Lecture 10 – 30/04/2025

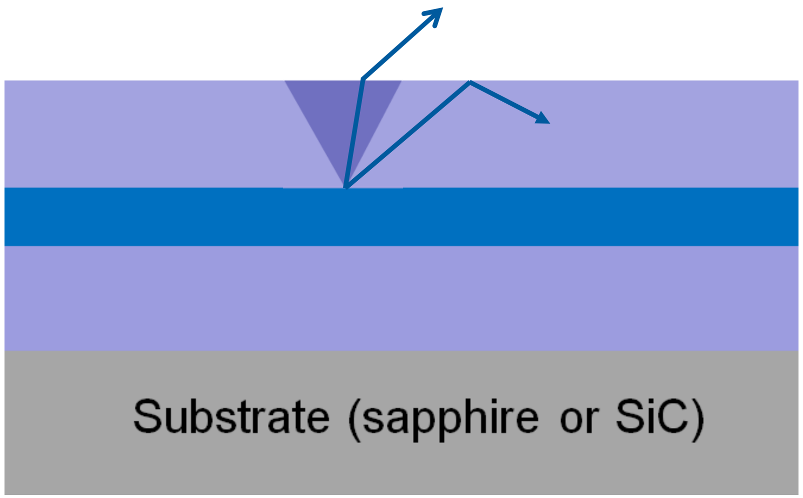
Light-emitting diodes

- Notion of efficiency
- Fabrication
- White LEDs

LED efficiency

External quantum efficiency (EQE, η): [emitted photons]/[electrons]

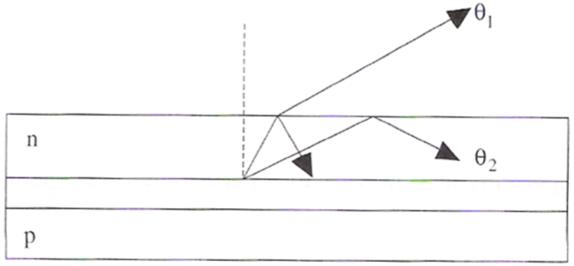
$$\eta = \eta_{inj}\eta_{i}\eta_{ext}$$ → extraction efficiency



LED efficiency

Extraction efficiency (η_{ext}):

Key issue: the generated photons must escape from the material (non-absorbing dielectric medium)!



Transmission $\theta_1 \approx 0$ $T = 1 - [(n_{sc}-1)^2/(n_{sc}+1)^2]$

Critical angle for total internal reflection (TIR): $\theta_c = \arcsin(1/n_{SC})$

For GaAs, $n_{sc} = 3.6 \Rightarrow \theta_c = 16°$ and $T = 0.7$

Solid angle leading to light extraction →

$$\frac{\Omega_c}{\Omega_{tot}} = \frac{\Omega_c}{4\pi} = \frac{1}{4\pi}\int_0^{2\pi} d\phi \int_0^{\theta_c} \sin\theta d\theta = \frac{1}{2}(1-\cos\theta_c)$$

For GaAs, only 2% of photons are extracted per facet

***The extraction efficiency η_{ext} is very low for a simple planar geometry* ⇒ major issue even for an IQE of 100%!**

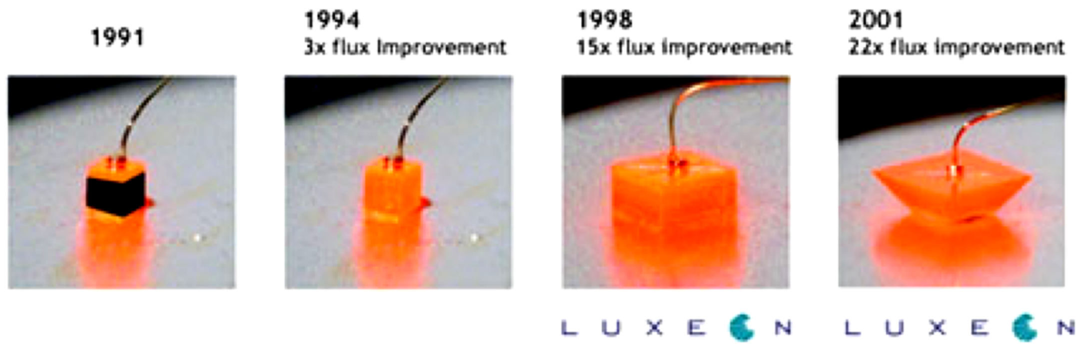
LED efficiency

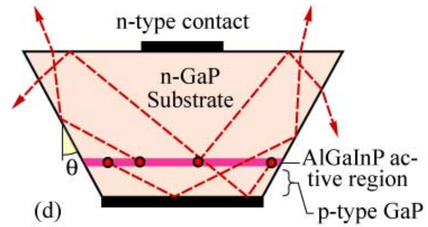
External quantum efficiency:

η = [emitted photons/electrons]

$\boldsymbol{\eta = \eta_{inj} \eta_i \eta_{ext}}$ (> 50% for state of the art LEDs)

How can we improve the EQE compared to the planar geometry?





After a 1st TIR, photons reach the second interface with an incident angle < θ_c

LED: output power and power efficiency

Optical output power P_{opt}

$$P_{opt} = \eta \frac{h\nu}{e} JS = \eta \frac{h\nu}{e} I = \eta_{inj}\eta_i\eta_{ext} \frac{h\nu}{e} I$$

Power efficiency or wall-plug efficiency (WPE) η_{wp}

$$\eta_{wp} = \frac{P_{opt}}{P_{el}} = \frac{P_{opt}}{IV_{app}}$$

$$\eta_{wp} = \eta \frac{h\nu}{eV_{app}}$$

Electrical power dissipated as heat through series resistance of the device
$\Rightarrow eV_{app} > h\nu$

Need to have a good control over the contact resistance and the conductivity of the injecting layers!

LED: brightness and photometric units

Brightness or radiance $B(\theta)$

$$B(\theta) = \frac{dP_{\text{opt}}(\theta)}{dA\,d\Omega}$$

Wavelength integrated emitted power per unit area per unit solid angle

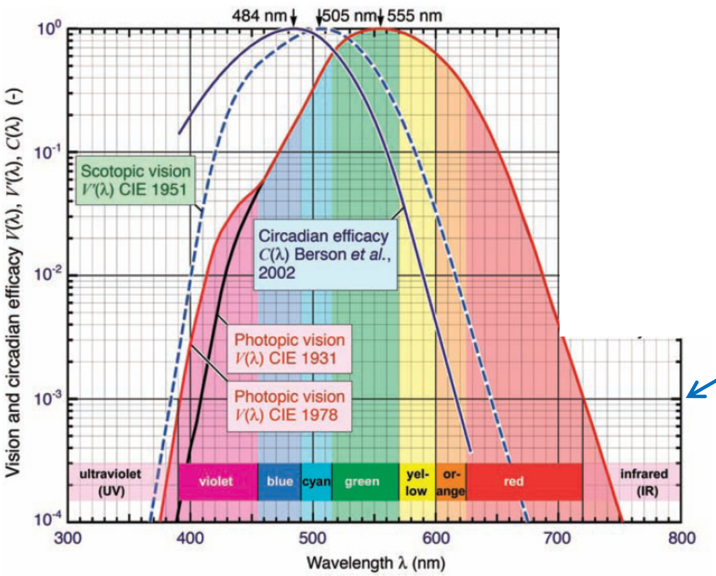
Luminous flux

normalization factor (in lm/W)

$$\phi_{\text{lum}} = 683\int V(\lambda) P_{\text{opt}}(\lambda)\, d\lambda$$

Output power of a source as perceived by the human eye (units expressed in **lumens**)

Eye sensitivity function $V(\lambda)$



10^{-3}: $V(\lambda)$ value defining the cutoff for the visible spectral range ($\in$ ~390-720 nm)

- Photopic vision: cone-dominated vision, good color perception dominating under normal daylight
- Scotopic vision: rod-dominated vision, dominating under low light conditions

LED: photometric units

Luminous efficacy ζ_{lum}

$$\zeta_{\text{lum}} = \frac{\phi_{\text{lum}}}{P_{\text{opt}}} = 683\frac{\int V(\lambda) P_{\text{opt}}(\lambda)\, d\lambda}{\int P_{\text{opt}}(\lambda)\, d\lambda}$$

Conversion efficiency from optical power to luminous flux (units expressed in **lm/W**)

Luminous efficiency η_{lum}

$$\eta_{\text{lum}} = \frac{\phi_{\text{lum}}}{P_{\text{el}}} = \frac{\phi_{\text{lum}}}{IV_{\text{app}}}$$

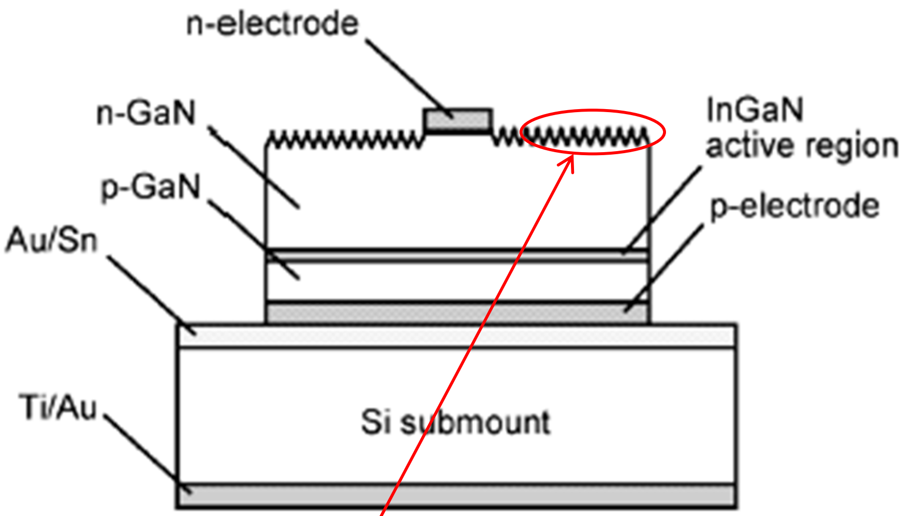
Ratio of the luminous flux of the light source to the electrical input power (units expressed in **lm/W**)

$$\eta_{\text{lum}} = \zeta_{\text{lum}} \eta_{\text{wp}}$$

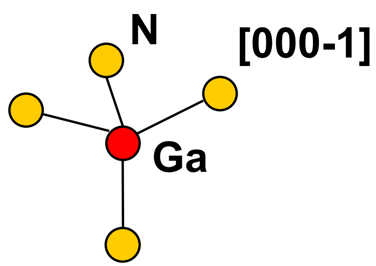
Luminous efficiency and luminous efficacy are related via the wall-plug efficiency

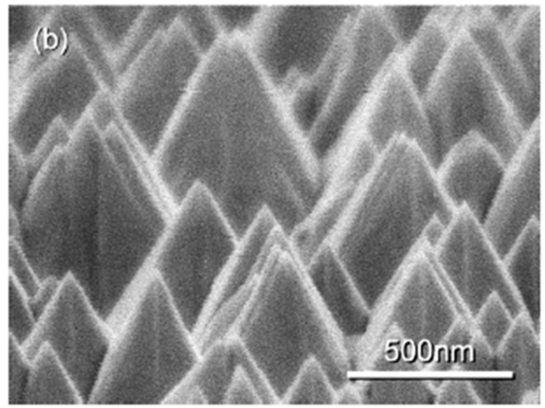
LED efficiency

Surface roughening



Nitrogen polarity ⇒ chemically sensitive surface that can be wet-etched

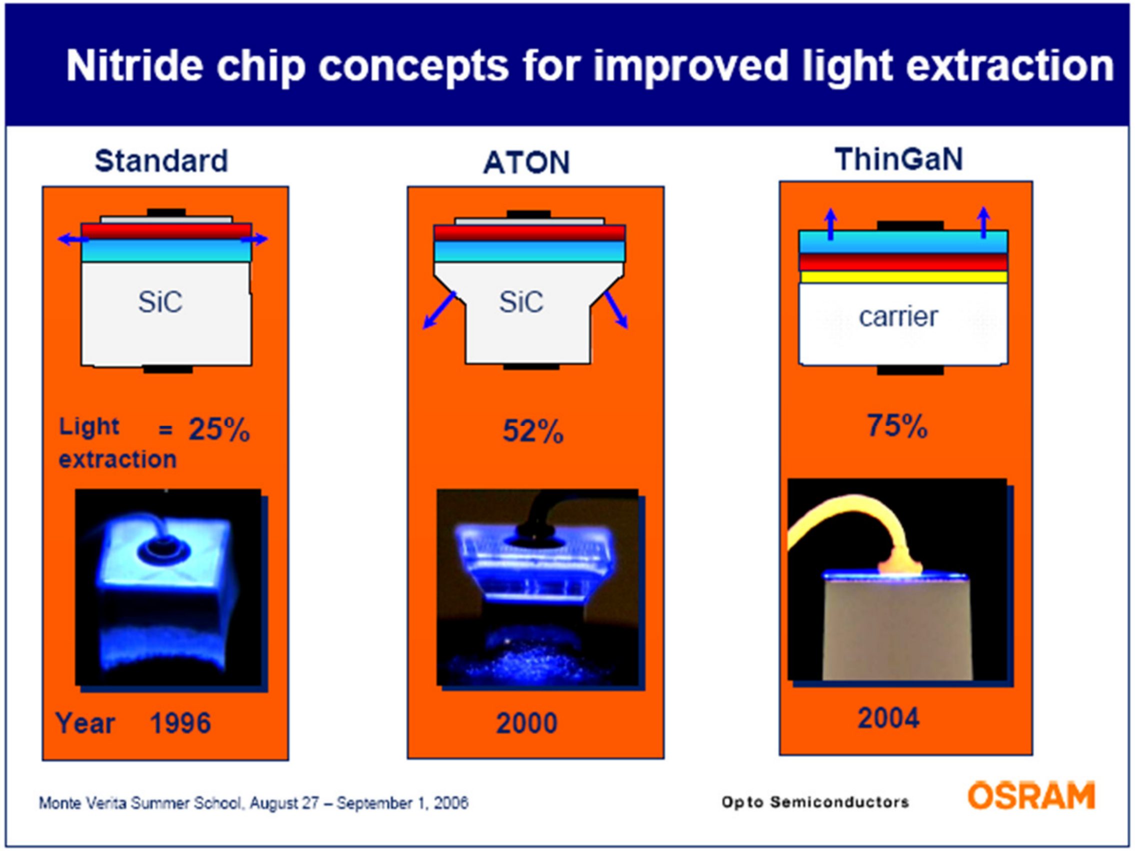




UCSB, Appl. Phys. Lett. **84**, 855 (2004)

Top surface consisting of nano-pyramids
⇒ Improved light extraction

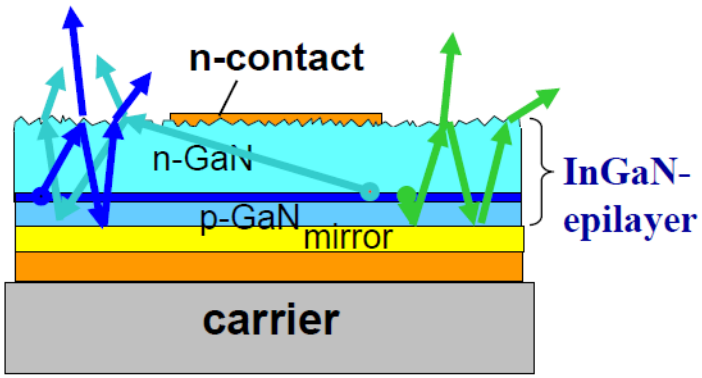
LED efficiency



Thin film allows reducing absorption losses

LED efficiency

ThinGaN - principle

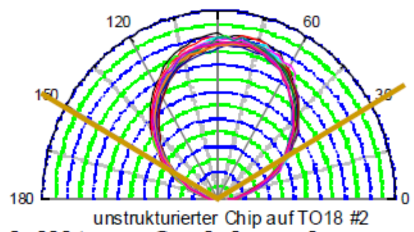


Advantages of Thin Film LEDs

1) **Best extraction efficiency (≥ 85%)**

2) **Lowest forward voltage**

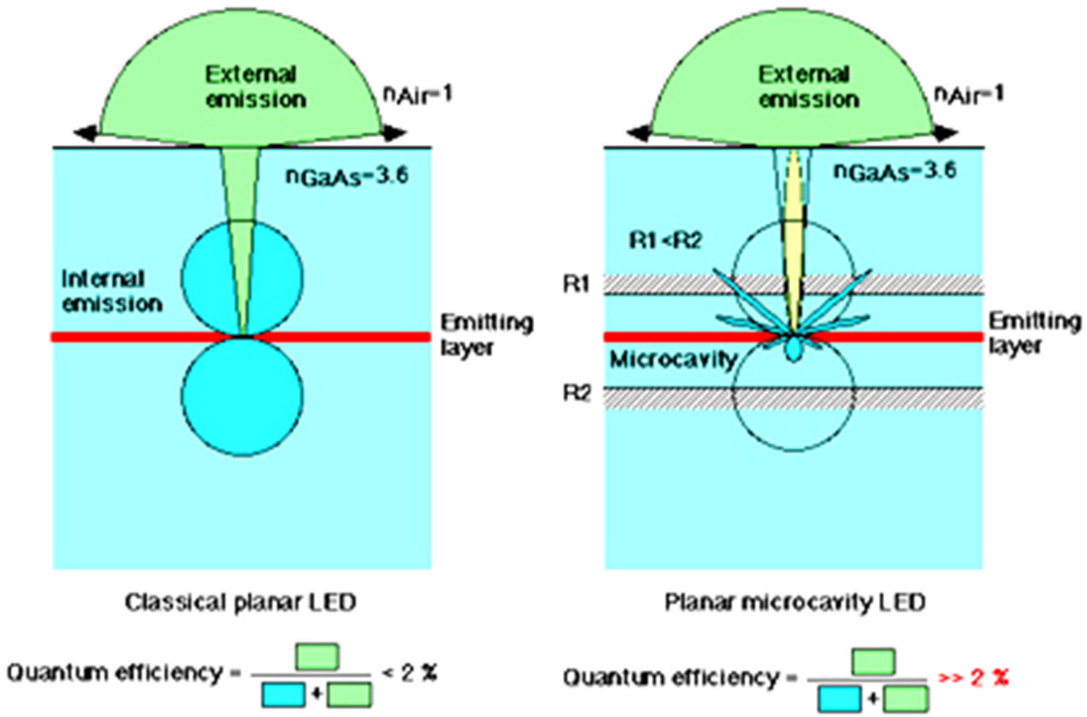
3) **Lambertian far field radiation pattern**



4) **Scalability of chip size**
@ same extraction efficiency

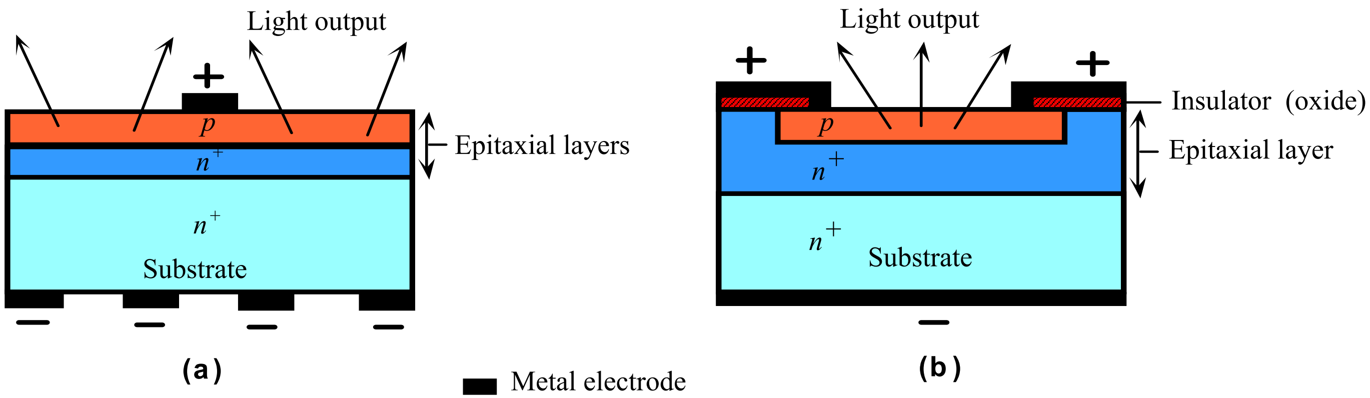
LED efficiency

Resonant cavity LEDs (RC-LEDs)

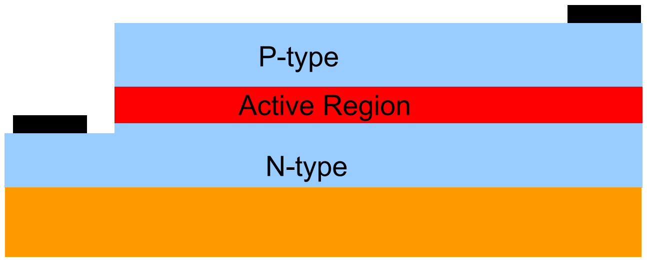


EQE/facet

LED fabrication

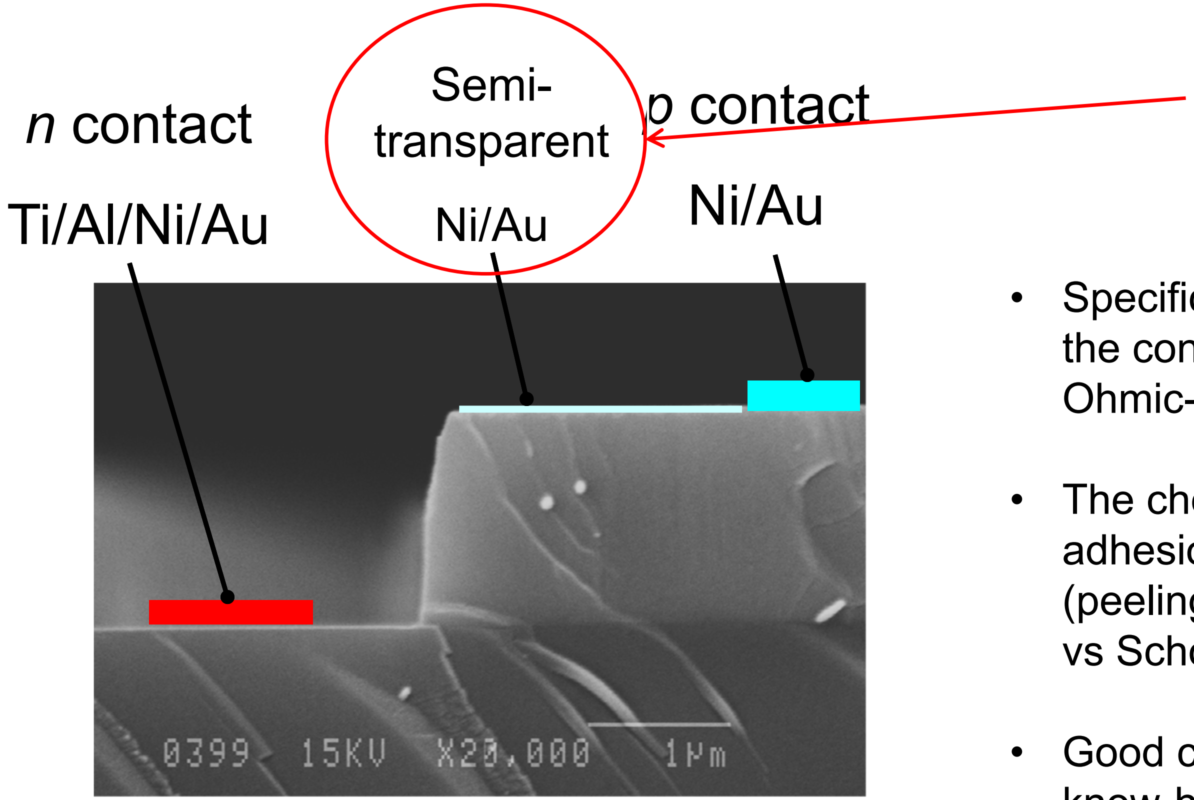


Conducting substrate



Insulating substrate (GaN/sapphire)

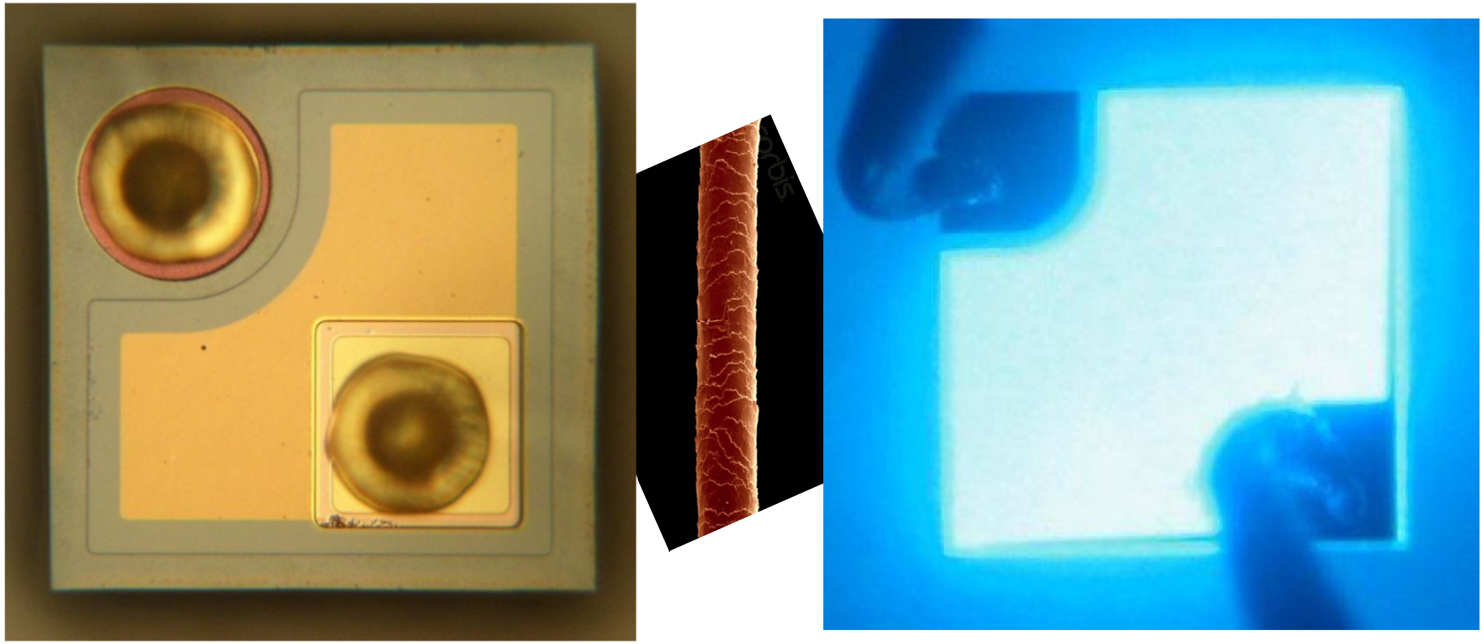
LED fabrication



Required to promote lateral hole injection due to their reduced mobility

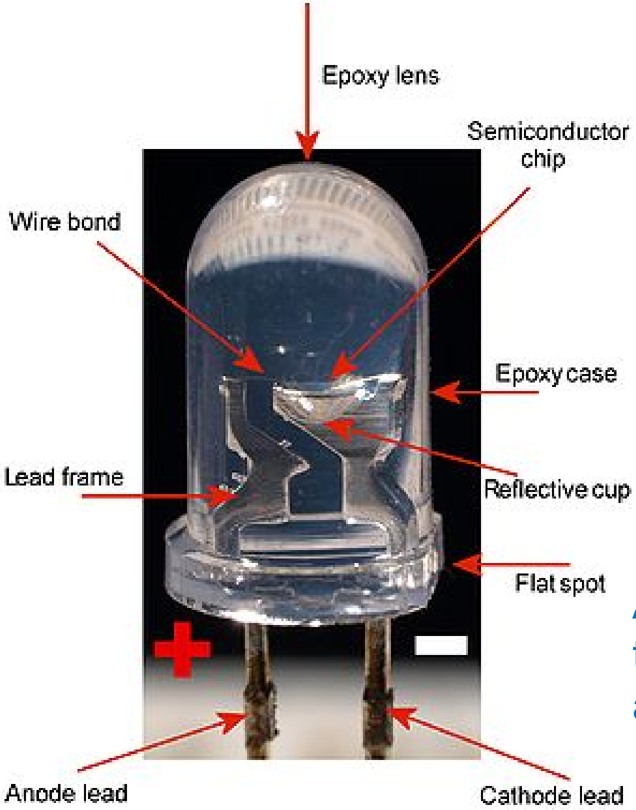
- Specific metal sequence used to decrease the contact resistance (R_c) and ensure Ohmic-like contacts
- The choice of metals depends on: (i) the adhesion of the metal to the semiconductor (peeling unwanted) and (ii) the work function vs Schottky barrier height (+ surface states)
- Good contacts (low R_c value) require a lot of know-how and recipes are kept secret by LED manufacturers

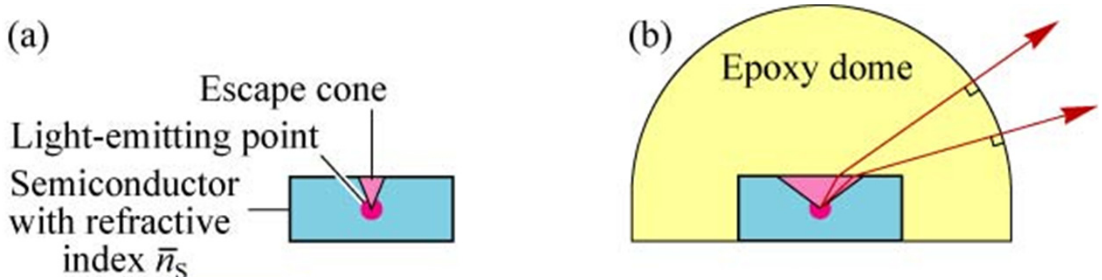
LED fabrication



3 volts

LED fabrication

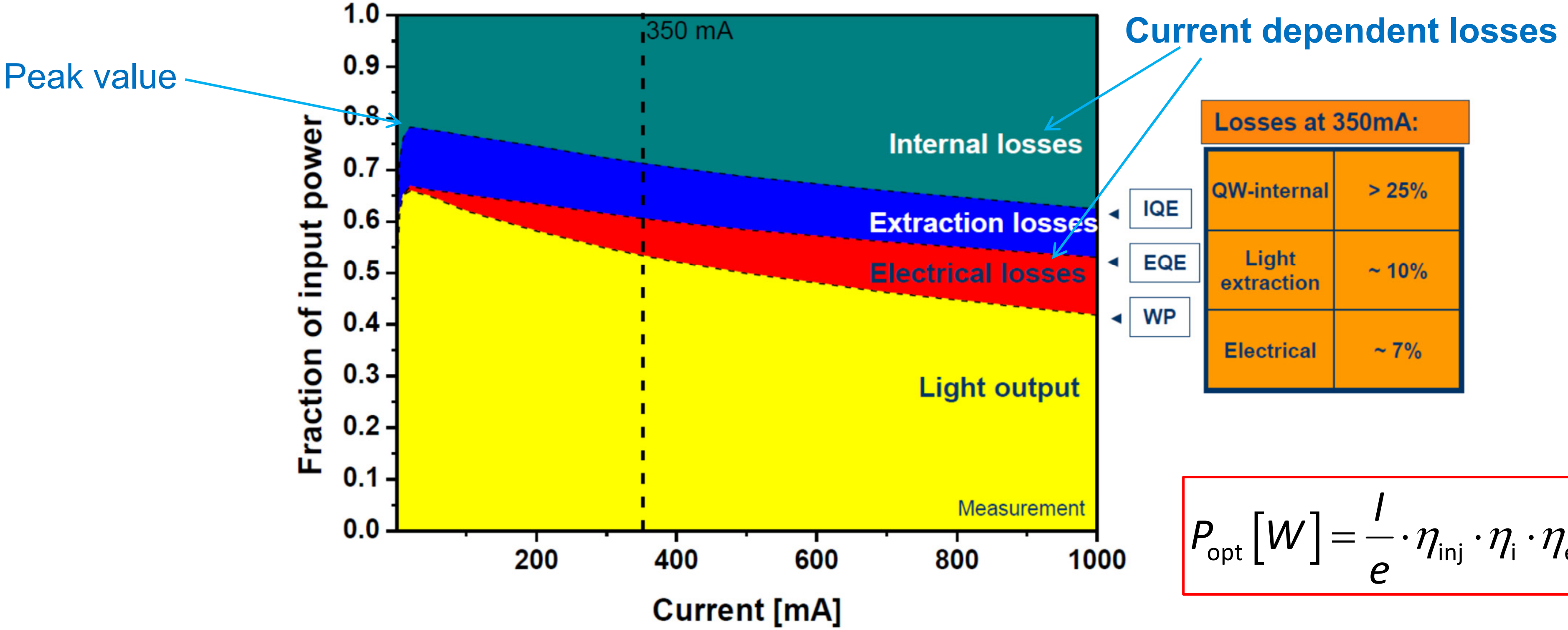




A larger escape angle is obtained for LEDs with an epoxy dome due to the lower refractive index contrast between the semiconductor and the epoxy (n_{epox}~ 1.5-1.57)

Loss analysis of high brightness blue LEDs

ThinGaN performance: loss analysis of 435nm LED



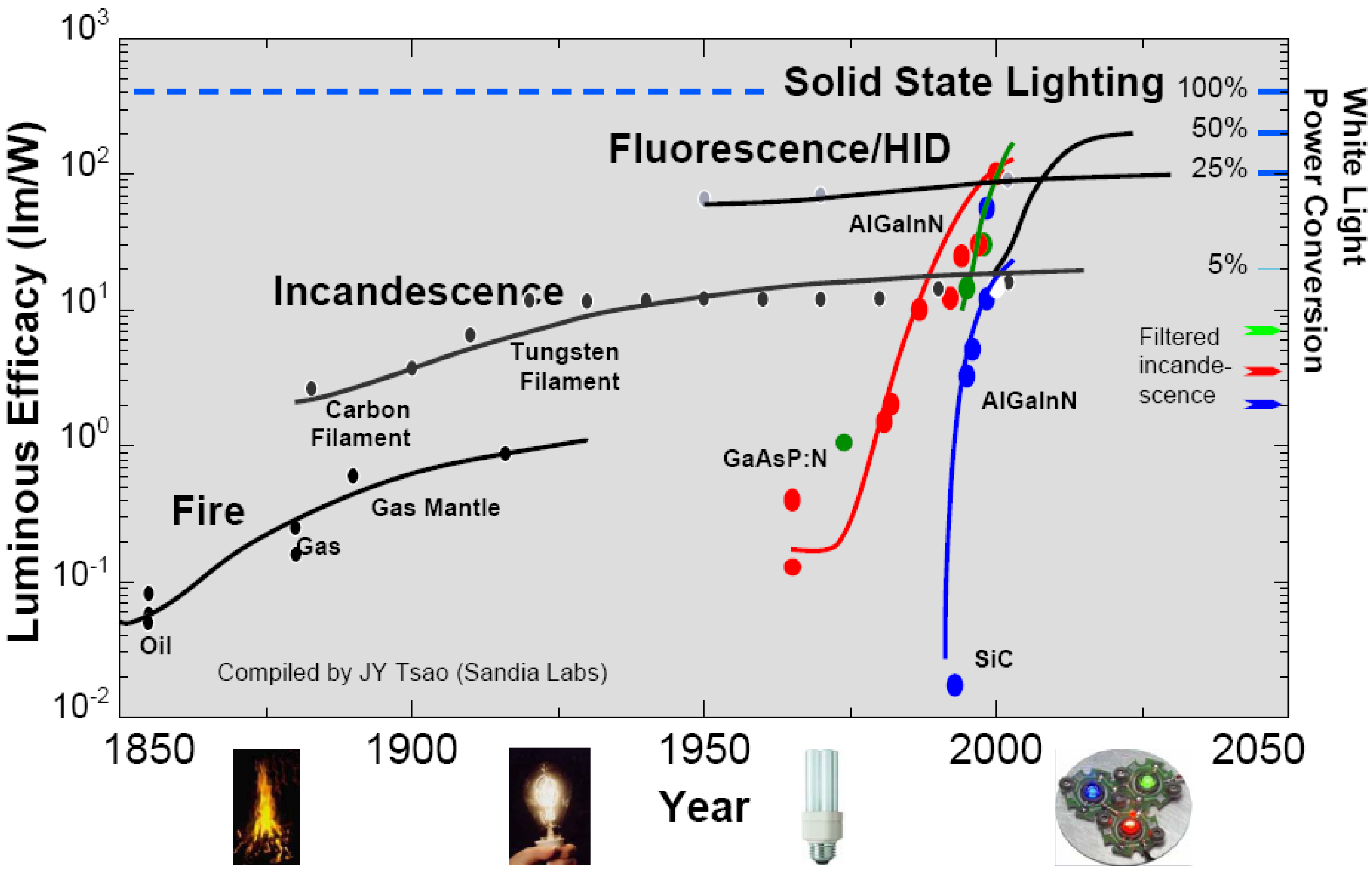
Losses at 350mA:	
QW-internal	> 25%
Light extraction	~ 10%
Electrical	~ 7%

$$P_{\mathrm{opt}}\left[W\right]=\frac{I}{e}\cdot\eta_{\mathrm{inj}}\cdot\eta_{\mathrm{i}}\cdot\eta_{\mathrm{ext}}E_{\mathrm{ph}}$$

Company Overview Page 30
2012 I OSRAM Opto Semiconductors I OS SMP I MR

White LEDs

A brief history of light sources

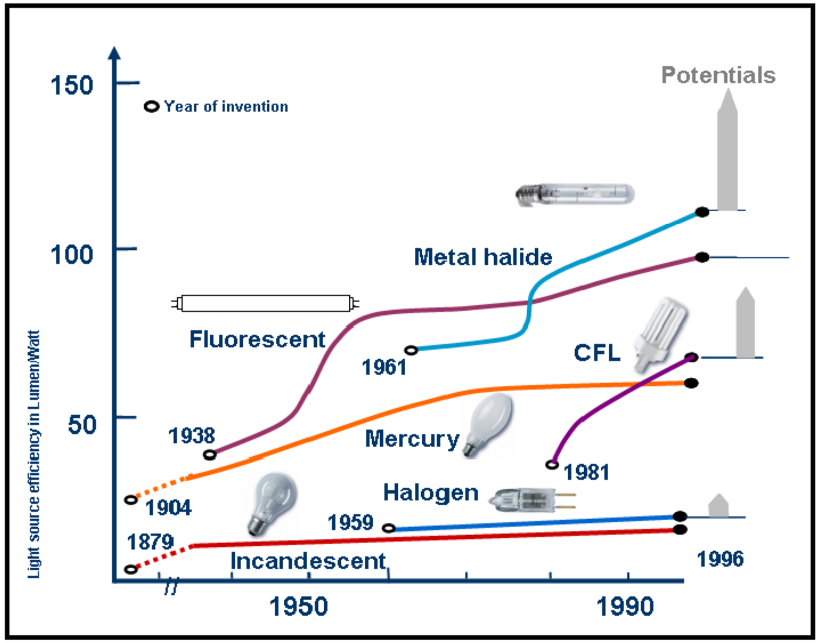


White LEDs

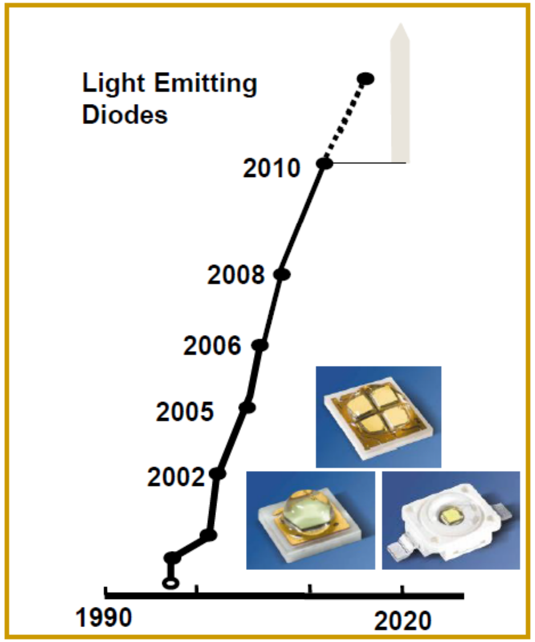
Growth potential in General Lighting keeps expanding as LED can now compete with all classical technologies

LED is the fastest developing technology with the highest potential.

Conventional Technologies



Solid State Lighting



Today's and Future InGaN/GaN LEDs | 27.06.2013 | Page 26
GaNex Summer School | Martin Strassburg

OSRAM
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White LEDs

Generation of white light with the use of blue InGaN LEDs with converter

Conversion

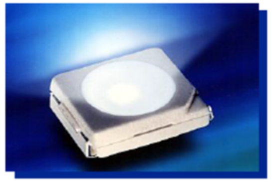
chip

+

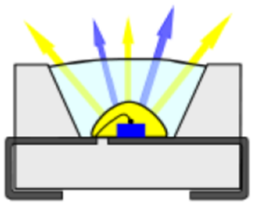
phosphor

+

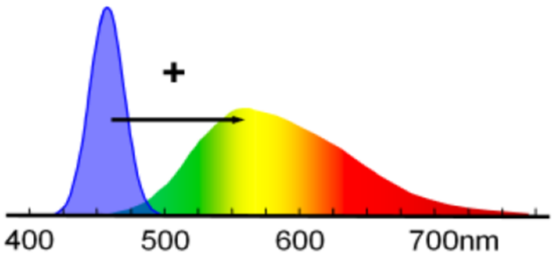
premold. LF



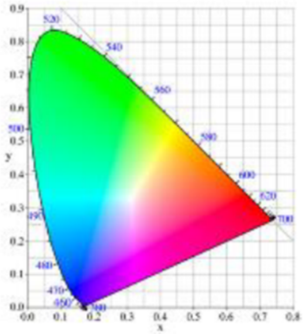
single chip device



LED

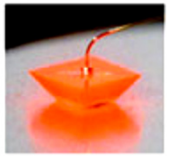


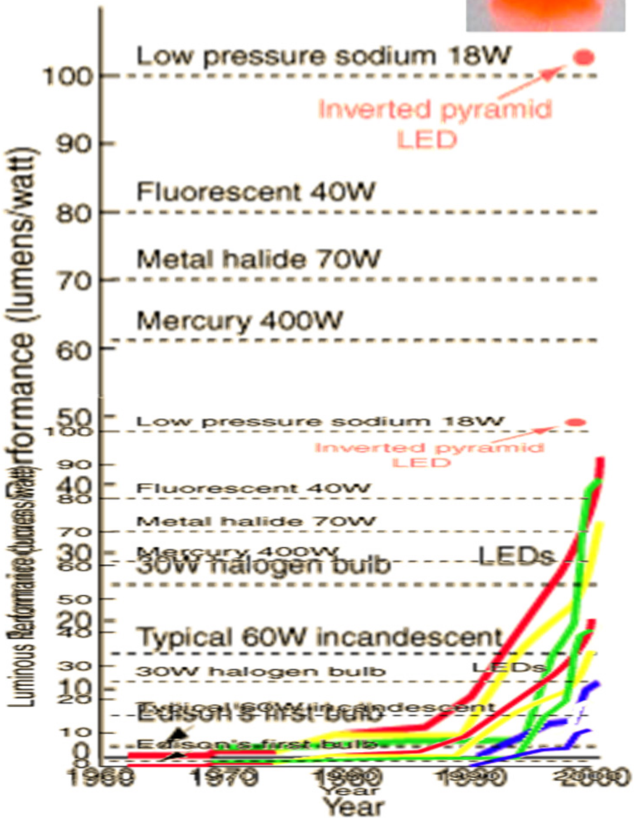
Planck's spectrum



CIE color space

White LEDs for general lighting





2009

2009: 249 lm/W (Nichia, peak value)

2014: 300 lm/W (Cree, peak value)

145 lm/W at high injection (efficiency droop)

10 x the luminous efficiency of modern Edison's light bulb

2020 (target): > 200 lm/W (value reached in 2014)

Energy consumption

Long lifetime (100 000 h)

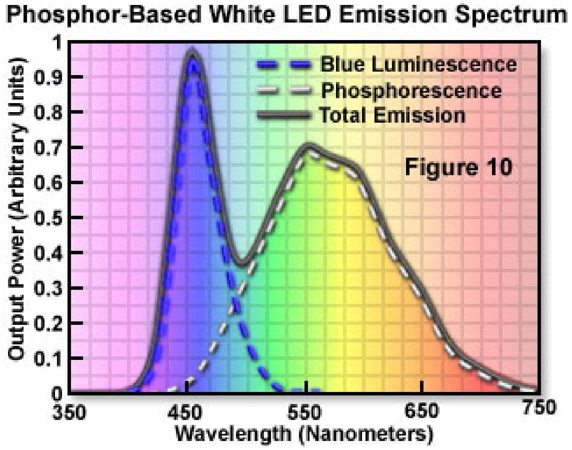
Safety

Compactness

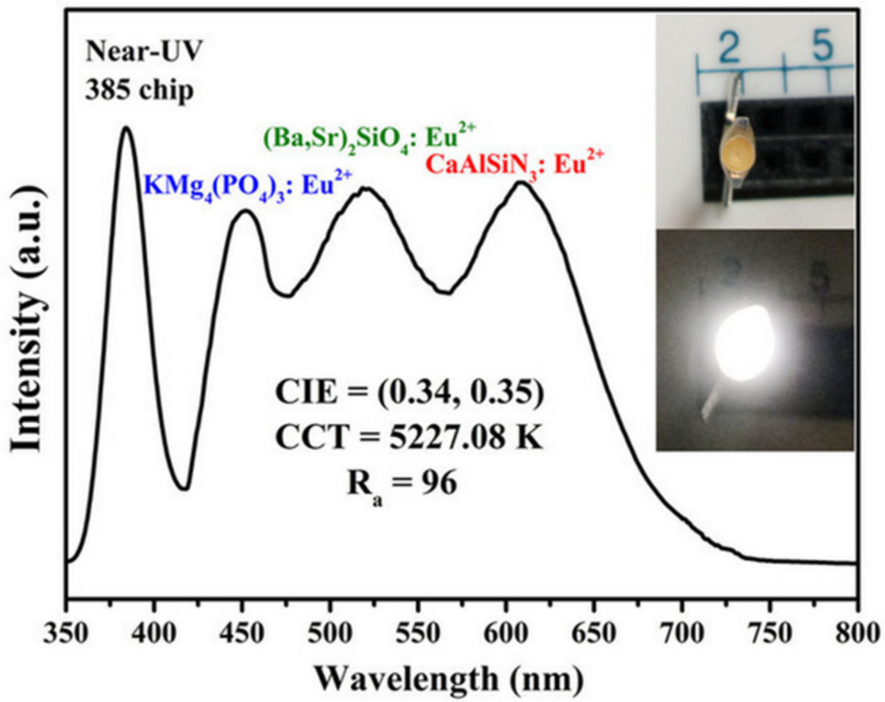
White LEDs

Issues:

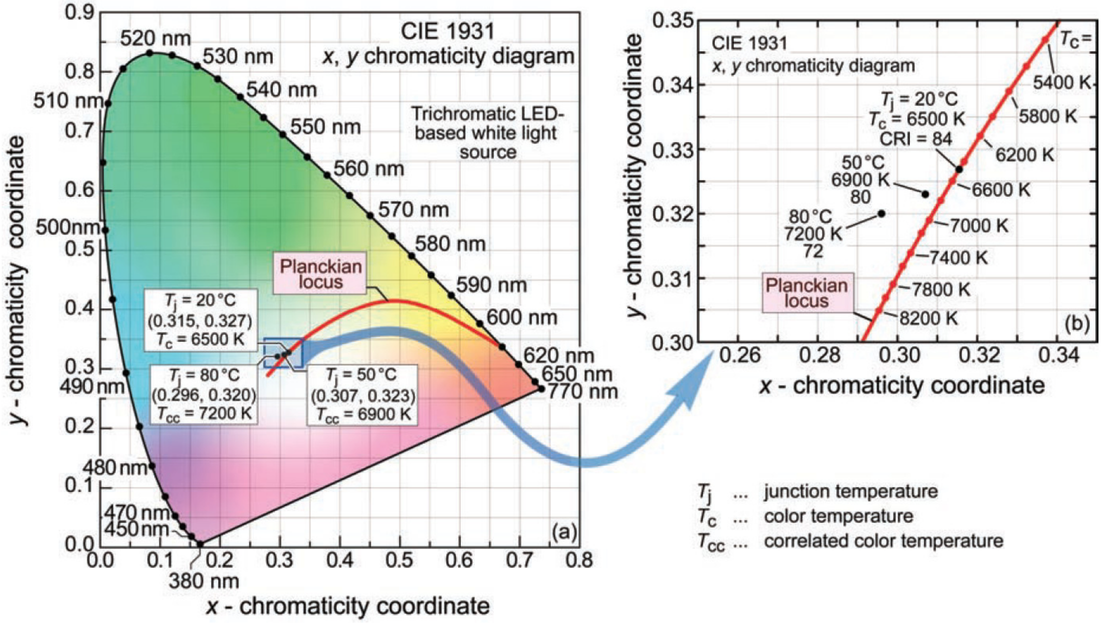
- Color rendering index (CRI)
- Efficiency at high injection current



Blue LED at ~450 nm + Ce^{3+}:YAG phosphor



Chromaticity and color rendering index (CRI)

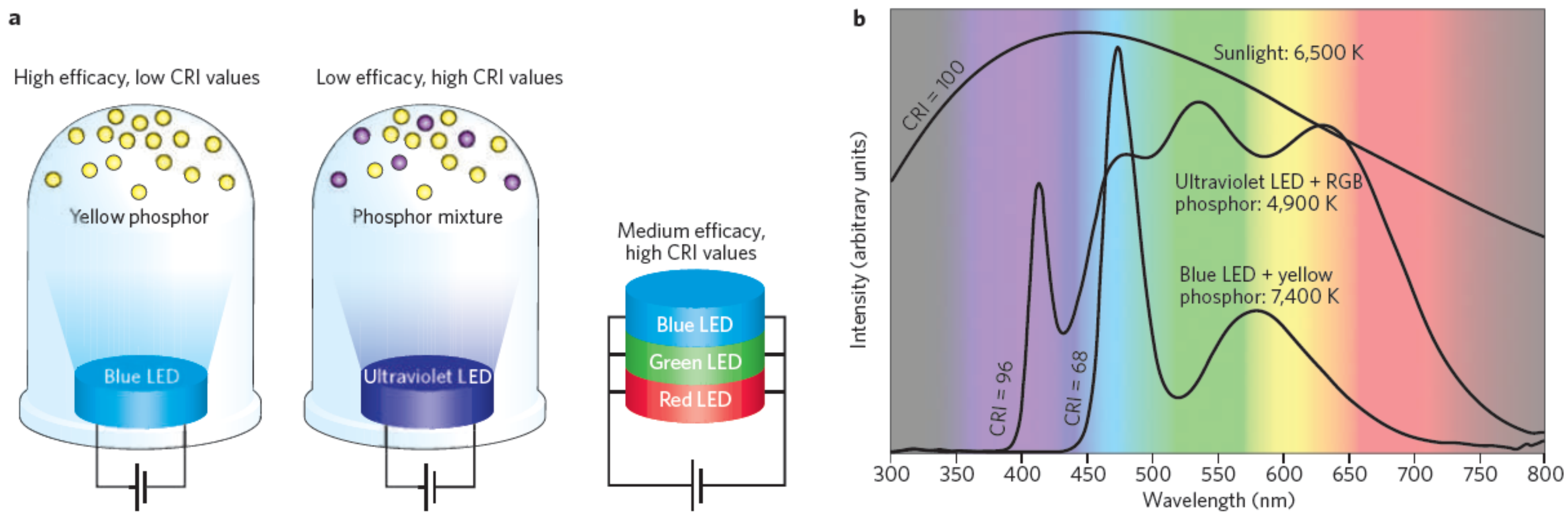


Color rendering index (CRI): *ability to reproduce colors of an object as seen under an ideal white-light source, such as the Sun.*

Sunlight and incandescent light bulbs have a CRI of 100 (ideal value).
Values > 80 sufficient for indoor lighting (lower values, street lighting).

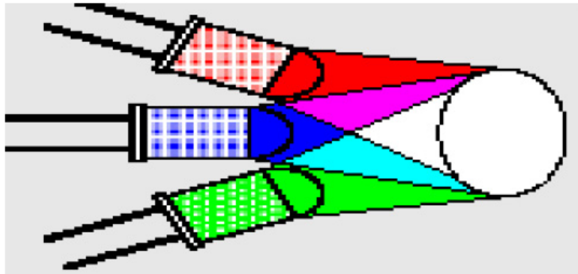
Common CRI values: metal halides 85-95, LED-based white-light sources 60-95, fluorescent lamps 50-90, mercury vapor 20-50 and sodium lamps 5-20.

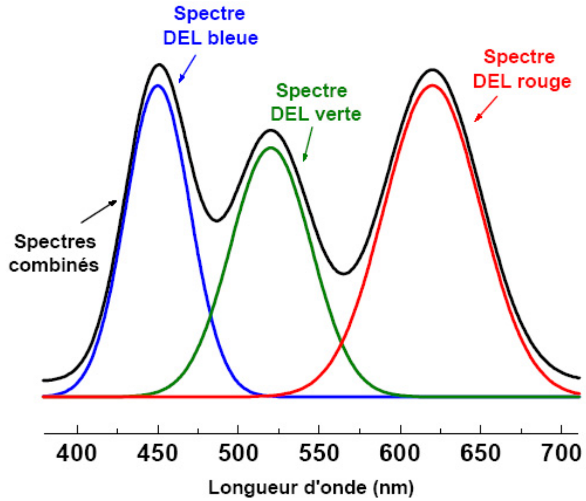
White LEDs



Color temperature: ranging from warm (2000 K) to cold (10000 K going through neutral), which is referenced with respect to the white light emitted by an ideal white-light source (temperature of an ideal black body).

White LEDs





The “Green gap”