Innovations in Light-Emitting Diodes and Solid-State Lighting

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Outline

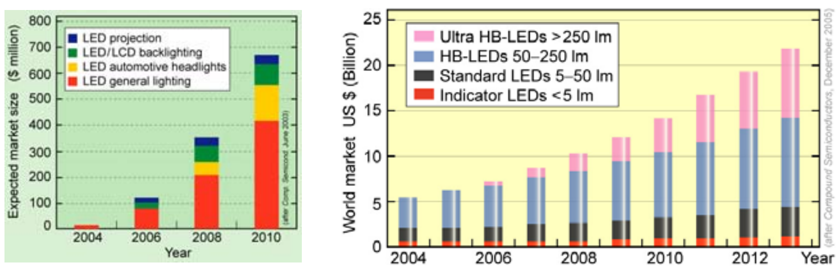
- **Introduction**
- **Materials:**
  - **Reflectors**
  - **Diffuse reflectors**
  - **New materials with very low refractive index**
  - **New materials with very high refractive index**
- **Devices:**
  - **White LEDs with remote phosphors**
  - **Solid-state lighting**
  - **Junction temperatures**
- **Systems:**
  - **Color rendering and luminous efficiency**
  - **Limits in efficiency and color rendering**
  - **Dichromatic and trichromatic sources**
- **Future:**
  - **Smart Lighting Systems**

Obsolete and traditional applications

Recent applications (not all of them are saving power)

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

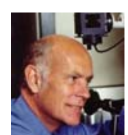


Predicted growth of LED market

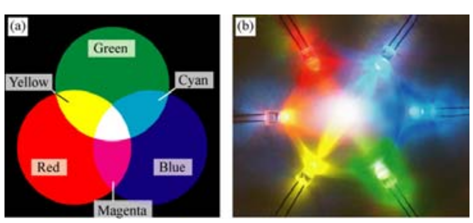
Energy Conservation – A Singular Opportunity

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

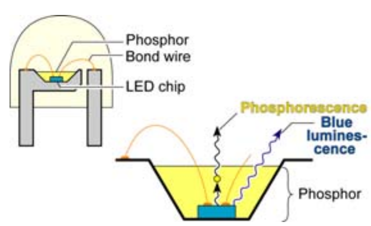
Testimony to US Senate Committee on Energy and Natural Resources, April 27, 2004


1943 – 2005

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



Multiple light-emitting diodes



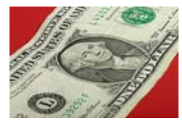
LED with wavelength (λ) converter

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 1,200 TWh (Tera = 10^{12})
  - 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

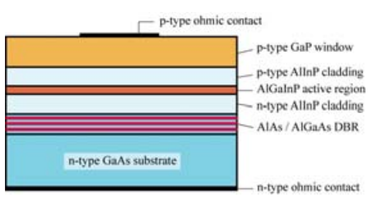


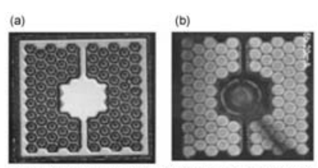
(*) 1.0 PWh = 11.05 PBtu = 11.05 quadrillion Btu "=" 0.1731 Pg of C = 173.1 Mtons of C
1 kg of C "=" [(12 amu + 2 × 16 amu) / 12 amu] kg of CO_2 = 3.667 kg of CO_2
OIDA and DOE predictions for US by 2025, see also R. Haitz *et al. Adv. in Solid State Physics*, *Physics Today* 2001
Economic benefits were 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

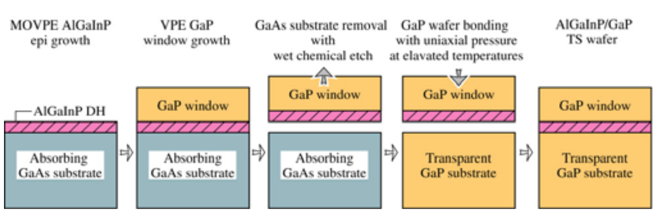
Example of **reflective** structure: (after Osram Corporation)





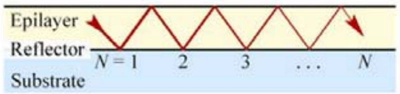
Top view (a) andi llumination pattern (b) of a 615-nm thin-film LED (after Streubel et al., 2002)

Example of **transparent** structure: (after Lumileds Corporation)



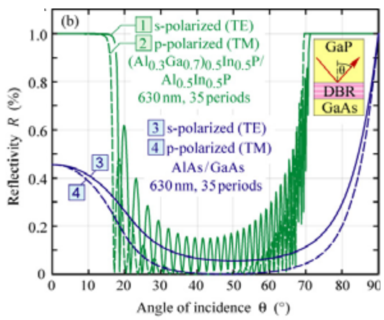
Why reflectors?

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

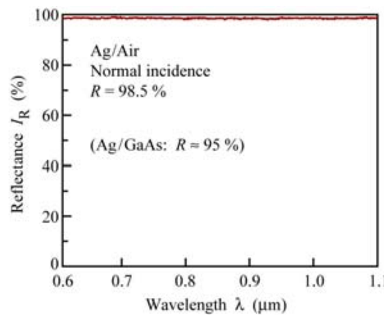


High reflectivity is important!

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



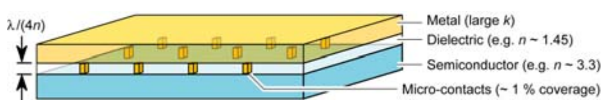
DBR



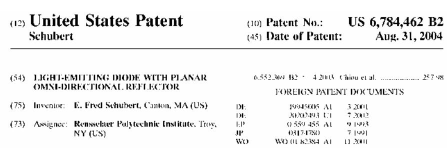
Metal reflector

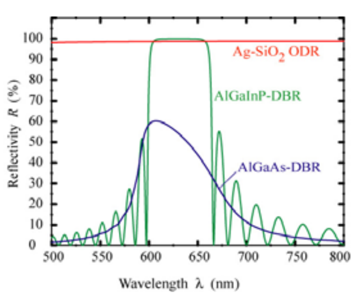
Triple-layer omni-directional reflector (ODR)

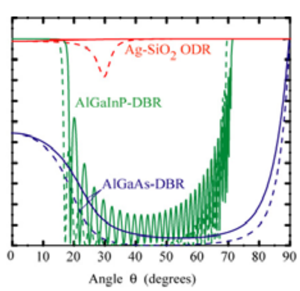
Planar semiconductor / dielectric / metal reflector perforated by an array of micro-contacts.



- 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)
FOREIGN PATENT DOCUMENTS





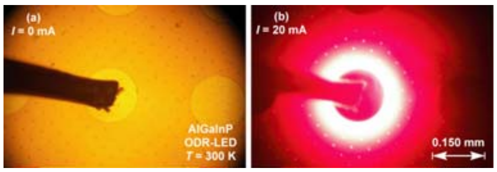
AlGaInP and GaInN LEDs with ODR

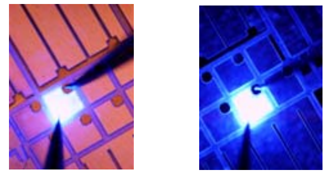
AlGaInP LED

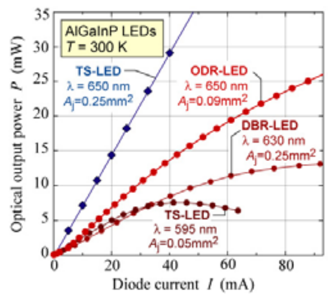
λ = 650 nm, MQW active region
AlGaAs window layer
GaAs substrate removed, Si submount

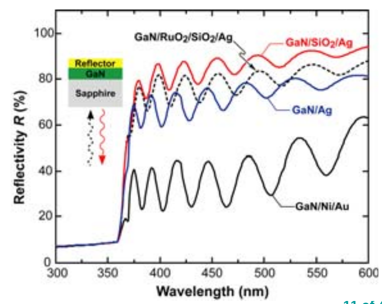
GaInN LED

λ = 460 nm, MQW active region
Sapphire substrate

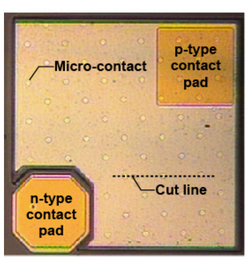




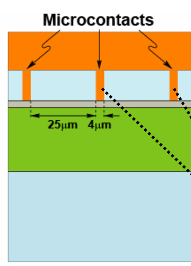




GaInN LEDs with omni-directional reflector (ODR)

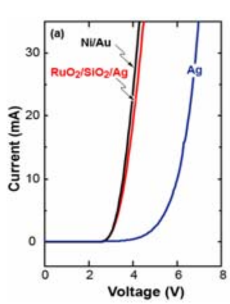


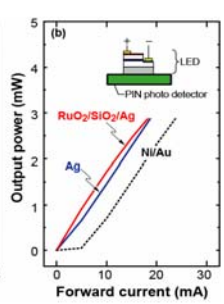
Top view



Cross-sectional view

- **Ag**
- **SiO_2 low index layer [λ/(4*n*)]**
  - high index contrast
- **RuO_2 layer (~6 nm)**
  - low resistance ohmic contact
  - virtually transparent contact
  - current spreading layer
- **Ag micro-contacts (~1% coverage)**
  - electrical conduction: Ag - RuO_2



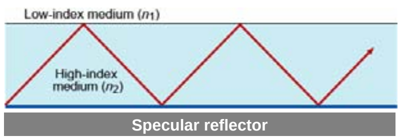


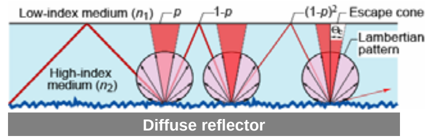
- The ODR-LEDs show
  - lower V_f than LEDs with Ag contact
  - Comparable V_f to LEDs with Ni/Au
  - Higher Light output

Kim *et al*., *Appl. Phys. Lett.* **Vol. 84**, p. 4508 (May 2004)

Employment of specular and diffuse reflectors in GaInN LEDs

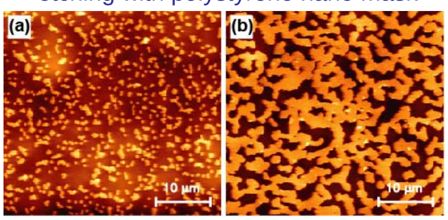
- Specular versus diffuse reflectors





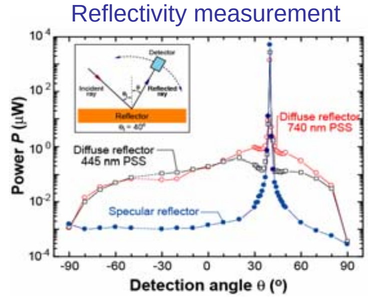
- Waveguided modes are trapped modes in specular reflector
- Light escape enabled by roughening reflector surface: diffuse reflector

AFM: Diffuse reflector roughened by dry etching with polystyrene nano mask



(a) Polystyrene 400 nm (b) Polystyrene 700 nm

Reflectivity measurement



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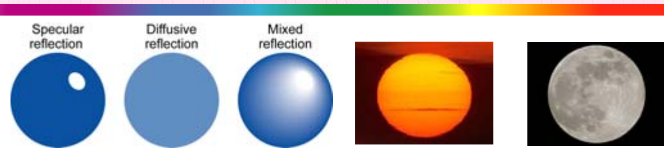
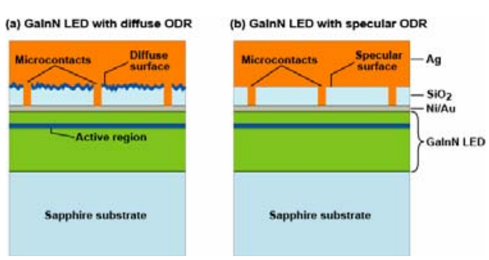
Employment of diffuse reflectors in GaInN LEDs



Illuminated sphere – Visualization of different types of reflectivities

LED structure with

Diffuse ODR Specular ODR



Experiments:
Improvement is 6.6 % for light reflected off diffuse reflector

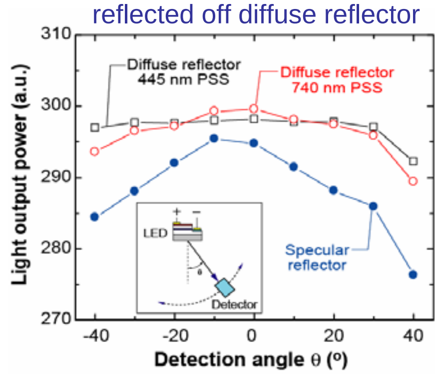


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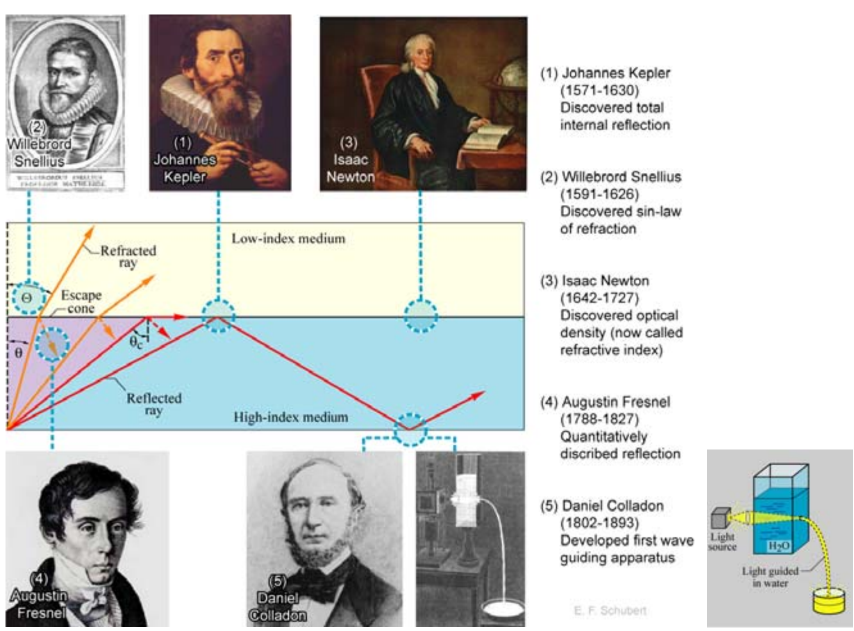
Figure of merit for DBR: Index contrast Δn

- **Fresnel reflectance of interface** $$r = \frac{n_h - n_l}{n_h + n_l} = \frac{\Delta n}{n_h + n_l}$$
- **DBR reflectance** $$R_{DBR} = |r_{DBR}|^2 = \left[\frac{1 - (n_l / n_h)^{2m}}{1 + (n_l / n_h)^{2m}} \right]^2$$
- **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***

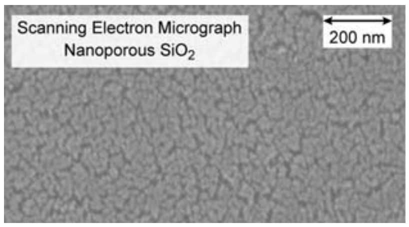
➔ ***New materials are required***

From total internal reflection … to waveguiding

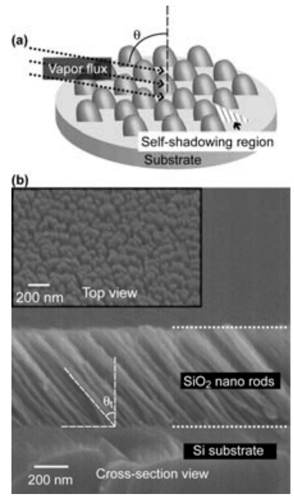


New class of materials: Low-*n* materials

- **Dense materials *n* ≈ 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**
  - Lu et al., 2005
  - Technique was developed in the 1950s
- **Both techniques suitable for low-loss LEDs**



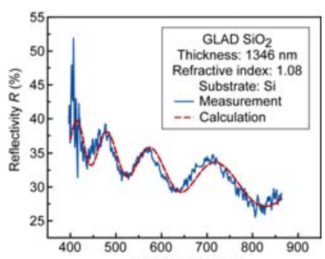
Low-*n* xerogels, after Gill and Plawsky, 2005



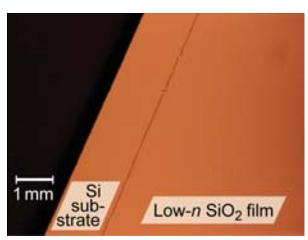
Low-*n* SiO_2

Triple-layer ODRs with nano-porous silica

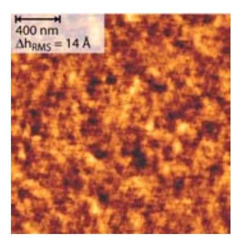
- Pore sizes << λ (Rayleigh scattering)
- Pore sizes 2 – 8 nm achieved
- Maxwell's equations: $n^2 = \varepsilon_r$ (= k)
- Low-*k* material in Si technology (field dielectric)
- Low-*n* films are new class of materials with distinct properties



Thin-film interference



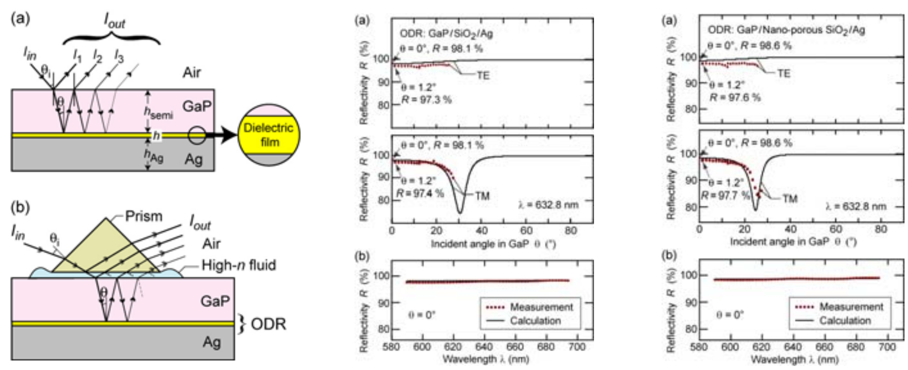
Optical micrograph



Atomic force micrograph

***n* = 1.08 – world record!**

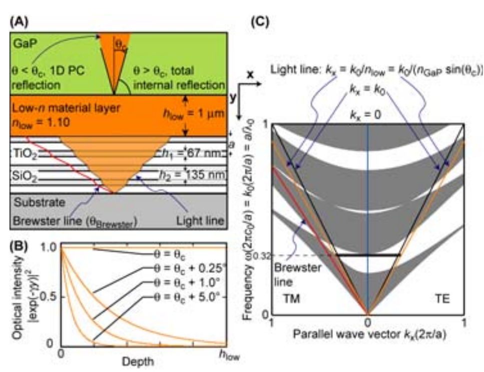
Low-index layer and reflector data

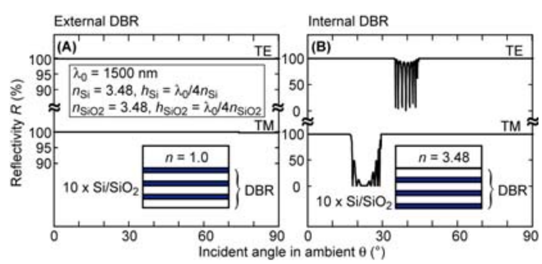


- Reflector has **100 × lower** mirror losses than metal reflectors
- Reflector has **> 100 × lower** mirror losses than DBRs
- Suitable for low-loss LEDs

DBR not suitable for high-index media

- New reflector uses
- Total internal reflection for grazing angles
- DBR for near-normal angles
- New reflector consists of
  - Semiconductor
  - Low-index layer
  - DBR

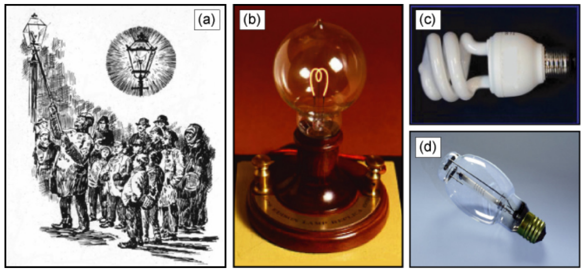




- DBR suitable as ***external*** reflector
- DBR unsuitable as ***internal*** reflector

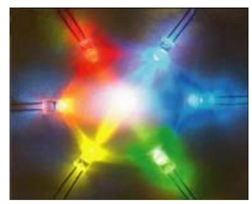
Solid-state lighting

Old lighting technologies



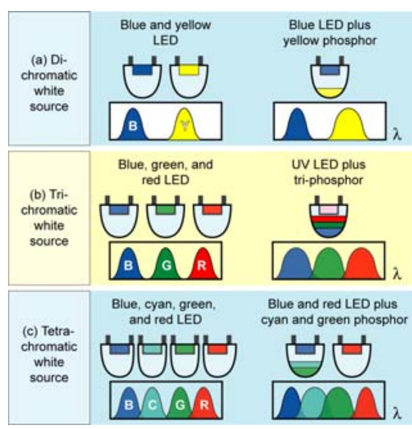
New lighting technologies

- Di-chromatic with phosphor: Commercial success but limited color rendering ability (CRI < 80)
- Phosphor approaches: Excellent color stability
- Phosphor approaches: *Stokes-shift* energy loss unavoidable
- Tri-chromatic LED-based approaches



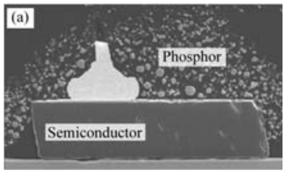
White LEDs

- **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

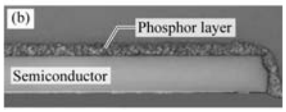


- **What is the optimum spatial distribution of phosphors?**
  - Proximate and remote distributions

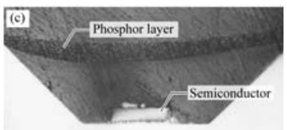
Innovation in white LEDs – Phosphor distribution



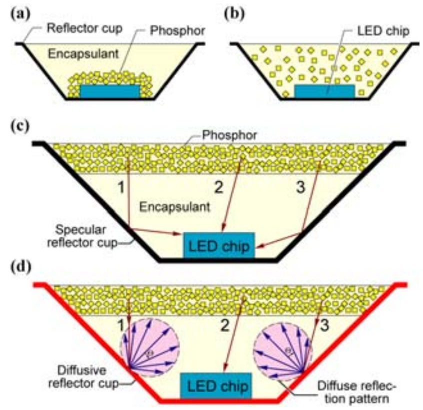
(a) **Proximate** distribution
(after Goetz et al., 2003)



(b) **Proximate** distribution
(after Goetz et al., 2003)



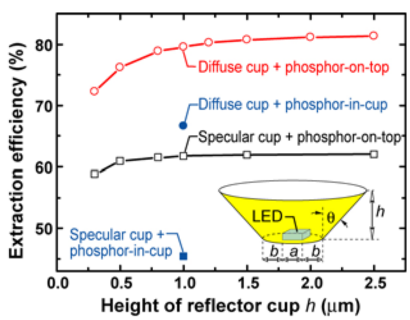
(c) **Remote** distribution
(after Kim et al., 2005)



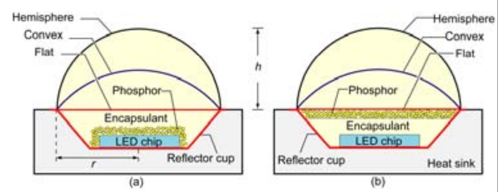
Remote phosphor distributions reduce absorption of phosphorescence by semiconductor chip

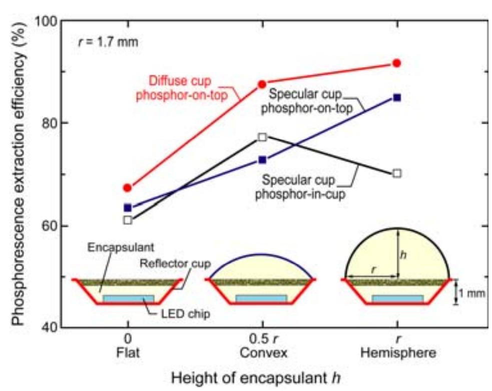
Kim *et al*., *Jpn. J. Appl. Phys. – Express Lett*. **44**, L 649 (2005)
Luo *et al*., *Appl. Phys. Lett*. **86**, 243505 (2005)
Narendran *et al*., *Phys. Stat. Sol. (a)* **202**, R60 (2005)

Ray tracing simulations

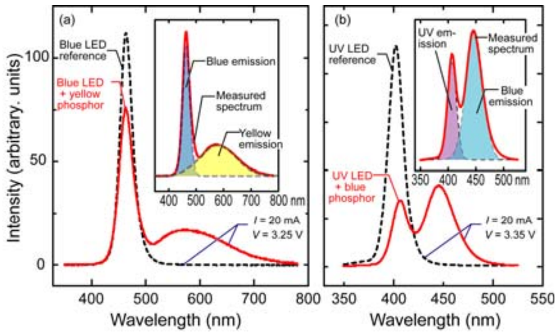


- **Ray tracing simulations prove improvement of phosphorescence efficiency for**
  - Remote phosphor
  - Diffusive reflector cup

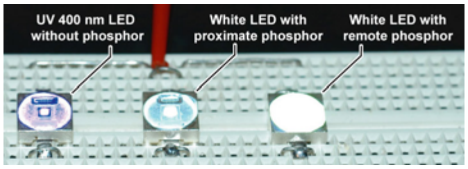




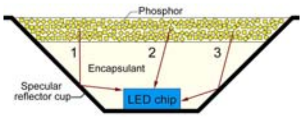
Experimental results

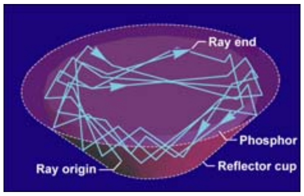


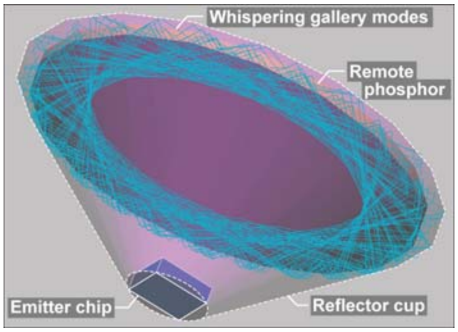
- Improvement of phosphorescence efficiency:
  - 15.4 % for blue-pumped yellow phosphor
  - 27.0 % for UV pumped blue phosphor



Novel loss mechanisms in white lamps with remote phosphor

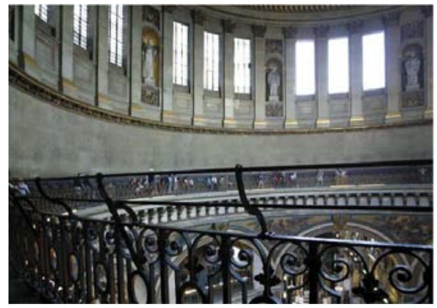




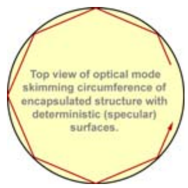


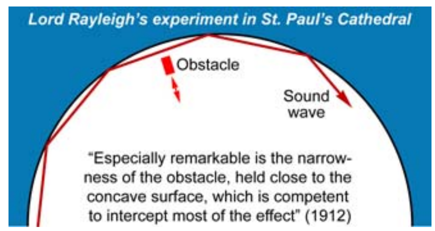
- ***Diffuse reflectors***
  - Non-deterministic element that breaks symmetry
  - Suppression of trapped whispering-gallery modes

Whispering-gallery modes in St. Paul's Cathedral (London)



Lord Rayleigh
(1842–1919)

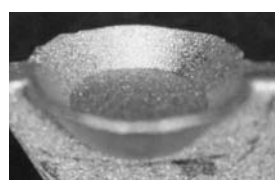




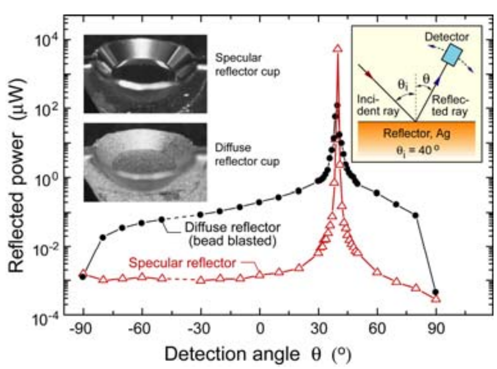
"Whispering Gallery"

Remote phosphors with diffuse and specular reflector cups

Specular reflector cup

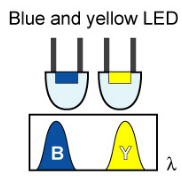


Diffuse reflector cup

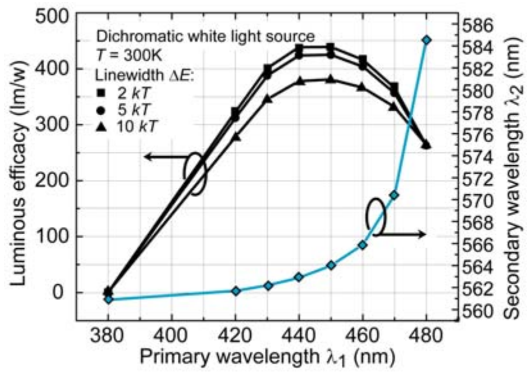


- Reflectance versus angle
- Surface texture by bead blasting
- Diffuse reflectance increased by two orders of magnitude

Luminous efficacy of dichromatic white sources



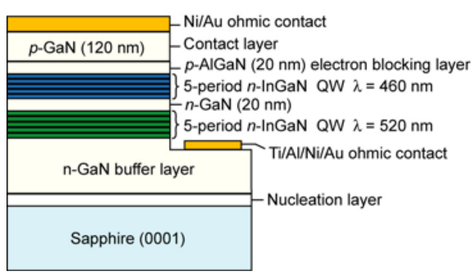
Fundamentally the **most efficient way** to create white light



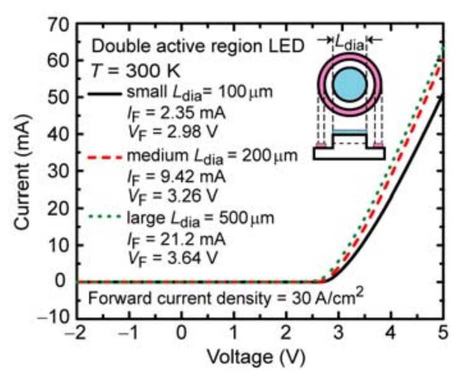
- Di-chromatic source has outstanding luminous efficacy (> 400 lm/W)
- However, color rendering is unsuitable for daylight illumination applications
- Great display device (e.g. pedestrian traffic signal, display, etc.)

Monolithically integrated two-active region LED

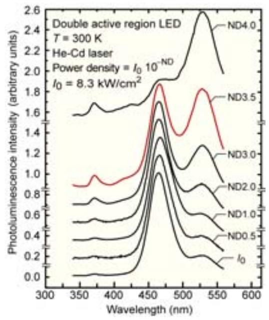
Device structure

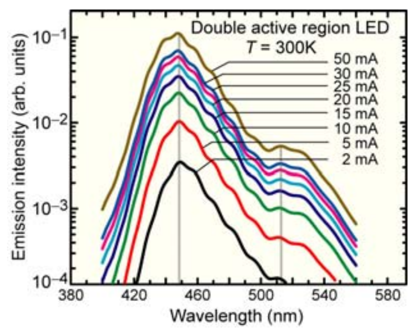


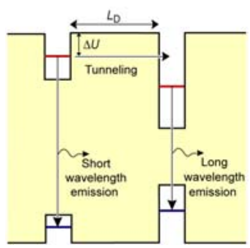
***I-V* characteristic**



Photoluminescence and electroluminescence

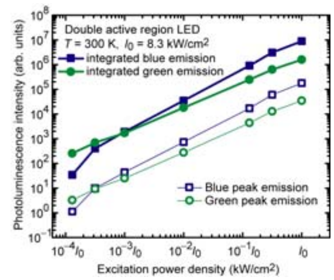






Tunnel model can explain different injection efficiency

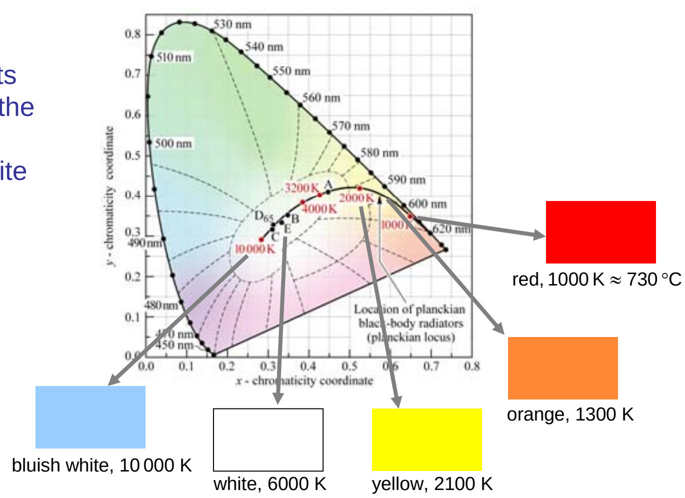
Intensity ratio is constant!



Color Temperature

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

Example: Red-hot horseshoe



- 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

Low CRI illumination source

High CRI illumination source

Clear differences in the color rendition can be seen in this painting

Color rendition

- The color rendering capability *of a test light source* is measured in terms of the *color rendering index*
- Color rendering index of a high-quality *reference light source* is CRI = 100
- An incandescent light source with the same color temperature serves as the reference light source
- Eight color sample objects serve as test objects

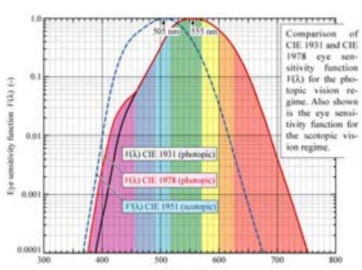
- **Example**:

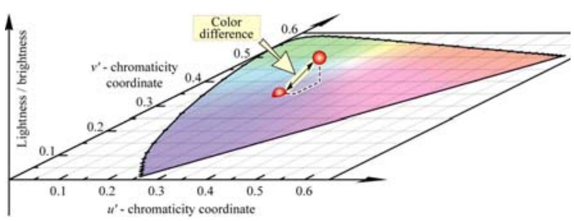
Color sample under reference source illumination

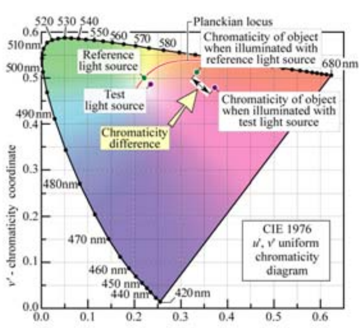
Color sample under test source illumination

➔ slight difference in color!

Luminous efficacy and color rendering







CIE color definition:

Color = Brightness, hue, and saturation

Color rendering index:

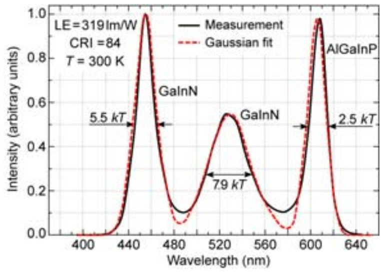
$CRI = 100 - \Sigma_{i=1...8} \Delta E_i^*$

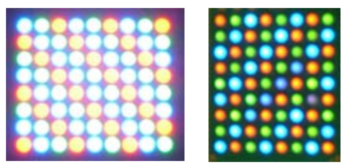
ΔE_i^* depends on color change and on luminance (brightness) change of object!

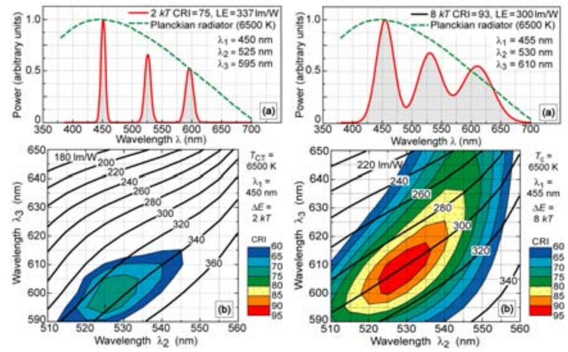
Further complication: Chromatic adaptation and adaptive color shift.

CRI is good metric – but not perfect!

Demonstration of trichromatic source

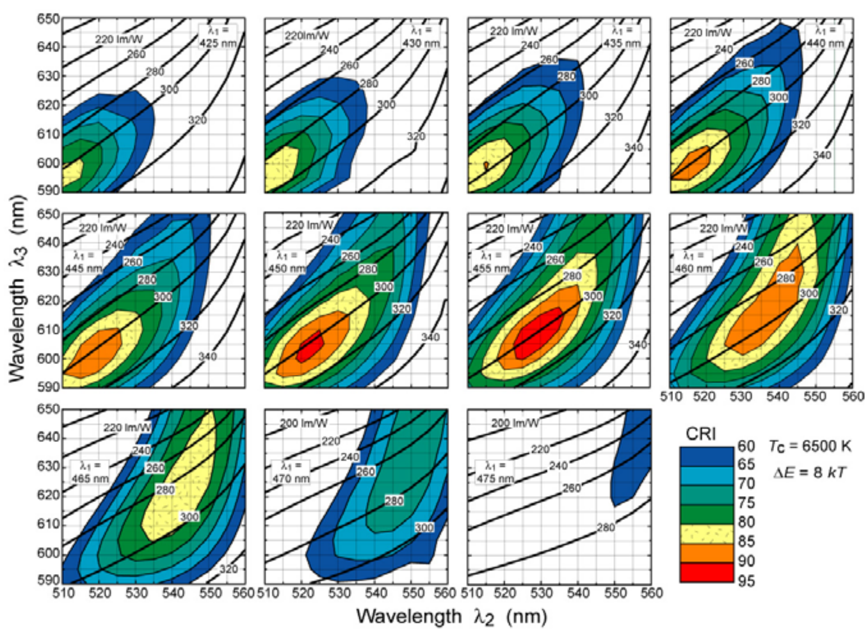






- CRI depends strongly on alloy broadening
- Trichromatic approach demonstrated with 32 lm/W and CRI of 84
- 64 lm/W possible at this time (CRI = 84)

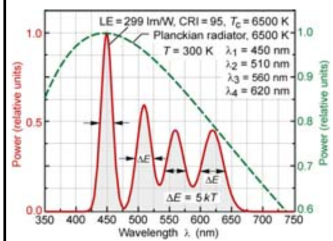
Luminous efficacy and CRI for tri-chromatic source

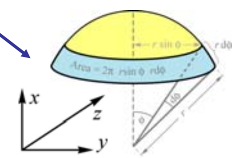


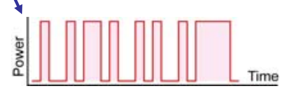
The Future: Smart Sources

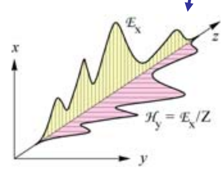
Smart light sources can be controlled and tuned to adapt to different requirements and environments

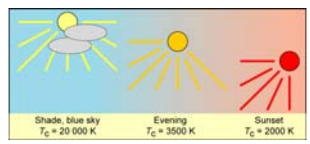
$$\lambda \quad \mathcal{E}_{\perp\parallel} \quad T_C \quad \tau \quad (x,y,z)$$









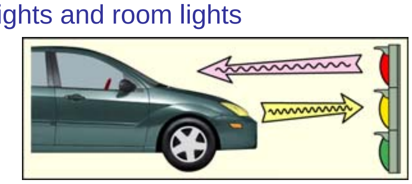


The Future: Smart Sources

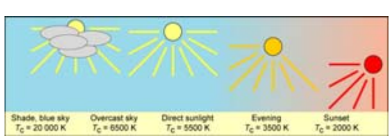
Smart light sources will enable a wealth benefits and new functionalities

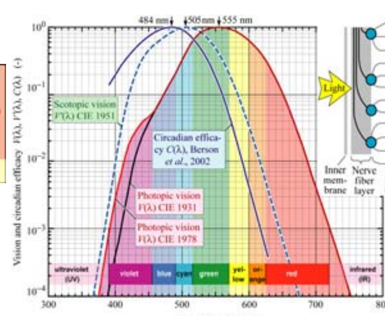
- Example: Communicating automotive lights and room lights

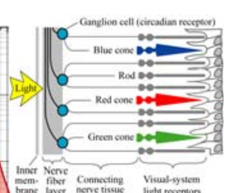




- Example: Circadian lights

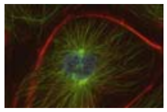






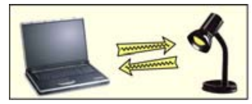
The Future: Smart Sources

- **Bio-imaging systems**



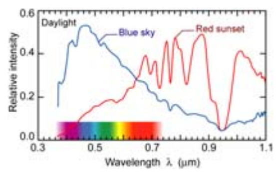
No phototoxicity!
Fast recognition!

- **Communications systems**



New modes of communication!

- **Circadian lighting systems**



Support of human health!

- **Transportation systems**

Safety!

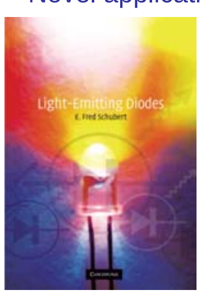
- Agriculture

- Space

- Display

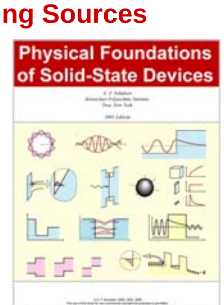
Conclusions

- Novel types of reflectors enable highly efficient light-emitting devices
- New low-*n* material demonstrated in ODR application ***n* = 1 .08**
- Mirror loss **100 times** lower than in metal reflectors
- High-refractive index encapsulants would be very beneficial
- **Remote phosphor** distributions demonstrated with higher performance
- Luminous efficiency, color rendering capability, and color temperature:
- Dichromatic source **> 400 lm/W** (with low CRI)
- Trichromatic source **> 300 lm/W** (with high CRI)
- Novel applications driven by **Smart Lighting Sources**



Light-Emitting Diodes, E. F. Schubert, *ISBN: 0521823307,* Publication 2003, 328 pages 154 diagrams, 21 half-tones, 21 tables

This book covers all aspects of the technology and physics of infrared, visible-spectrum, and white-light-emitting diodes (LEDs) made from III–V semiconductors.



Free textbook
"Physical Foundations of Solid-State Devices"
E. F. Schubert
www.rpi.edu/~schubert

www.LightEmittingDiodes.org