1. LED BASICS

1.1. How LED works

A light-emitting diode (LED) is a semiconductor device that emits light on certain wavelength (color). A die (active area of LED) is encased in plastic or ceramic housing. The housing may incorporate one or many dies. When LED is forward-biased (switched on), electrons are able to recombine with holes within the device, releasing energy in the form of photons (Figure 1.1.1). This effect is called electroluminescence.

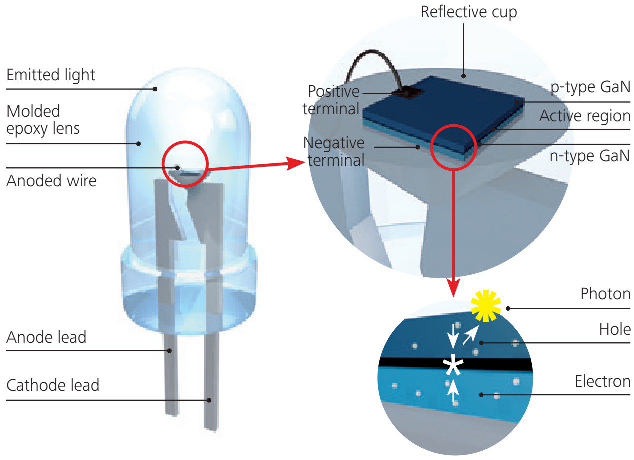


Figure 1.1.1:

When LED is switched on, electrons recombine with holes within the device, releasing energy in the form of photons with certain wavelength (color).

Photon: Unit of light

The term SSL (Solid State Lighting) is common term for LED technology being used for lighting applications. It refers to technology in which the light is emitted by solid-state electroluminescence as opposed to incandescent bulbs (where the light is emitted via thermal radiation in visible part of spectrum – incandescence).

White LED working principle

The most common method involves coating LEDs of one color (mostly blue LEDs made of InGaN) with phosphor (Figure 1.1.2a) of different colors to form white light; the resultant LEDs are called phosphor-based white LEDs. The "blue" photons emitted by High-brightness LED (HB LED) (Figure 1.1.2b) either passes through the phosphor layer without alteration, or they are converted to the "yellow" photons in the phosphor layer (Figure 1.1.2c). The combination of "blue" and "yellow" photons leads to white light (Figure 1.1.2d). In order to watch explanatory animation please visit http://www.omslighting.sk/ledacademy/276/introduction.

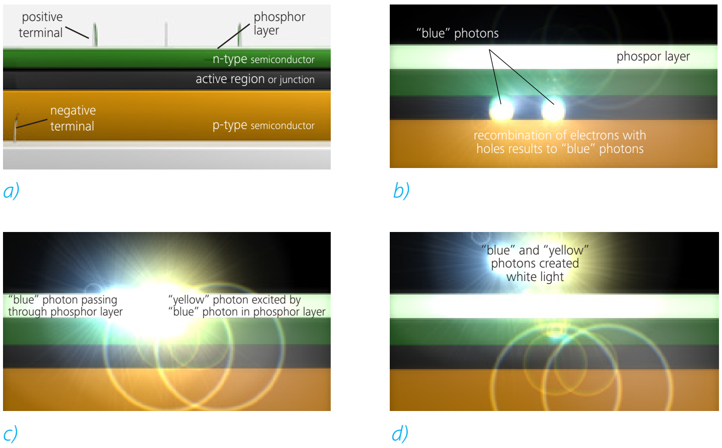


Figure 1.1.2:

a) Cross-section of standard phosphor-based white HB LED.
b) Recombination of electrons with holes results to "blue" photons.
c) "Blue" photons either passes through the phosphor layer without alteration, or they are converted to the "yellow" photons in the phosphor layer.
d) Combined together, they create white light.

Spectrum of a phosphor-based white LED clearly showing blue light directly emitted by the LED die and the more broadened yellow light emitted by the phosphor (Figure 1.1.3).

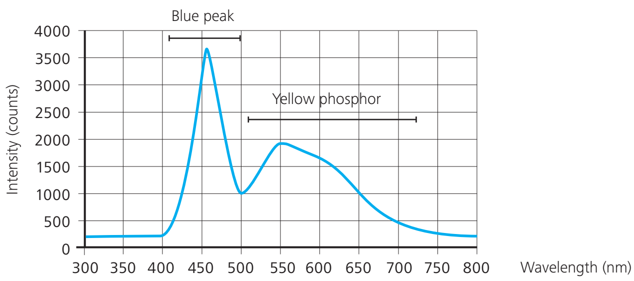


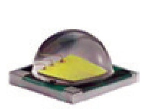
Figure 1.1.3:

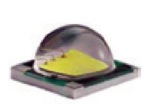
White light can be produced only by combining blue and yellow light. Sir Isaac Newton discovered this effect when performing color-matching experiments in early 1700s.

1.2. LED basic parameters

Figure 1.2.1 depicts basic parameters of LED light source compared with the most common traditional light sources. LED shows better or at least comparable numbers for all important parameters than traditional light sources.

Figure 1.2.1:
Various light sources versus LED.

Lamp type	Incandescent bulb	Halogen lamp	Metal halide lamp	Mercury vapor lamp	LED
					
Technical	Incandescent bulb makes light by heating metal filament wire to light temperature until it glows.	Halogen gas increases the lifetime of the wolfram filament and avoid the darkening of the bulb. The bulb can be operated on higher temperatures, which allows colder CCT.	Adding rear earth metal salts to mercury vapor lamp enables high efficiency. It works on high pressure and temperatures, so special fixtures are required. The advantage is the compact size in comparison to fluorescent and incandescent lamps. Mixture of halides influences the CCT. After 10 000 hours the lumen output is approx. 83% of nominal.	The outer bulb is coated with a phosphor for thermal insulation and converts some UV emissions into red light. After 2000 hours only 50% of nominal light output.	Compact and highly durable light source enables both new designs and advantages in the light control. LEDs are switched on instantly and this makes applications with frequent switching easy. Tunable white and RGB versions are already on the market. LEDs offer several benefits which can be employed in combination with all well being applications.
Efficacy (lm/W)	6 - 16	16 - 30	75 - 125	40 - 75	80 - 160
Input power (W)	20 - 60	55 - 100	20 - 24 000	50 - 500	0,2 - 100
Hazardous chemical content	no	Halogens	Argon, Mercury	Argon, Mercury	no*
Electronic ballast	no	in general no	needed to control the current	needed	needed
CRI	100	100	70 - 95	40 - 60	65 - 97
Application	Indoor, outdoor	Indoor applications like shops, residential	Floodlight, outdoor, shops	Outdoor applications, streetlights, facade	Indoor, outdoor
Additional info	high IR radiation	high IR radiation	High UV radiation	High light pollution	little UV and IR radiation
Lifetime (hours)	1000	1000 - 3000	6000 - 20 000	4000	50 000
CCT (K)	2700	2700 - 3500	3800 - 7000	3200 - 4200	2700 - 8000
Dimmable	yes, 0 - 100%	yes, 0 - 100%	yes, 50 - 100%	no	yes, 0.1 - 100%

Lamp type	Compact fluorescent lamp	Fluorescent lamp	Low pressure sodium	High pressure sodium	LED
					
Technical	Light output decreases shortly after first use 5-10%, end of lifetime is approx. 70-80%. Full power is not reached after 1 second. The latest versions are CCFL (cold cathode). In general, for outdoor applications all FLs have problems at lower ambient temperatures, sometimes it is not possible to start lamp.	The lamp reaches best efficacy if the temperature of lamp cold-spot is around 35°C. A problem is stroboscopic effect in some applications. Problems occur at lower ambient temperatures, sometimes it is not possible to start the lamp. After 25 000 hours lumen output decreases down to 50%.	LPS lamps have an outer glass vacuum envelope around the inner discharge tube for thermal insulation. Yellow light is very insect friendly. The fact is the light source is quite spacious and the recycling process costs a lot of money. Practically, this type of the lamp is running out version because of low CRI.	Smaller than LPS. Yellow light is insect friendly.	Compact and highly durable light source enables both new designs and advantages in the light control. LEDs are switched on instantly and this makes applications with frequent switching easy. Tunable white and RGB versions are already on the market. LEDs offer several benefits which can be employed in combination with all well being applications.
Efficacy (lm/W)	46 - 80	70 - 120	up to 200	100 - 150	80 - 160
Input power (W)	10 - 50	8 - 80	10 - 180	50 - 600	0,2 - 100
Hazardous chemical content	Small amount of Mercury	Mercury, Neon	Sodium, Neon, Argon	Sodium, Neon, Argon, Mercury	no*
Electronic ballast	needed or build in	needed	needed	needed	needed
CRI	80 - 90	80 - 99	30	25 - 85	65 - 97
Application	Indoor applications	Indoor	Outdoor, streetlight, security	Outdoor, streetlight, security	Indoor, outdoor
Additional info	Frequent on/off reduce lifetime; high UV radiation	Frequent on/off reduce lifetime; high UV radiation	Reaches full brightness rapidly; no lumen degradation over lifetime; relatively big light source	Less light pollution as Mercury vapor lamps; frequent on/off reduce lifetime	little UV and IR radiation
Lifetime (hours)	15 000	15 000 - 45 000	16 000 - 23 000	10 000 - 24 000	50 000
CCT (K)	2700 - 5000	2700 - 8000	difficult to describe	2000 - 3000	2700 - 8000
Dimmable	yes, 3 - 100%, continuous dim damage the light source	yes, 3 - 100%, continuous dim damage the light source	no	yes, 50 - 100%	yes, 0.1 - 100%

*LEDs have to be, as all semiconductor devices, disposed in a correct way, otherwise hazardous chemicals such as arsenic or phosphorus may occur.

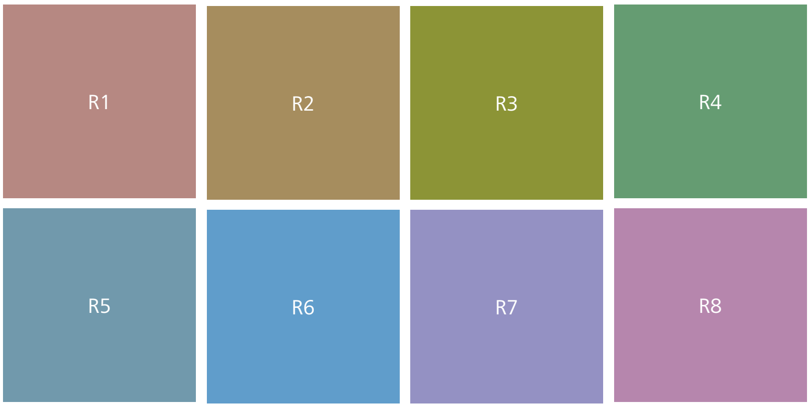
Efficacy of LED luminaires

The efficacy (energy efficiency) of LED lighting fixtures is ratio between net lumen output (in lumens) and input power (in watts) of a luminaire, or lm/W. LEDs with the highest efficacy are the coolest whites – 5000 K and above. Present (Q2, 2012) commercially available LEDs show efficacies up to 160 lm/W and already surpass the most efficient fluorescent lamps. Warm white LEDs (ranging from 2600 K to 3500 K) approach efficacies up to 120 lm/W. Efficacy higher than 250 lm/W has been achieved in Cree Ltd. labs, April 2012. Highest LED luminaire efficacies are currently in the 100 lm/W range and daily increasing.

Color rendering index – CRI

Color rendering index measures the ability of a light source to render colors of illuminated objects faithfully in reference to an ideal light source – sun or incandescent bulb. By definition, ideal light source has CRI equal to 100. Therefore CRI varies from 0 to 100, higher means better. Color rendering score Ra is derived from the results for all sample colors (standard set: R1 – R8, or extended set: R1 – R14) tested (Figure 1.2.2).

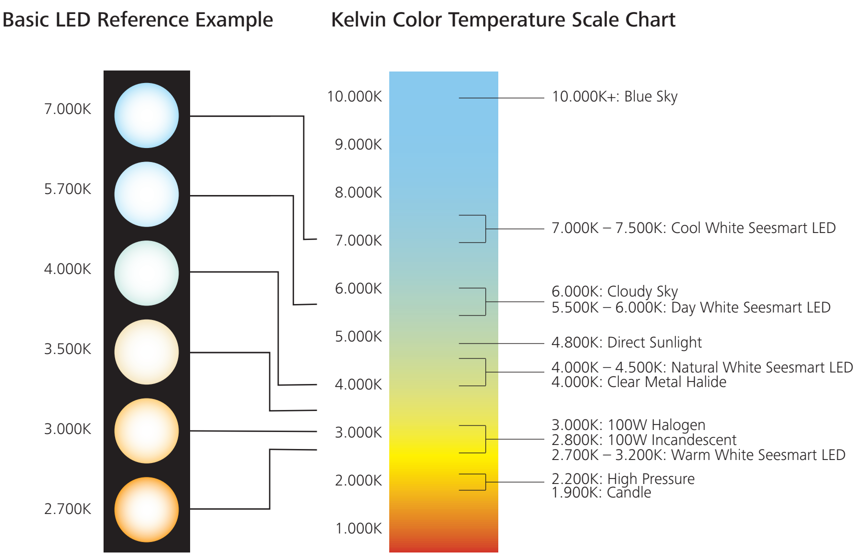
Figure 1.2.2:
Standardized color samples set.



Correlated color temperature – CCT

Color temperature of a light source is the temperature of an ideal black-body radiator (solid object with certain properties heated up to point of incandescence) that radiates light of comparable hue to that of the light source, and its temperature is expressed in Kelvins (K). As a black body gets hotter, wave lenght of light emits progress through a sequence of colors from red to blue (Figure 1.2.3). Sequence of colors is described by curve (Planckian locus) within a CIE 1931 color space (Fig 1.2.4).

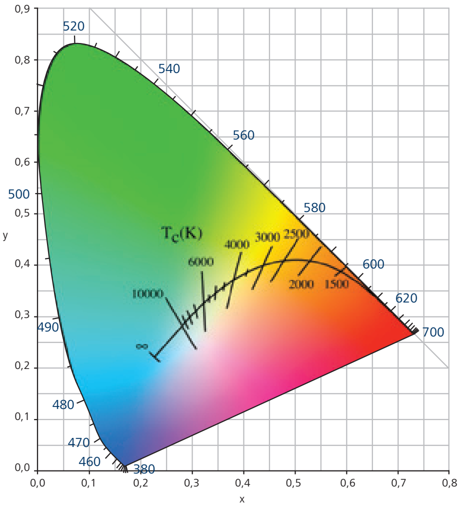
Figure 1.2.3:
Example of LED color temperature correlation.



For colors based on black body theory, blue occurs at higher temperatures, while red occurs at lower temperatures. This is the opposite of the cultural associations attributed to colors, in which "red" is "hot", and "blue" is "cold".

Figure 1.2.4:

The black-body curve (Planckian locus) defines the range of color temperatures, from warm (reddish) to cold (bluish), within the CIE 1931 color space



An incandescent bulb emits light with color temperature around 2700 K (reddish end on the black-body curve). Because incandescent lamp uses heated filament in order to emit light, the temperature of the filament is also the color temperature of emitted light.

Spectral analysis of visible light makes it possible to define color temperature for non-incandescent white light sources such as fluorescent tubes and LEDs. LED which emits light with color temperature of 2700 K has actual temperature of active area around 350 K (~80 °C), thus the temperature of outgoing light correlates with the temperature of black-body radiator and not with actual temperature of LED light source. It is the reason why we, in case of non-incandescent light sources, have to speak about correlated color temperature (see also Figure 1.2.3).