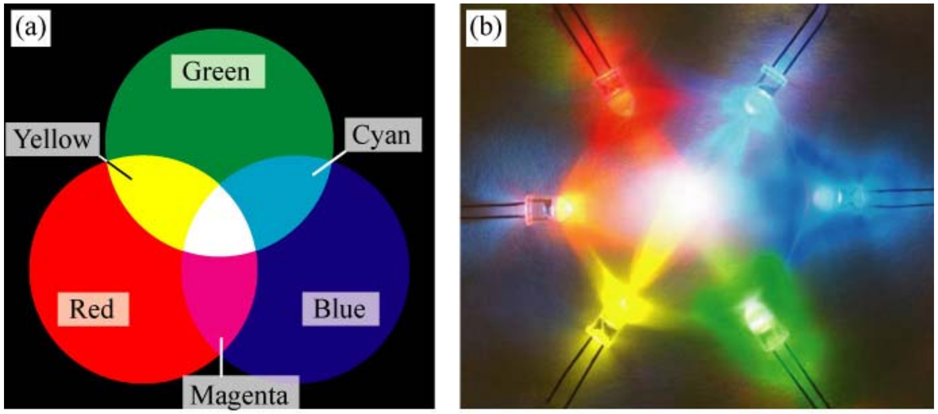
Nobel Laureate Richard Smalley: “Energy is the single most important problem facing humanity today” and “conservation efforts will help the worldwide energy situation”.

Testimony to US Senate Committee on Energy and Natural Resources, April 27, 2004

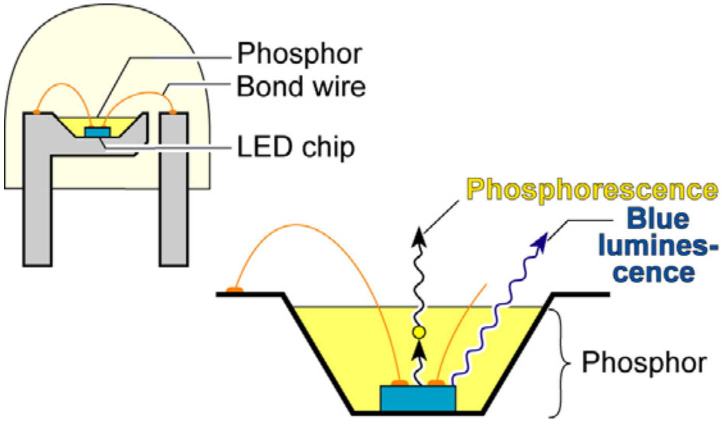


1943 – 2005

- **Solid-state light-sources offer singular opportunity for conservation of energy**



Multiple light-emitting diodes



LED with wavelength (λ) converter

Quantification of Solid-State Lighting Benefits

- **Energy benefits***
  - 22 % of electricity used for lighting
  - LED-based lighting can be **20** × more efficient than incandescent and **5** × more efficient than fluorescent lighting
  - Annual electrical energy savings 1.20 PWh (Peta = 10^{15})
  - Alleviate need for 133 power stations

- **Environmental benefits***
  - Reduction of **CO_2** emissions, 952 Mtons, **global warming gas**
  - Reduction of **SO_2** emissions, **acid rain**
  - Reduction of **Hg** emissions by coal-burning power plants
  - Reduction of hazardous **Hg** in homes

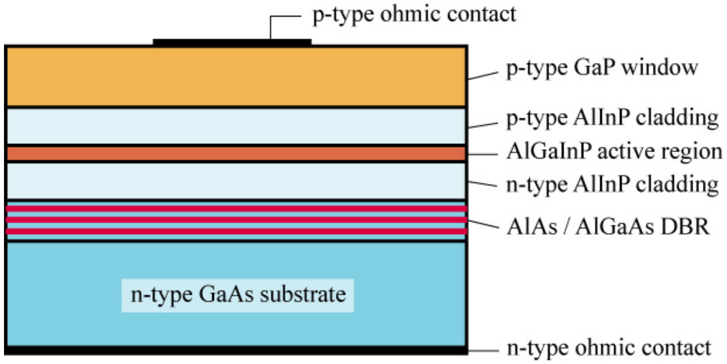
- **Economic benefits***
  - A 10% reduction in electricity consumption would result in financial savings of $ 25.0 Billions per year

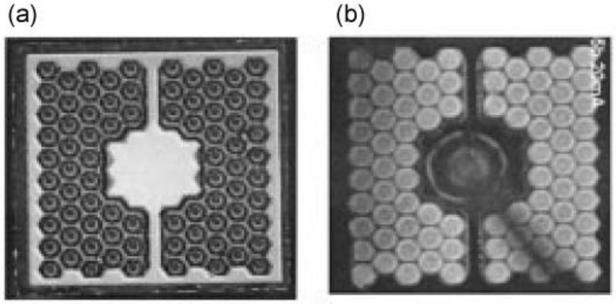
(*) 1.0 PWh = 11.05 PBtu = 11.05 quadrillion Btu “=” 0.1731 Pg of C = 173.1 Mtons of C
1 kg of C “=” [(12 amu + 2 × 16 amu) / 12 amu] kg of CO_2 = 3.667 kg of CO_2
OIDA and DOE predictions for US by 2025, see also R. Haitz *et al*. *Adv. in Solid State Physics*, *Physics Today* 2001
Economic benefits were detailed by Sandia National Laboratories, 2006
Information on mercury from Associated Press article, March 15, 2005 “EPA targets utilities’ mercury pollution”
1.20 PWh energy savings and alleviated need for 133 power stations are extrapolated data for year 2025

Light-emitting diodes with reflectors

To avoid optical losses, ideal device structures possess either:
Perfect Transparency* or *Perfect Reflectivity

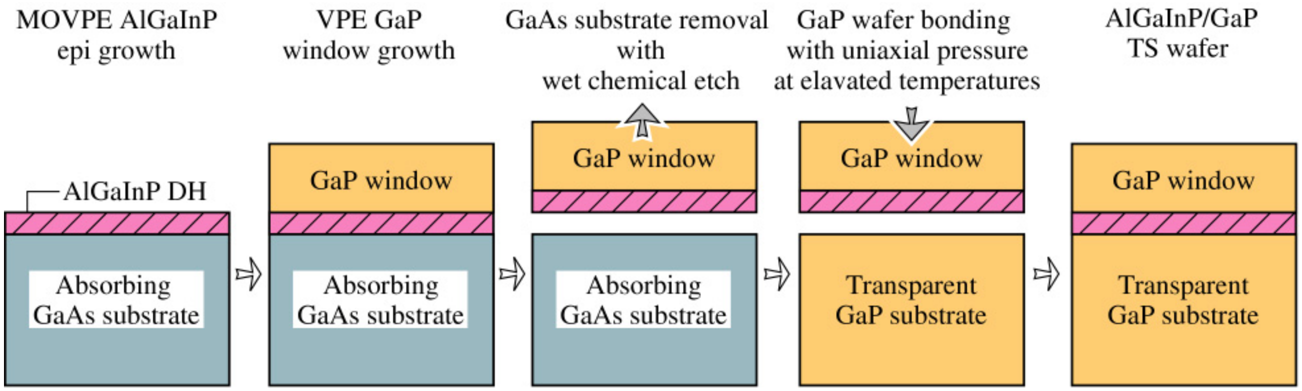
Example of **reflective** structure: (after Osram Corp.)





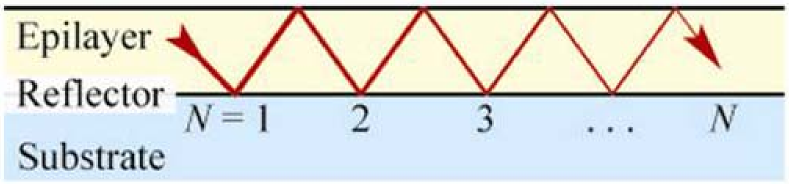
Top view (a) andi llumination pattern (b) of a 615-nm thin-film LED (after Streubel et al., 2002)

Example of **transparent** structure: (after Lumileds Corp.)



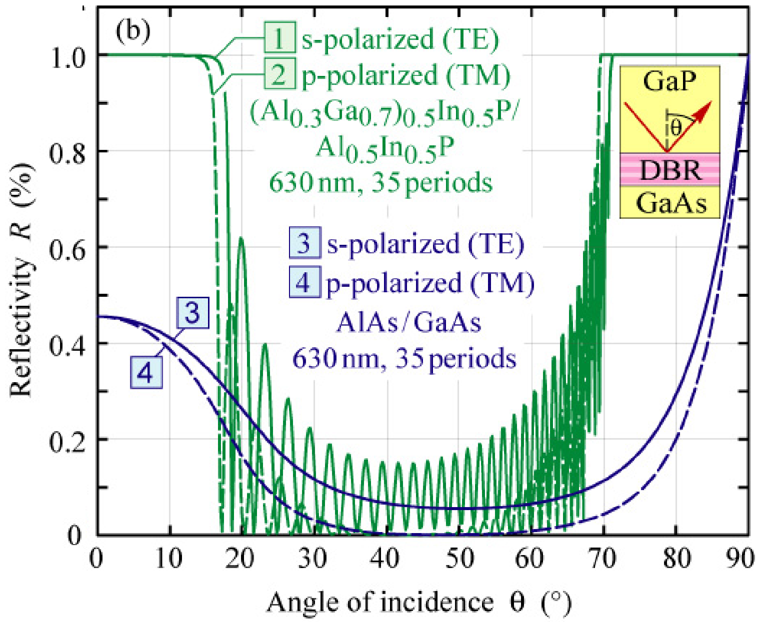
Why reflectors?

- **Totally reflective** **structure (*R* = 100 % for all Θ_i and TE and TM polarization)**

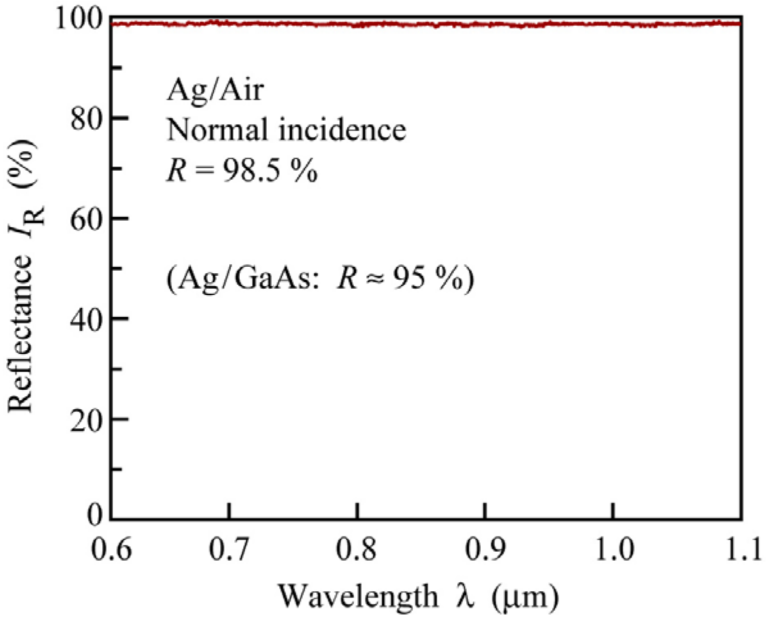


High reflectivity is important!

- **DBRs: transparent for oblique incidence angles; Metal mirror: *R* < 95 %**
- **DBR** and **metal mirrors** are **un**suitable!



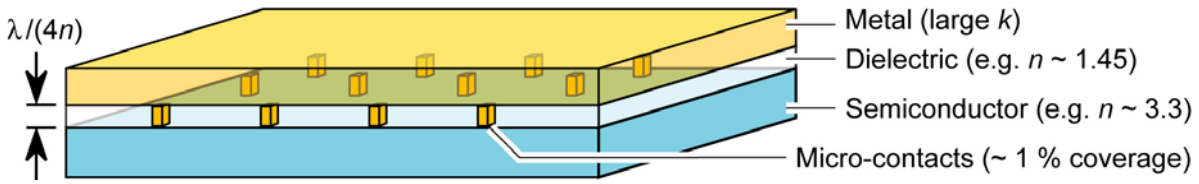
DBR



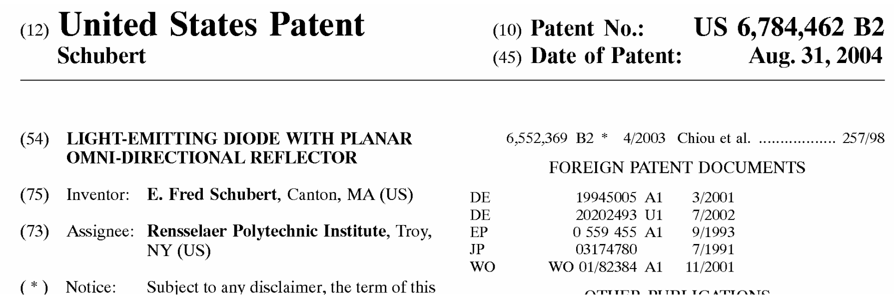
Metal reflector

Triple-layer omni-directional reflector (ODR)

Planar semiconductor / dielectric / metal reflector perforated by an array of micro-contacts.



- Omni-directional reflection characteristics
- High reflectivity (> 99 %)
- Electrical conductivity
- Broad spectral width



(12) **United States Patent**
Schubert

(10) **Patent No.:** **US 6,784,462 B2**
(45) **Date of Patent:** **Aug. 31, 2004**

(54) **LIGHT-EMITTING DIODE WITH PLANAR OMNI-DIRECTIONAL REFLECTOR**

(75) Inventor: **E. Fred Schubert**, Canton, MA (US)

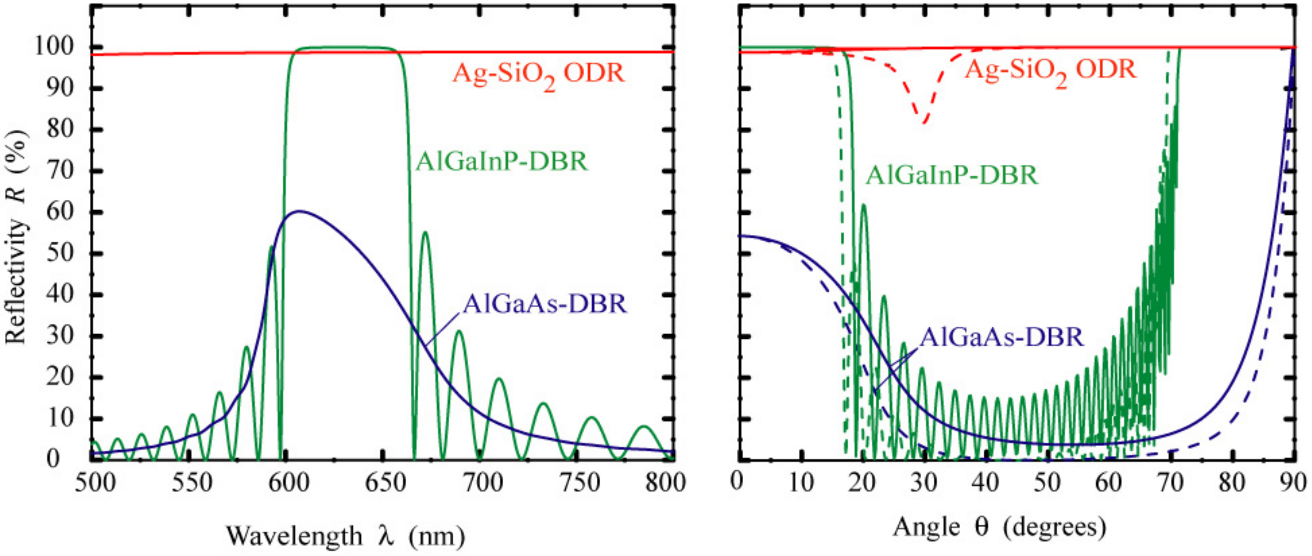
(73) Assignee: **Rensselaer Polytechnic Institute**, Troy, NY (US)

(*) Notice: Subject to any disclaimer, the term of this

6,552,369 B2 * 4/2003 Chiou et al. 257/98

FOREIGN PATENT DOCUMENTS

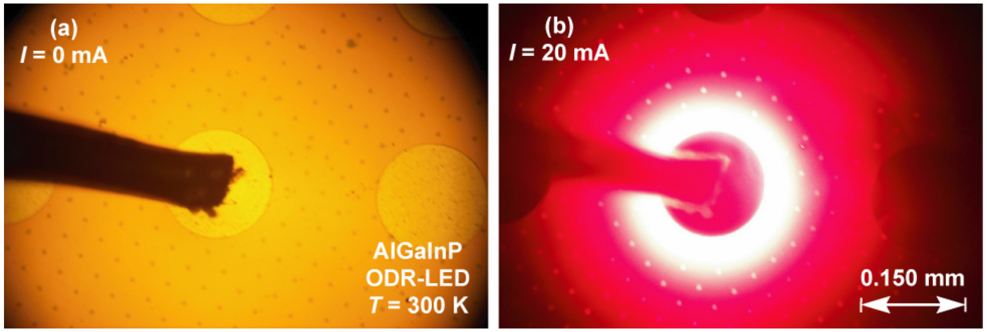
DE	19945005	A1	3/2001
DE	20202493	U1	7/2002
EP	0 559 455	A1	9/1993
JP	03174780		7/1991
WO	WO 01/82384	A1	11/2001

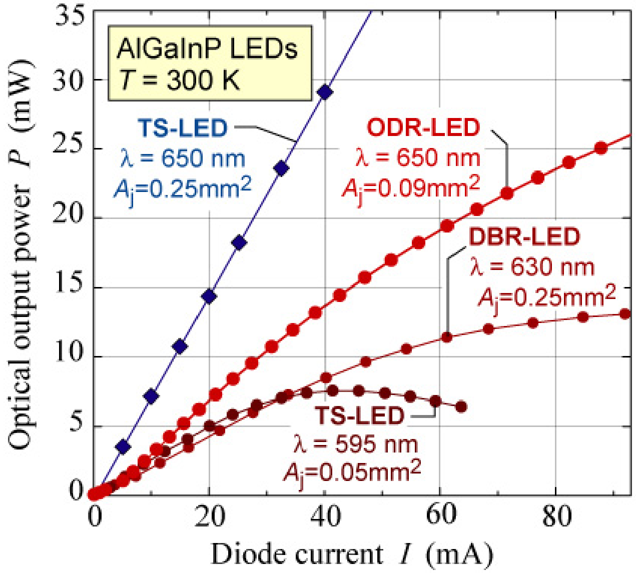


AlGaInP and GaInN LEDs with ODR

AlGaInP LED

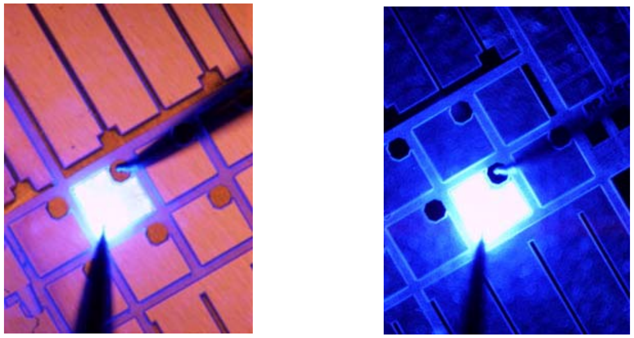
λ = 650 nm, MQW active region
AlGaAs window layer
GaAs substrate removed, Si submount





GaInN LED

λ = 460 nm, MQW active region
Sapphire substrate



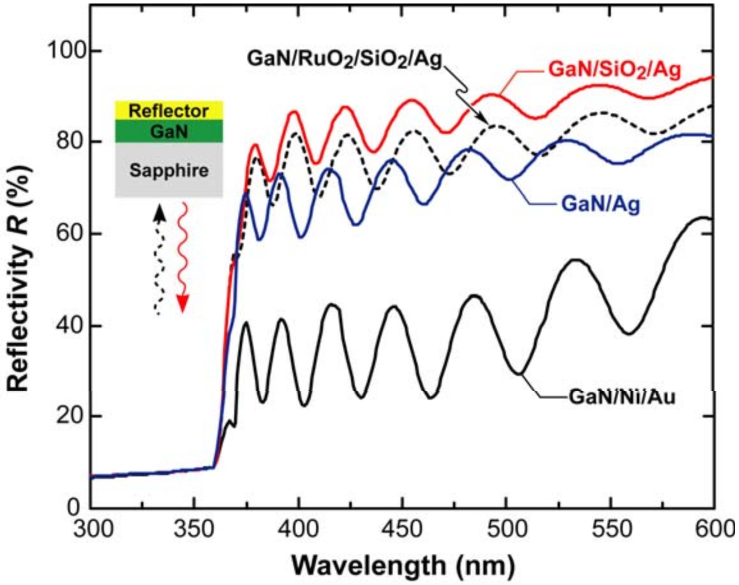


Figure of merit for DBR: Index contrast Δ*n*

- **Fresnel reflectance of interface**

$$r = \frac{n_h - n_1}{n_h + n_1} = \frac{\Delta n}{n_h + n_1}$$

- **DBR reflectance**

$$R_{DBR} = \left| r_{DBR} \right|^2 = \left[\frac{1 - (n_l / n_h)^{2m}}{1 + (n_1 / n_h)^{2m}} \right]^2$$

- **Spectral width of stop band**

$$\Delta\lambda_{stop} = \frac{2 \lambda_{Bragg} \Delta n}{n_{eff}}$$

- **Penetration depth**

$$L_{pen} \approx \frac{L_1 + L_2}{4 r} = \frac{L_1 + L_2}{4} \frac{n_1 + n_2}{\Delta n}$$

- **Critical angle (max. angle for high reflectivity)**

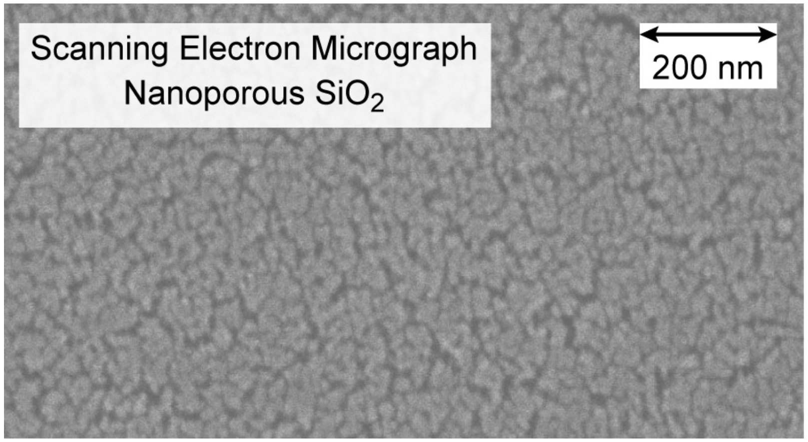
$$\theta_c \approx \frac{n_1}{n_0} \sqrt{\frac{2}{n_0} \frac{2\Delta n}{n_1 + n_2}}$$

➔ ***By increasing index contrast Δn, figures of merit improve***

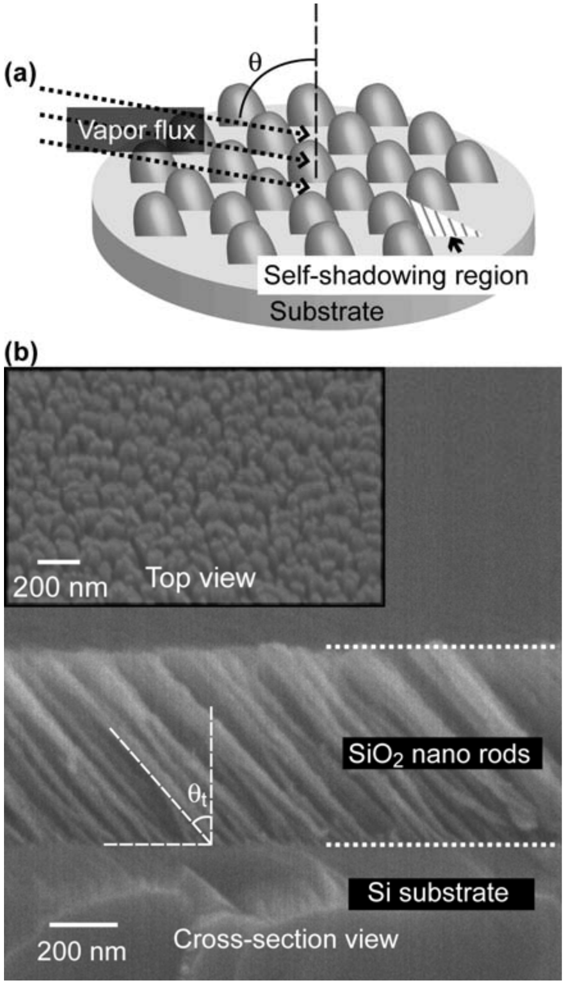
➔ ***New materials are required***

New class of materials: Low-*n* materials

- **Dense materials $n \approx 1.4$: SiO_2** (n = 1.45); **MgF_2** (n = 1.39)
- **Low-*n*: refractive index $n < 1.25$**
- **Xerogels (porous SiO_2)**
  - Gill, Plawsky, et al. 2001, 2005
- **Oblique-angle evaporation**
  - Technique was developed in the 1950s
  - Lin, Lu et al., 2002
- **Both techniques suitable for low-loss LEDs**



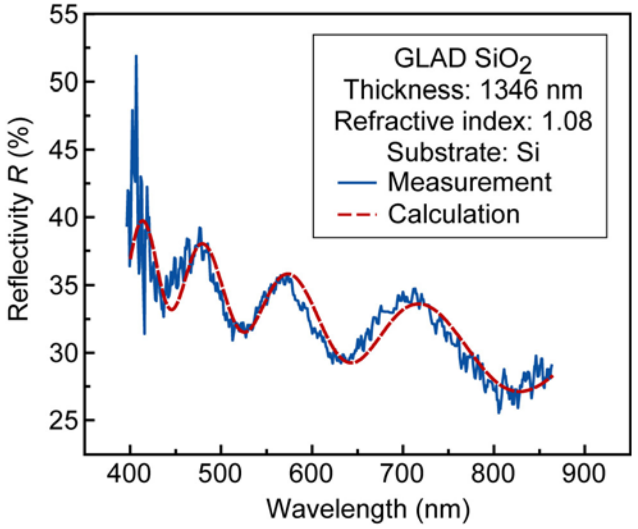
Low-*n* xerogels, after Gill and Plawsky, 2005



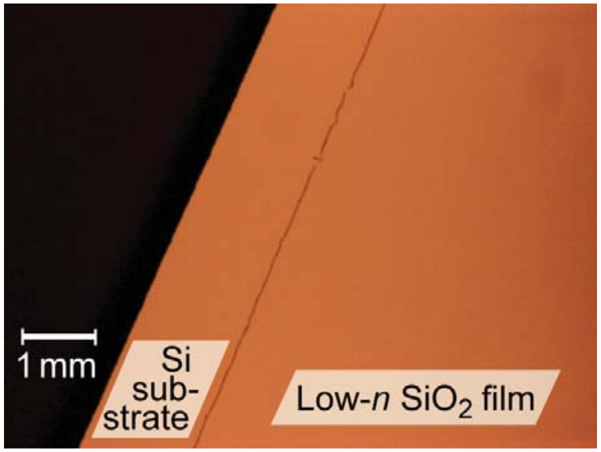
Low-*n* SiO_2

Triple-layer ODRs with nano-porous silica

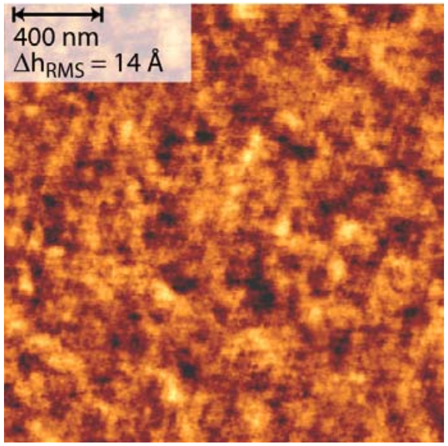
- Pore sizes << λ (Rayleigh scattering)
- Pore sizes 2 – 8 nm achieved
- Maxwell's equations: $n^2 = \varepsilon_r$ (= k)
- Low-*k* material in Si technology (field dielectric)
- Low-*n* films are new class of materials with distinct properties



Thin-film interference



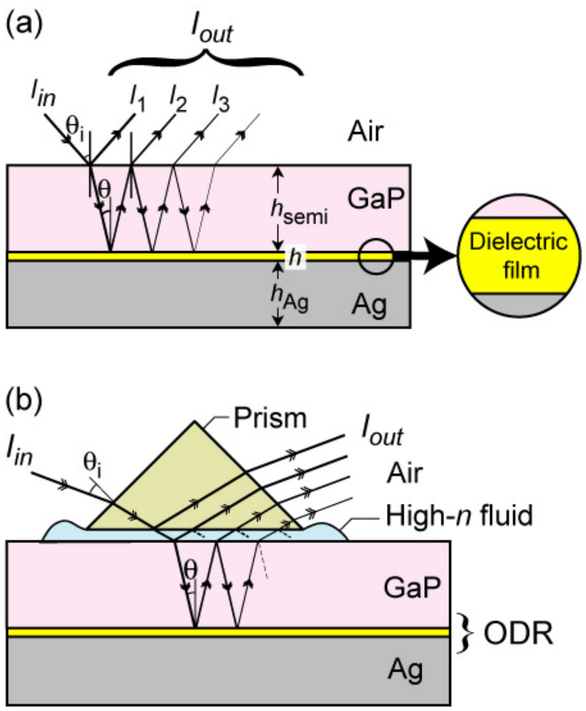
Optical micrograph

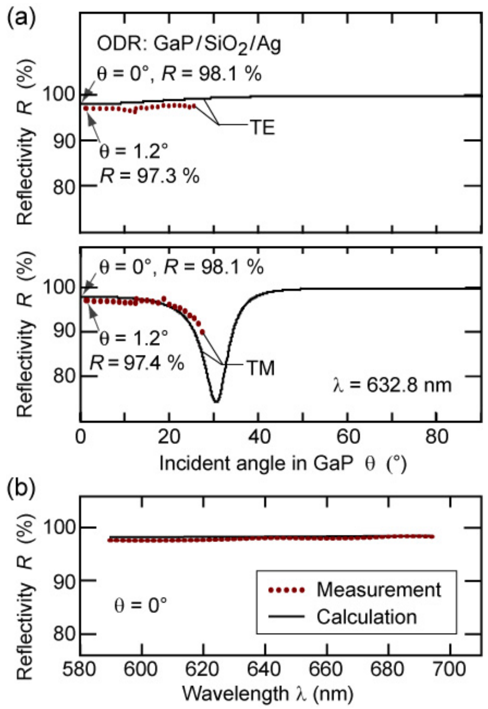


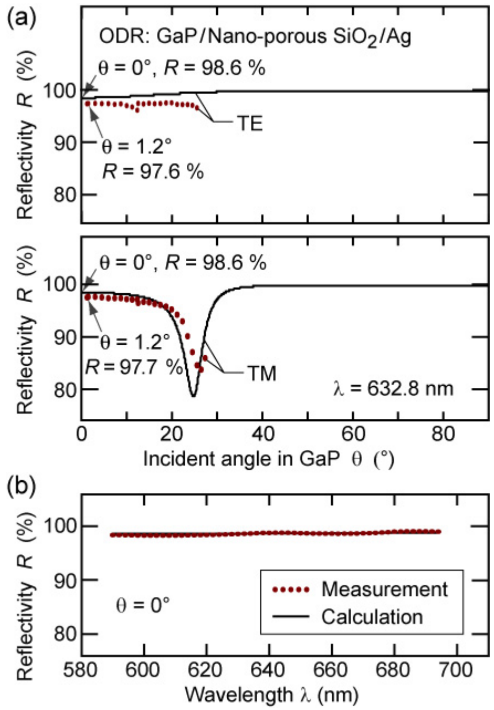
Atomic force micrograph

World record! *n* = 1.08

Low-index layer and reflector data



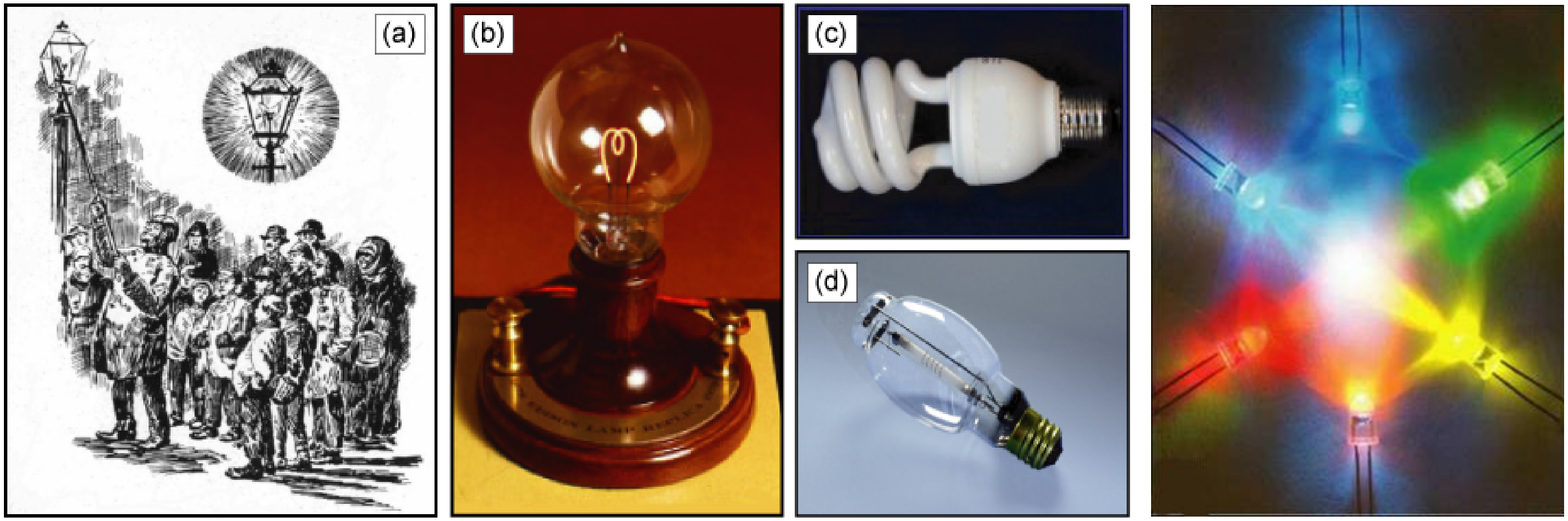




- Reflector has **100 × lower** mirror losses than metal reflectors
- Reflector has **> 100 × lower** mirror losses than DBRs
- Suitable for low-loss LEDs

Solid-state lighting

Old and new lighting technologies

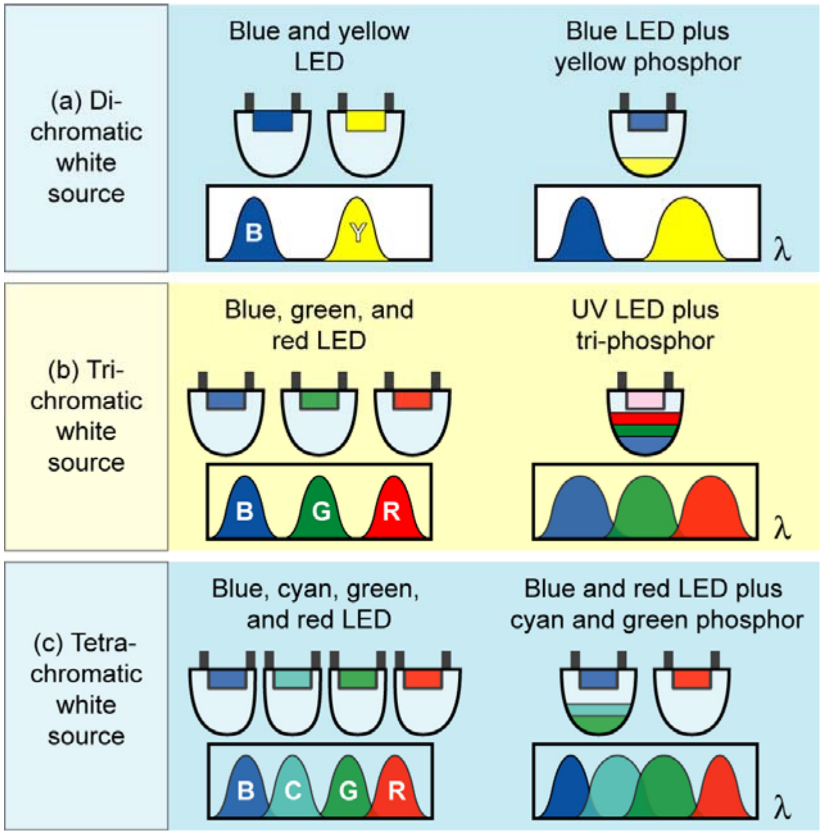


Figures of merit

Luminous source efficiency	(lumens per watt)
Color temperature	(Kelvin)
Color rendering index	(CRI)
Cost of ownership	($)

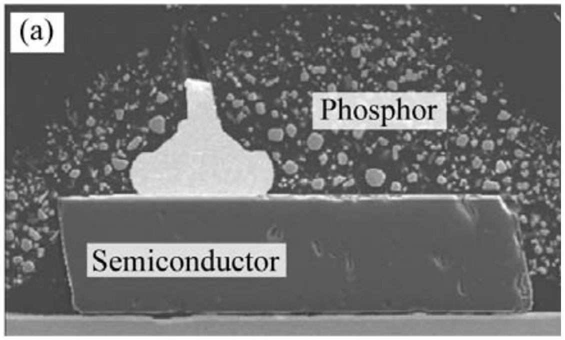
White LEDs

- **Different technical approaches**
  - Blue LED plus yellow phosphor
  - UV LED plus RGB phosphor
  - Multiple LEDs
  - Which one is best?
- **Efficiencies**
  - Incandescent light bulb: 17 lm/W
  - Di-chromatic source: 420 lm/W (limit)
  - Trichromatic source: 300 lm/W with excellent color rendering (CRI > 90)
  - LED with phosphor converter: 275 lm/W (CRI > 90)
  - Demonstrated with solid-state sources: 60 lm/W



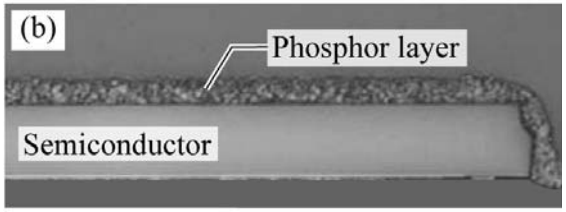
- **What is the optimum spatial distribution of phosphors?**
  - Proximate and remote distributions

Innovation in white LEDs – Phosphor distribution



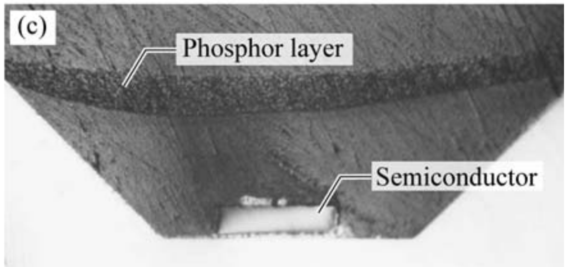
(a) **Proximate** distribution

(after Goetz et al., 2003)



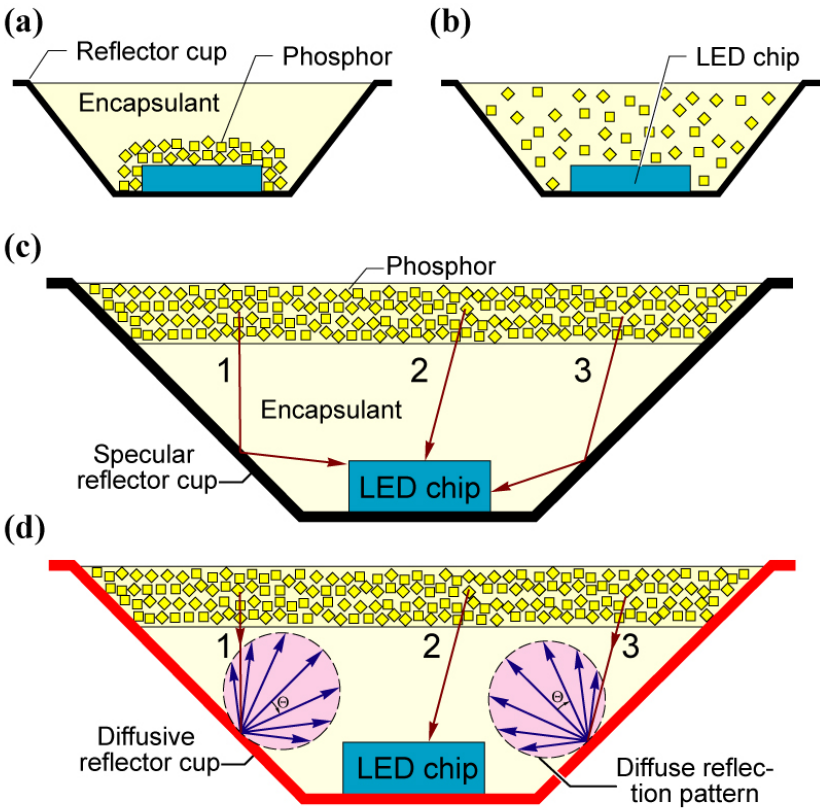
(b) **Proximate** distribution

(after Goetz et al., 2003)



(c) **Remote** distribution

(after Kim et al., 2005)



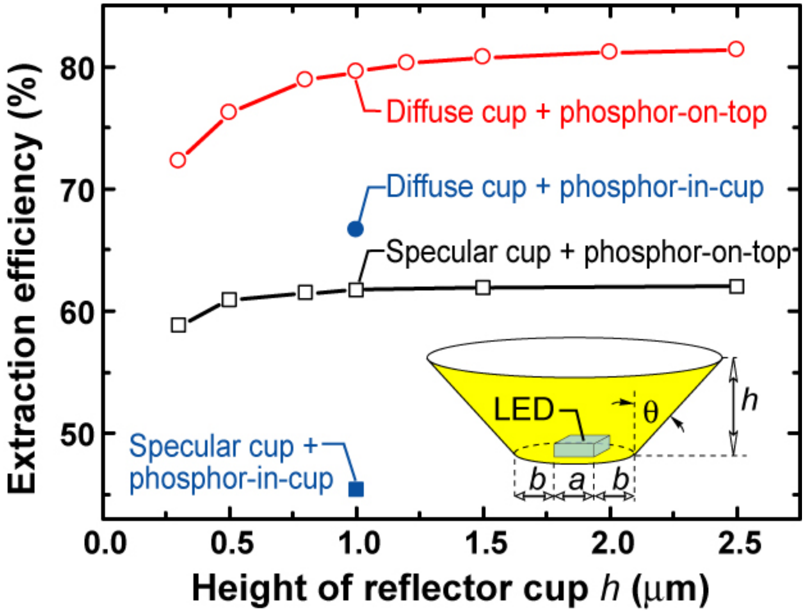
Remote phosphor distributions reduce absorption of phosphorescence by semiconductor chip

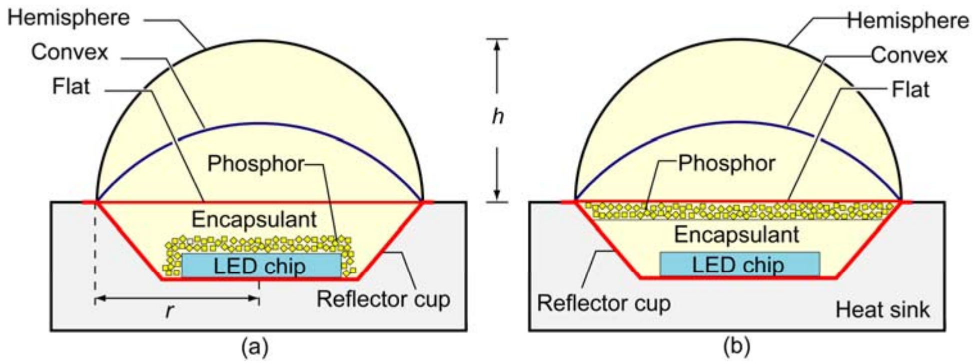
Kim *et al.*, *Jpn. J. Appl. Phys. – Express Lett.* **44**, L 649 (2005)

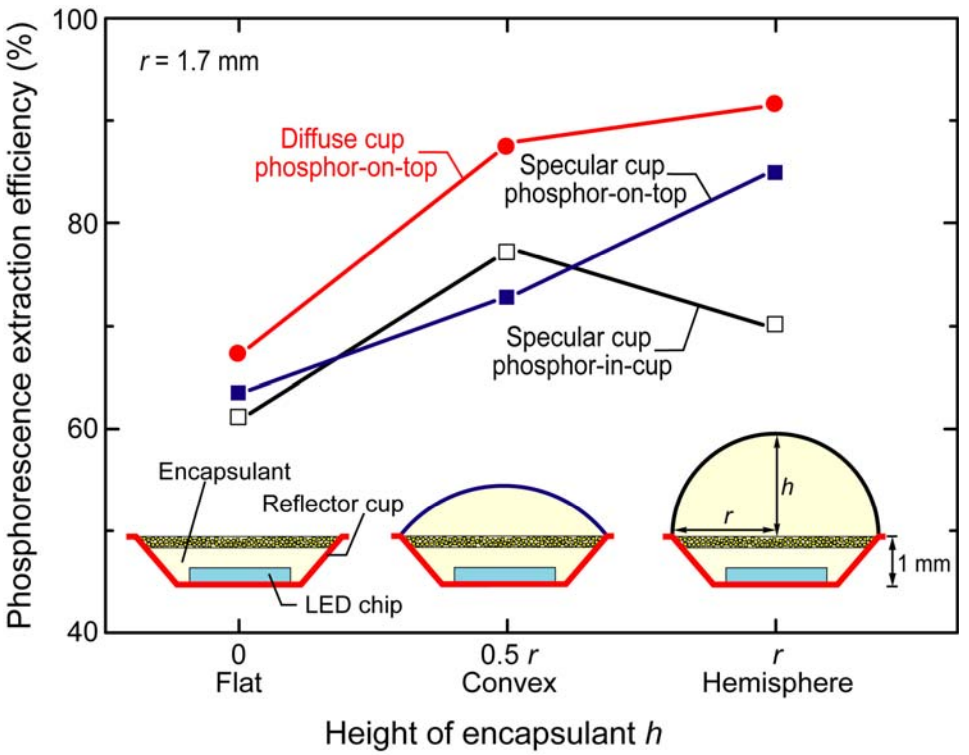
Luo *et al.*, *Appl. Phys. Lett.* **86**, 243505 (2005)

Narendran *et al.*, *Phys. Stat. Sol. (a)* **202**, R60 (2005)

Ray tracing simulations

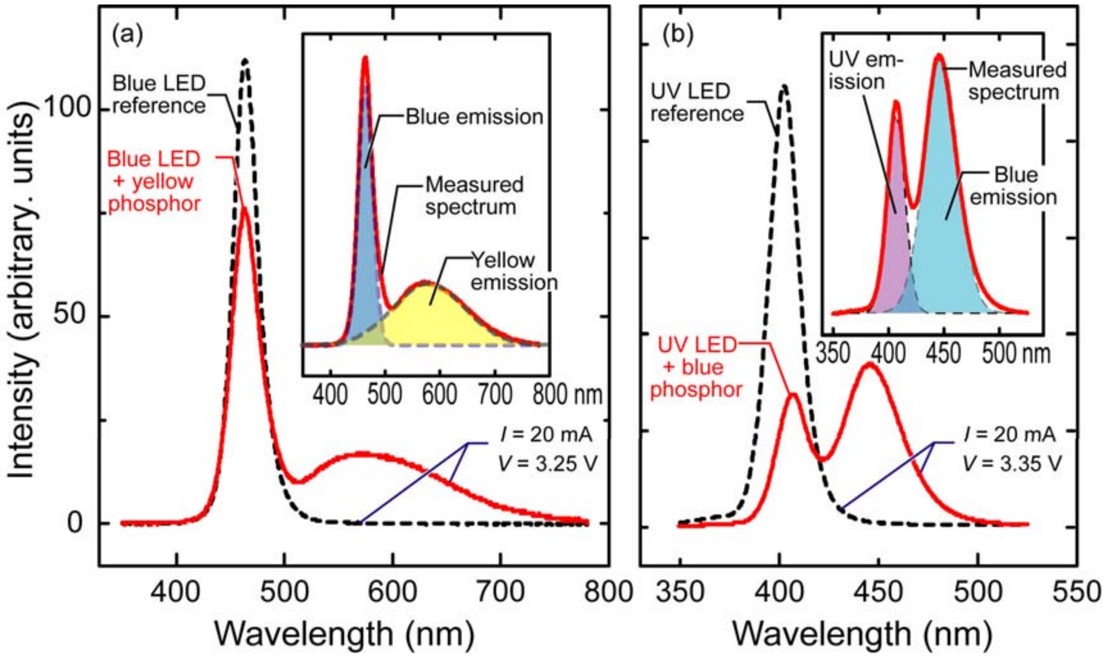


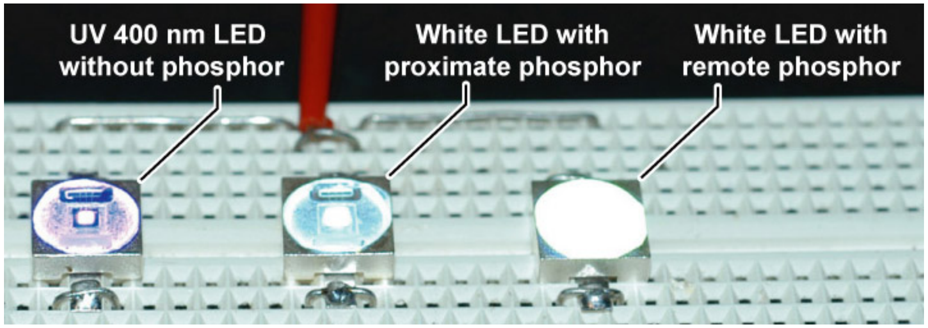




- **Ray tracing simulations prove improvement of phosphorescence efficiency for**
  - Remote phosphor
  - Diffusive reflector cup

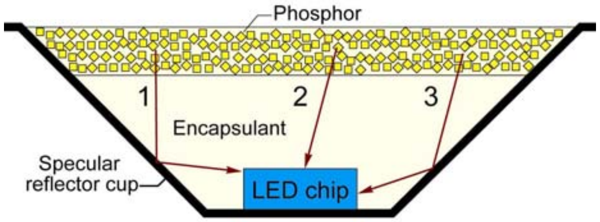
Experimental results

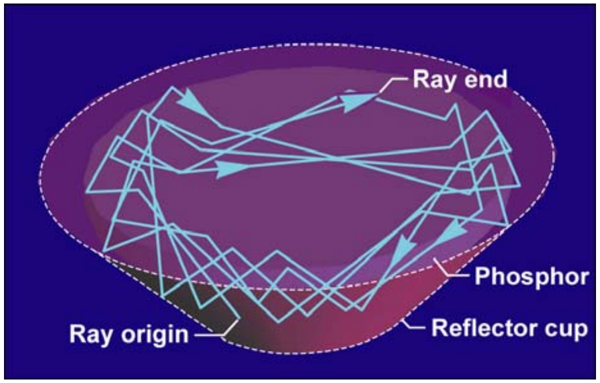


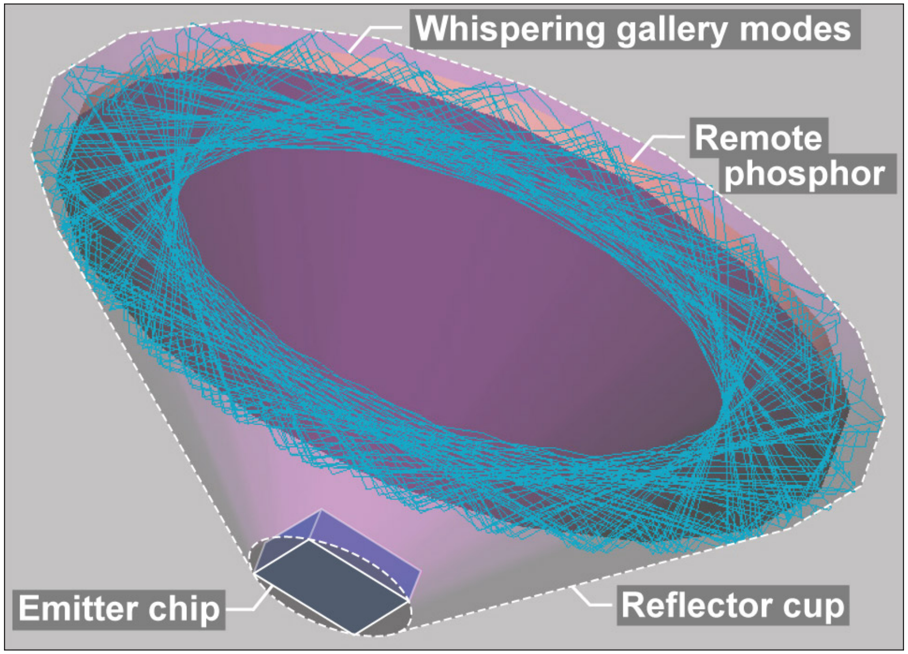


- **Improvement of phosphorescence efficiency**:
  - 75 % by ray-tracing simulations
  - 27.0 % for UV pumped blue phosphor
  - 15.4 % for blue-pumped yellow phosphor

Novel loss mechanisms in white lamps with remote phosphor

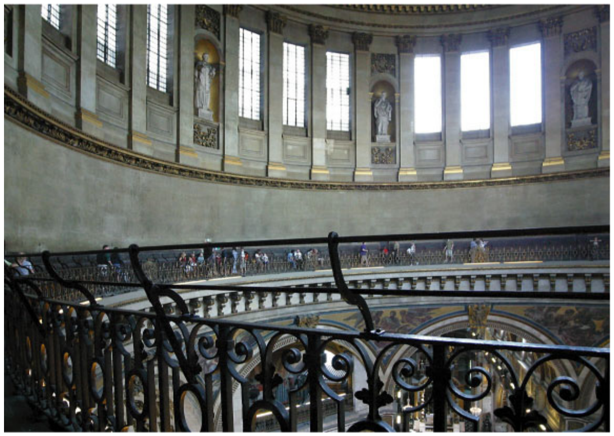






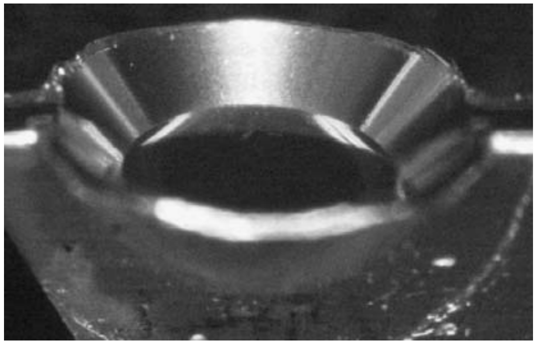
- ***Diffuse reflectors***
  - Non-deterministic element that breaks symmetry
  - Suppression of trapped whispering-gallery modes

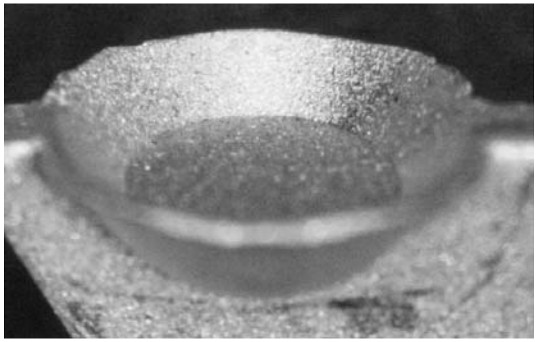
Lord Rayleigh
(1842–1919)

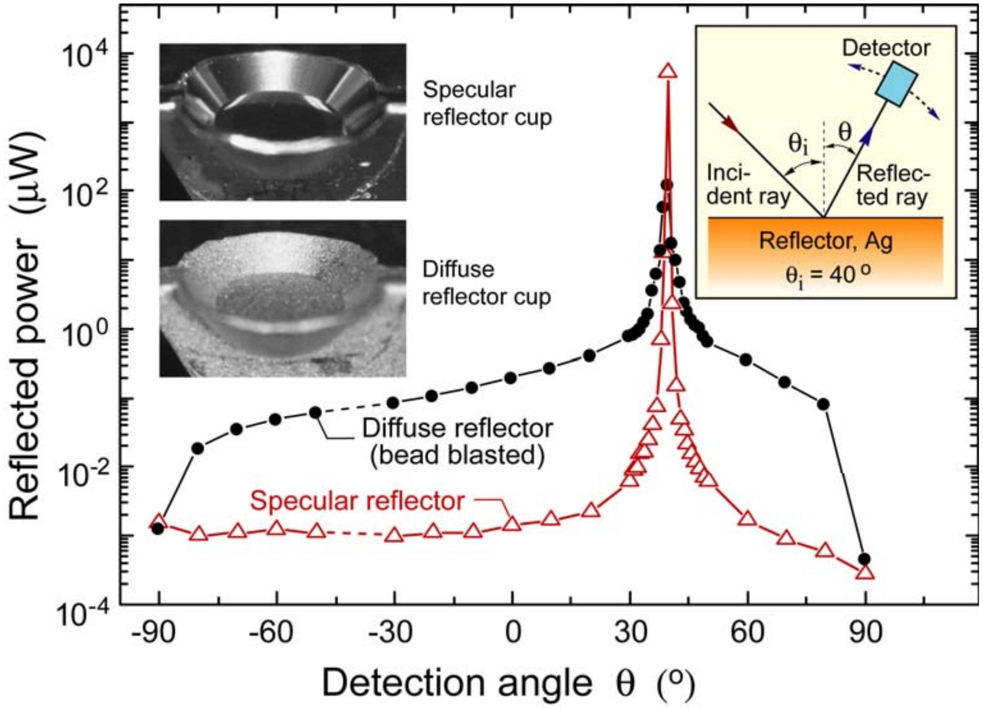


“Whispering Gallery”

Remote phosphors with diffuse and specular reflector cups


Specular reflector cup


Diffuse reflector cup

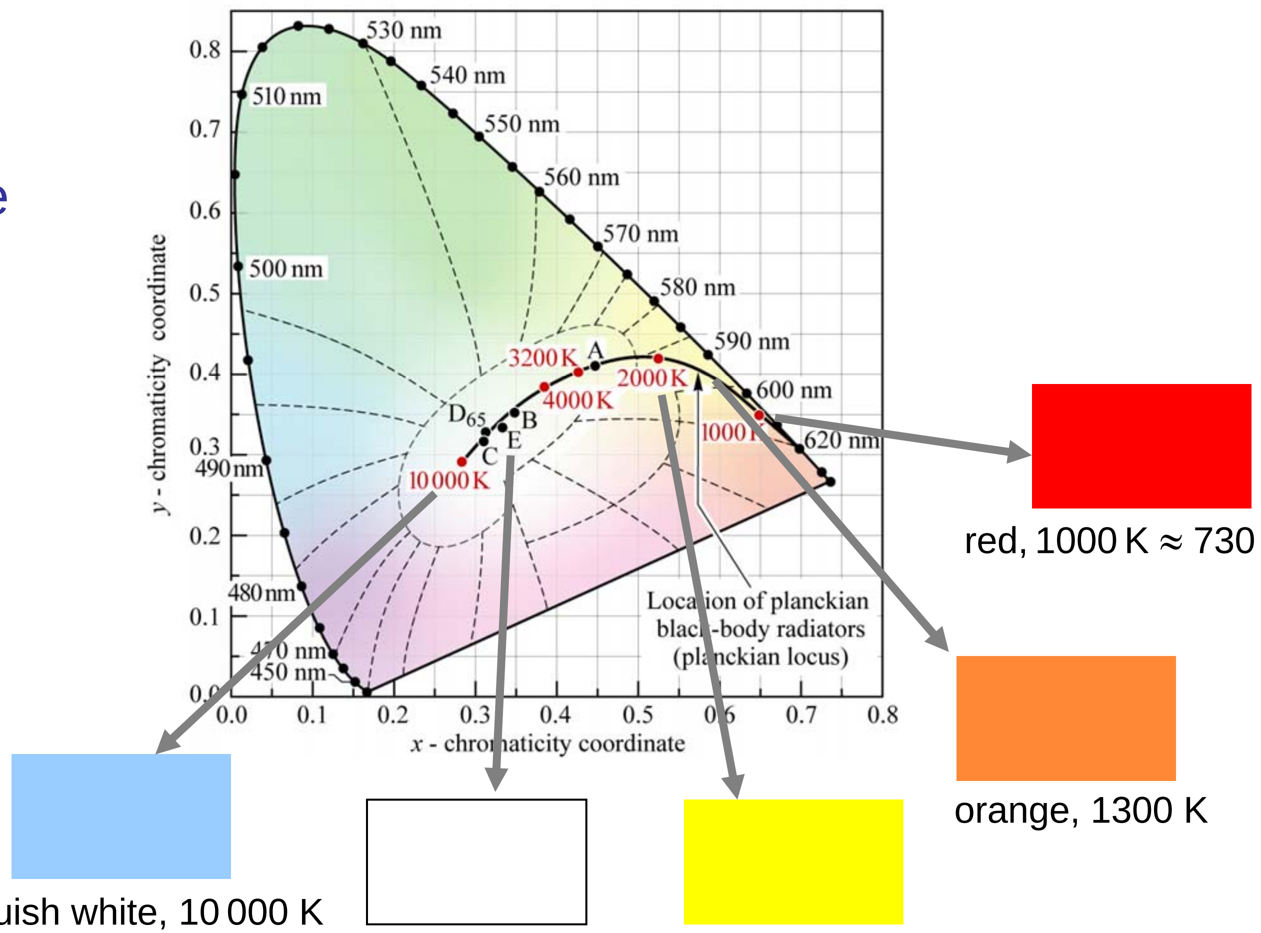


- Reflectance versus angle
- Surface texture by bead blasting
- Diffuse reflectance increased by two orders of magnitude

Color Temperature

As temperature increases, hot objects sequentially glow in the red, orange, yellow, white, and bluish white

Example: Red-hot horseshoe



red, 1000 K ≈ 730 °C

orange, 1300 K

bluish white, 10 000 K

white, 6000 K

yellow, 2100 K

- Hot physical objects exhibit heat glow (incandescence) and a color
- Planckian radiator = Black, physical object with temperature *T*
- Color temperature = Temperature of planckian radiator with same location in chromaticity diagram

Color rendition

- A light source has ***color rendering capability***
- This is the capability to render the true colors of an object

Example: ***False color rendering***

- What is the color of a yellow banana when illuminated with a red LED?
- What is the color of a green banana when illuminated with a yellow LED?

Example of color rendition

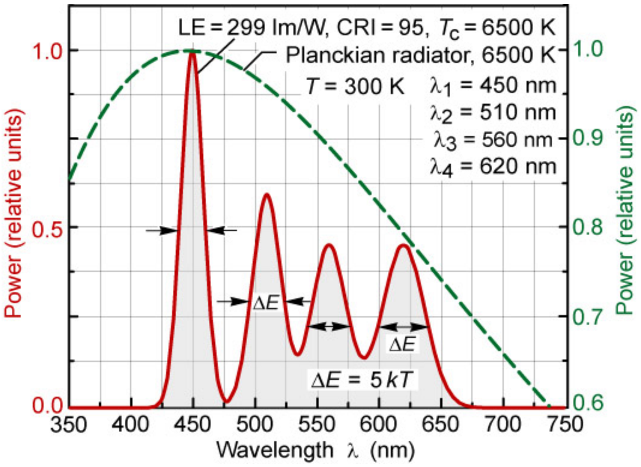
Note the differences in color

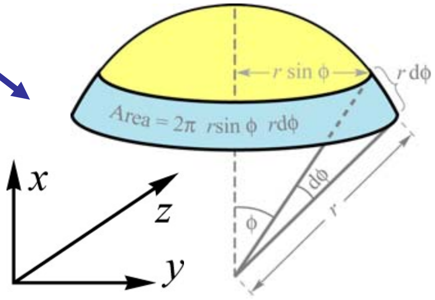
- **Clear differences in the color rendition can be seen in this painting**
  - Left-hand side: high CRI
  - Right-hand side: low CRI

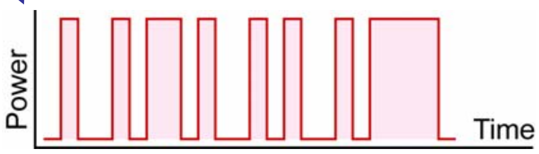
The Future: Smart Sources

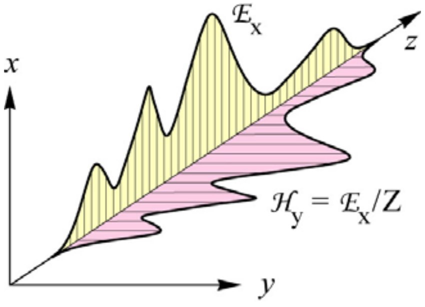
Smart light sources can be controlled and tuned to adapt to different requirements and environments

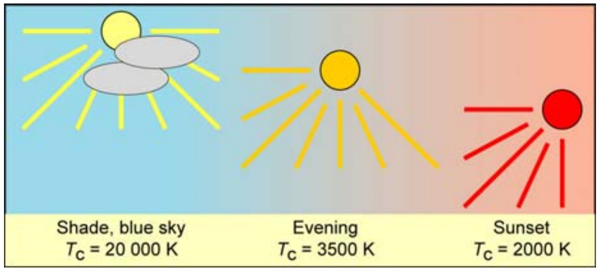
$$\lambda \quad \mathcal{E}_{\perp\parallel} \quad T_C \quad \tau \quad (x,y,z)$$











Conclusions

- Novel types of reflectors enable highly efficient light-emitting devices
- Materials with extreme refractive indices required
- New low-*n* material demonstrated in ODR application ***n* = 1 .08**
- Mirror loss **100 times** lower than in metal reflectors
- High-refractive index encapsulants
- **Remote phosphor** distributions demonstrated with higher performance
- Figures of merit: Luminous efficiency, color temperature, and color rendering capability
- Novel applications driven by **Smart Lighting Sources**