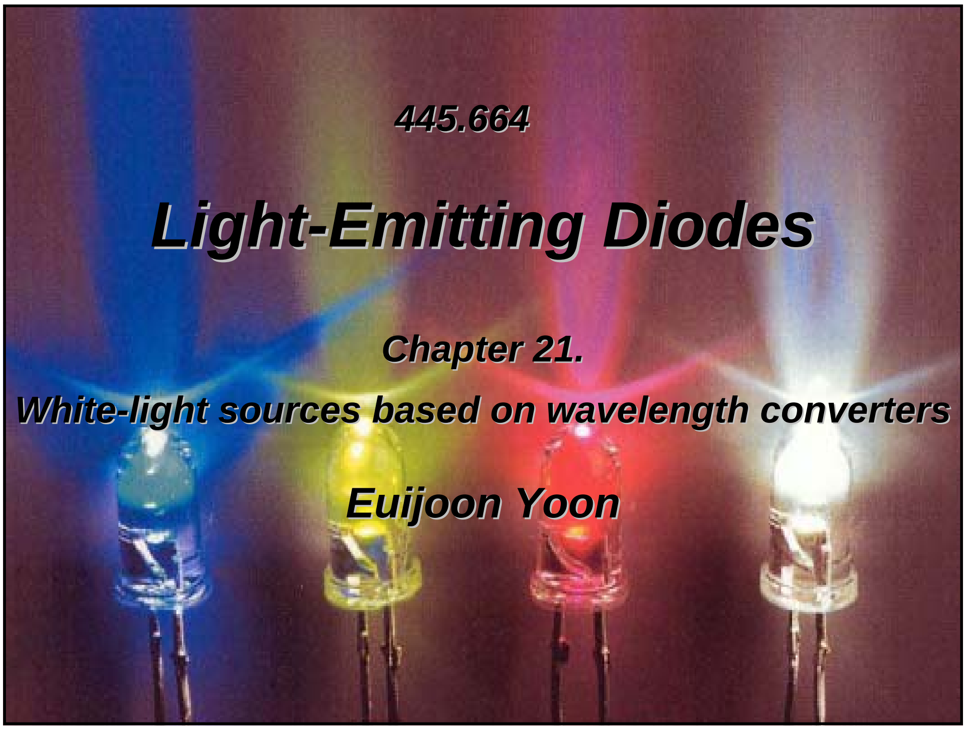

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Light-Emitting Diodes

Chapter 21.

White-light sources based on wavelength converters

Euijoon Yoon

White sources using phosphors

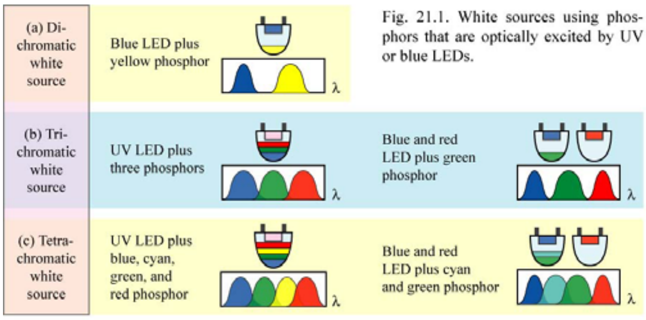

Fig. 21.1. White sources using phosphors that are optically excited by UV or blue LEDs.

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- **The luminous source efficiency decreases with increasing multi-chromaticity of the source.**
  - **Dichromatic sources : highest potential luminous source efficiency**
- **Color-rendering capability is lowest for dichromatic sources.**
- **Close to CRI=100 for tetrachromatic sources**

Wavelength-converter materials

- There are different types of wave-length converters.
  - Dyes
  - Phosphors
  - Semiconductors
- Phosphor converters are most common type of converter.
  - Ce-doped YAG (yttrium aluminum garnet) is a common type of converter.
  - Phosphor based white light emitters are very stable (no temperature dependence).
- Semiconductors and dyes have used as converters but are not very common.
  - Narrow emission lines with linewidth of the order of 2kT
  - Emission spectrum with good precision

Wavelength converter materials - phosphors

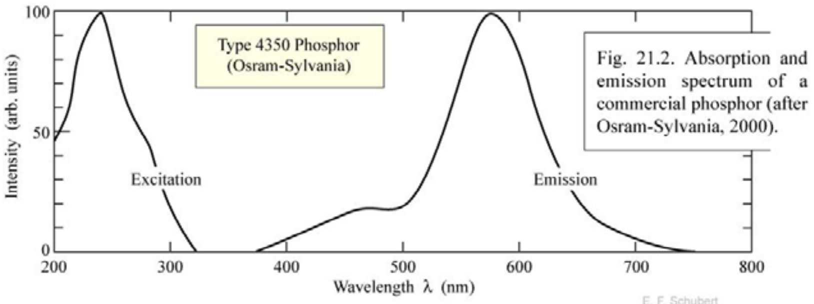

Fig. 21.2. Absorption and emission spectrum of a commercial phosphor (after Osram-Sylvania, 2000).

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- Typical phosphor used in a fluorescent tube
- Very stable, quantum efficiency ~100%
- Hg-lamp excitation at 200-250 nm
- Typical LED excitation at 405 nm

Wavelength converter materials - dyes

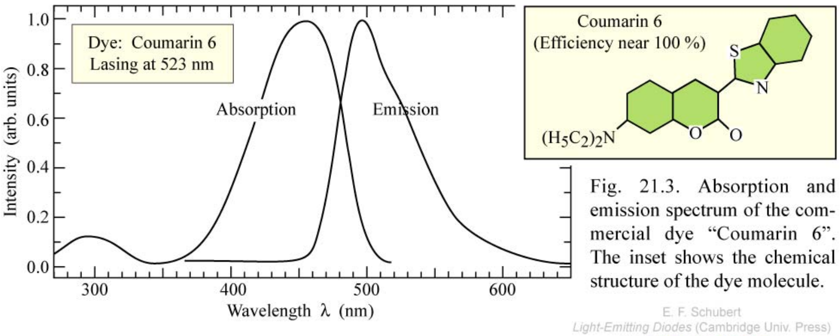

Fig. 21.3. Absorption and emission spectrum of the commercial dye "Coumarin 6". The inset shows the chemical structure of the dye molecule.

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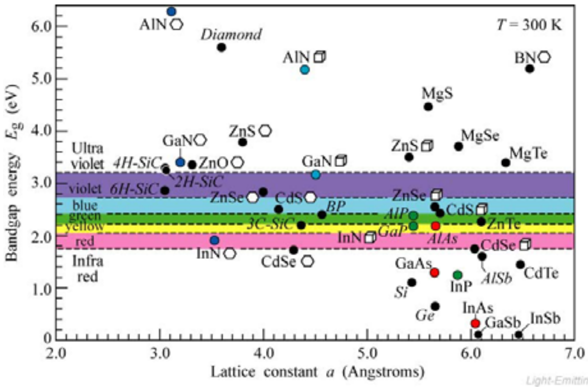
- **Quantum efficiency ~100%**
- **Lack of long term stability afforded by phosphors and semiconductors**

Wavelength converter materials - semiconductors



"*Italics*" = indirect gap
"Roman" = direct gap
○ hexagonal structure
▢ cubic structure

Fig. 21.4. Room-temperature bandgap energy versus lattice constant of common elemental and binary compound semiconductors.

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- **Internal quantum efficiency ~100%**
- **Great variety of semiconductors is available.**
- **Using ternary or quaternary alloys, wavelength converters operating at virtually any visible wavelength can be fabricated.**

YAG phosphor

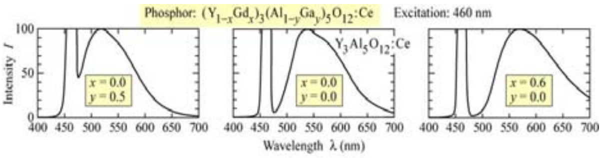

Fig. 21.5. Emssion spectrum of Ce-doped yttrium aluminum garnet (YAG:Ce) phosphor for different chemical compositions. The excitation wavelength is 460 nm (after Nakamura and Fasol, 1997).

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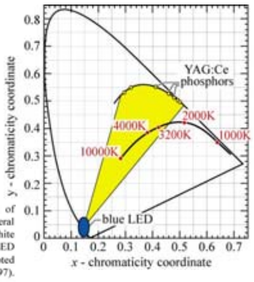

Fig. 21.6. Chromaticity points of YAG:Ce phosphor, and the general area (shaded) accessible to white emitters consisting of a blue LED and YAG:Ce phosphor (adopted from Nakamura and Fasol, 1997). Also shown in the planckian locus with color temperatures.

- Phosphors consist of an inorganic host material doped with an optically active element.
  - Common host : garnet ($A_3B_5O_{12}$)
  - Common host material
    - Yttrium aluminum garnet (YAG)
    - $Y_3Al_5O_{12}$
  - Dopant : Rare earth materials (Ce, Nd, Er, Th, etc.)

White LEDs based on phosphor converters

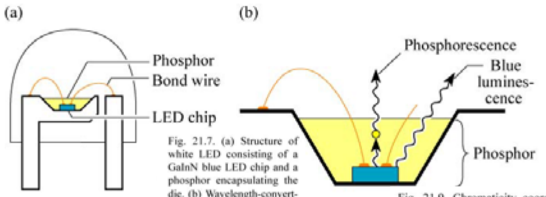

Fig. 21.7. (a) Structure of white LED consisting of a GaInN blue LED chip and a phosphor encapsulating the die. (b) Wavelength-converting phosphorescence and blue luminescence (after Nakamura and Fasol, 1997).

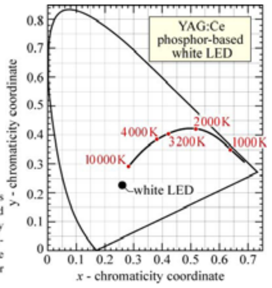

Fig. 21.9. Chromaticity coordinates of a commercial phophor-based white LED manufactured in 2001 by Nichia Corporation (Anan, Tokushima, Japan). Also shown is the planckian locus and associated color temperatures.

- Emission color is white with a bluish tint.

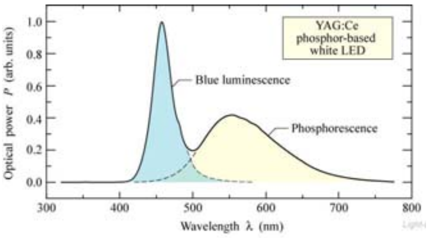

Fig. 21.8. Emission spectrum of a phosphor-based white LED manufactured by Nichia Corporation (Anan, Tokushima, Japan).

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Spatial phosphor distribution

Fig. 21.11. (a) Proximate phosphor distribution, (b) proximate conformal phosphor distribution, and (c) remote phosphor distribution in which phosphor and chip are separated by at least one times the lateral dimension of the chip (after Kim *et al*., 2005).

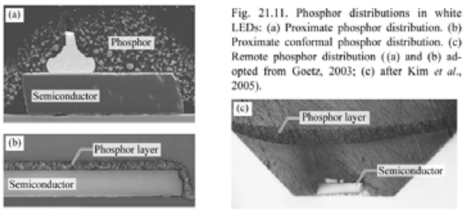

Fig. 21.11. Phosphor distributions in white LEDs: (a) Proximate phosphor distribution. (b) Proximate conformal phosphor distribution. (c) Remote phosphor distribution ((a) and (b) adopted from Goetz, 2003; (c) after Kim *et al*., 2005).

- Three phosphor distributions
  - Proximate phosphor distribution
    - Larger phosphor particles close to the chip surface
  - Conformal phosphor distribution
    - Point-like source
    - Small emission area and high luminance
  - Remote phosphor distribution
    - To overcome the drawback of proximate phosphor distribution
      - -Absorption of phosphorescence by the semiconductor chip
    - Less phosphorescence impinges on the low-reflectance semiconductor chip due to the spatial separation

---

UV-pumped phosphor-based white LEDs

- White LEDs can also be fabricated with optical excitation of phosphor in the UV range.
  - Conventional semiconductor sources : 320~390 nm , 390~410 nm
- For deep-UV semiconductor sources (200~320 nm)
  - Conventional phosphors used in fluorescent lighting can be used for wavelength conversion.
  - Drawback : large Stokes shift
- CRI of 60~100
- A fundamental drawback of UV-pumped white LEDs is the energy loss (Stokes shift) incurred when converting UV light to white light.

White LEDs based on semiconductor converters

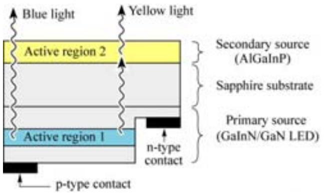

Fig. 21.12. Schematic structure of a photon-recycling semiconductor LED with one current-injected active region (Active region 1) and one optically excited active region (Active region 2) (after Guo *et al.*, 1999).

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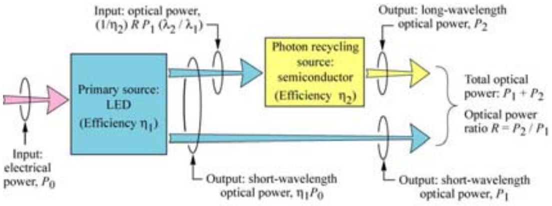

Fig. 21.13. Photon-recycling semiconductor LED power budget with electrical input power P_0 and optical output power P_1 and P_2.

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- **A fraction of the light emitted by the blue GaInN LED is absorbed by a AlGaInP secondary active region and re-emitted (or "recycled") as lower-energy photons.**

Photon recycling LED (PRS-LED)

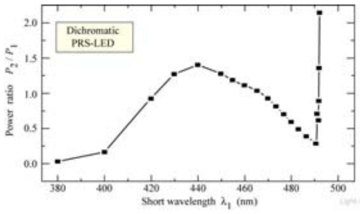

Fig. 21.14. Calculated power ratio between the two optical output powers P_1 and P_2 required to obtain white light emission (after Guo *et al.*, 1999).

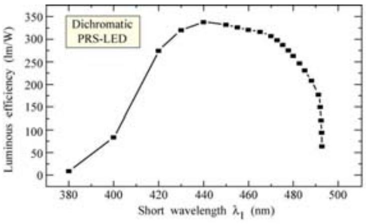

Fig. 21.15. Calculated luminous efficiency of a dichromatic PRS-LED versus its primary emission wavelength (after Guo *et al.*, 1999).

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- **Blue and red part of the spectrum**
- **All-semiconductor LED**

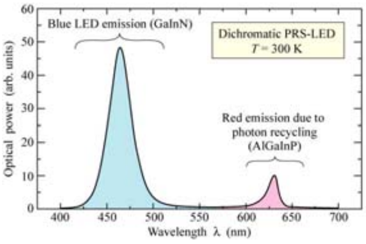

Fig. 21.16. Emission spectrum of dichromatic PRS-LED with current-injected GaInN blue LED primary source and AlGaInP photon recycling wafer (secondary source) emitting in the red (after Guo *et al.*, 2000).

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