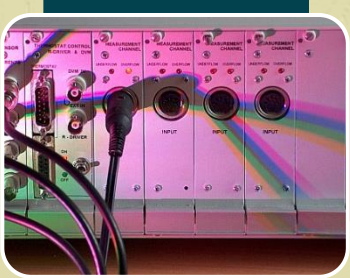
MŰEGYETEM 1782

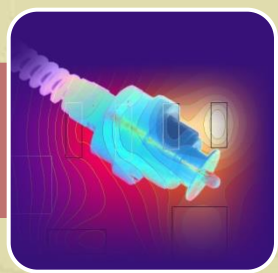
Budapest University of Technology and Economics

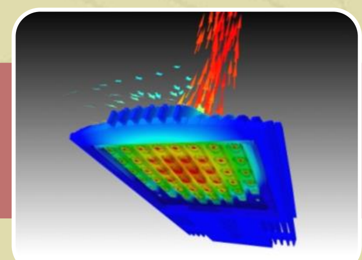
Department of Electron Devices

Microelectronics: Power LEDs

Prof. András Poppe, BME-EET



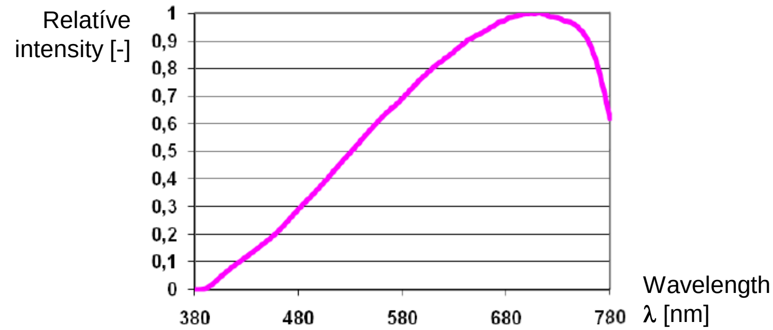


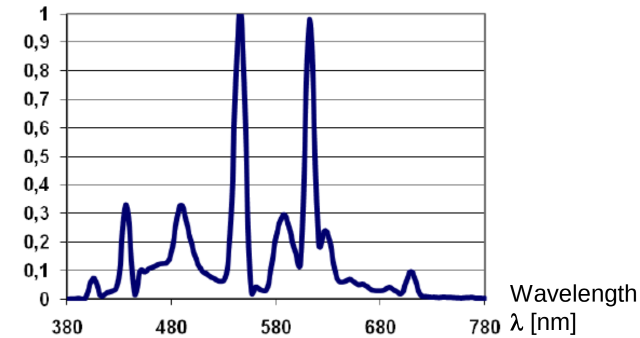


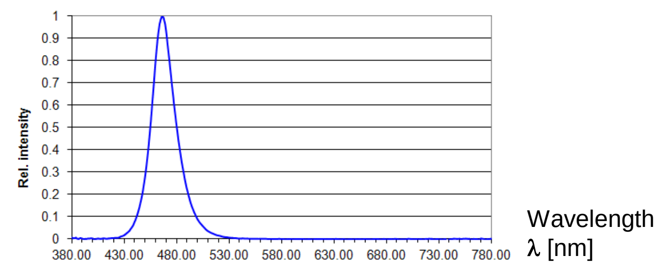
Types of light sources

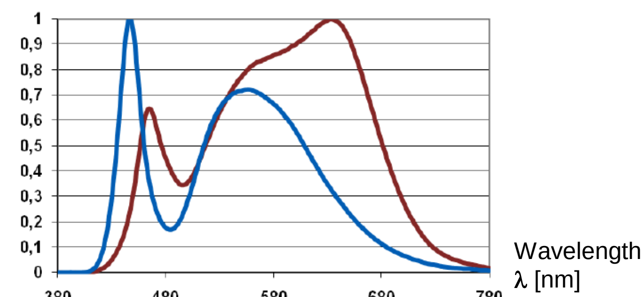
- Incandescent bulb:
  - Black-body radiator
  - Continuous spectrum
- Gas discharge lamps:
  - discrete electron state transition in ionozed gas or vapor
  - Discrete spectrum lines (even multiple ones)
  - Primary radiation
- Mercury lamp, CFL:
  - Like above but phosphor is also used to convert primary radiation to longer wavelengths as well
- Color LED:
  - Electron state transitions in a semiconductor crystal lattice
  - Almost monochromatic primary radiation
- White LED:
  - Electron state transitions in a semiconductor crystal lattice ➔ primary emission
  - + wavelength conversion with phosphor

(relative) spectral power distributions

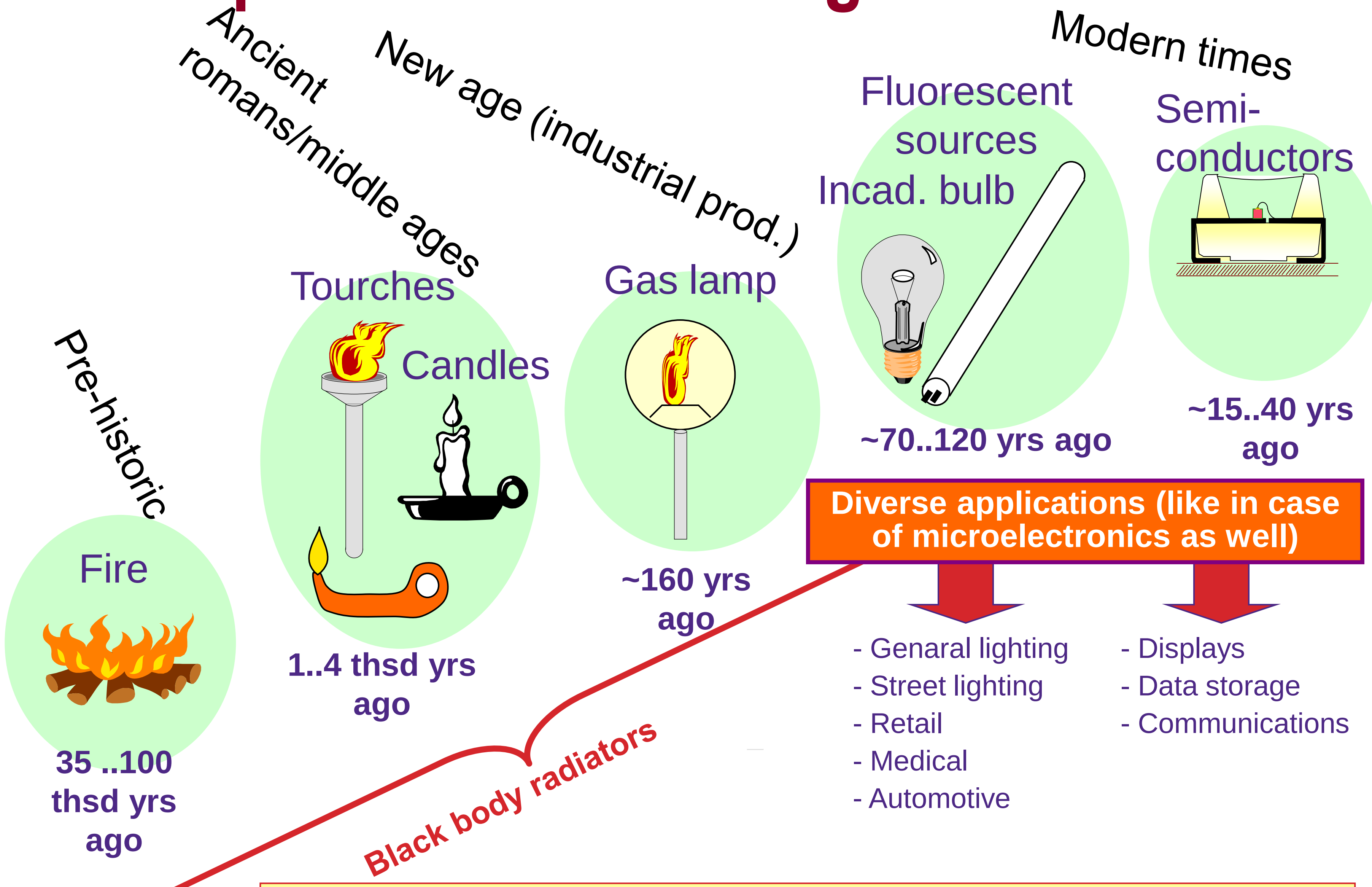








Development of artifical light sources



The innovation cycle of artificial light sources is getting shorter…

The first LEDs…

A Note on Carborundum.

To the Editors of Electrical World:

SIRS:—During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 10 volts between two points on a crystal of carborundum, the crystal gave out a yellowish light. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 110 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole, a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current; but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermoelectric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

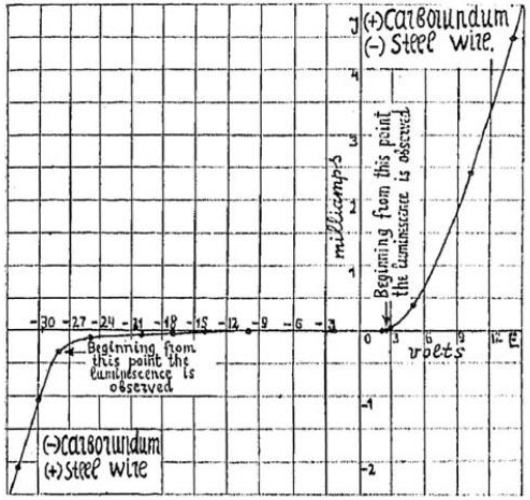
NEW YORK, N. Y. H. J. ROUND.

Henry Joseph Round
(1881 – 1966)

- 1907: first detection and description of electroluminescence
  - 1907: the first LED
  - Siliconcarbide (SiC) aka *carborundum*

The first LEDs…

- ► Oleg V. Losev (Олег В. Лосев) already had publications at the age of 20..
- ► first detailed description of electroluminescence of SiC
  - Major coclusion: emitted light is not from black-body radiation,
  - First LED (measurements between 1924 and 1928)
  - Light emission in both directions
- ► Soviet patent: 1929



Oleg Vladimirovich Losev (1903 – 1942)

Класс 21 a, 27

№ 12191

ПАТЕНТ НА ИЗОБРЕТЕНИЕ

ОПИСАНИЕ

светового реле.

К патенту О. В. Лосева, заявленному 28 февраля 1927 года (заяв. свид. № 14672).

О выдаче патента опубликовано 31 декабря 1929 года. Действие патента распространяется на 15 лет от 31 декабря 1929 года.

Source: PatentsFromRU.com

Предлагаемое изобретение использует общеизвестное явление свечения в карборундовом детекторе и состоит в том, что в световом реле для быстропишущего телеграфного или телефонного приема, передачи изображений на расстояние и других целей, в качестве модулируемого электрическим током источника света, применяется свечение в точке контакта карборундового детектора, включенного непосредственно в цепь модулирующего тока.

На чертеже фиг. 1 изображает схему предлагаемого светового реле и фиг. 2— схему устройства для фотографической записи сигналов с применением светового реле.

К зажимам *A* источника тока сигналов, подлежащих записи, через потенциометр P включается светящийся карборундовый детектор *D*, в цепь которого включена батарея *B*, дающая дополнительное постоянное напряжение для наложения его на напряжение тока сигналов и усиления действия реле; путем регулировки этой батареи создаются наивыгоднейшие условия работы детектора *D*. Оптическая система *L* предназначена направлять световой поток, излучаемый карборундовым детектором, на движущуюся фотографическую пластинку *F*, на которой производится запись изменений этого потока. Детектор *D*, оптическая система *L* и пластина *F* заключены в светонепроницаемую камеру. Примерное включение светового реле показано на чертеже 2, где *E*— приемник-усилитель высокой частоты, *T*— автотрансформатор высокой частоты, а остальная часть схемы вполне аналогична только-что описанной.

Предмет патента.

1. Световое реле для быстропишущего телеграфного или телефонного приема, передачи изображений на расстояние и для других целей, характеризующееся применением, в качестве модулируемого электрическим током источника света, свечения в точке контакта карборундового детектора общеизвестного устройства, каковой детектор включен непосредственно в цепь модулирующего тока.

2. Видоизменение охарактеризованного в п. 1 светового реле, отличающееся тем, что последовательно с указанным детектором *D* включен источник дополнительного напряжения постоянного тока *B* (фиг. 1 и 2) с целью усиления действия реле.

History of commercial LEDs

- 1962: TI – 1st commercial GaAs IR LED,
- 1962: GE – 1st commercial red LED (N. Holonyak)
- 1972: yellow / greenish LED-ek
- 1978: 1st high intensity LED
- 1989: GaN homo-junction LED
- 1993: Efficient blue LED
- 1997: White LED (blue+phosphor)
- 2001: White LED (UV LED + phosphor)
- Toady: various hight powe LED-ek
  - 1 .. 10 .. 100 W – HPS lamps also replaced

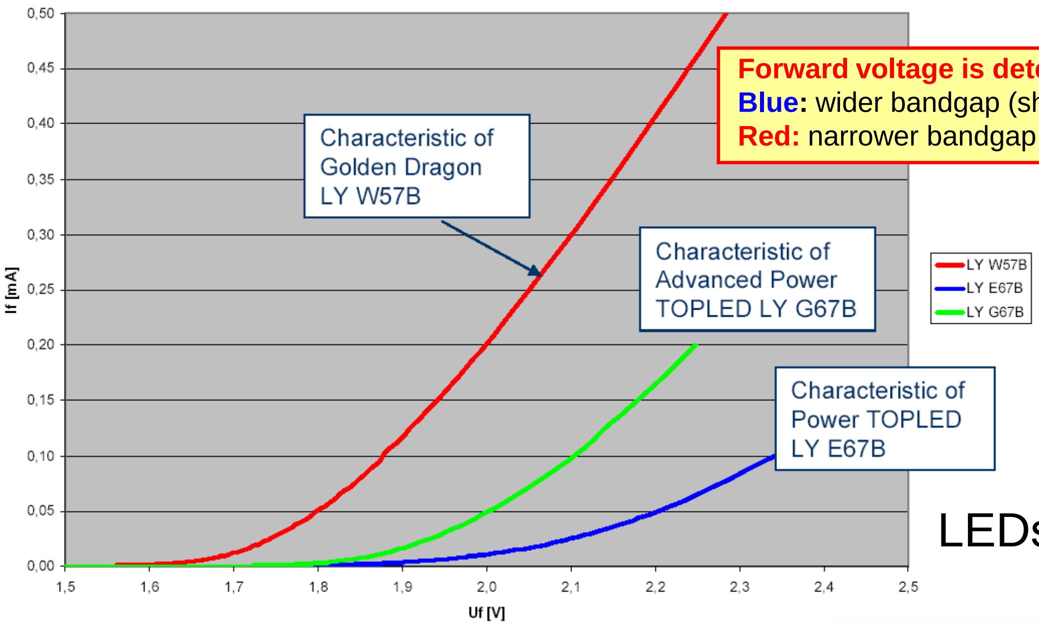
Akasaki, Amano and Nakamura professors
Nobel prize in physics 2014

First LEDs were used as indicators only, modern high efficiency LEDs completely changed the lighting industry by now…

Characteristic features of LEDs

- Electrical parameters
  - **Forward voltage:** 2.5 V .. 4 V, depending on the color;
    - Larger V_F: multiple PN junctions connected in series
    - CoB LEDs: cca. 50 V, AC LEDs: 120 V / 230 V
  - **Forward current:**
    - Low power classical LEDs: ~10 mA
    - High power LEDs: 300 mA … 800 mA …1500 mA
  - Reverse direction: small breakdown voltage $\Rightarrow$ protection diode (is also an LED – red)
- Characteristics of the package:
  - **Thermal resistance:** 300 K/W .. 10 K/W .. 1 K/W .. 0.1 K/W
  - Package style: exposed cooling surface/MCPCB, type of optics
- Optical parameters
  - **Luminous flux** [lm], fluminous efficacy [lm/W]
  - Emitted optical power aka radiant flux [W]
  - spectrum + dominant wavelength (colour LEDs) or correlated colour temperature + x,y coordinates (fwhite)
  - Radiation pattern
- Efficiencies – many of them

Forward voltage and colour of lighth



Forward voltage is determined by the bandgap
Blue: wider bandgap (shorter wavelengths) ➔ higher V_F (e.g. 3 V)
Red: narrower bandgap (longer wavelengths) ➔ lower V_F (e.g. 1.5 V)

LEDs' forward volatge ~ $U_g = W_g/q$

Example

$U_g = (c \cdot h)/(\lambda \cdot q)$

Peak wavelength from the spectrum of a blue LED: **447nm**

$c \cdot h = 3e8 \cdot 6.625e\text{-}34 = 1.988e\text{-}25$
$\lambda \cdot q = 4.47e\text{-}7 \cdot 1.602e\text{-}19 = 7.16e\text{-}26$
$U_g = 1.988/7.16 \cdot 10 = 2.777$ V

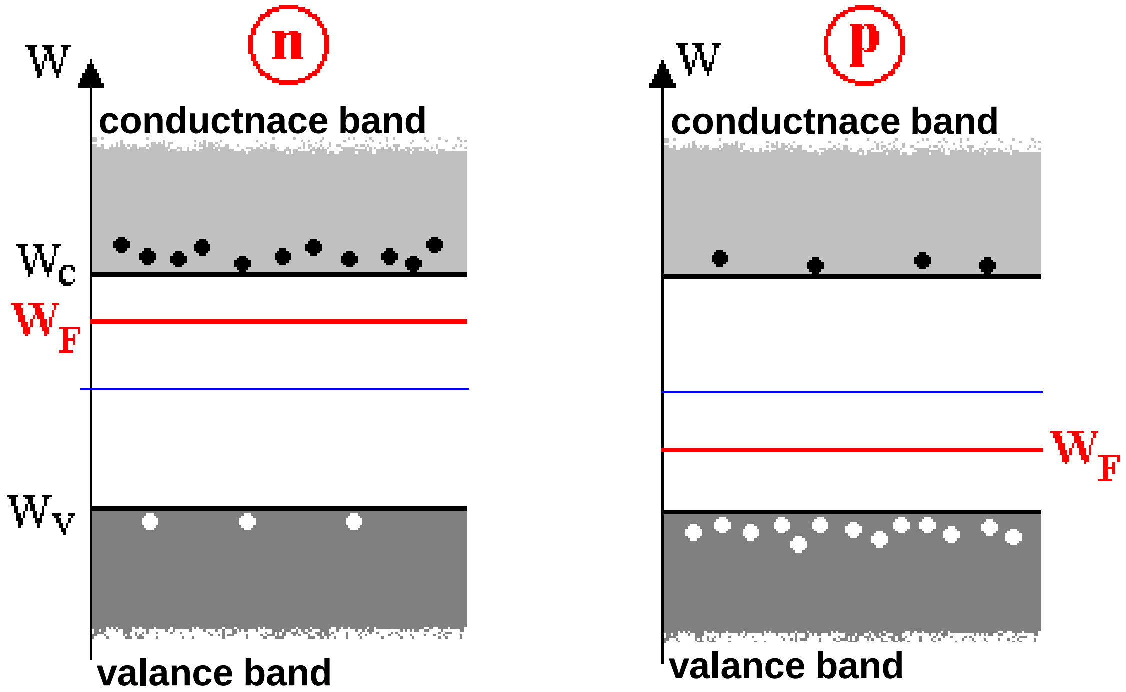
Different efficiencies of LEDs

- ***Quantum efficiency*** (kvantumhatásfok) [%]
  - Number of emitted photons per number of injected electrons
  - *For PC whitle LEDs:* ***conversion efficiency of phosphor***
- ***Extraction efficiency*** [%]
  - Number of photons leaving the LED to free space per photons generated in the junction
- ***Power efficiency / wall-plug efficiency – WPE /*** η_e [%] (energy conversion efficiency)
  - Emitted optical power (*total radiant flux*) per supplied electric power ($P_{opt} / P_{el} = \Phi_e / P_{el}$)
- ***Efficacy / luminous efficiency*** η_V [lm/W]
  - Emitted total luminous flux per supplied electrical power

RECAP SOME PN-JUNCTION BASICS…

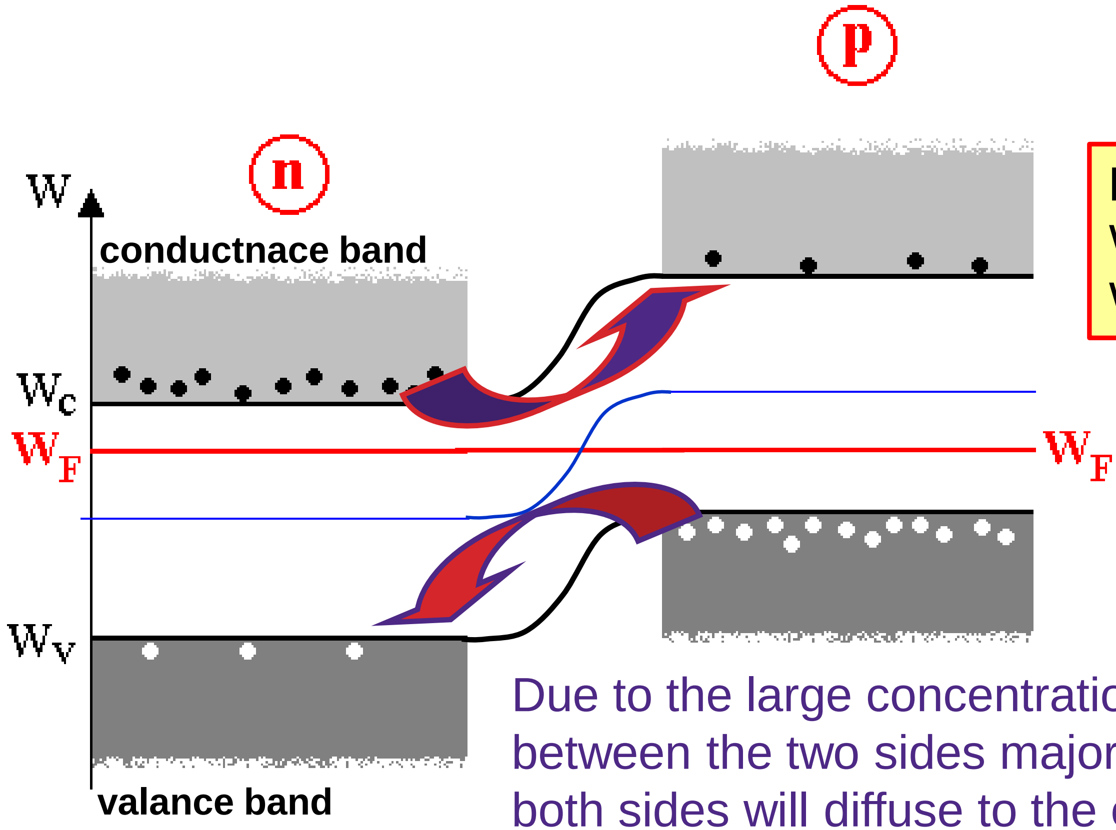
N and P type layers: *separated*

- Fermi levels shifted with respect to the intrinsic Fermi level according to doping:



PN junction

- A potential step develops between the p and n sides. This will be so high that the Fermi-levels of both sides will be equal:

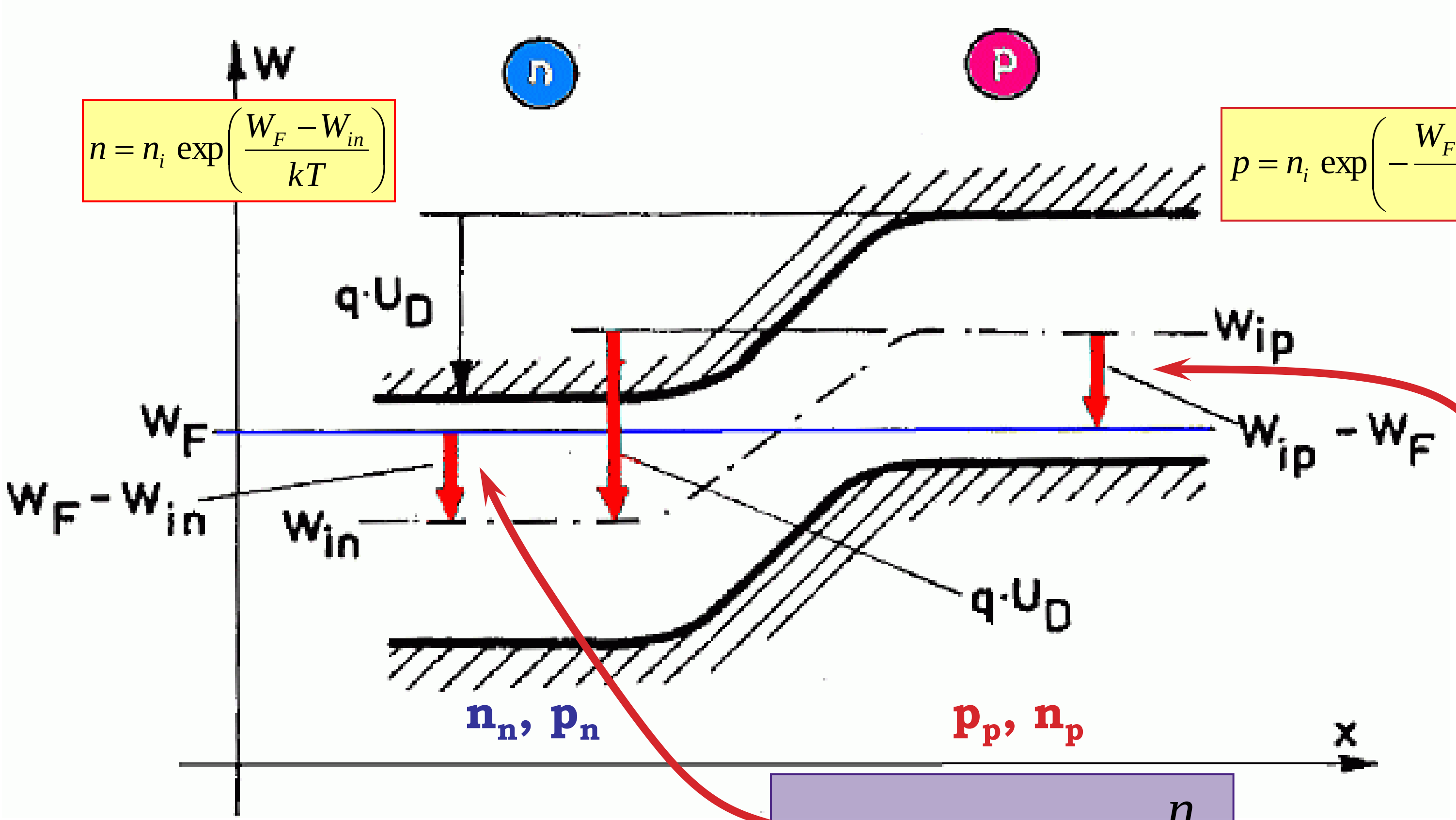


Homo-junction:
W_c, W_v change,
W_g constant

Due to the large concentration gradient between the two sides majority carriers of both sides will diffuse to the other side until the Fermi-levels get equal.

- Carrier gradient between the two sides of the junction $\rightarrow$ diffusion current $\rightarrow$ depletion layer / spacecharge

Diffusion potential



$$n = n_i \exp\left(\frac{W_F - W_{in}}{kT}\right)$$

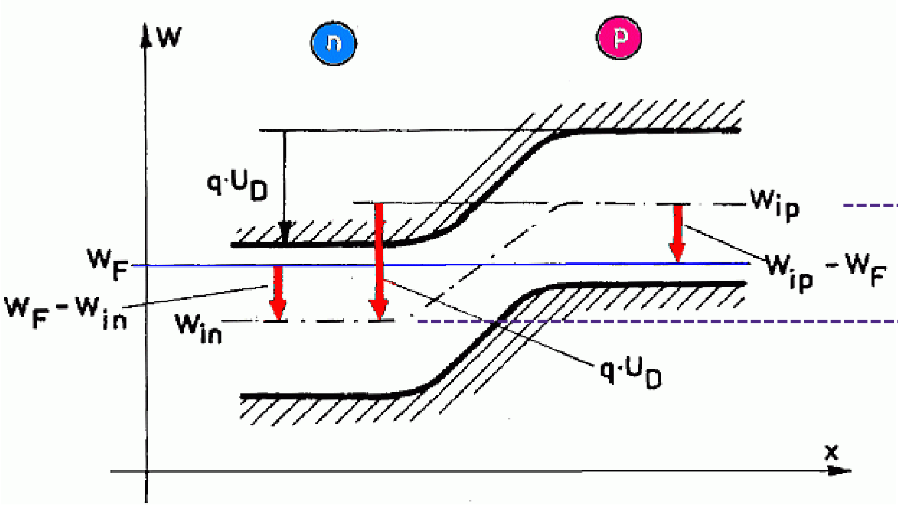
$$p = n_i \exp\left(-\frac{W_F - W_{ip}}{kT}\right)$$

$$W_F - W_{in} = kT \ln \frac{n_n}{n_i}$$

$$W_F - W_{ip} = kT \ln \frac{n_p}{n_i}$$

$$n_n = n_i \exp\left(\frac{W_F - W_{in}}{kT}\right)$$

Diffusion potential



$$W_F - W_{in} = kT \ln \frac{n_n}{n_i}$$

$$W_F - W_{ip} = kT \ln \frac{n_p}{n_i}$$

$$W_{ip} - W_{in} = kT \ln \frac{n_n}{n_p}$$

$$U_D = \frac{W_{in} - W_{ip}}{-q} = \frac{kT}{q} \ln \frac{n_n}{n_p} = \frac{kT}{q} \ln \frac{n_n p_p}{n_i^2}$$

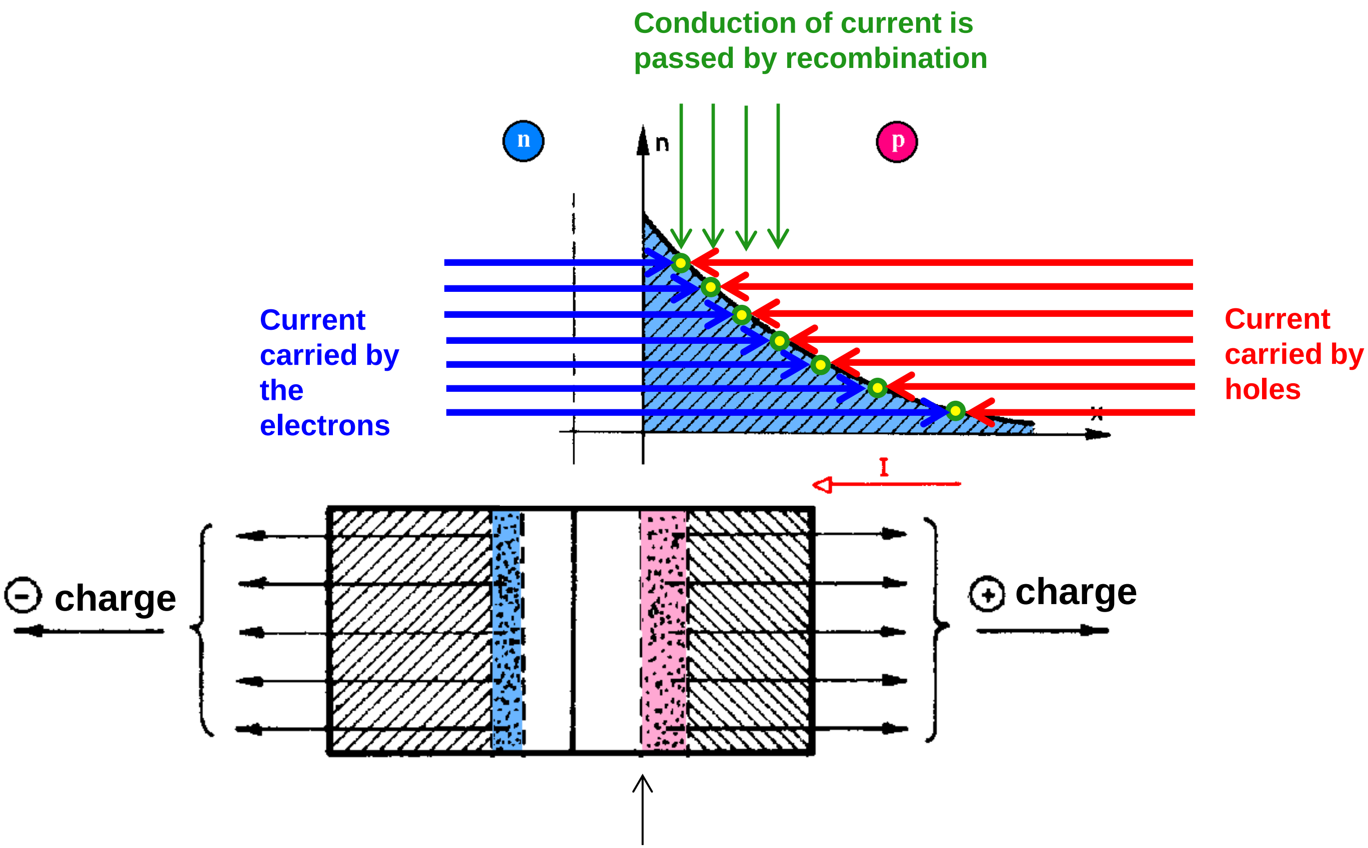
$$n_p = n_i^2 / p_p$$

mass effect law

$$\boxed{U_D = U_T \ln \frac{N_d N_a}{n_i^2}}$$

„built-in" voltage

Recombination at the PN junction



Electrons injected into a p-type material

The type of recombination matters (direct: light, indirect: heat)

TODAY'S LED STRUCTURES: DOUBLE HETEROJUNCTION MQW

Double heterojunction

- ► Nowadays it is typical for all LEDs

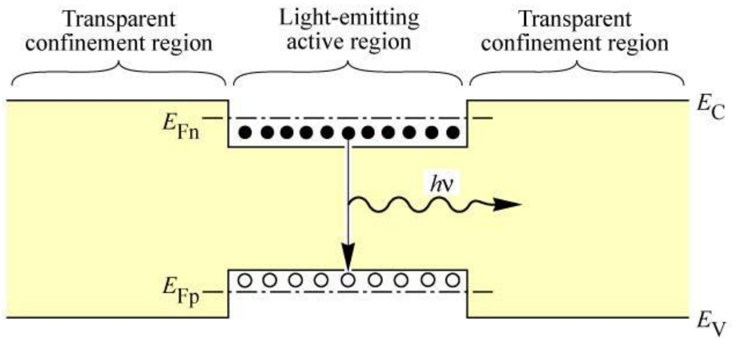


Fig. 9.2. Double hetero-structure with optically transparent confinement regions. Reabsorption in the active region is unlikely due to the high carrier concentration in the active region and the resulting Burstein–Moss shift of the absorption edge.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

- ► Explanation of the benefit:

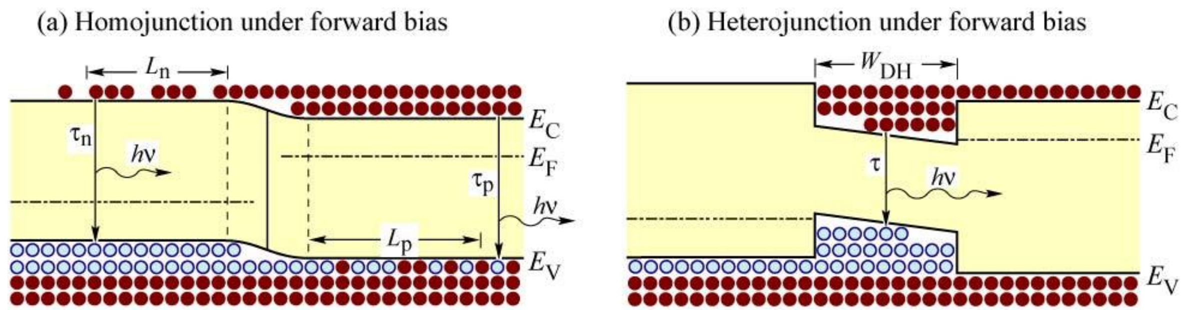


Fig. 7.2. Free carrier distribution in (a) a homojunction and (b) a heterojunction under forward bias conditions. In homojunctions, carriers are distributed over the diffusion length. In heterojunctions, carriers are confined to the well region.

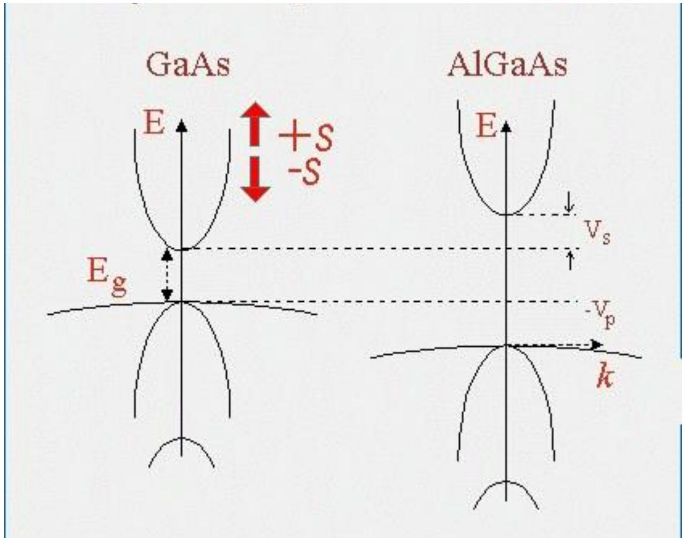
E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

http://www.ecse.rpi.edu/~schubert/Light-Emitting-Diodes-dot-org/chap07/chap07.htm

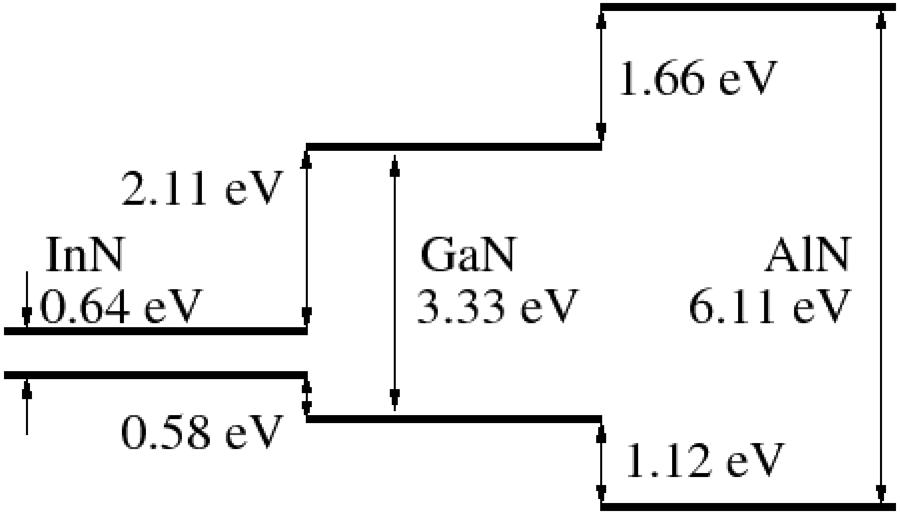
The heterojunction

A heterojunction is formed when two materials with different bandgap mate…

Compound semiconductors: the valence and conduction bands are shifted, sometimes asymmetrically…



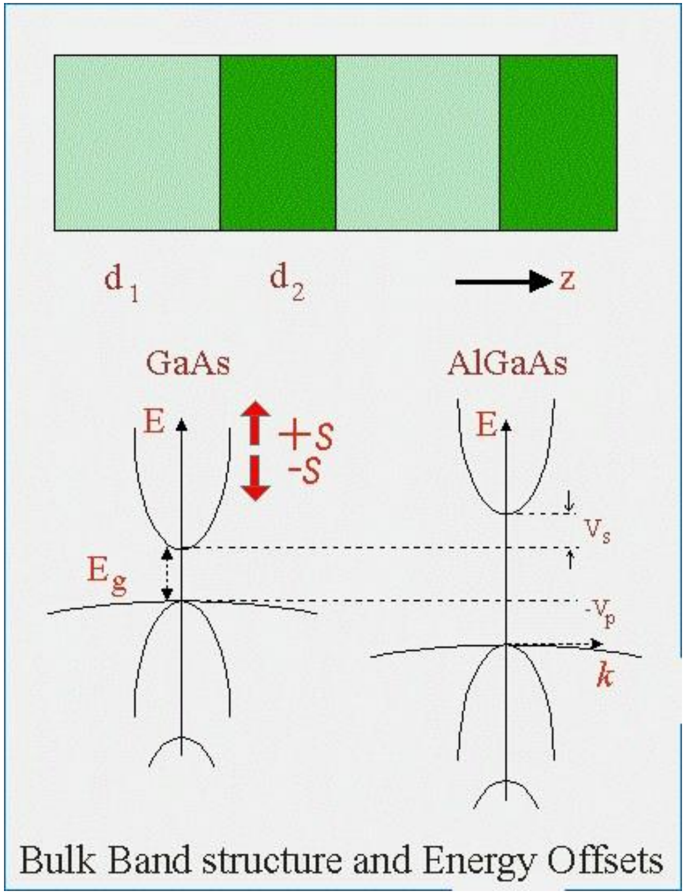
Bulk Band structure and Energy Offsets



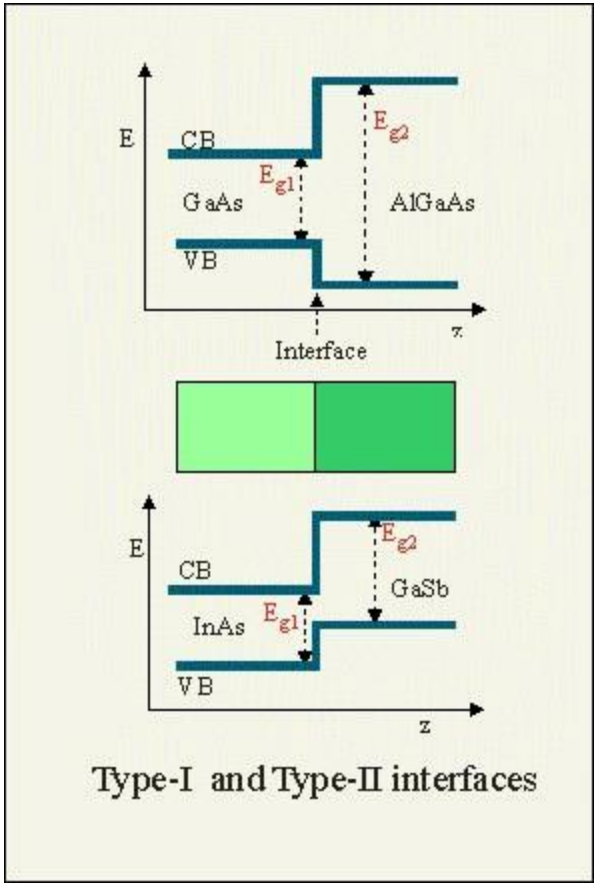
$$\mathcal{E}_{\mathrm{off}}^{\mathrm{ABC}} = \frac{\mathcal{E}_{\mathrm{off}}^{\mathrm{AC}}(\mathcal{E}_{\mathrm{g}}^{\mathrm{ABC}} - \mathcal{E}_{\mathrm{g}}^{\mathrm{BC}}) - \mathcal{E}_{\mathrm{off}}^{\mathrm{BC}}(\mathcal{E}_{\mathrm{g}}^{\mathrm{ABC}} - \mathcal{E}_{\mathrm{g}}^{\mathrm{AC}})}{\mathcal{E}_{\mathrm{g}}^{\mathrm{AC}} - \mathcal{E}_{\mathrm{g}}^{\mathrm{BC}}},$$

http://quantum-algorithms.com/semicon/bulk.jpg
http://www.iue.tuwien.ac.at/phd/vitanov/node59.html

Heterojunction: A change in the semiconductor material when not only the positions of the valence and conductance bands change (homojunction) but the bandgap also changes:



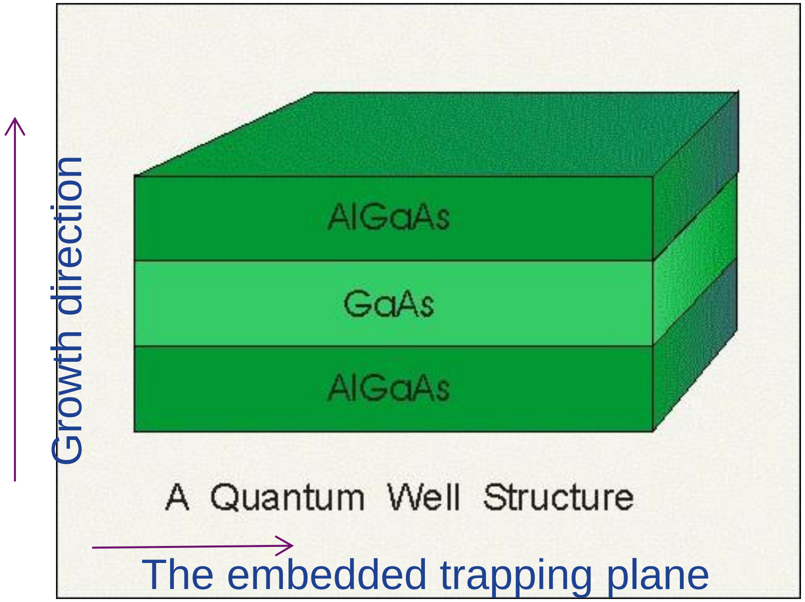
Bulk Band structure and Energy Offsets

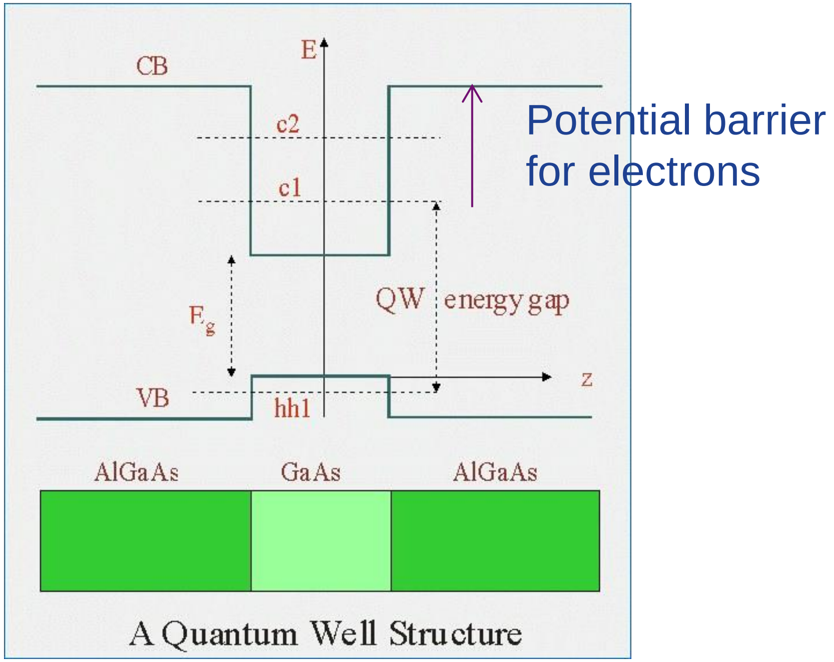


Type-I and Type-II interfaces

http://quantum-algorithms.com/semicon/bandiface.jpg

The Quantum Well (QW) structure





- The charge carriers are trapped in the GaAs layer
  - They cannot move in the direction of layer growth
  - They are free to move in the trapping plane

- **Charge carriers confined into a small region → increased probability of recombiantion**

- The gap of the QW is wider than the gap of the bulk material.
- The QW gap energy can be controlled by the width of the QW.

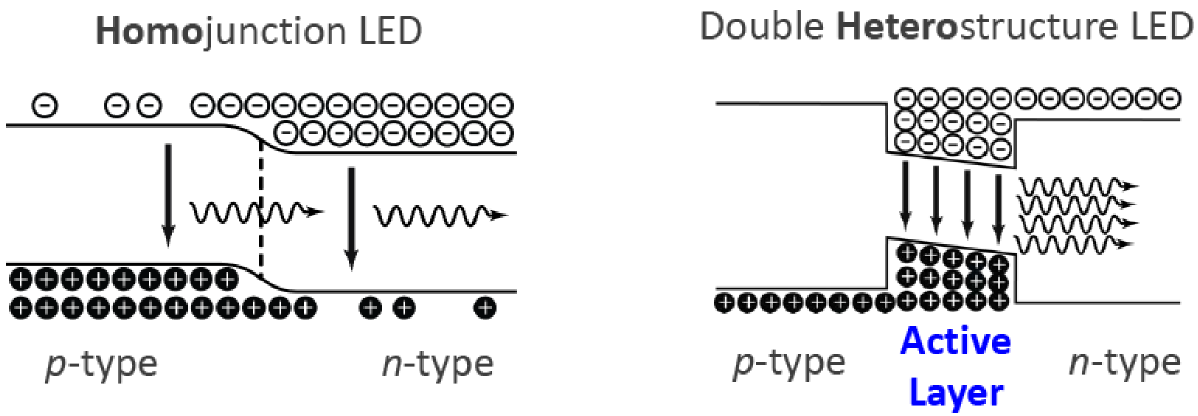
GaN QW: p-GaN – InGaN – n-GaN

- **MQW: Multiple Quantum Well**

http://quantum-algorithms.com/waveeng.html

Double heterojunction

Energy Band Diagrams



Internal Quantum Efficiency

$$\eta_{IQE} = \frac{\text{Light generated}}{\text{Electrons injected}} = \frac{R_{radiative}}{R_{radiative} + R_{non-radiative}} = \frac{Bn^2}{An + Bn^2 + Cn^3}$$

Auger

Shockley-Read-Hall (SRH) ***Spontaneous Emission***

Double heterostructures **increase carrier concentrations (*n*)** in the active layer and **enhance radiative recombination** rates (more light generated).

Source: http://www.nobelprize.org/nobel_prizes/physics/laureates/2014/nakamura-lecture-slides.pdf

MODELLING LED OPERATION

Ideal diode characteristic

$$J_n\big|_{x=0} = \frac{qD_n n_p}{L_n}(\exp(U/U_T)-1)$$

$$J_p = \frac{qD_p p_n}{L_p}(\exp(U/U_T)-1)$$

$$I = A(J_n + J_p)$$

I_0 is proportional with the minority carrier concentration!

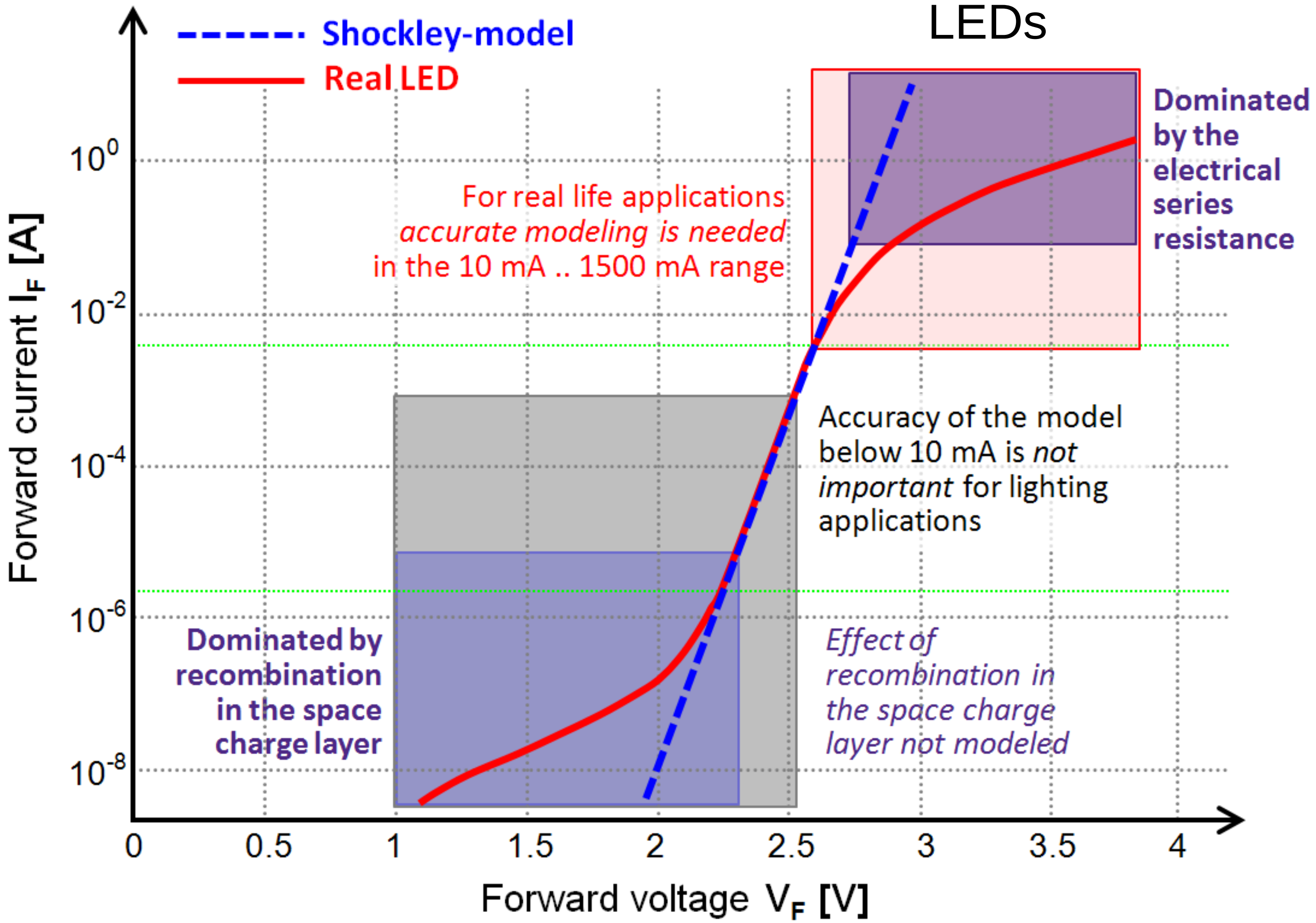
$$I = \underbrace{Aq\left(\frac{D_n n_p}{L_n} + \frac{D_p p_n}{L_p}\right)}_{I_0}(\exp(U/U_T)-1)$$

$$I = I_0\left(\exp(U/U_T)-1\right) \Rightarrow U = U_T \ln(I/I_0+1)$$

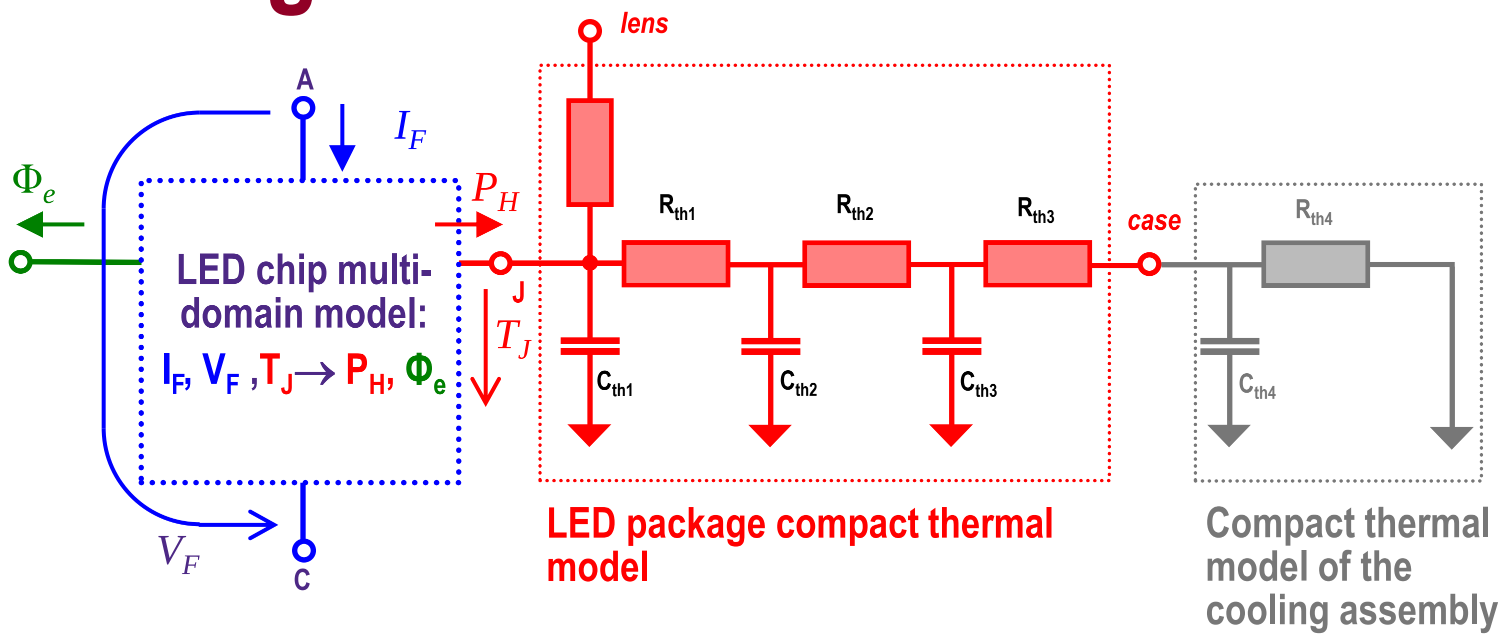
A real LED I-V characteristic

$$I_F(V_F) = I_0 \cdot [\exp(V_F / (m\, V_T)) - 1]$$

The classical diode characteristic is also valid for LEDs



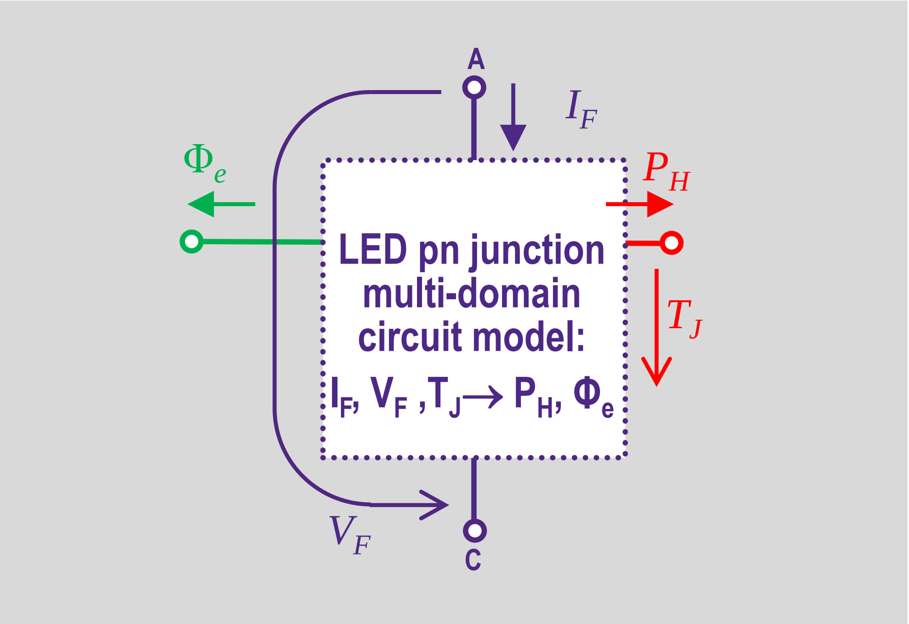
Modelling LEDs and LED luminaires



- **Thermal model:** represents the junction to ambient heat-flow path by means of an RC network model
  - Using within a CFD simulator: only the package model
  - Using an electro-thermal circuit simulator: the package model and the model of the cooling assembly
- **LED chip modell**: electro-thermal and also calculates the emitted optical power $\rightarrow$ **multi-domain**
  - Further properties: Φ_V, spectrum $\rightarrow$ **hot lumens**
  - ***Black box***: no deep physics of the device $\rightarrow$ **this is the compact model**

Chip level model for an ideal LED

- I_F – 2 components:
  - I_{dis} – heat generation (non-radiative recombination)
  - I_{rad} – light emission (radiative recombination)



$$I_{rad}(V_F) = \Phi_e / V_F$$

- Measuredl=: $P_{el} = P_H + \Phi_e$

$$I_F = \frac{P_H}{V_F} + \frac{\Phi_e}{V_F}$$

$$I_F(V_F) = I_{dis}(V_F) + I_{rad}(V_F)$$ ahol

$$\boxed{I_{rad}(V_F) = I_{0\_rad} \cdot [\exp(V_F/(n_{rad} V_T)) - 1]}$$

$$\boxed{I_{dis}(V_F) = I_{0\_dis} \cdot [\exp(V_F/(n_{dis} V_T)) - 1]}$$

$$I_{dis}(V_F) = I_F - \Phi_e / V_F$$

$$I_{rad}(V_F) = \Phi_e / V_F$$

Chip level model for an ideal LED

- I_F – 2 components:
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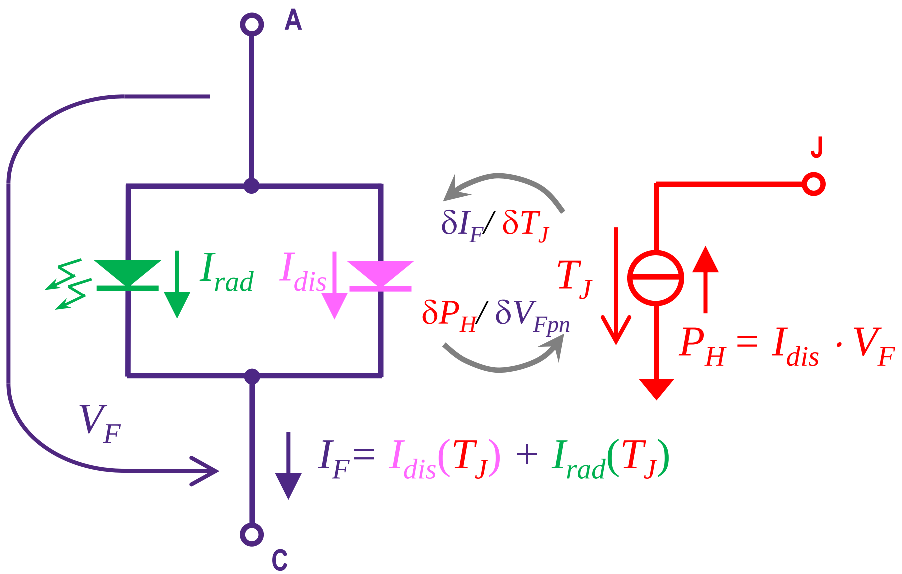

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$$I_F(V_F) = I_{dis}(V_F) + I_{rad}(V_F)$$ ahol $$\boxed{I_{rad}(V_F) = I_{0\_rad} \cdot [\exp(V_F /(n_{rad} V_T)) - 1]}$$ $$\boxed{I_{dis}(V_F) = I_{0\_dis} \cdot [\exp(V_F /(n_{dis} V_T)) - 1]}$$

$$I_{dis}(V_F) = I_F - \Phi_e / V_F$$
$$I_{rad}(V_F) = \Phi_e / V_F$$

Light emission and dissipation

- The total supplied electric power: $P_{el} = V_F \cdot I_F$

$$I_F(V_F) = I_{dis} \cdot \left[\exp(V_F / nV_T) - 1\right] + I_{rad} \cdot \left[\exp(V_F / mV_T) - 1\right]$$

$$\boxed{P_{el} = I_{dis} \cdot \left[\exp(V_F / nV_T) - 1\right] \cdot V_F + I_{rad} \cdot \left[\exp(V_F / mV_T) - 1\right] \cdot V_F}$$

$$P_{el} = I_{dis} \cdot \left[\exp(V_F / mV_T) - 1\right] \cdot V_F + I_{rad} \cdot \left[\exp(V_F / nV_T) - 1\right] \cdot V_F$$

heat

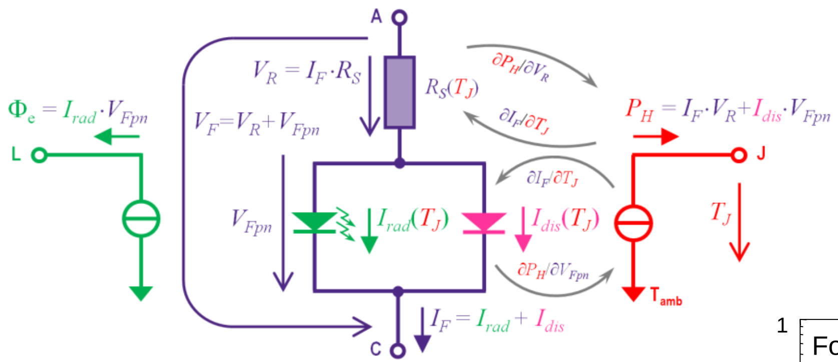
light

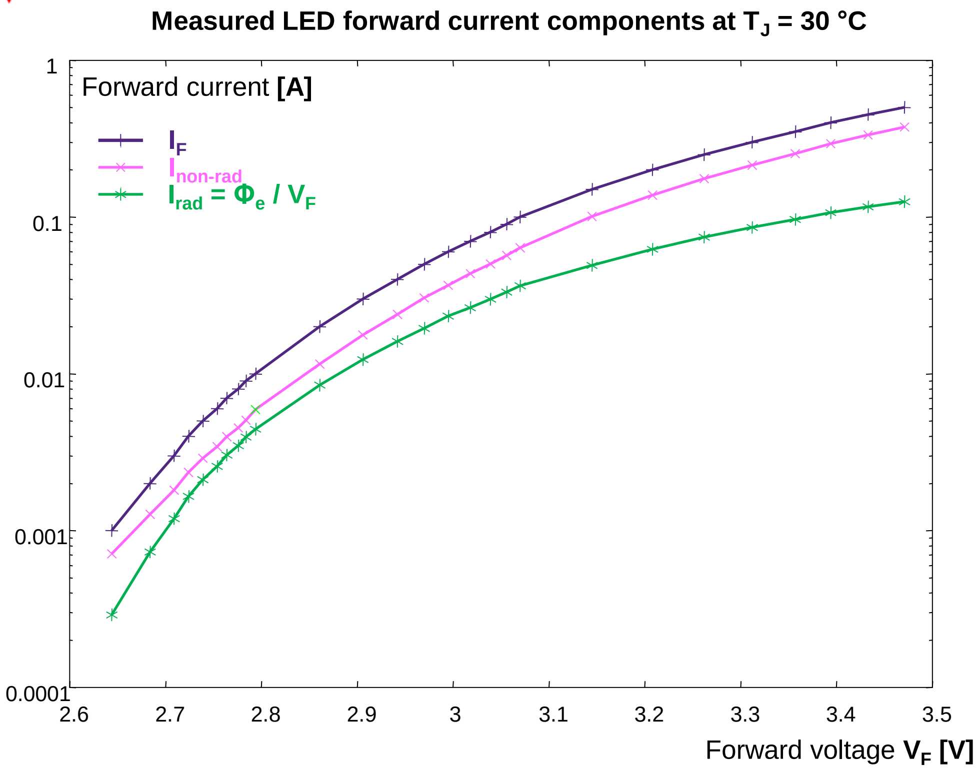
This is the **radiant flux** Φ_e [mW]
or **optical power** P_{opt} [mW]

$$\boxed{P_{diss} = P_{el} - \Phi_e}$$

Ideal LED + series resistance

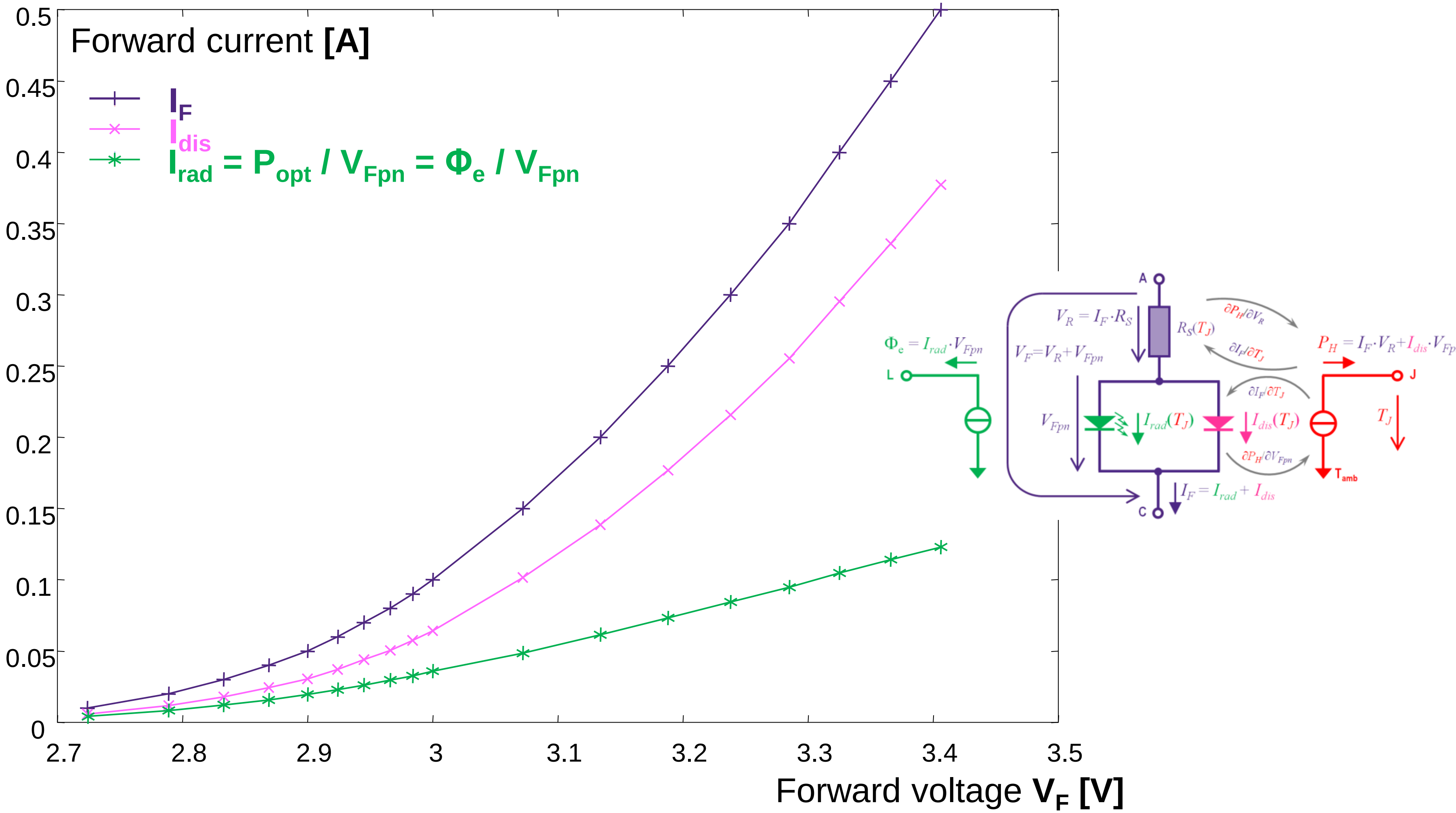
► Modelling the series resistance is important since LEDs for lighting are used at high current operating point





Some measurement results:

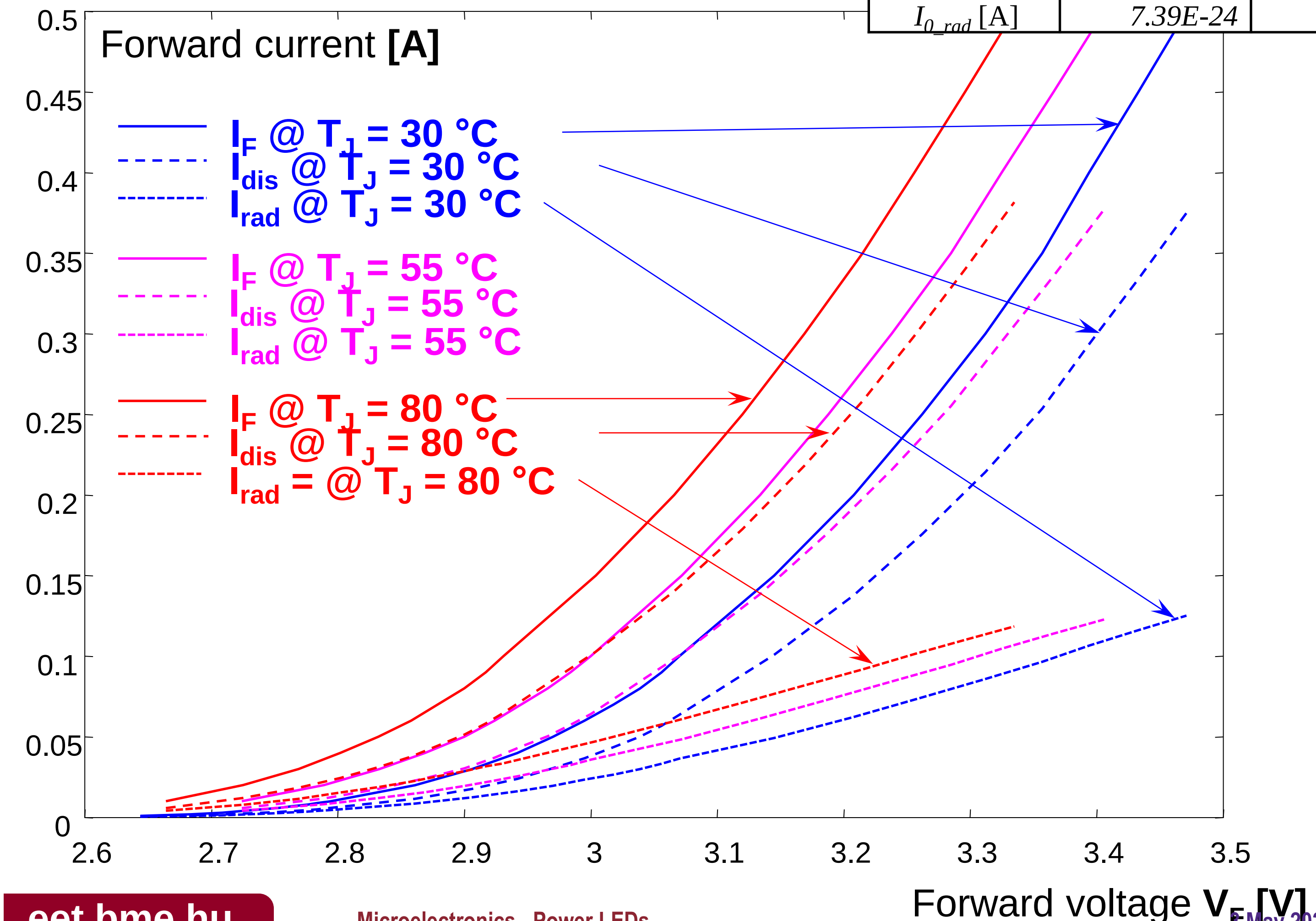
Measured LED forward current components at T_J = 55 °C



Some measurement results:

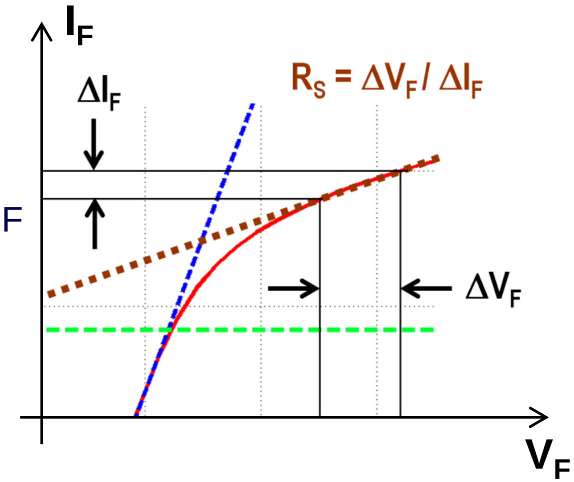
Measured LED forward current components at T_J = 30 °C, 55 °C, 80 °C

	T_J = 30 °C	T_J = 55 °C	T_J = 80 °C
R_s [Ω]	0.77	0.81	0.85
m [-]	2.63	2.46	2.29
I_{0_dis} [A]	3.94E-20	1.70E-19	3.01E-19
n [-]	2.17	1.94	1.71
I_{0_rad} [A]	7.39E-24	5.85E-24	4.31E-24



Parameter extraction (overview):

1. For all set T_J
   a) Find R_S (see diagram)
   b) Internal junction voltage: $V_{Fpn} = V_F - R_S(T_J) \cdot I_F$
      $I_F(V_{Fpn})$ is the characteristc of the inner junction (free of effect of R_s)
   c) Find components of I_F :
      - $I_{rad}(V_{Fpn}) = P_{opt}(I_F)/V_{Fpn}$
      - $I_{dis}(V_{Fpn}) = I_F(V_{Fpn}) - I_{rad}(V_{Fpn})$
   d) Curve fitting
      - $I_{rad}(V_{Fpn})$ points to the $I_{rad}(V_{Fpn}) = I_{0\_rad} \cdot [\exp(V_{Fpn}/(n_{rad}V_T)) - 1]$ equation
      - $I_{dis}(V_{Fpn})$ points to the $I_{dis}(V_{Fpn}) = I_{0\_dis} \cdot [\exp(V_{Fpn}/(n_{dis}V_T)) - 1]$ equation

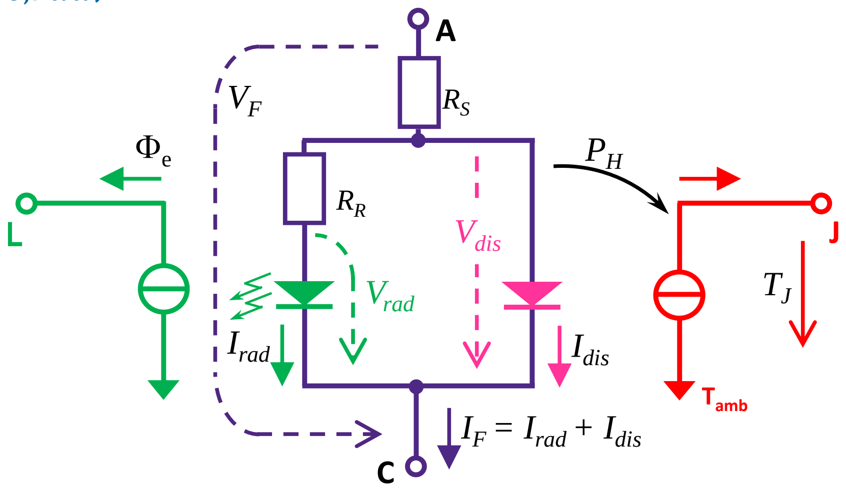


2. Continue at step 1 for the next T_J
3. Fit the data series of the parameters $I_{0\_rad}(T_J)$, $n_{rad}(T_J)$, $I_{0\_dis}(T_J)$, $n_{dis}(T_J)$ és $R_S(T_J)$ approximate formulae (e.g. linear temperature dependence of R_S)

Improved LED model

- The previous model (2014) overestimated light emission at high currents, disregarding some optical losses…
- R_R is added to account for these losses

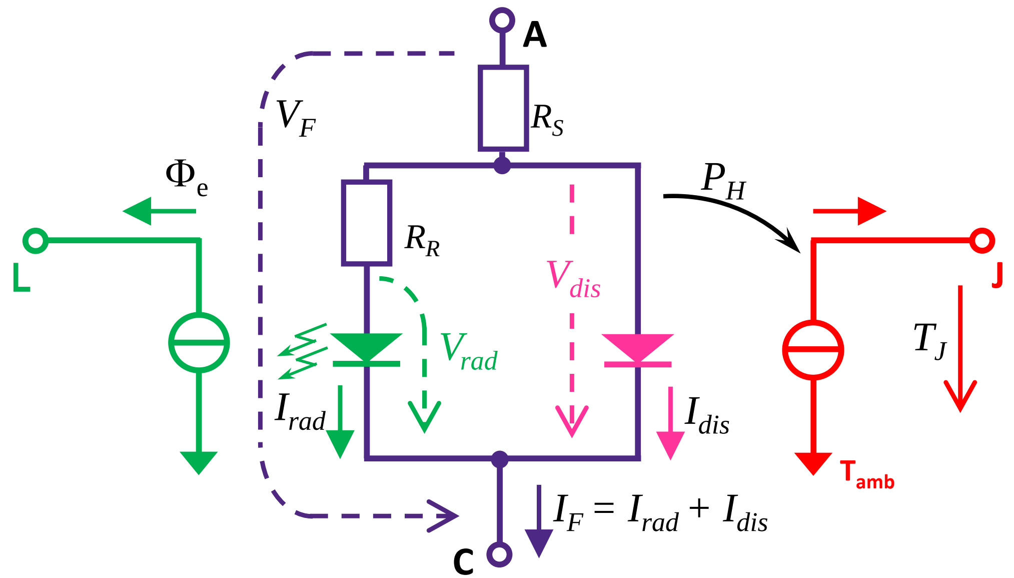
$$V_{dis} = I_{rad} \cdot R_R + m_{rad} \cdot U_T \cdot \ln\left(\frac{I_{rad}}{I_{0,rad}}\right)$$



- Developed and implemented in the Delphi4LED project of the EU (Visual Basic macro for Excel, generic SPICE circuit macro for LT-Spice)

Improved LED chip level multi-domain model

The two diode branches represent the dissipative and radiative recombination processes



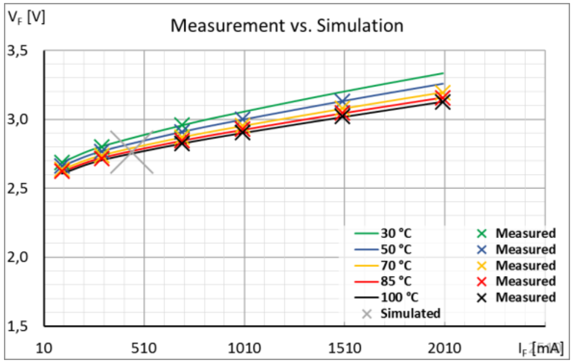
Implementations:
- VB macro
- LT Spice (electrical only Spice)

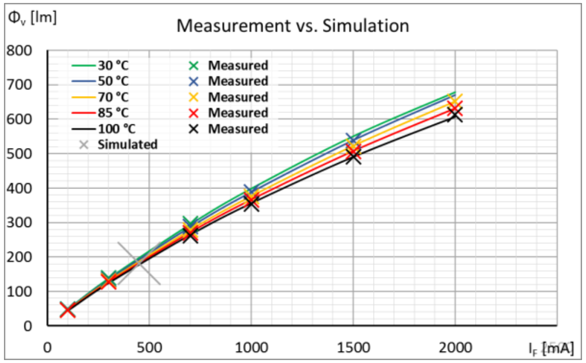
In about 2 decades of the total forward current I-V-L characteristics fits the measured data within ~1-2%

Parameter identification

- **New model topology, reformulated equations and set of parameters assure ~1% fit to measured characteristics of individual LED samples**

A	B	C	D	E	F	G	H
15			4				
Sample:			**XPG3_01**	**XPG3_02**	**XPG3_03**	**XPG3_04**	**XPG3_05**
Max Vf error:			0%	1%	0%	0%	0%
Max Fi_e error:			1%	1%	1%	1%	1%
Max Fi_v error:			1%	1%	1%	1%	1%
	UT	=	0,0296	0,0296	0,0296	0,0296	0,0296
	I0	=	7,6395E-24	6,9812E-24	8,1736E-24	7,2375E-24	7,6335E-24
	m	=	1,7354	1,7349	1,7359	1,7353	1,7358
	R	=	0,1929	0,2141	0,197	0,2138	0,1973
	I0_rad	=	4,0317E-23	3,4889E-23	3,4027E-23	3,3826E-23	3,1585E-23
	m_rad	=	1,8150	1,8131	1,8075	1,8107	1,8089
	R_rad	=	0,0190	0,021001	0,020001	0,021001	0,019001
	a_el	=	-8,079E-06	-2,501E-06	-6,348E-06	1,973E-07	-3,155E-06
	b_el	=	2,153E-05	1,209E-05	1,762E-05	7,854E-06	1,475E-05
	c_el	=	-1,050E-06	2,362E-06	-5,003E-08	2,998E-06	-4,546E-07
	d_el	=	1,326E-03	5,207E-04	1,085E-03	1,150E-04	4,845E-04
	e_el	=	-4,104E-03	-2,919E-03	-3,586E-03	-2,243E-03	-2,982E-03
	f_el	=	-8,353E-04	-1,348E-03	-9,861E-04	-1,462E-03	-9,515E-04
	a_rad	=	-8,304E-06	-2,668E-06	-6,589E-06	2,394E-07	-3,053E-06
	b_rad	=	2,209E-05	1,261E-05	1,824E-05	8,137E-06	1,492E-05
	c_rad	=	-8,946E-07	2,563E-06	8,893E-08	3,154E-06	-1,960E-07
	d_rad	=	1,364E-03	5,481E-04	1,127E-03	1,034E-04	4,618E-04
	e_rad	=	-4,173E-03	-2,981E-03	-3,670E-03	-2,259E-03	-2,985E-03
	f_rad	=	-8,187E-04	-1,338E-03	-9,643E-04	-1,449E-03	-9,417E-04
	a_Kap	=	0,000	-0,002	-0,001	-0,002	-0,003
	b_Kap	=	-0,057	0,320	0,123	0,326	0,463
	c_Kap	=	2,306	-12,216	-5,028	-12,613	-17,489
	d_Kap	=	0,000	0,002	0,000	0,002	0,002
	e_Kap	=	0,081	-0,181	-0,028	-0,221	-0,324
	f_Kap	=	-6,896	3,296	-0,971	5,542	8,955
	g_Kap	=	0,000	0,000	0,000	0,000	0,000
	h_Kap	=	-0,066	-0,082	-0,088	-0,055	-0,057
	i_Kap	=	334,911	333,904	333,653	333,397	333,066



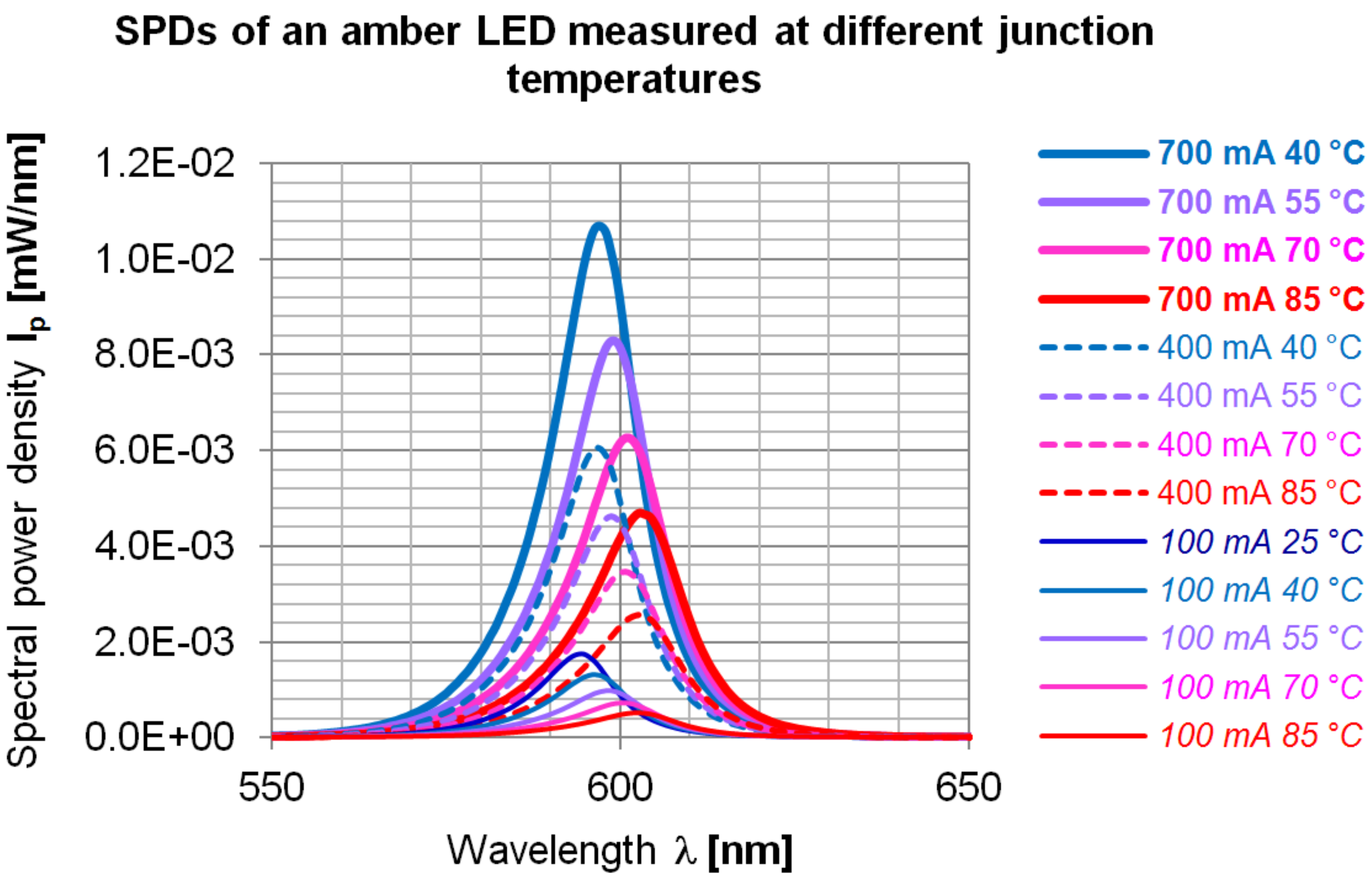


Delphi4LED

TEMPERATURE DEPENDENCE

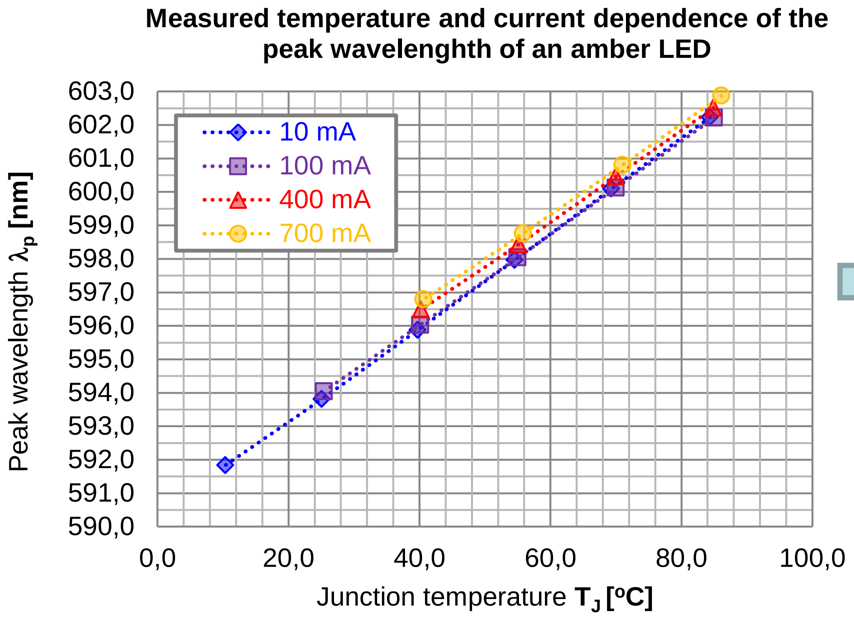
Peak wavelength, intensity vs. T_J

- Peak wavelength shifts
- Intensity deminishes

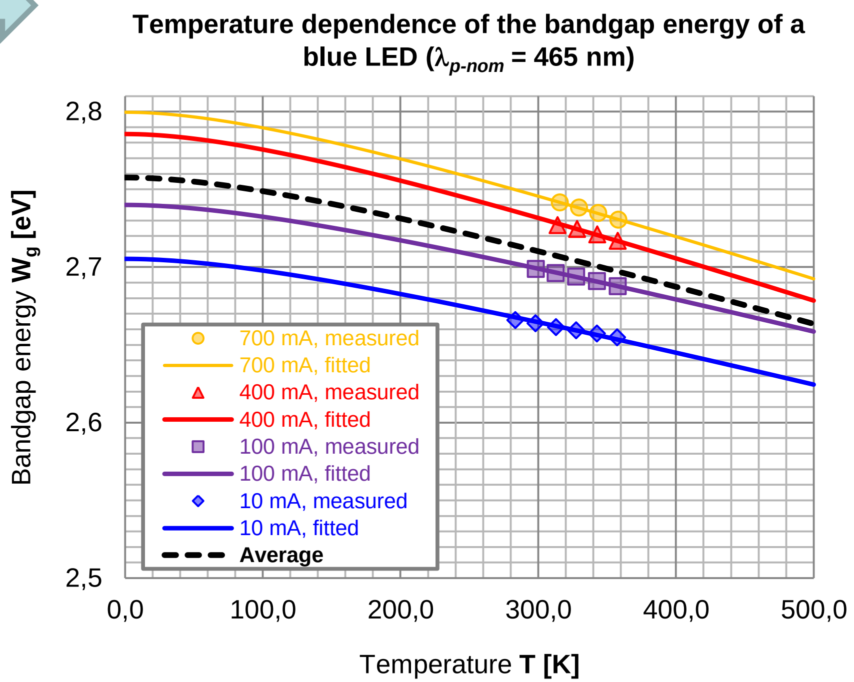


Bandgap vs. T_J

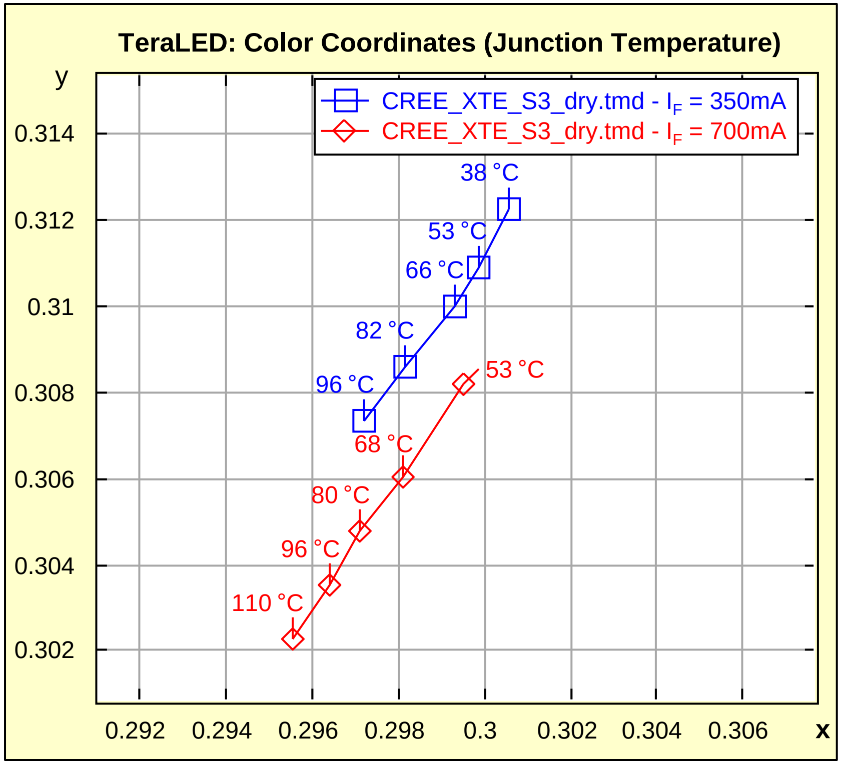
- Peak wavelength shifts
  - Due to the temperature dependence of W_g



$$W_g(T) = W_{g0} - \frac{\alpha \cdot T^2}{\beta + T}$$

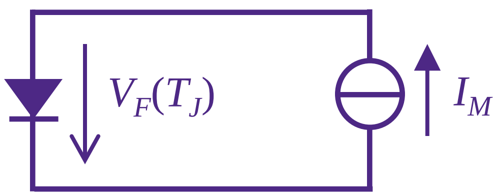


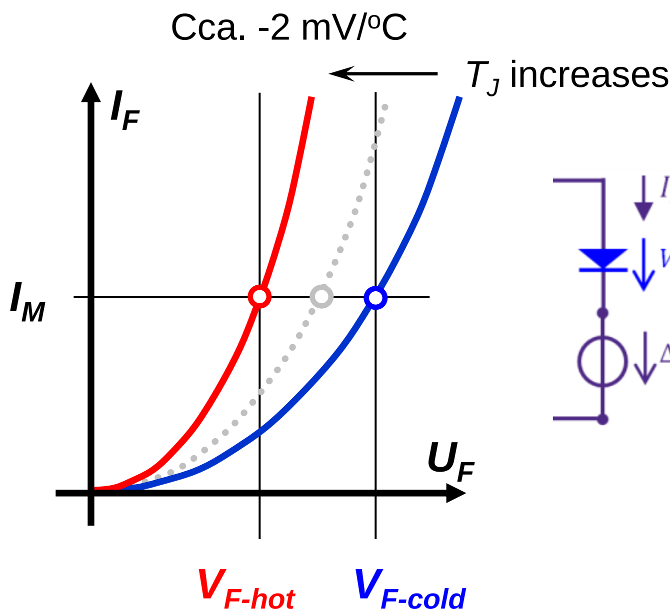
Color coordinates (CIE 1931 2° xy)

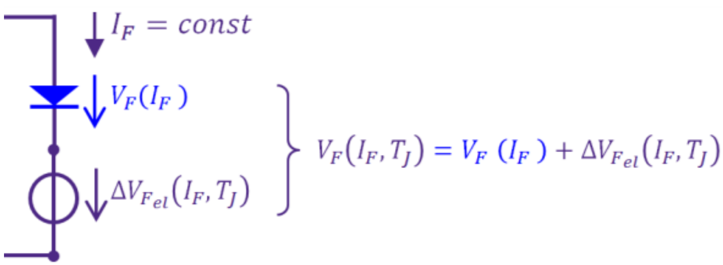


Basic powering: current driven scheme

- The forward voltage depends on T_J (almost linearly)







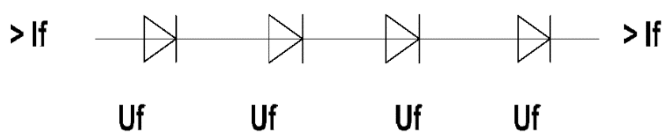
- ... all other properties (efficiency, efficacy) are also T_J dependent

- These are more stable in current driven operation than in voltage driven mode
  - *Recap from diodes*:

$$\Delta V_F = 60\text{ mV} \rightarrow 1 \text{ order of magnitude change of } I_F$$

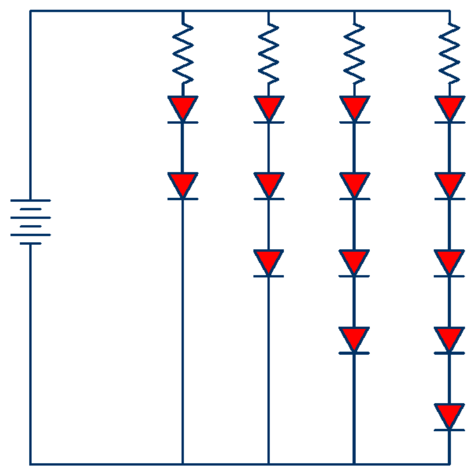
Consequence: *design of the electrical environment*

- Multiple LEDs must always be connected in series!
  - The forward current is the same, resulting in the
  - same brightness and color



- The *simples approximation* of a current generator: large ***load resistor***
  - The current can be well set by the load resistor

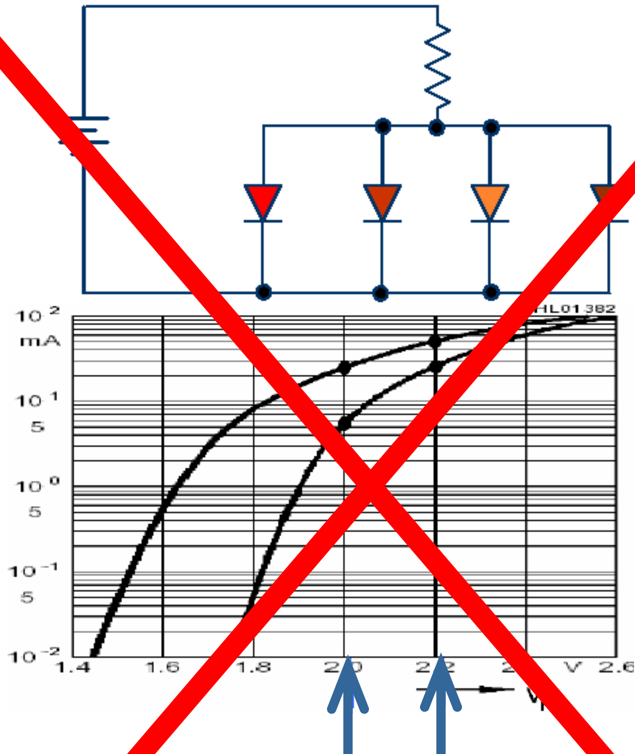
    Such LED strings can already be connected in parallel:



Source– LED Light For You course, 2006 (Electrical basics for LED)

Consequence: *design of the electrical environment*

- LEDs connected in parallel

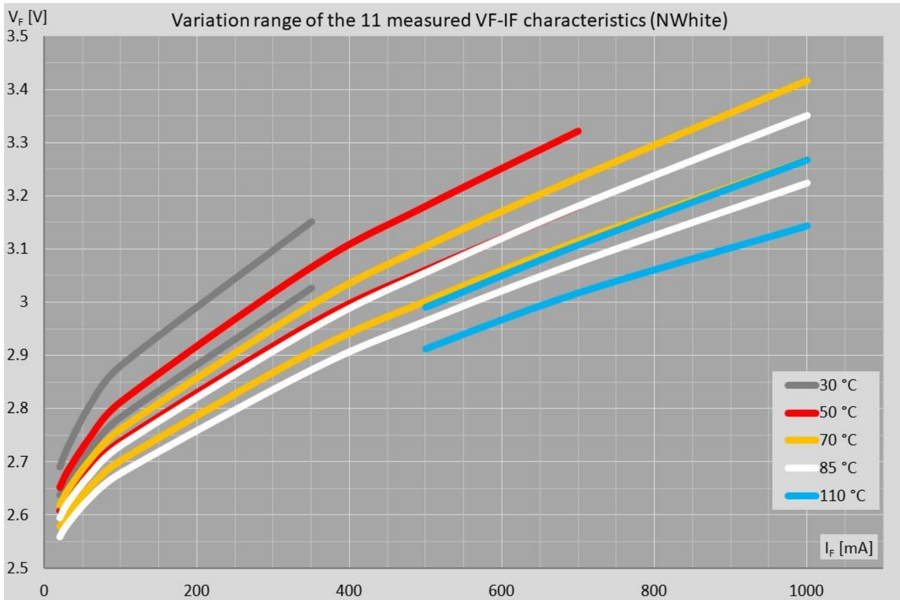


The voltage is determined by the LED with the smallest V_F

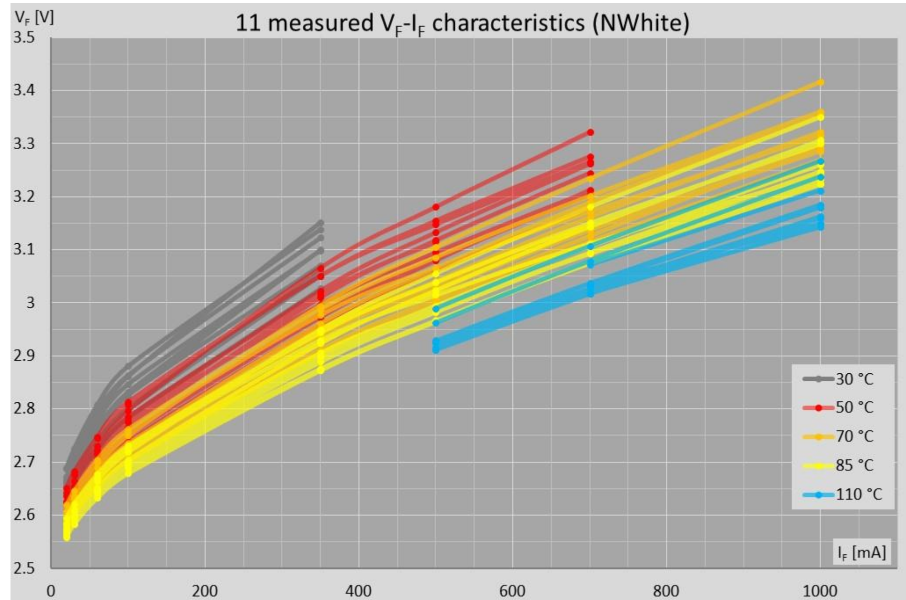
- The overall voltage is determined by the LED with the smallest V_F
- Huge differences of the forward currents of the different LEDs will develop
- **Due to these differences some LEDs will be overheated and will die quickly**
- Some LEDs may not emit light at all (e.g if they are from a different bin)
- Binning at in-line test is never perfect, therefore there is always a scatter of V_F. The differences are more pronounced if the applied I_F is smaller than the binning I_F.

Source– LED Light For You course, 2006 (Electrical basics for LED)

XPE2 PCW IVL from BME and extraction



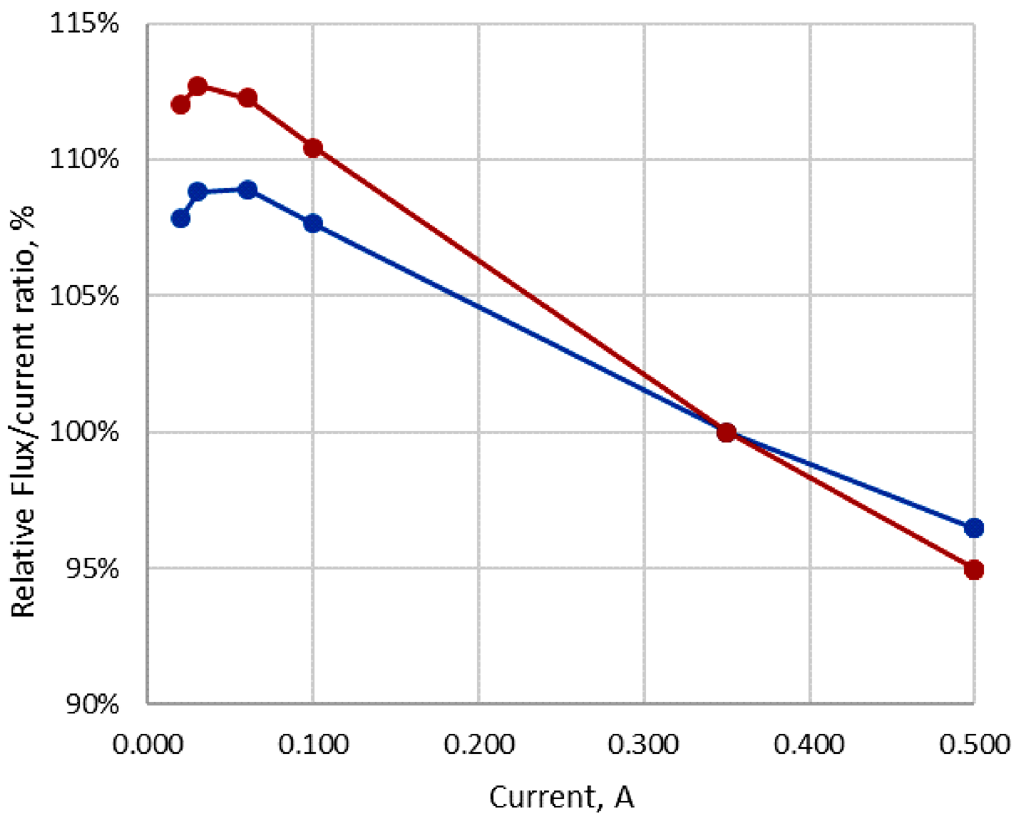
2 extreme LEDs at each temperature



all LEDs at all temperatures

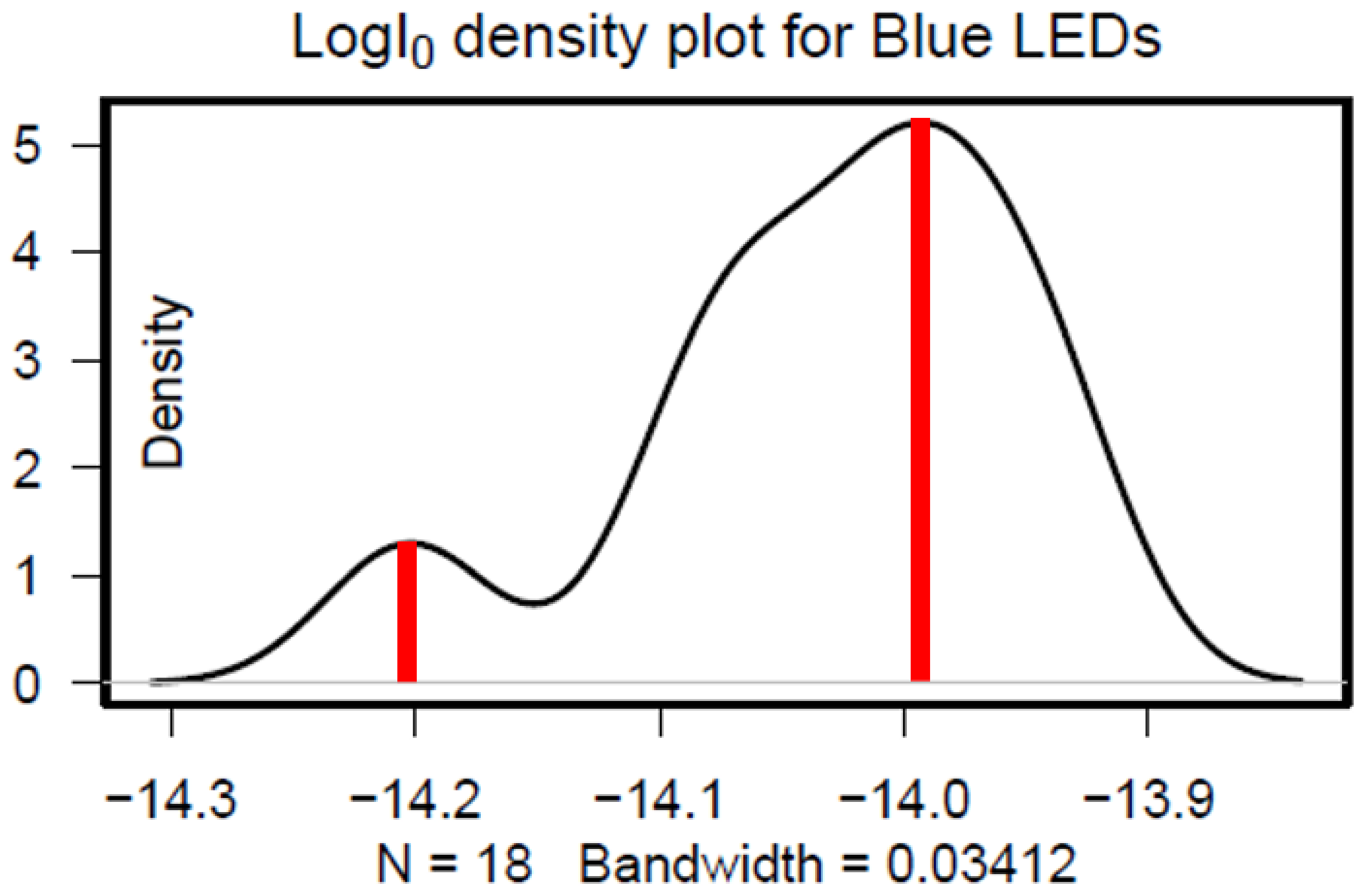
- Overlap between the sets of characteristics belonging to adjacent temperatures. This blurs the picture significantly

Multiple "LED types" in one bin

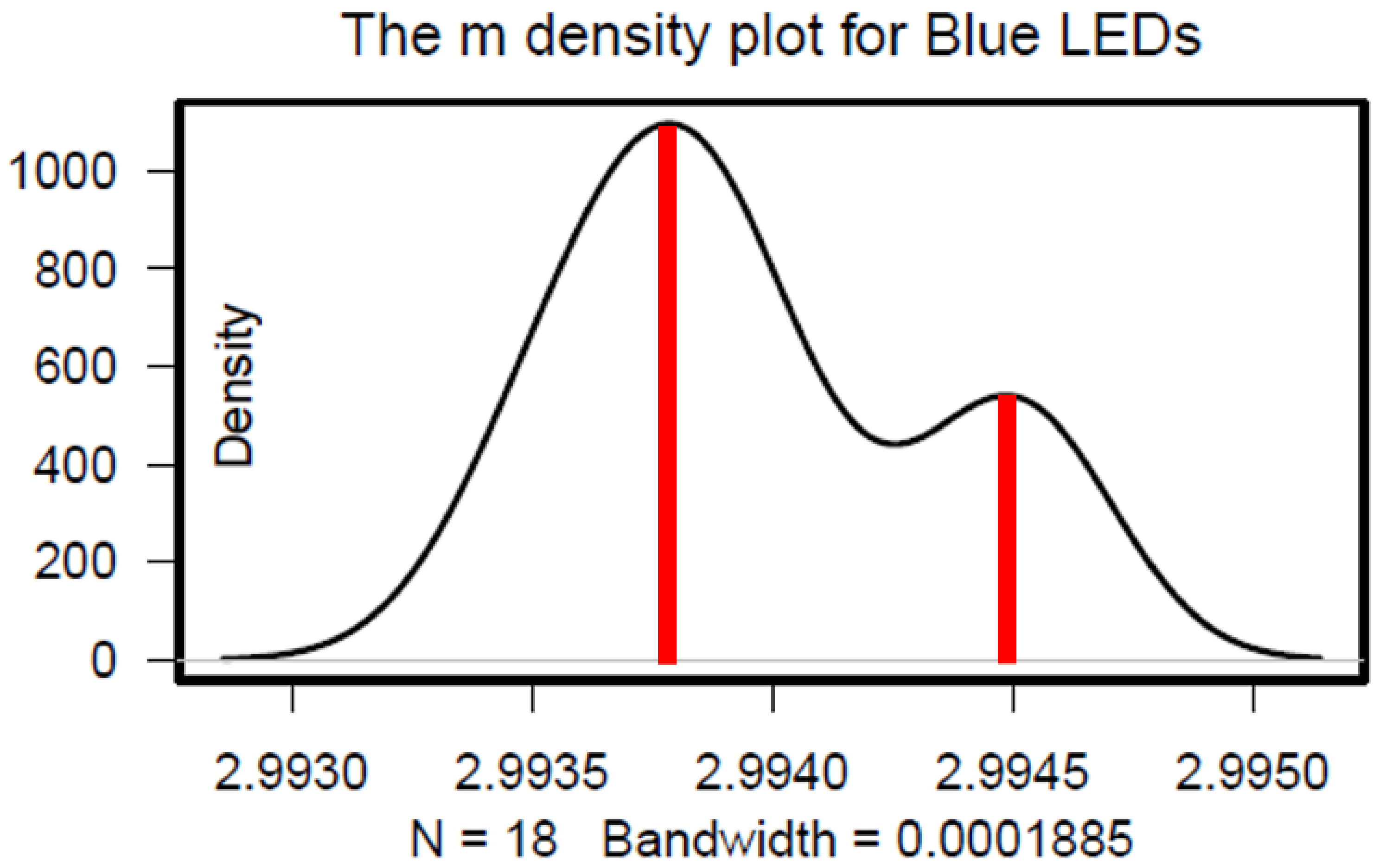


The **[$\Phi_e(I_F, T_J)/I_F](I_F)$** and **[$\Phi_V(I_F, T_J)/I_F](I_F)$** curves are like <u>fingerprints</u> of LED manufacturing processes

Multiple “LED types” in one bin

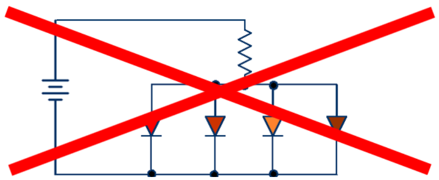


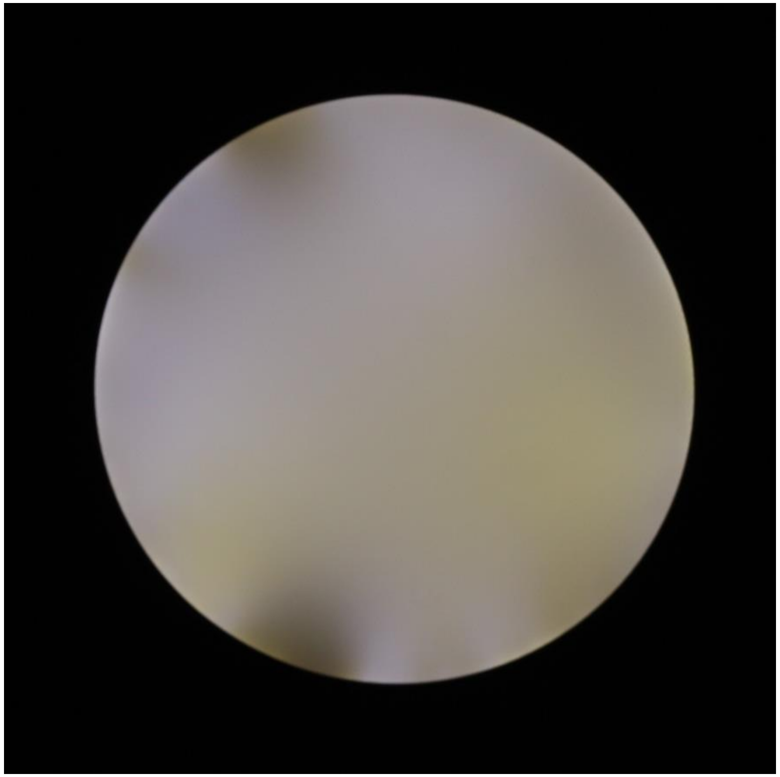
Multiple “LED types” in one bin



Photos of a luminaire with wrong circuitry

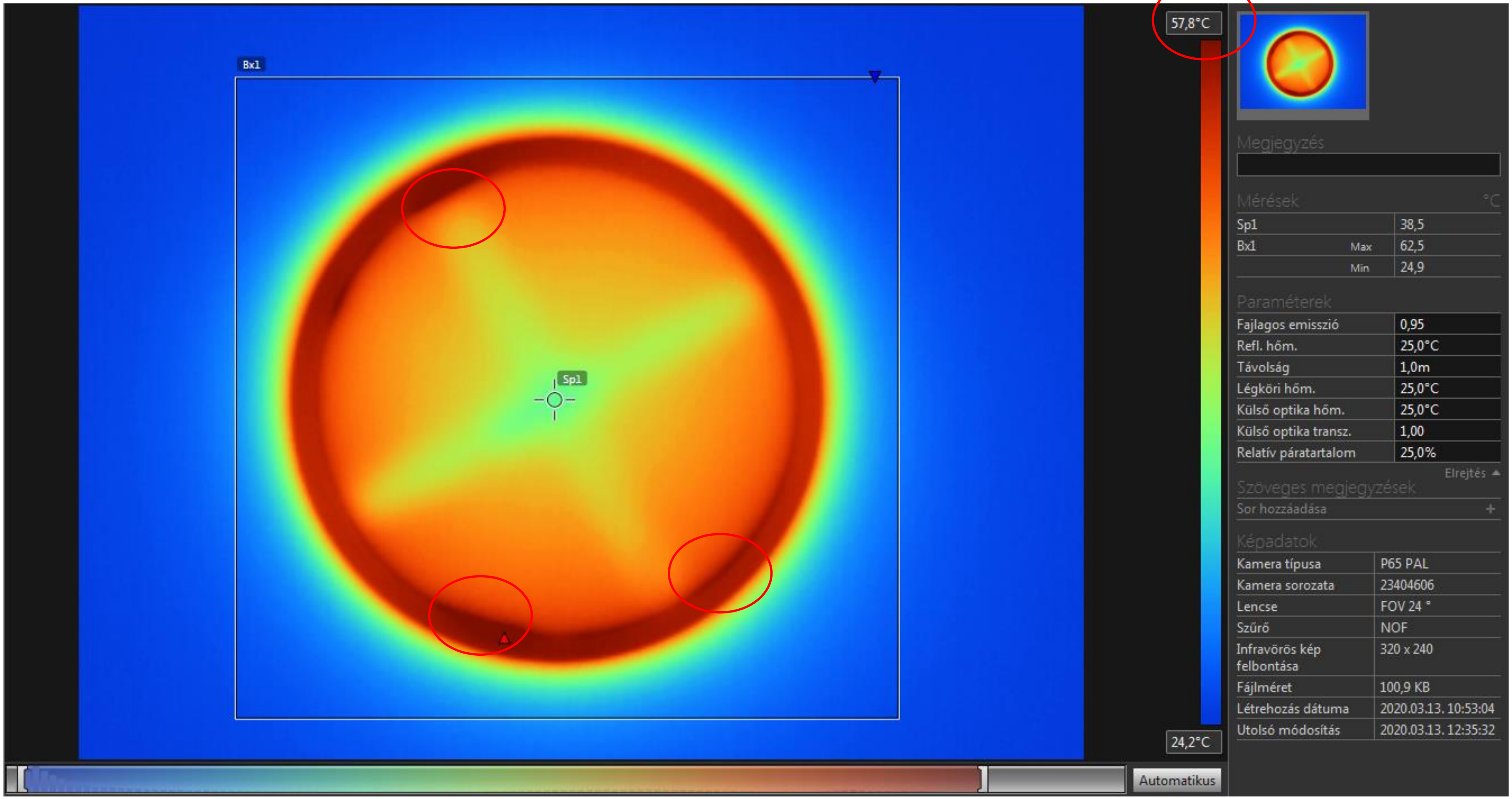
- Some regions got burnt due to local overheating:





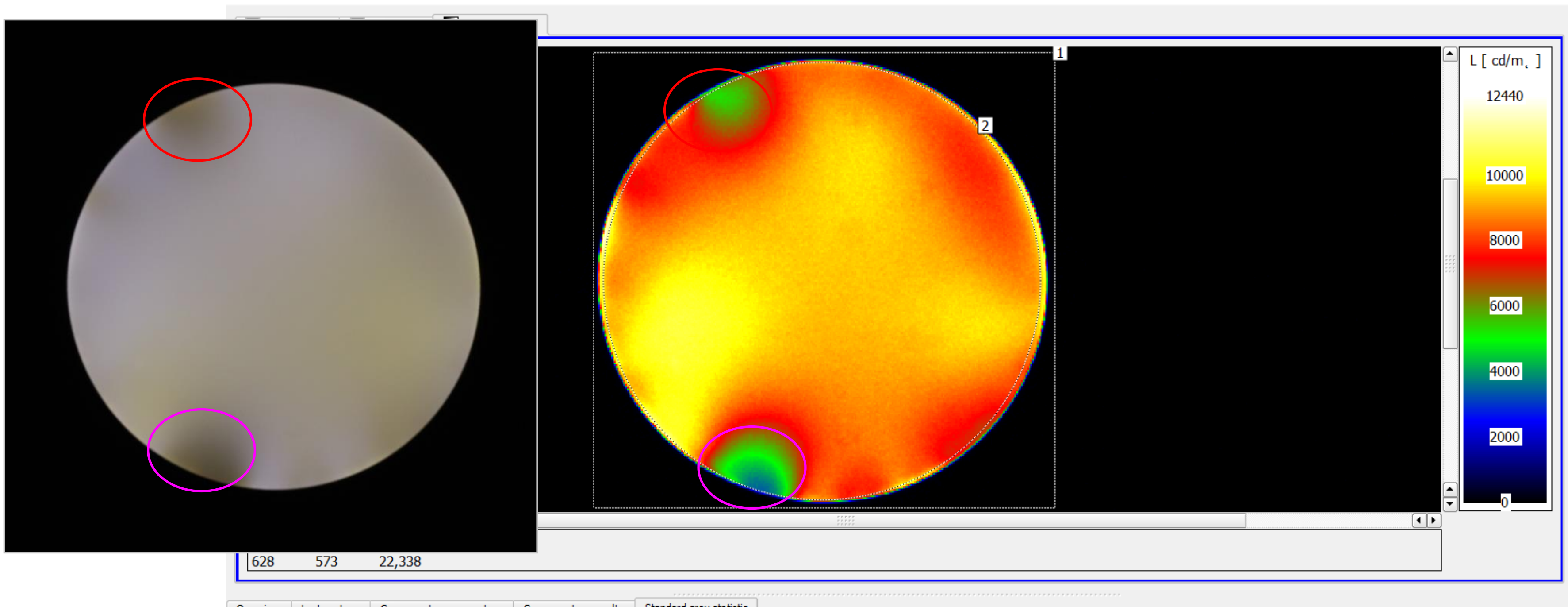
IR image of the same LED lamp

- Hightest temperature measured by IR camera on the metallic frame of the luminaire 57.8 ºC.



Normal photo and measured luminance maps

- ► At the hot spots ~50% drop in luminance was measured:



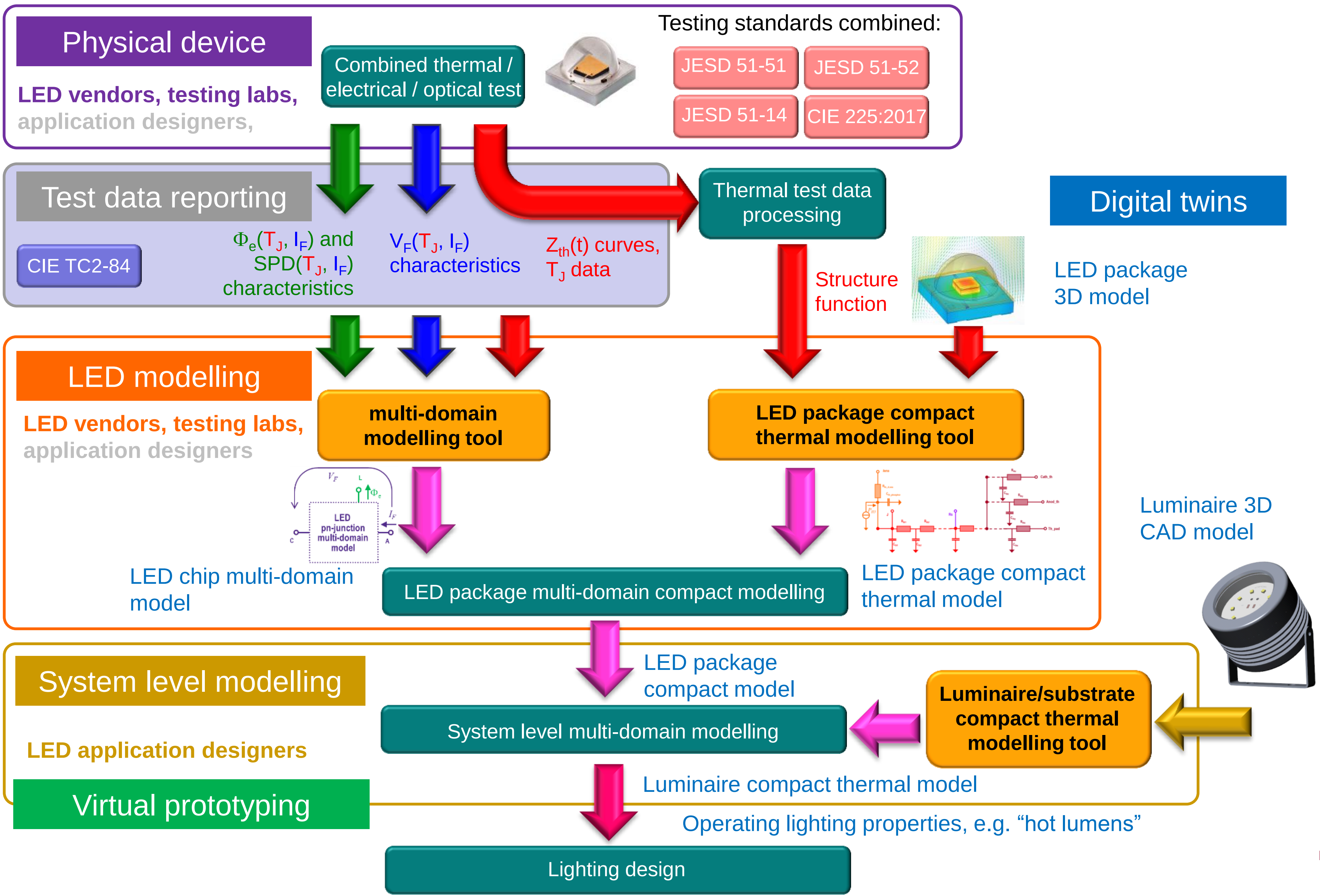
Stat.No.	Parameter	Image	Region	Area	Min	Max	Mean	Disp
				pix^2	cd/m¸	cd/m¸	cd/m¸	cd/m¸
1	Std_Gr[1]	Luminance image	1	330600	0	12440	6577	3935
2	Std_Gr[1]	Luminance image	2	235800	3394	11350	8855	1045

Fatal failures

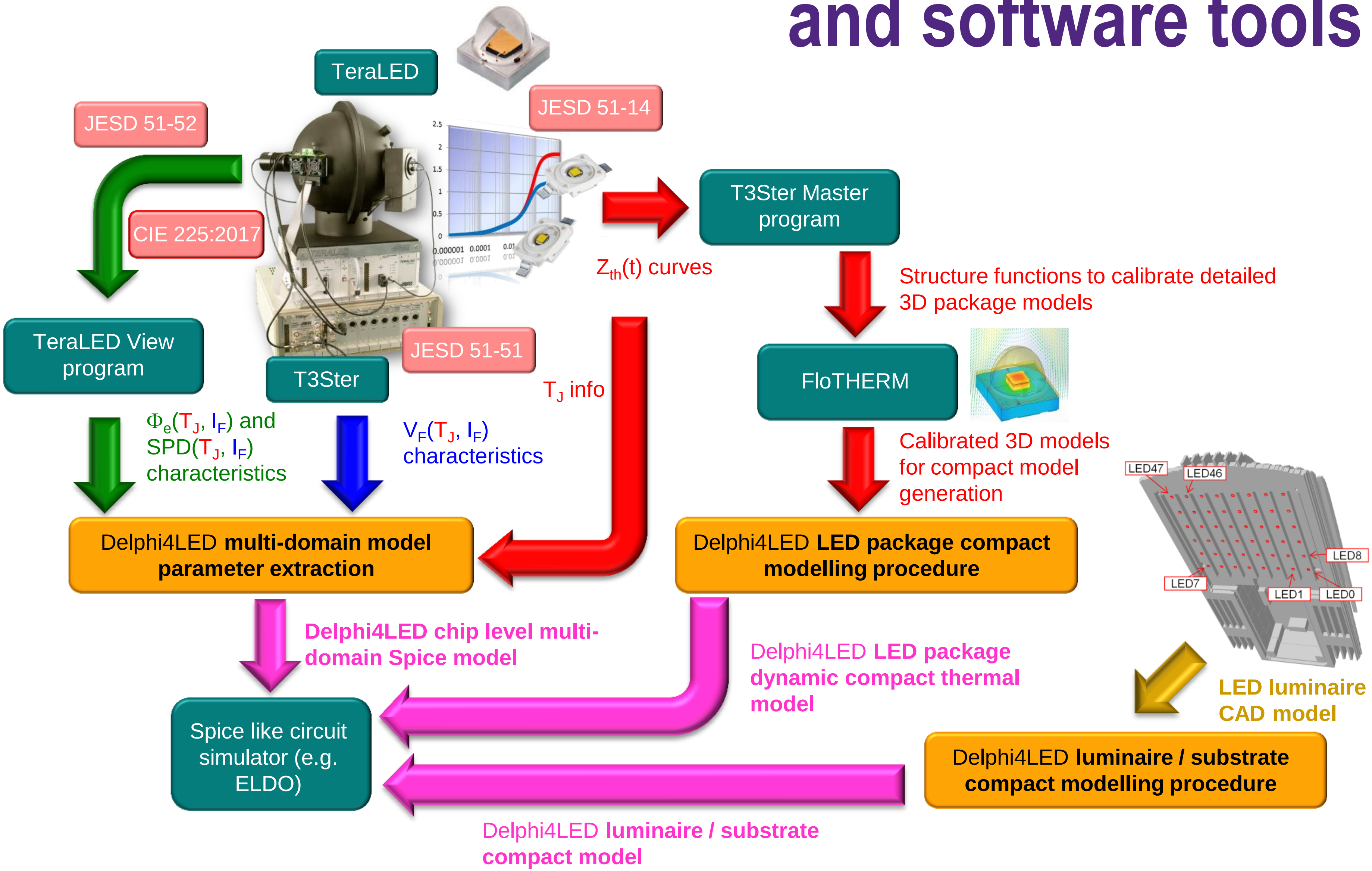
- Burnt diffusor plane
- LED lenses burnt
- LED carrier tape delaminated and burnt

MEASURING AND MODELLING OF LED-S IN AN INDUSTRY 4.0 APPROACH

The Delphi4LED Industry 4.0 workflow

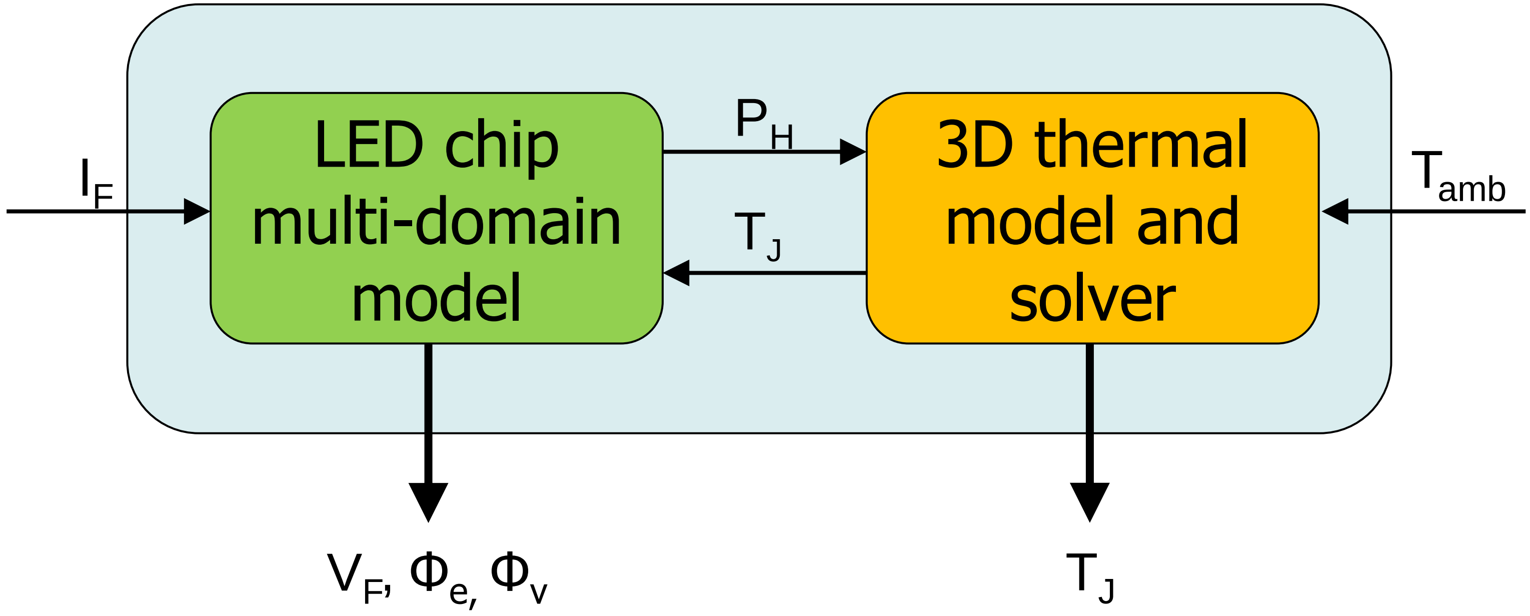


Realized by SIEMENS hardware and software tools



All models intgegrated: *luminaire design tool*

- Co-simulation between LED chip multi-domain model and the thermal model of the 3D environment (substrate, luminaire)
- Used for different project demonstrators
  - Support of both chip level LED models
  - Support of different parameter sets for these models



Demo tool: *Luminaire Design Calculator*

Microsoft Excel application:

GOALS	
Luminous Flux (lm)	1200
CONSTRAINTS	
Tj max (degC)	150
Ts max (degC)	85
Ta (degC)	45
Total Power Consumption (W)	15
DESIGN	
Number of LEDs	6
Substrate Type	SMI 3W
Heatsink Rth (K/W)	2.5
Forward Current (A)	1.5
Optics Efficiency	0.8
Driver Efficiency	0.9

SIMULATE

RESULTS	
Highest Tj (degC)	**85.38**
Highest Ts (degC)	**79.27**
Total System Power Consumption (W)	**29.96**
Total System Luminous Flux (lm)	**2465**
Total Luminous Flux from LEDs (lm)	3082
Total System Optical Power (mW)	7582
Total Optical Power from LEDs (mW)	9478
Total System Lumens/Watt (lm/W)	82.28
Total Lumens/Watt from LEDs (lm/W)	113.1

PER LED RESULTS	Vf (V)	Luminous Flux (lm)	Tj (DegC)	Ts (DegC)	P (W)	Pdis (W)
1	3.03	513.47	85.38	79.27	4.5	2.96
2	3.03	513.69	85.17	78.84	4.5	2.96
3	3.03	513.61	85.25	79.00	4.5	2.96
4	3.03	513.63	85.23	78.96	4.5	2.96
5	3.03	513.62	85.24	78.98	4.5	2.96
6	3.03	513.65	85.21	78.92	4.5	2.96

Test results vs. simulation

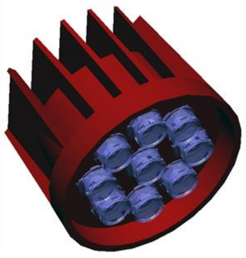
System electrical power and luminaire total luminous flux comparison (new process / Major)

GOALS	
Luminous Flux (lm)	1200

CONSTRAINTS	
Tj max (degC)	150
Ts max (degC)	85
Ta (degC)	25
Total Power Consumption (W)	15

DESIGN	
Number of LEDs	5
Substrate Type	SMI 8W
Heatsink Rth (K/W)	2.5
Forward Current (A)	0.8
Optics Efficiency	0.8
Driver Efficiency	1

SIMULATE



RESULTS	
Highest Tj (degC)	**47.55**
Highest Ts (degC)	**43.33**
Total System Power Consumption (W)	**11.71**
Total System Luminous Flux (lm)	**1302**
Total Luminous Flux from LEDs (lm)	1628
Total System Optical Power (mW)	3971
Total Optical Power from LEDs (mW)	4964
Total System Lumens/Watt (lm/W)	111.2
Total Lumens/Watt from LEDs (lm/W)	139

10,7 W measured

1339 lm measured

Cost benefits of using compact models

- Considerable savings in terms of development time and development costs

Main design costs	"SME" old process	"SME" new proces	Gain
Personal costs	0.896	0.633	29%
Material costs	0.049	0.028	43%
Testing	0.056	0.056	0%
Total	1.000	0.717	**28%**
Main design costs	**"Major" old process**	**"Major" new proces**	**Gain**
Personal costs	0.819	0.502	39%
Material costs	0.055	0.028	48%
Testing	0.126	0.045	65%
Total	1.000	0.575	**42%**

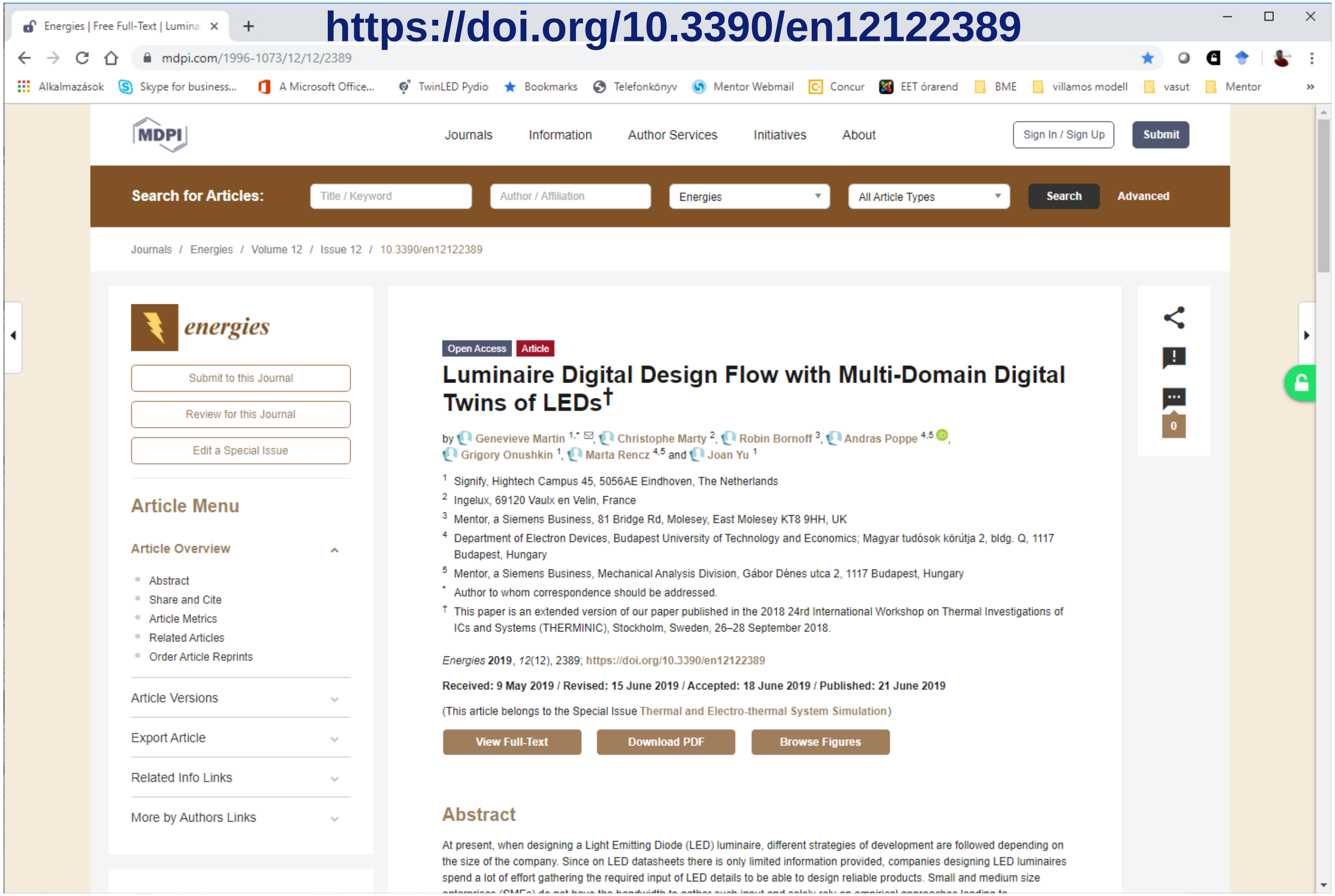
Demo experiments in Delphi4LED

- Luminaire designs also realized and physically tested

Open access summaries

https://doi.org/10.3390/en12101909

https://doi.org/10.3390/en12122389



The future beyond Delphi4LED

- **Standardize LED test data reporting**
  - Technical report of CIE TC2-84 is in an advanced state thanks to Delphi4LED, finalize the report and go for a standard
- **Include LED reliability / lifetime issues in LED digital twins**
  - First results based on LM-80 test data
  - Connect standard LED ageing tests of LEDs to real current, temperature and power cycles
- **Extend LED modelling** from total fluxes to metrics of light quality, such as “alphaopic” fluxes
- **On the overall benefits:**
- How precise LED modeling helps better design ‘artistic effects’ for end-users

Modelling beyond 0h of operation

- **Elapsed lifetime in the multi-domain LED model (fixed current and temperature)**
  - 100% … 78% aging range (in terms Φ_V)
- **Successful implementation of this very first approach – fitting LM80 test data**
  - 0.5% absolute and
  - 1.2% maximum simulation inaccuracy