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

United States

Germany

Japan

Taiwan
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

![Expected market size and world market value over years](chart.png)

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

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

Multiple light-emitting diodes

LED with wavelength (\( \lambda \)) converter
Quantification of Solid-State Lighting Benefits

- **Energy benefits***
  - 22% of electricity used for lighting
  - LED-based lighting can be \(20\times\) more efficient than incandescent and \(5\times\) 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 \(\text{CO}_2\) emissions, 952 Mtons, global warming gas
  - Reduction of \(\text{SO}_2\) emissions, acid rain
  - Reduction of \(\text{Hg}\) emissions by coal-burning power plants
  - Reduction of hazardous \(\text{Hg}\) in homes

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

(*\) 1.0 PWh = 11.05 PBtu = 11.05 quadrillion Btu
\(\approx\) 0.1731 Pg of C = 173.1 Mtons of C\n1 kg of C \(\approx\) \( [(12\text{ amu} + 2 \times 16\text{ amu}) \div 12\text{ amu}] \) kg of \(\text{CO}_2 = 3.667\) kg of \(\text{CO}_2\)

OIDA and DOE predictions for US by 2025, see also R. Haiz 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.)

![Reflective structure diagram](image)

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

![Transparent structure diagram](image)
Why reflectors?

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

- **DBRs**: transparent for oblique incidence angles; **Metal mirror**: $R < 95\%$

- **DBR** and **metal mirrors** are unsuitable!

[Diagram showing reflectivity and polarization for DBR and 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
**AlGaInP and GaInN LEDs with ODR**

**AlGaInP LED**
\[ \lambda = 650 \text{ nm}, \text{ MQW active region} \]
AlGaAs window layer
GaAs substrate removed, Si submount

**GaInN LED**
\[ \lambda = 460 \text{ nm}, \text{ MQW active region} \]
Sapphire substrate

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**Graphs and Images:**
- AlGaInP LEDs with ODR, showing optical output power vs. diode current.
- Reflectivity R (%) vs. Wavelength (nm) for different GaN and GaAlN layers.
Figure of merit for DBR: Index contrast $\Delta n$

- Fresnel reflectance of interface

- DBR reflectance

- Spectral width of stop band

- Penetration depth

- Critical angle (max. angle for high reflectivity)

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

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

\[ \Delta \lambda_{\text{stop}} = \frac{2 \lambda_{\text{Bragg}} \Delta n}{n_{\text{eff}}} \]

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

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

- By increasing index contrast $\Delta n$, figures of merit improve

- New materials are required
New class of materials: Low-\textit{n} materials

- Dense materials $n \approx 1.4$: $\text{SiO}_2 (n = 1.45)$; $\text{MgF}_2 (n = 1.39)$
- Low-\textit{n}: refractive index $n < 1.25$
- Xerogels (porous $\text{SiO}_2$)
- Oblique-angle evaporation
  - Technique was developed in the 1950s
  - Lin, Lu et al., 2002
- Both techniques suitable for low-loss LEDs
Triple-layer ODRs with nano-porous silica

- Pore sizes $\ll \lambda$ (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

World record! $n = 1.08$
- Reflector has $100 \times$ lower mirror losses than metal reflectors
- Reflector has $>100 \times$ 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** ($)

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**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

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

- 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.

- 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.

Example: Red-hot horseshoe.

- Red, $1000\,K \approx 730^\circ C$.
- Orange, $1300\,K$.
- Bluish white, $10,000\,K$.
- White, $6000\,K$.
- Yellow, $2100\,K$. 

![Color Temperature Diagram](image)
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

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

Note the differences in color
Smart light sources can be controlled and tuned to adapt to different requirements and environments.
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