Topic 17-18

17-18. Solid-state lighting (SSL) and white LEDs

Introduction

Earth's City Lights (Image from NASA))

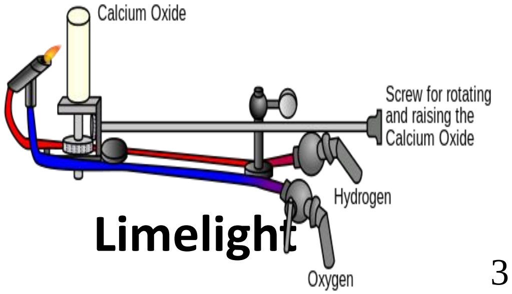
- Artificial lighting plays a vital role in the civilisation process.
- Artificial lighting shaped our health, safety, and happiness.

History of lighting: early stage

- 500,000 years ago- first torch
- 70,000 BC- first lamp; Dried plant material soaked in animal fat
- 3,000 BC- stone oil lamps
- 700 BC- Terracotta oil lamps used by Greeks

- 1792 - William Murdoch: gas lighting by heating coal
- 1807- Frederick Albert Winsor: light up the street of Pall Mall, London, with gas lighting
- 1826- Thomas Drummond: Limelight

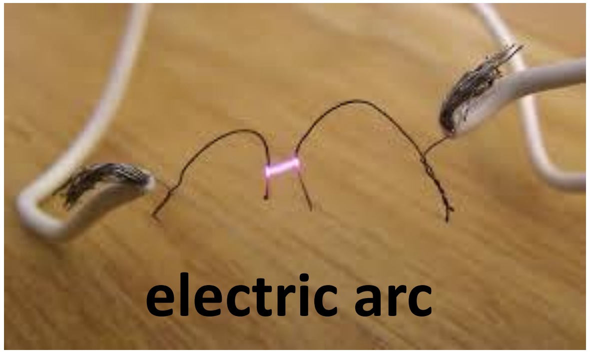
Gas lighting

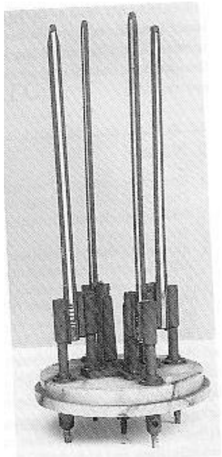


Limelight

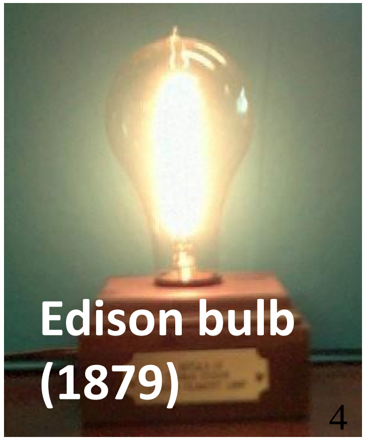
History of lighting: electric lighting

- 1663- Otto von Gericke: demonstrate 1st electric arc
- 1809- Humphry Davy: electric carbon arc
- 1876- Pavel Yablochkov: 1st practical electric lighting
- 1878- Joseph Swan: demonstrated 1st practical incandescent lamp
- 1879- Thomas Edison Edison: demonstrated his lamp
- 1897- Nernst: a filament made of cerium oxide-based solid electrolyte
- 1900- Peter Cooper Hewitt: mercury vapor lamp.
- 1903- A. Just and F. Hanaman: tungsten filament
- 1938- GE and Westinghouse Electric Corporation put on the market the new colored and white fluorescent lamps.





Yablochkov (1876): 1st electric arc-based lighting



Global Warming and Energy Savings

End Use Applications*	
Motor Control	32%
Lighting	29%
Heating & Cooling	24%
Information Technology	15%

- U.S. DOE has chosen, energy efficient LED lighting to play the key role in reducing our electric light consumption by 50% by 2025

- Over the next 20 years, rapid adoption of LED lighting in the U.S. can:
  - Reduce electricity demands from lighting by 62%/year
  - Eliminate 300 million metric tons of carbon emissions/year
  - Avoid building 133 new power plants
  - Anticipate financial savings that could exceed $200 billion/year

Solid State Lighting- inorganic SSL

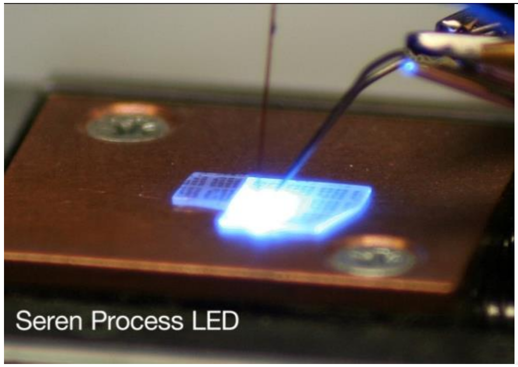
- Definition of solid-state lighting (SSL)
- Advantages of solid state lighting
- Category of solid-state lighting
- Key components of solid-state Lighting: LEDs
- Operational mechanism of LEDs
- Operational mechanism of white LEDs
- Fabrication of LEDs and white LEDs
- Characteristics of white LEDs
- Other applications of white LEDs
- Future development of solid-state lighting

Definition of solid-state lighting

• SSL: refer to a type of lighting that utilizes light-emitting diodes (LEDs), which are solid state as a sources of illumination rather than electrical filaments or gas.

• Term "solid-state“: refers to the fact that the light in an LED is emitted from a solid object—a block of semiconductor—rather than from a vacuum or gas tube, as in the case of incandescent and fluorescent lighting.

•Key components of SSL: semiconductor based LEDs



Category of solid-state lighting

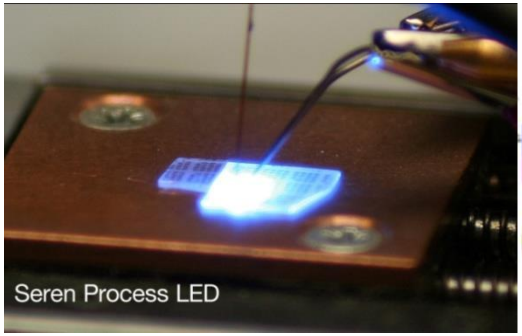
- **Inorganic LED (usually termed as LED):**

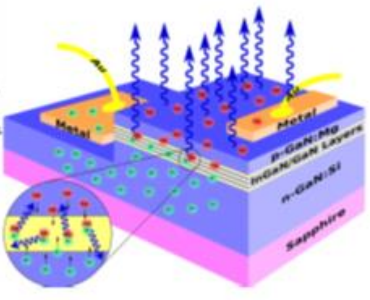
  Basically, III-V semiconductors

  470 nm InGaN (blue)

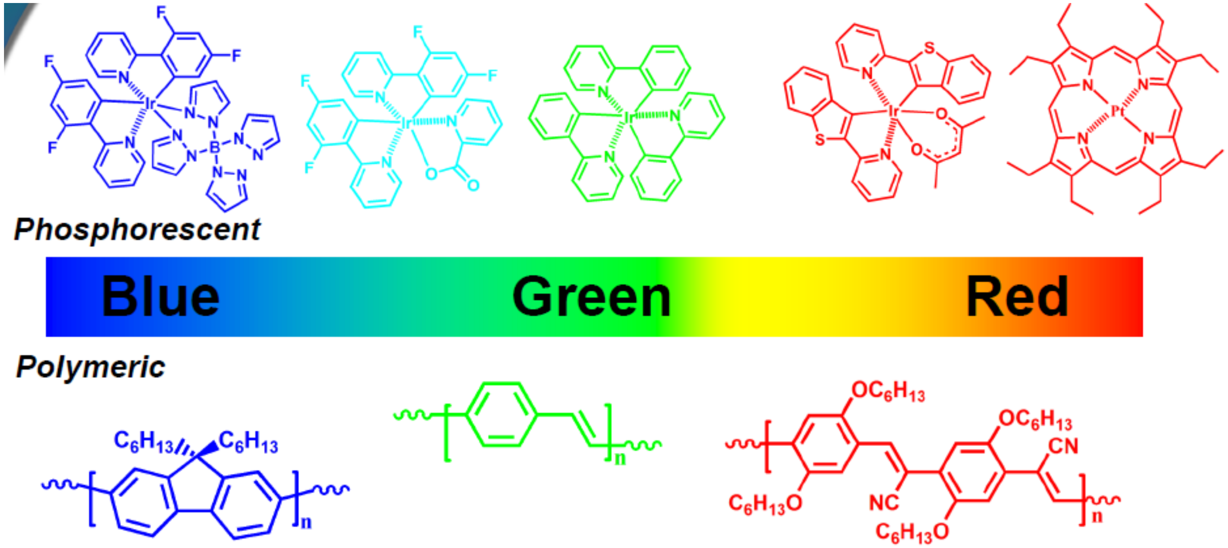
  540 nm InGaN (green)

  670 nm InGaP/AlGaInP (red)





- **Organic LED (usually termed as OLED):**



Color is determined by Molecular Structure

Major advantages of SSL (I)

• **Incandescent lamps (light bulbs)**: generate light by using electricity to heat a thin filament to a very high temperature and then producing visible light.

>90% of its energy is emitted as invisible infrared light (or heat) during the incandescing process (**highly inefficient!**)

Typical lifespan: **1,000 hours**.

• **Fluorescent lamps**: create light when electricity passes through mercury vapor to produce ultraviolet light, which is then absorbed by a phosphorous coating inside the lamp, generating glow or fluoresce.

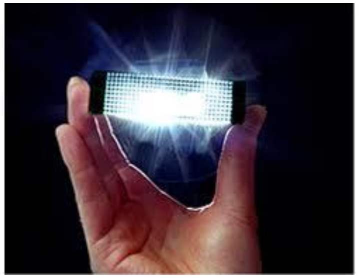
Energy loss in generating UV light & converting into visible light.

Mercury is **detrimental to health**

Typical lifespan: **10,000 hours**.

Major advantages of SSL (II)

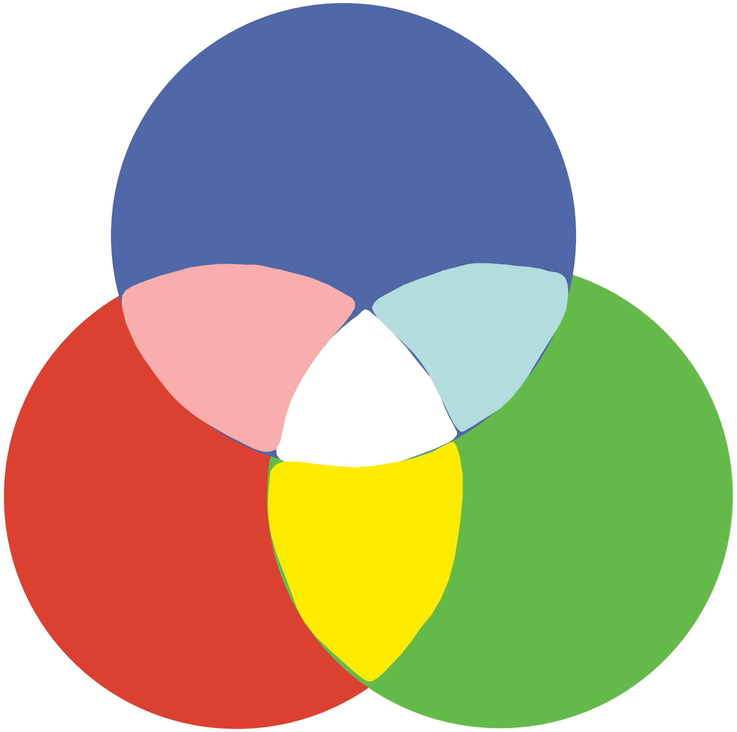
- SSL: grouping one or a number of LEDs creating a unified beam.
  - High durability - no filament or tube to break
  - Long life span - approximately 100,000 hours
  - Low power consumption
  - Flexible application – small size of LEDs devices
  - Low heat generation – very little energy loss

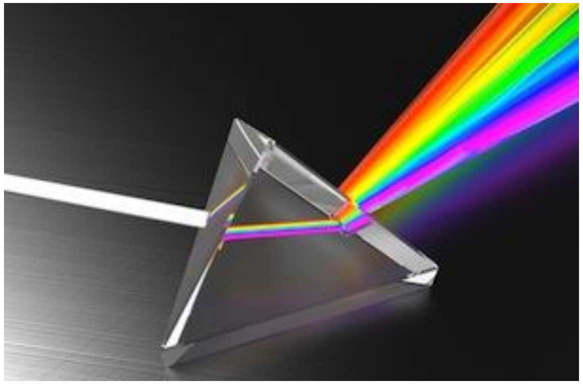


Light Source	Luminous Efficiency	Lifetime
Incandescent bulb	16 lumens/watt	1000 hours
Fluorescent lamp	85 lumens/watt	10,000 hours
Today's white LEDs	80-100 lumens/watt	20,000 hours
Future white LEDs	>200 lumens/watt	100,000 hours

White lighting

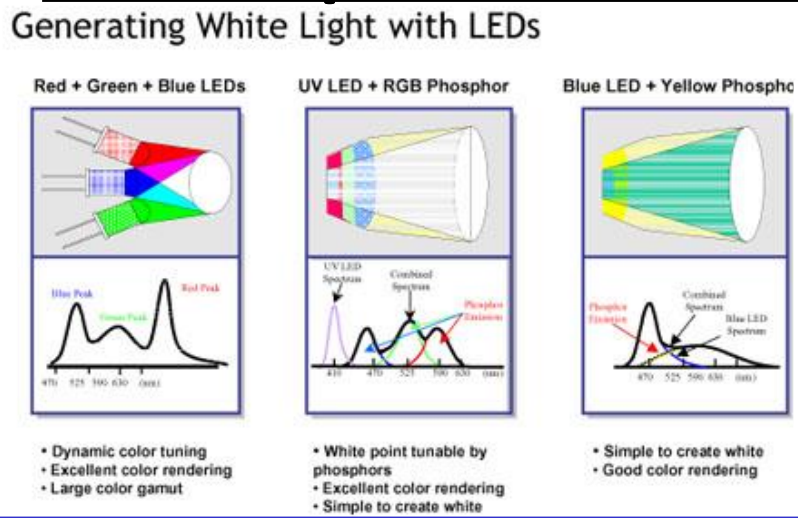
- Red + green: yellow
- Red + blue: magenta
- Green + blue: cyan
- Yellow (Red+ green)+ blue: white

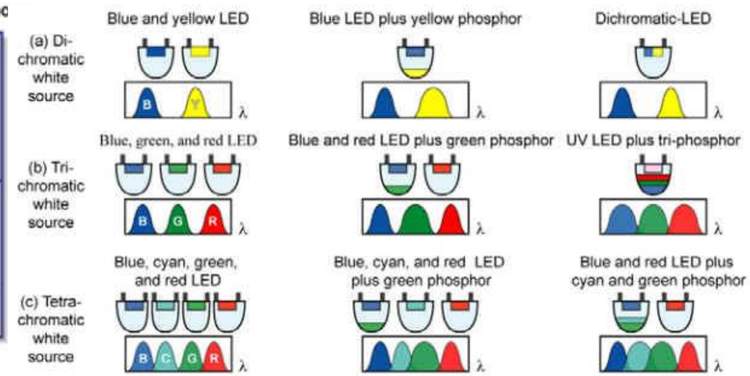




Newton originally (1672) divided the solar spectrum into 5 main colours (red, yellow, green, blue and violet). Later he included orange and indigo.

How to produce white light using inorganic LEDs?





Main components: UV, BLUE, Green, Red
UV/Blue/Green: III-nitrides

- **Wavelength Conversion**.
  - Blue LED + yellow phosphor: simple but energy loss due to down conversion
  - Blue LED + several phosphors: similar to the above method, except that blue light excites several phosphors, each emitting different color (blue, green, yellow, red)
    Higher color-quality; energy loss due to down conversion
  - Ultraviolet (UV) LEDs + red, green and blue phosphors: UV LED to excite several phosphors, each emitting different color (blue, green, yellow, red).
    Highest color-quality light; but issue on UV LED; energy loss due to down conversion
- **Color Mixing:** multiple LEDs in a single lamp, mixing the light to produce white light.
  Two LEDs (blue and yellow); three (red, blue, and green) or four (red, blue, green, yellow).
  No down conversion energy losses;
  Highest efficiency; highest color quality; but issue on fabrication

Light quality on healthy

Students under full spectrum light:

- **Learn faster**
- **Test higher**
- **Grow faster**
- **1/3 fewer absences due to illness**

- **LED: has a significant advantage over conventional lamps**
- **LED: color rendering index (CRI) can potentially be up to 100**

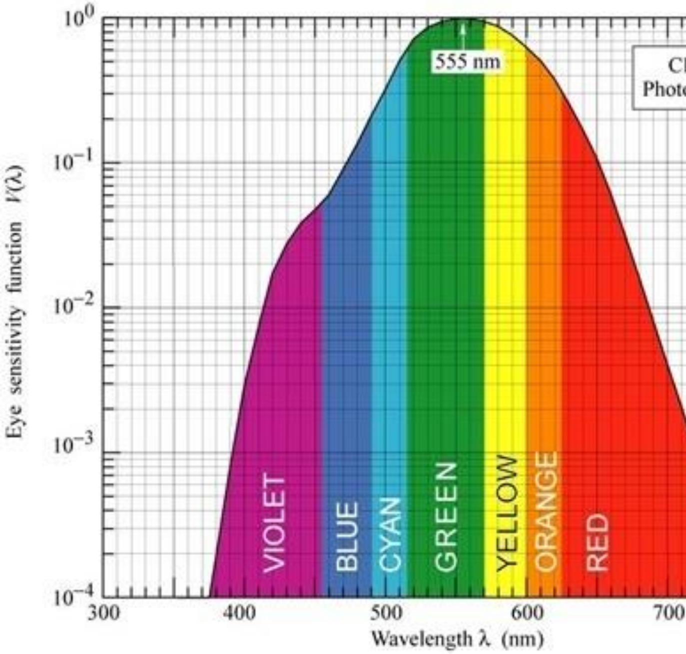
Experiments on mice, and on average mice can live

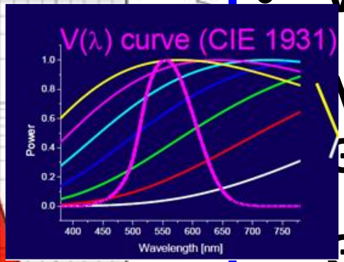
- Under **pink fluorescent** light: **7.5 months**
- Under **cool white** fluorescents (office) : **8.2 months**
- Under **natural sunlight**: **16.1 months**.

Characteristics of white lighting

- **Lumen:** SI unit of **luminous flux**, a measure of the total "amount" of visible light emitted by a source, depending on sensitivity of **human eye to different wavelengths**
- **Optical Power:** a measure of **radiant flux,** the total power of all electromagnetic waves emitted, **independent of human eye's sensitivity**. (Unit: Watt)
- **Luminous efficiency:** **(Different from "efficacy", misleading in current literature)**
  - A measure of the efficiency with which electricity converts into visible light, and is defined as the ratio of **luminous flux** to **power** (**lumen/Watt**)**,** namely, the ratio of luminous flux to radiant flux.
  - Not all wavelengths of light are detected by human eyes; radiation in the **infrared and ultraviolet** parts of the spectrum is useless for illumination.
  - The product of radiant efficiency (converts energy to electromagnetic radiation), and fraction (the emitted radiation detected by the human eye)
- **Correlated color temperature (CCT)**
- **Color rendering index (CRI)**

Luminous efficiency





- Eye sensitivity function, V(λ)
- Visible range: 380-780 nm
- Most sensitive wavelength: Green light at 555 nm
- Green Light with 1 Watt : 683 lumens

$$Luminous \cdot efficiency = \boxed{\frac{Optical \cdot Power(W)}{Electric \cdot Power(W)}} \times \boxed{\frac{Luminous \cdot flux(lm)}{Optical \cdot Power(W)}}$$

- 1^{st} item: wall plug efficiency; radiation efficiency
- 2^{nd} item: not all radiation contributes to visible light. Eye sensitivity drops upon moving away from the 555 nm wavelength
- luminous efficacy: fraction of the emitted radiation detected by human eyes

$$luminous \cdot efficacy = \frac{683 \times \int_{380}^{780} V(\lambda) S(\lambda) d\lambda}{\int_{0}^{\infty} S(\lambda) d\lambda} (lm / Watt)$$

Correlated color temperature

•**Color temperature**: define as surface temperature of electromagnetic radiation emitted from an ideal black body (SI unit: kelvins),

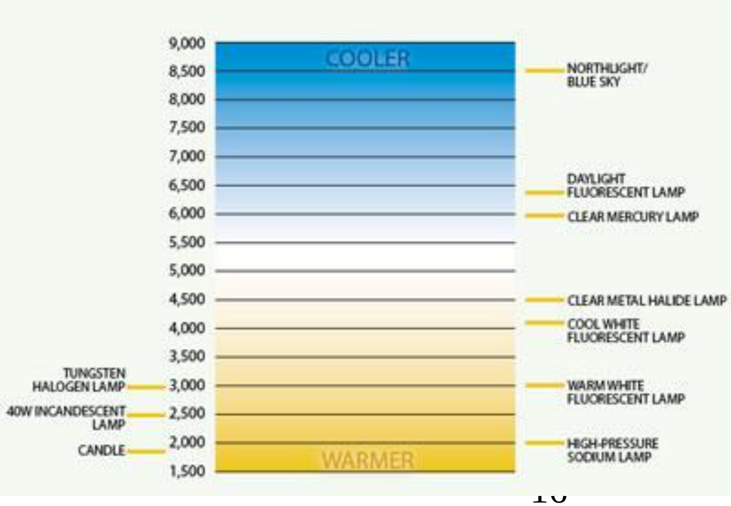
•**Wien's displacement law:** $\lambda = \dfrac{b}{T}$ **b:** 2.8977721×10^{-3} m K

As a black body is getting hotter, it turns red, orange, yellow, white and finally blue. The light incandescent lamp is thermal radiation, and it is a good black body. Its color temperature is the temperature of the filament.

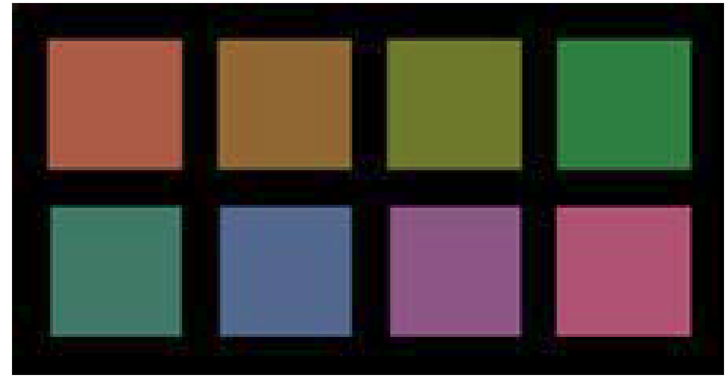
•LEDs emit light primarily not by thermal radiation, and the emitted radiation does not follow the form of a black-body spectrum. These sources are assigned what is known as a **correlated color temperature** (CCT).

•**CCT** is the color temperature of a black-body radiator which to <u>human color perception</u> most closely matches the light from the LED.
CCT refers to the appearance of a black body heated to high temperature.

•Higher CCT (blue): “cool”; lower CCT (red): “warm”



Color rendering index (CRI)



•CRI: is defined as being the measure of the degree of color shift of an object when illuminated by a light source as compared to when illuminated by a reference source of comparable Color Temperature. .

The test procedure involves comparing the appearance of eight color samples (see upper right for an approximation) under the light in question and a reference light source. The average differences measured are subtracted from 100 to get the CRI.

•Reference light: incandescent light or outdoor north sky day light (CRI 100)

•Higher CRI : render those eight color samples well, i.e., very much like the incandescent or daylight references

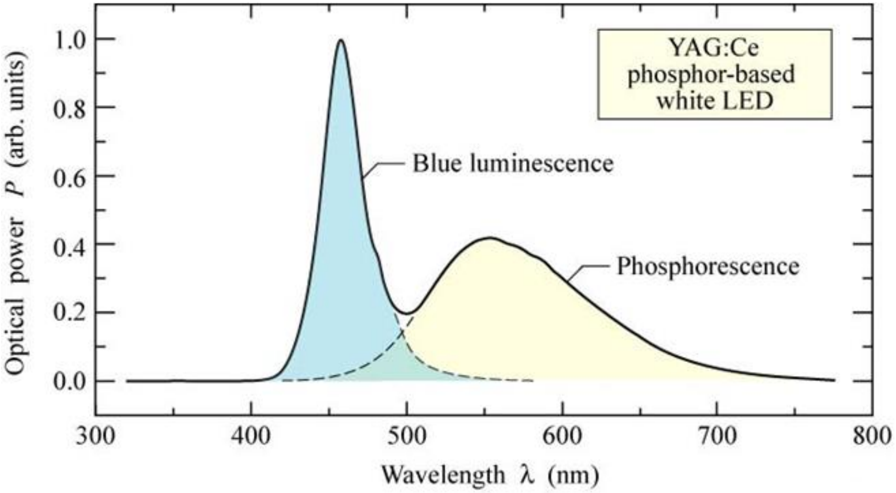
Illuminance

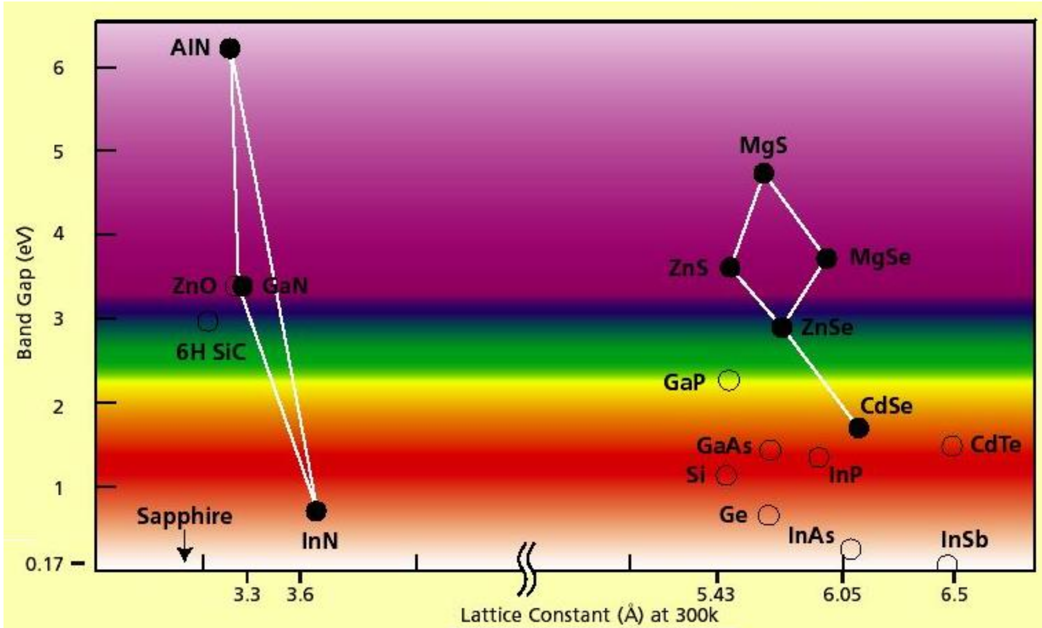
- **Practical applications of lighting usually deal with illuminance**
- **lux (lx): the measurement unit for illuminance, which is density of the illuminous flux incident on a surface (lumen per square meter)**
- **Sun generates the illuminance on the earth's surface: 10^4 lx to 10^5 lx, depending on weather**
- **Moon generates the illuminance on the earth's surface $\leq$ 0.1 lx.**
- **Higher illuminance help the eyes distinguish details, small contrasts and color hues.**
- **Different activities require different levels of illuminance.**

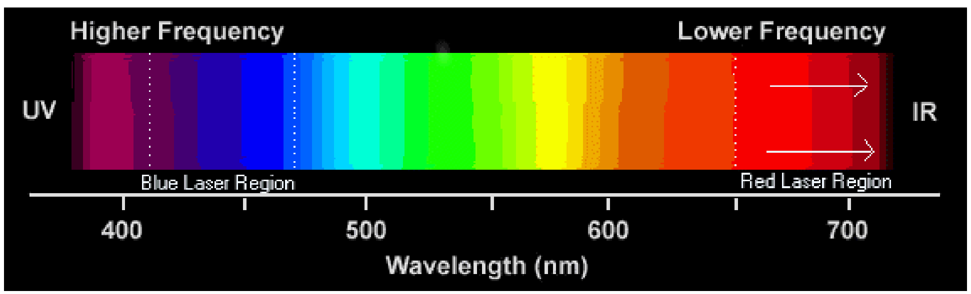
How much light do you need?

Type of Activity	Illuminance ($lx = lm/m^2$)
Orientation and simple visual tasks (public spaces)	30-100
Common visual tasks (commercial, industrial and residential applications)	300-1000
Special visual tasks, including those with very small or very low contrast critical elements	3,000-10,000

- **Key components: blue LEDs**
- **Improve efficiency of blue LEDs**
- **Improve quality of light**

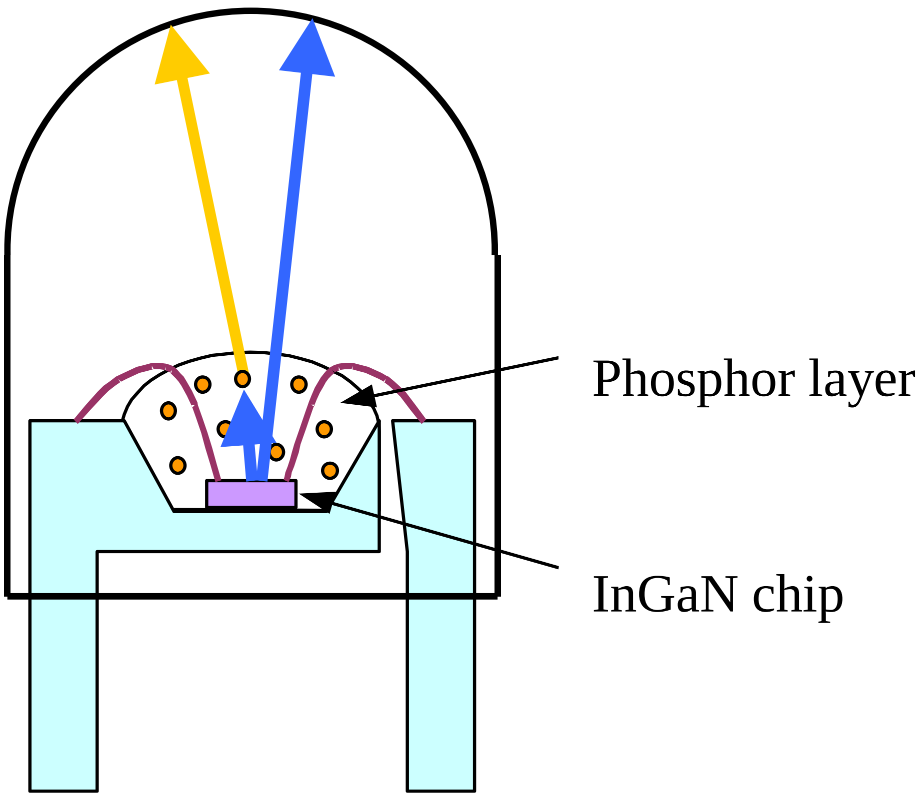




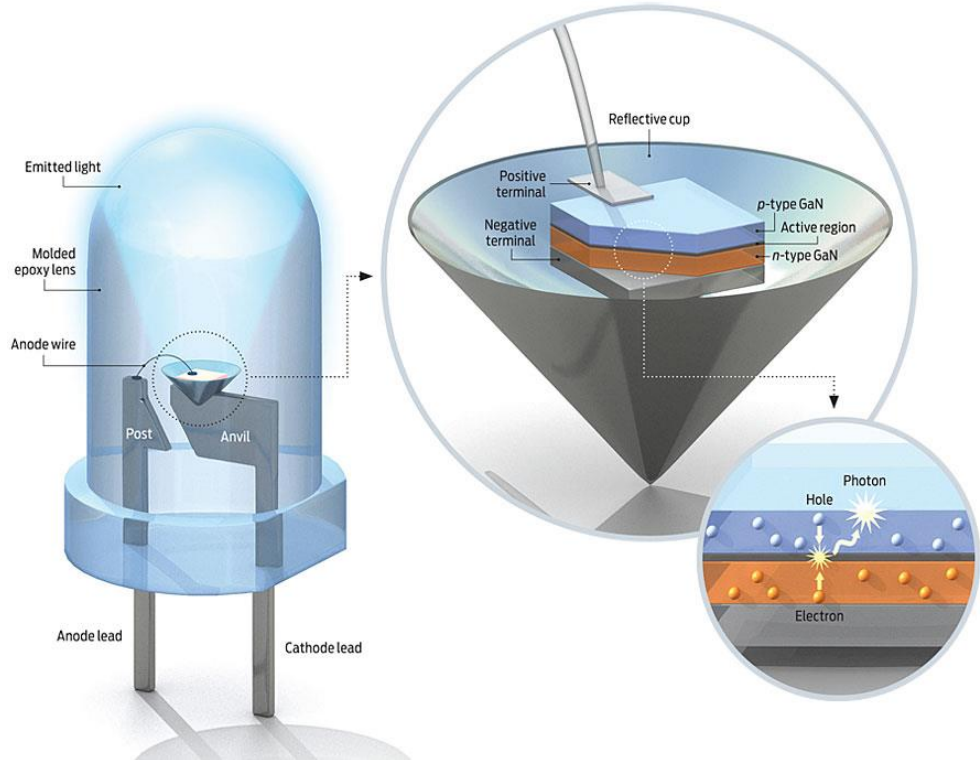


LED: Bandgap determines the emission wavelength (colour)
Band structure: direct bandgap
UV: III-nitrides, ZnO, II-VI groups
Visible: III-nitrides, GaNP, AlGaInP
Infrared: III-nitrides, InAs, InSb, InGaAs, etc

Turning blue LEDs to white LEDs

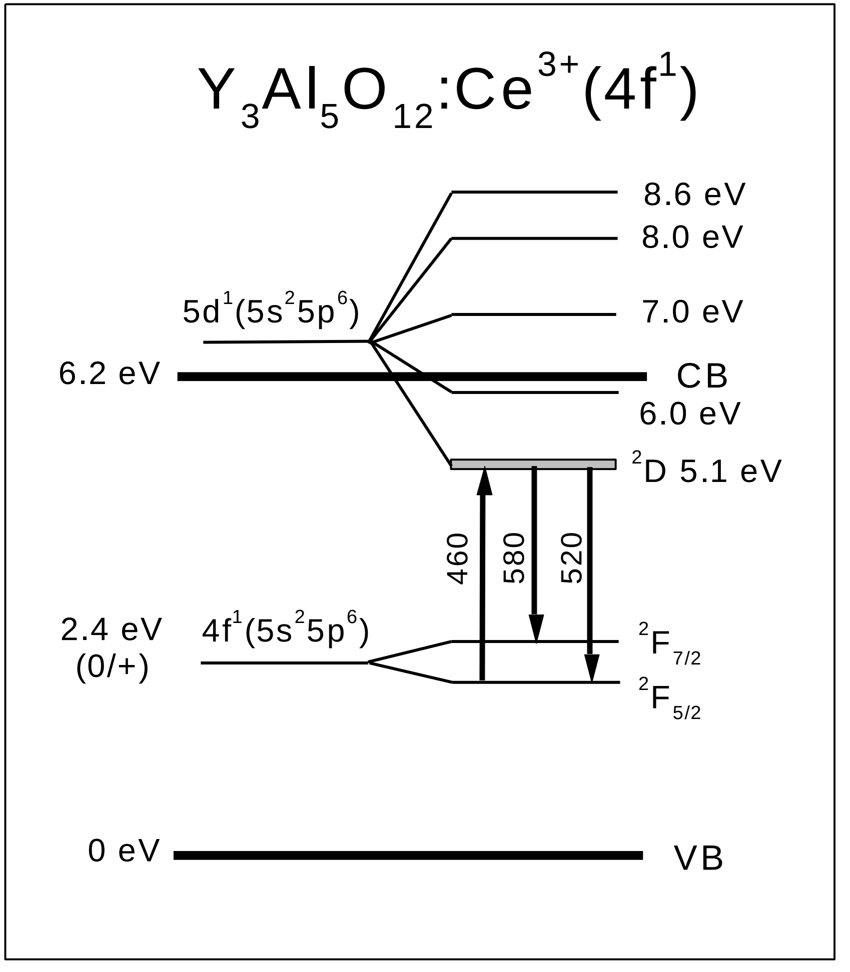


White LED

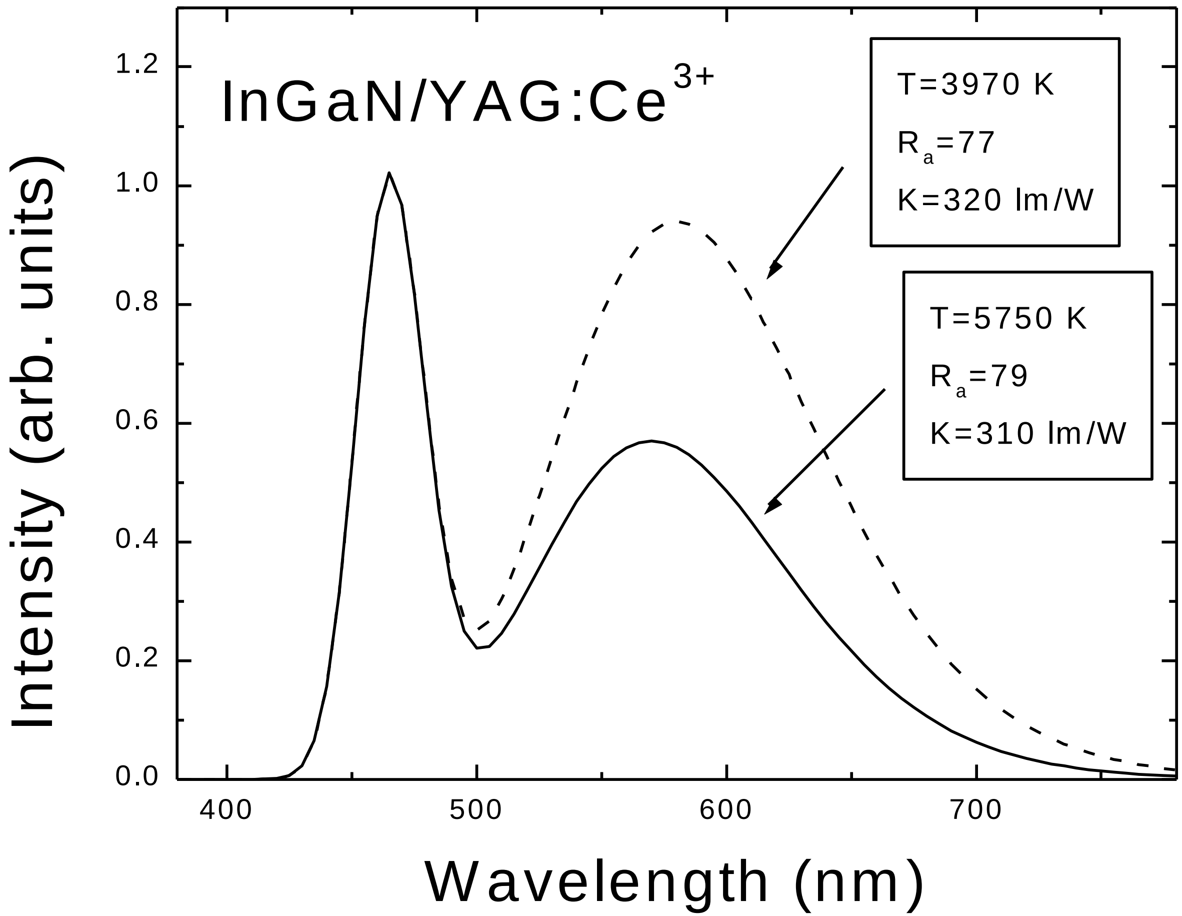


Blue LED

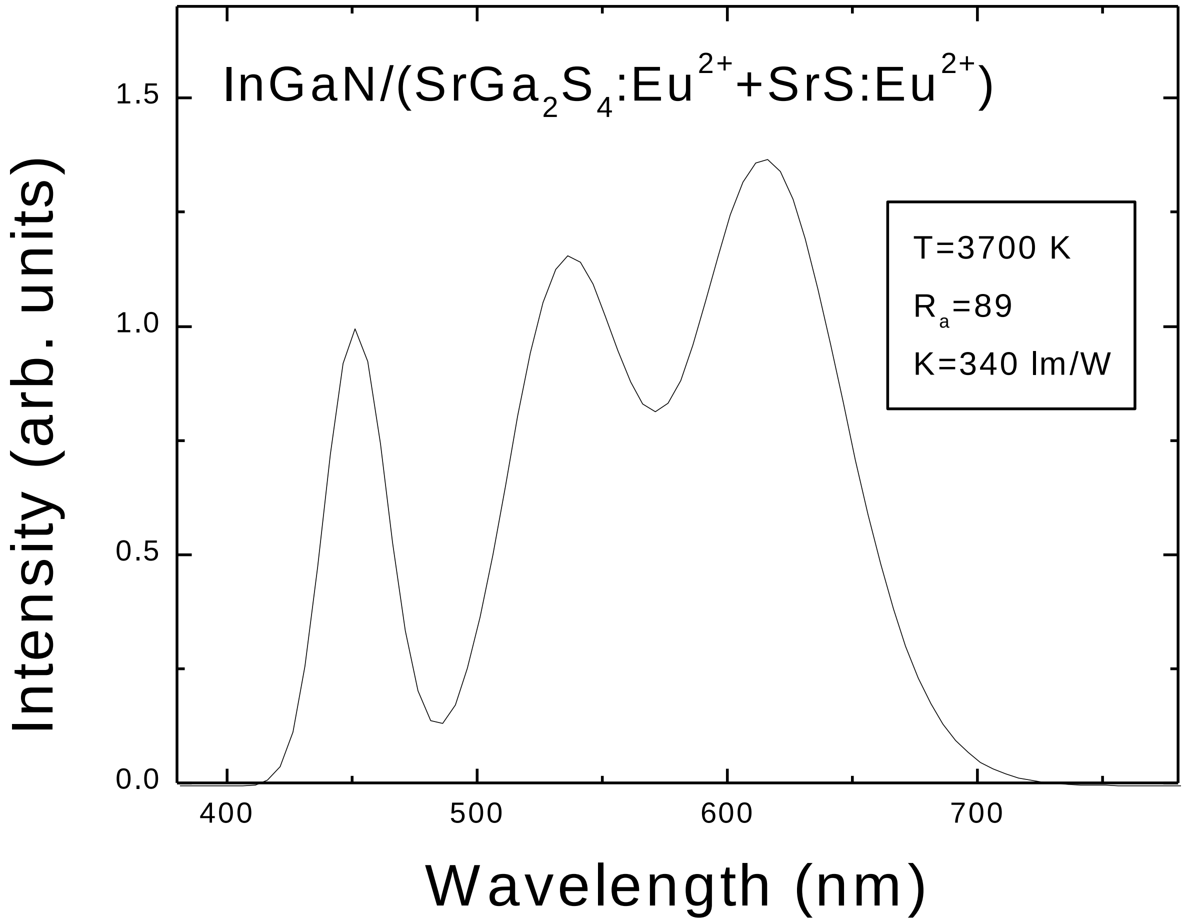
InGaN based luminescence conversion white LED



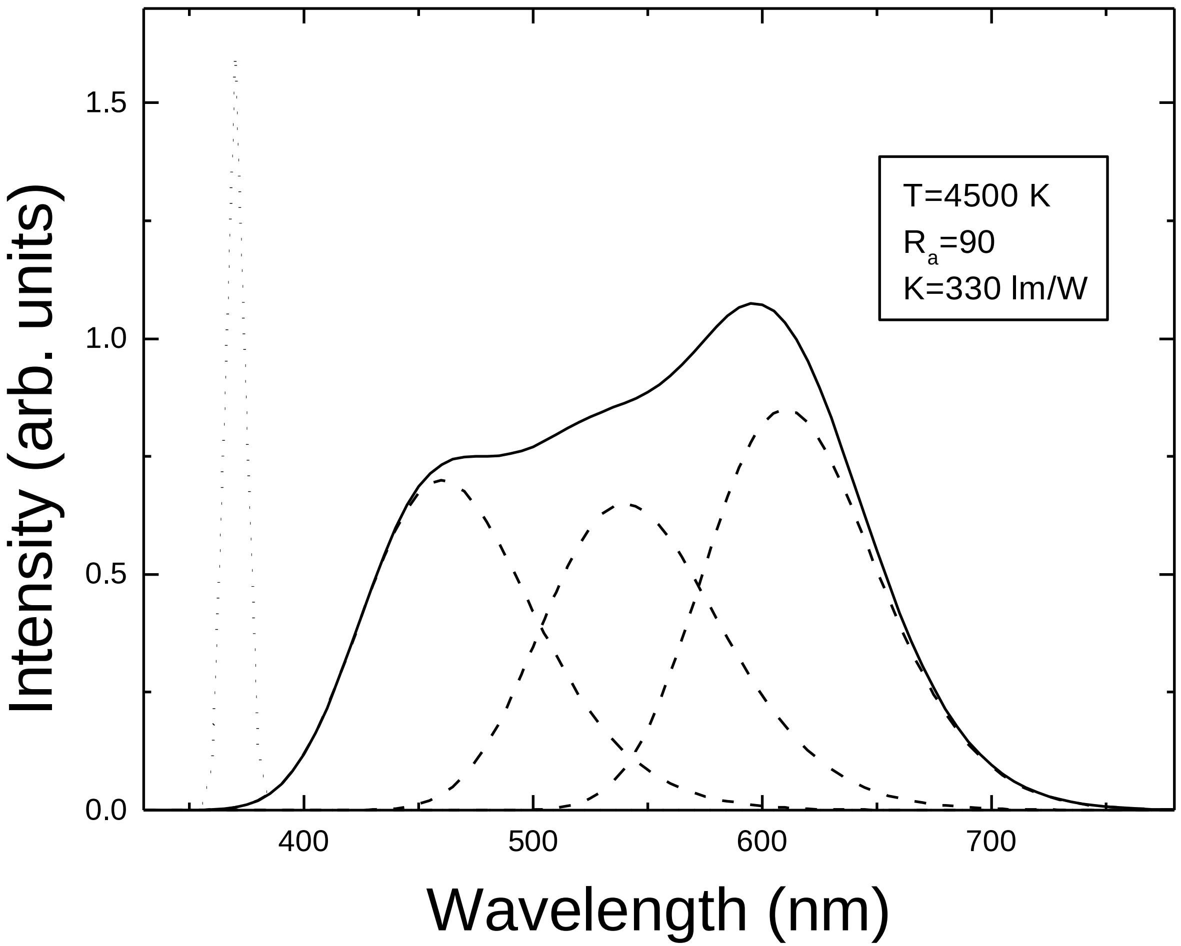
<u>Energy levels of Ce3+ (4f1) in yttrium aluminum garnet Y3Al5O12 (after M.Batenschuk *et al., MRS Symp. Proc. 560, 215,* 1999).</u>



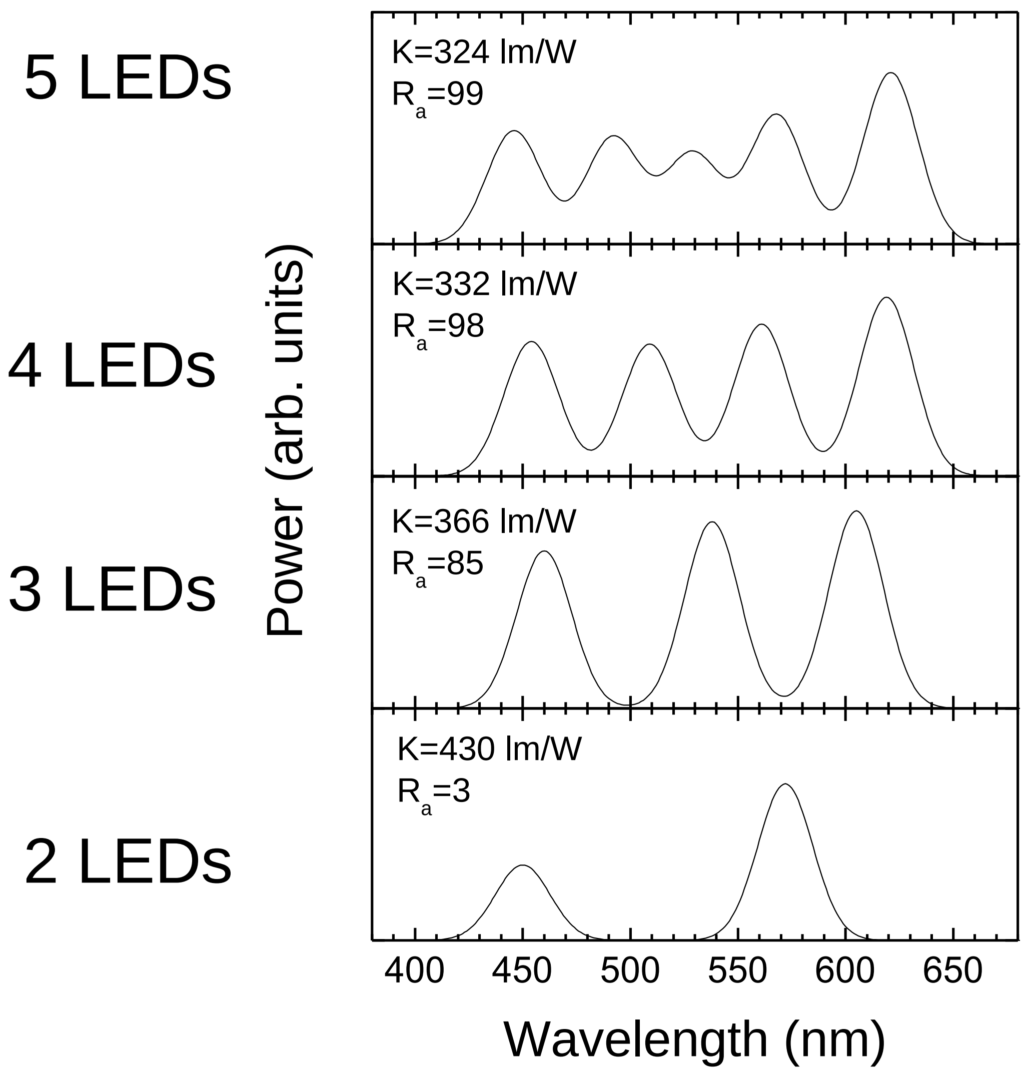
Simulation:
Model emission spectra of AlInGaN+(Y1-aGda)3(Al1-bGab)5O12:Ce3+ white LEDs for two compositions of garnet.
Solid line: 570 nm phosphor; and dashed line: 580 nm phosphor



Simulation: white emission spectrum from AlInGaN+(SrGa2S4:Eu2++SrS:Eu2+) system (after R.Mueller-Mach and G.O.Meuller, *Proc. SPIE* 3938, 30, 2000).

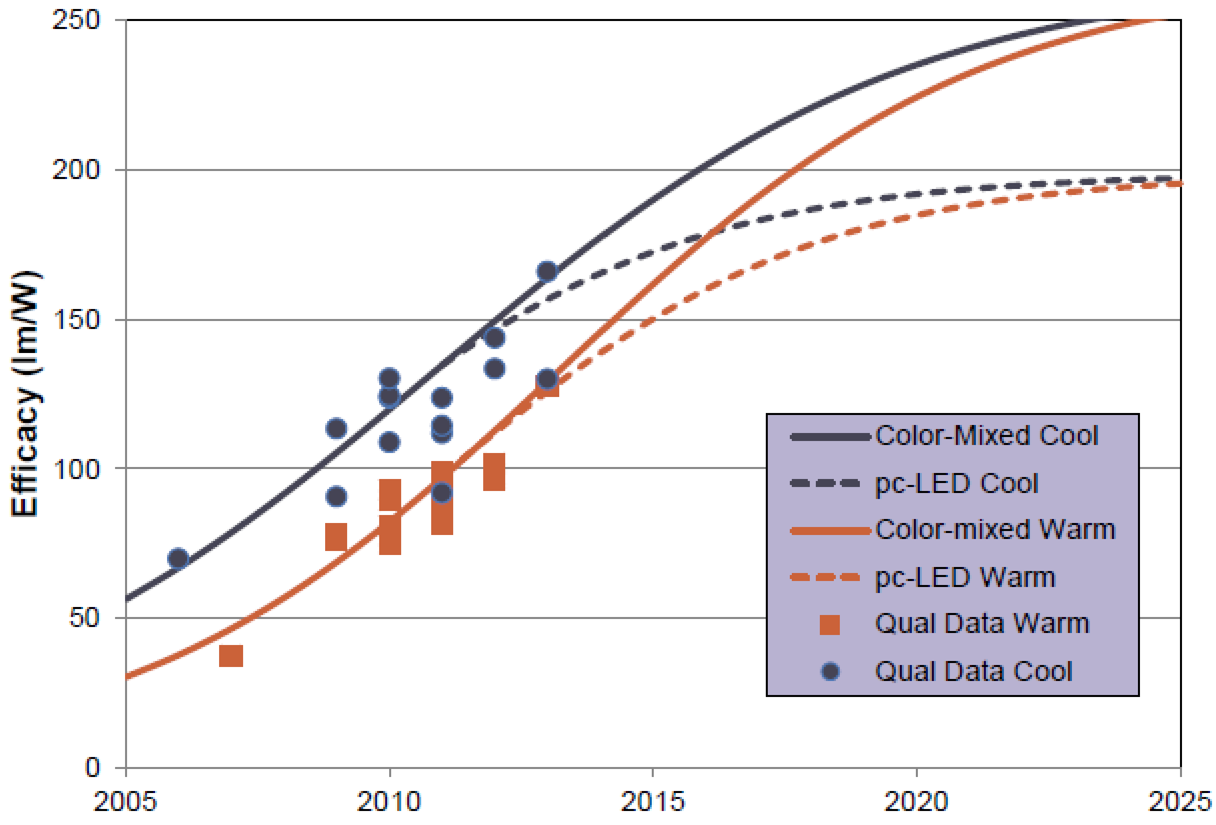


Simulation: white emission spectrum from UV pump + 3 phosphors (after D.Eisert *et al., Inst. Pure Appl. Phys. Conf. Ser.* 1, 841, 2000).



- **Simulation: optimized spectral power distributions**
- **4 or 5 LEDs with different colors from blue to red would be ideal**

US DOE road-map for SSL



- Blue LED +Yellow phosphor: <200 lm/Watt
- Color Mixed LEDs: Blue, Green, Yellow LEDs (red LED is no problem at all) requested
- Challenges: green/yellow LEDs (high indium content)

T17-18 Tutorial Questions

• For a white LED commercially available, which is fabricated using “blue LED + Yellow phosphor” approach, the measurements of the luminous flux of the LED is performed, starting from a low injection current in a pulse mode. The luminous flux increases linearly with increasing injection current until 300 mA at a forward bias of 2.9 V, where the measured luminous flux is 185 lumen. For practical application, an injection current of 3000 mA at a bias of 3.5 V in a continuous mode is used, assuming the efficiency droop is 50% and thermal droop is 20%. For an office with 5x5 m, 900 lux is required

• Estimate an actual luminous efficiency of the white LED (lm/W)
• Estimate the number of such white LEDs
• Estimate the saved energy per day compared with the Incandescent bulbs (20 lumen/watt) and fluorescent tubes (80 lumen/watt) used previously, respectively.

T17-18 Tutorial Questions

- State the major advantage of visible light communication (VLC) system over than the present-day radio frequency based Wi-FI technology

- State the major limit if the above white LEDs are directly used for the application of visible light communication; Provide any comments on minimising the limit.