micro and nanoelectronics microsystems ambient intelligence image chain biology and health

Thermal Management of High Brightness LEDs

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leti

cea

Outline

- Introduction to LED technology
- Thermal effects in LEDs
- Modelling and characterization of LEDs
- Applications of LEDs
- Advanced thermal management
- Conclusion

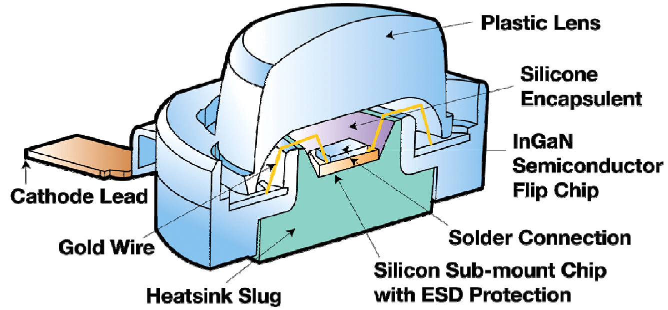
Introduction

Aim of the presentation

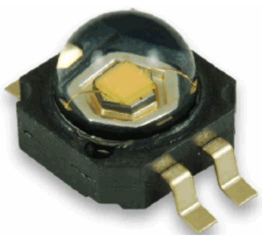
- Awareness of LED technology and use

- Solutions and keys to make fully effective luminaires with LEDs
  - You will then be confident to put on your products…

Introduction - LEDs benefits



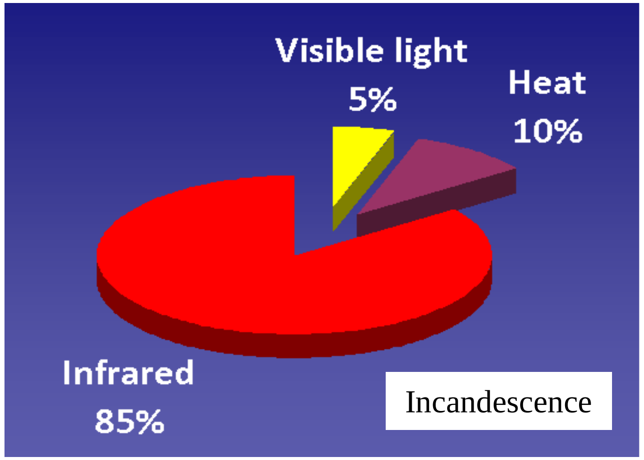
- Efficient light source
  - Low energy consumption
  - No Infrared or UV energy loss
- Quite all the visible spectrum is available
- Long life duration
  - More than 50000 hours
  - Robust and compact
- Environment friendly
  - No mercury or lead
  - Only made of minerals and metals



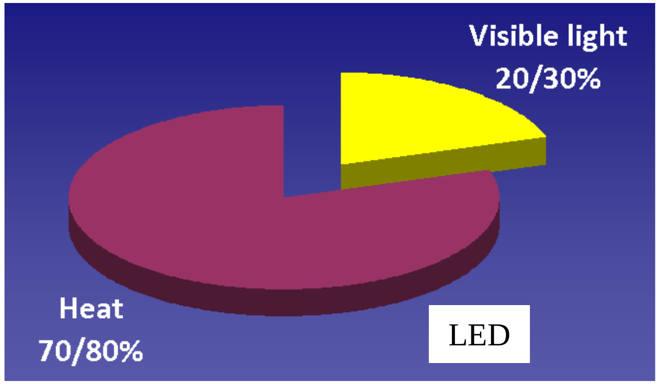
- … But as an electronic component, LEDs are thermally sensitive device !

Introduction - Comparison

- **Incandescent light**
  - Only 5% of the energy used for lighting
  - Joule heating + Infrared radiation (also converted into heat) = 95% of energy loss

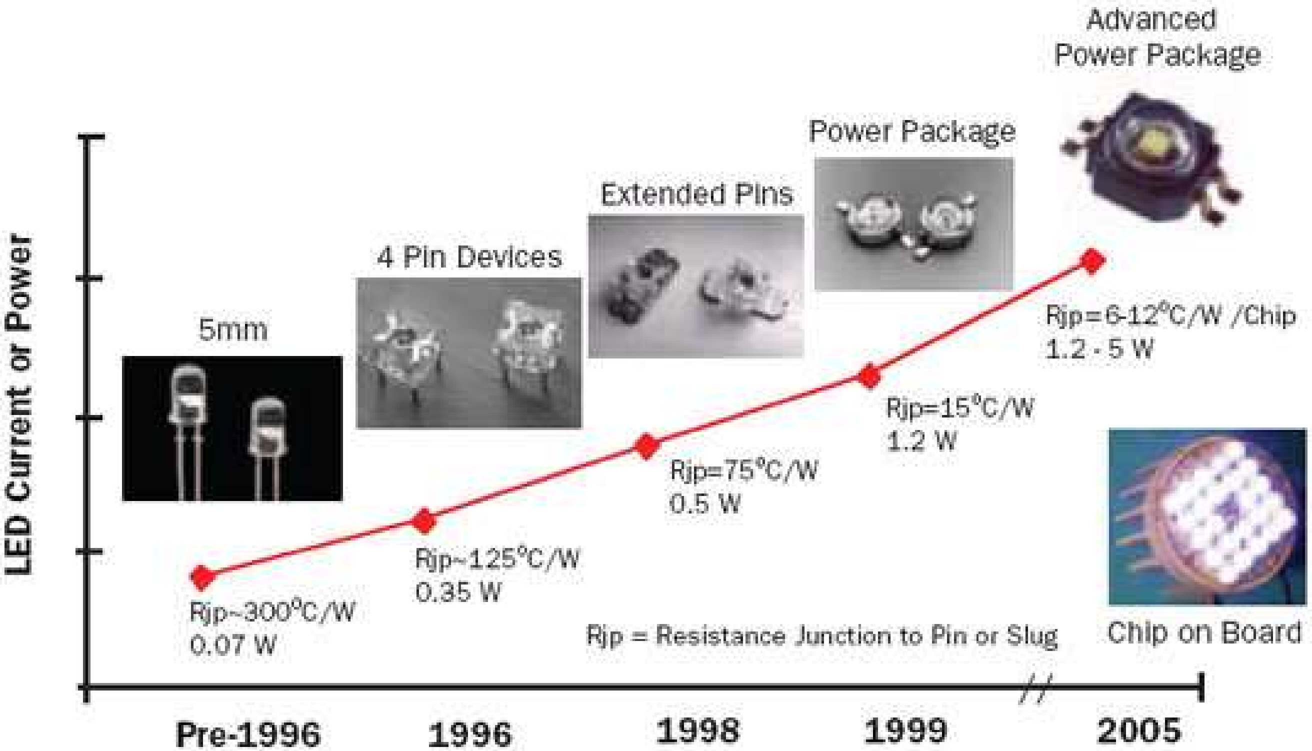


- **LED light**
  - 25% of the energy converted into light
    - Goal : 50% of energy conversion for 2025 !
  - Moderate Joule heating
    - Thermal transfer mainly by conduction



Introduction – LED evolution

- Heat dissipated by conduction + constant increase in LED power



Source : Petroski – Electronics Cooling - 2006

Outline

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- Thermal effects in LEDs
- Advanced characterization of LEDs
- Applications of LEDs
- Advanced thermal management
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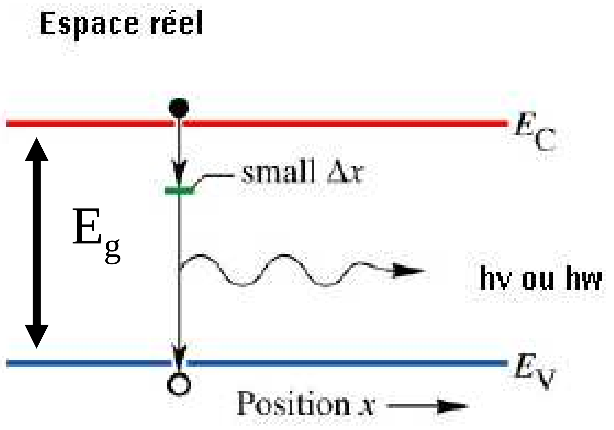
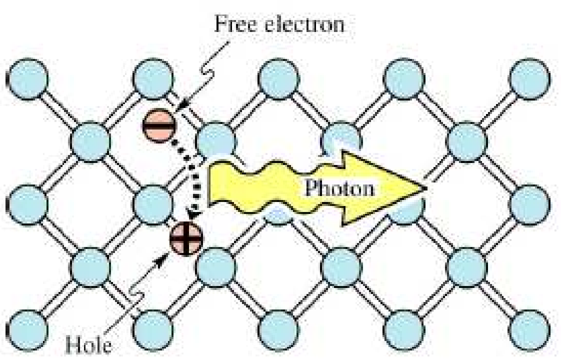
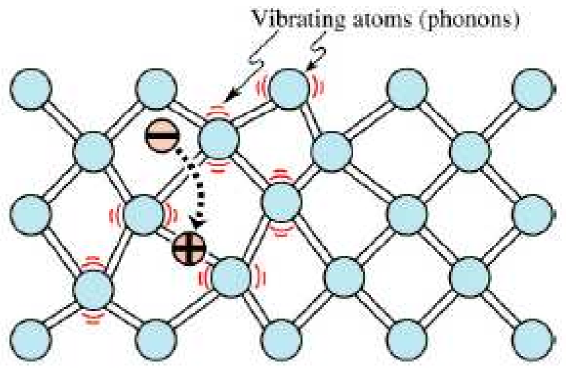
Thermal effects – LED technology

- LED is an electronic component
  - Semiconductor material
    - Electrical insulator or conductor
      - Depending on operating conditions (temperature, electric field, doping)
    - Radiative or non-radiative transition
      - Gap Energy E_g defines the Wavelength (color) of the photon





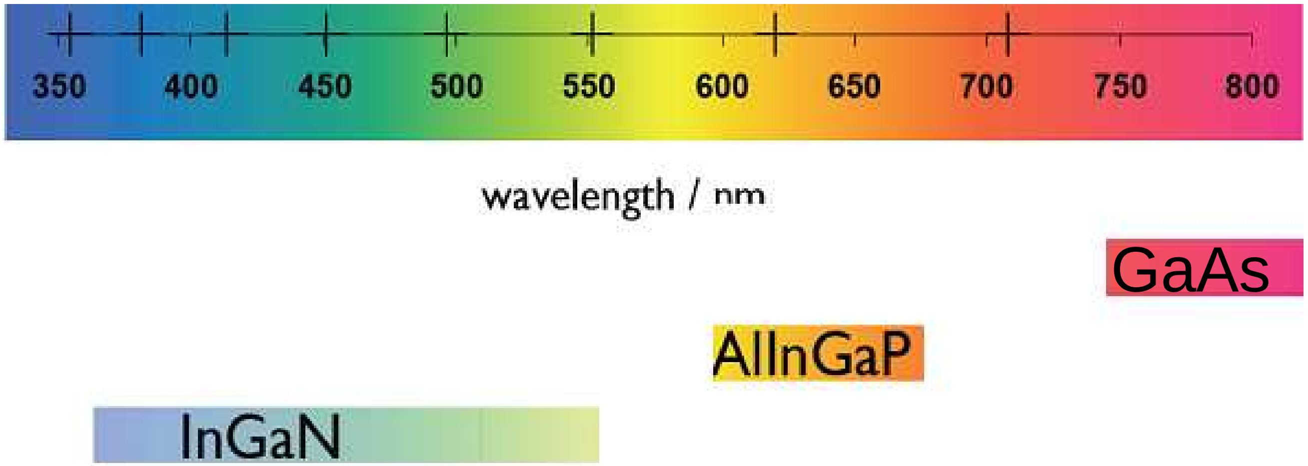
Radiative recombinaison



Non radiative recombinaison

Thermal effects – LED technology

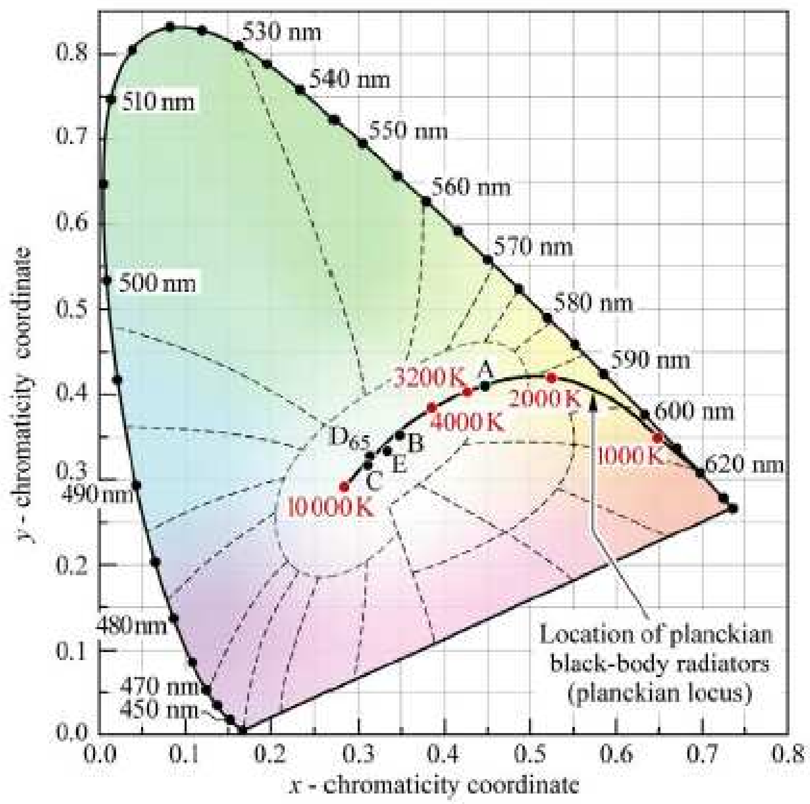
- LED materials
  - Gallium nitride : (UV) Blue to Green
  - Gallium phosphide : Amber to Red
  - Gallium arsenide : Red to Infrared



- No direct Yellow (550-590 nm) and low efficient Green

Thermal effects – White color with LEDs

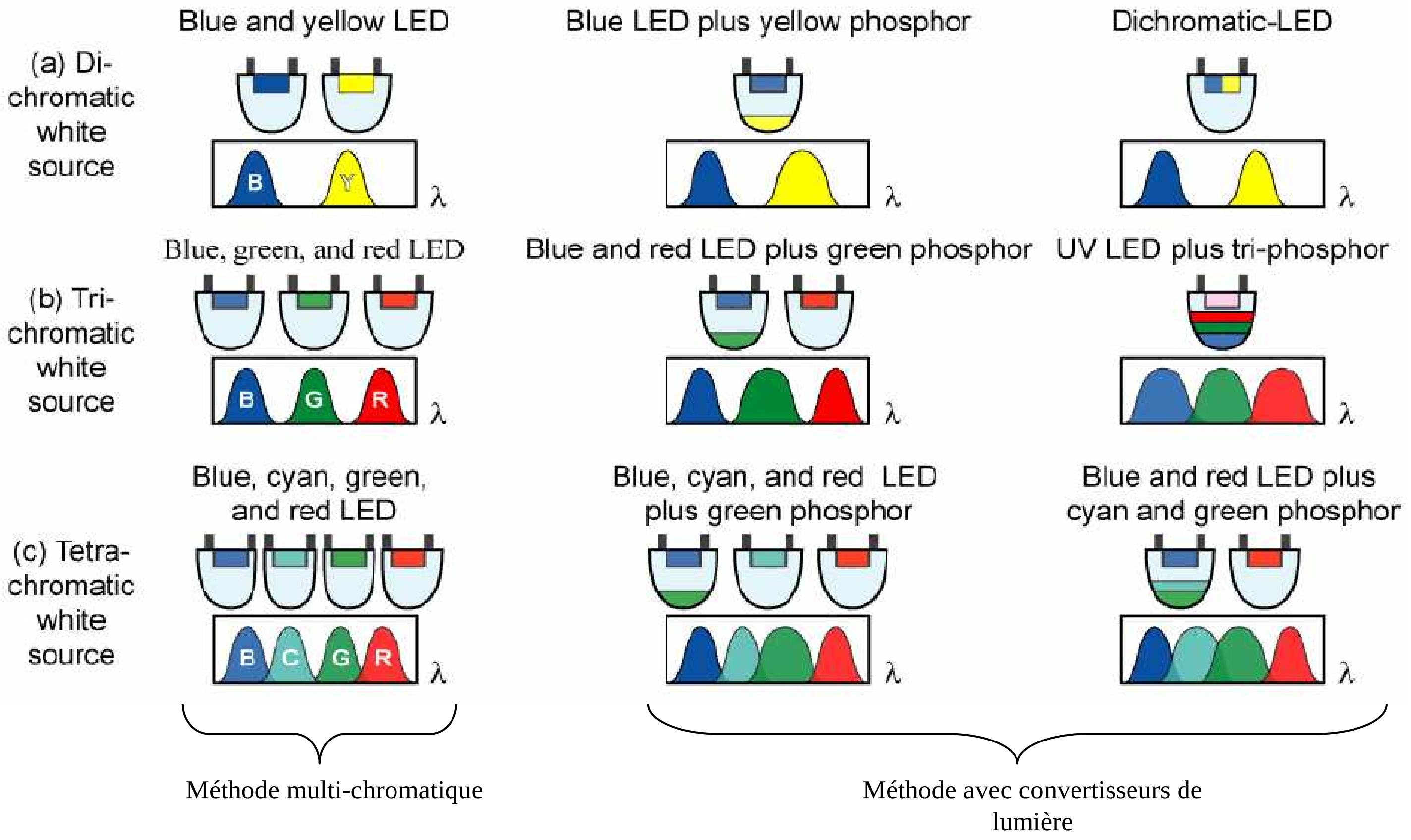
- Warm White vs. Cold White
  - Beware: Correlated Color Temperature (CCT) is inverted !
    - High CCT for cold white (>3000K)
    - Low CCT for warm white (~2700K to 3000K)



CCT description

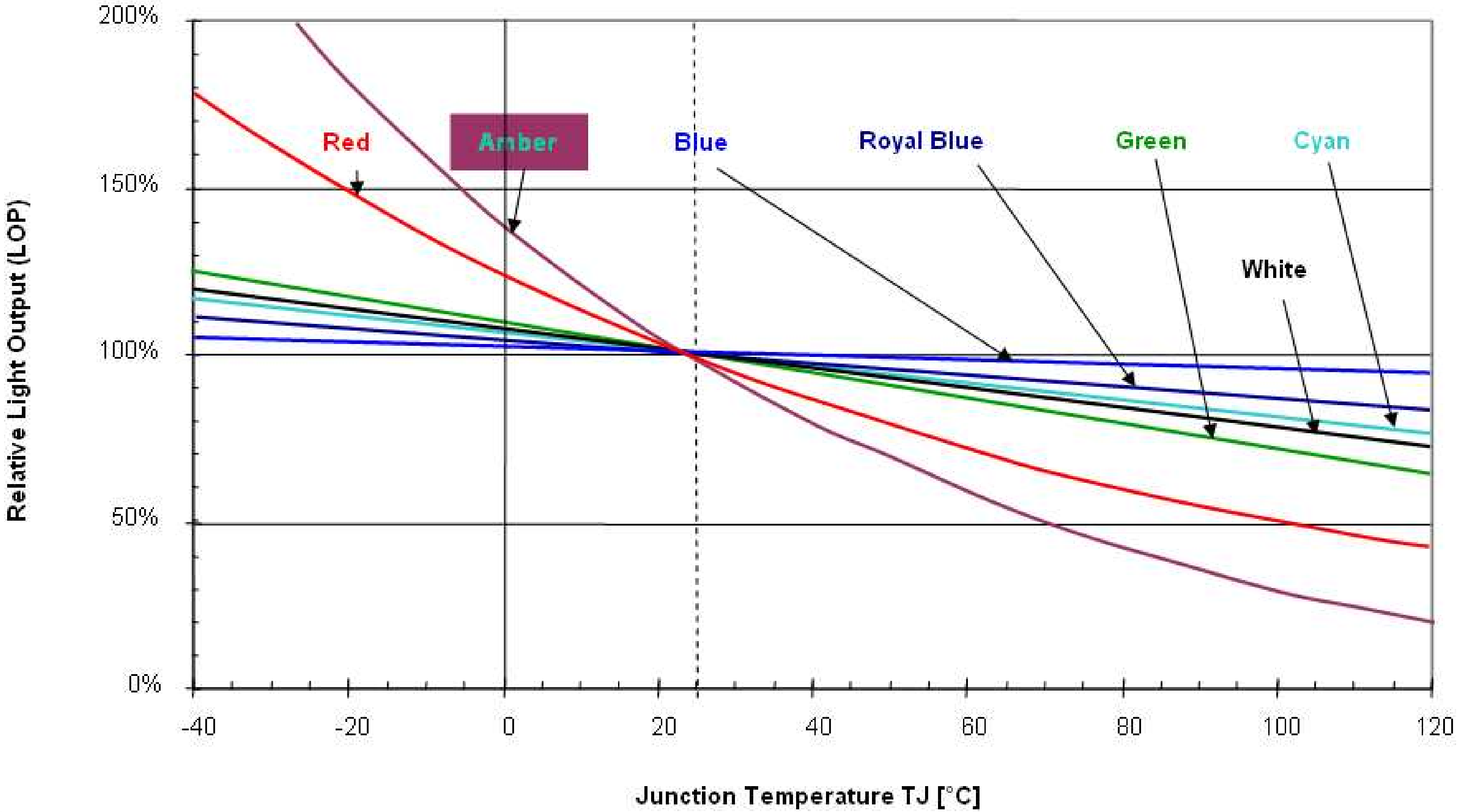
Thermal effects – White color with LEDs

How to make white with LEDs



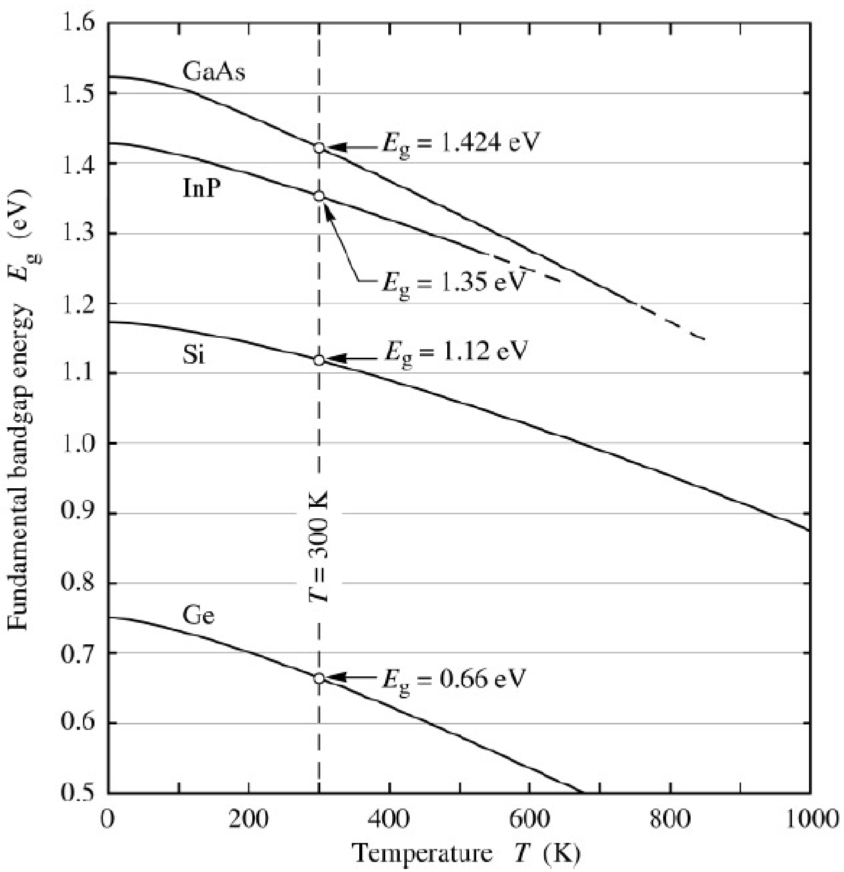
Thermal effects – Light output

- Efficiency degradation with the temperature



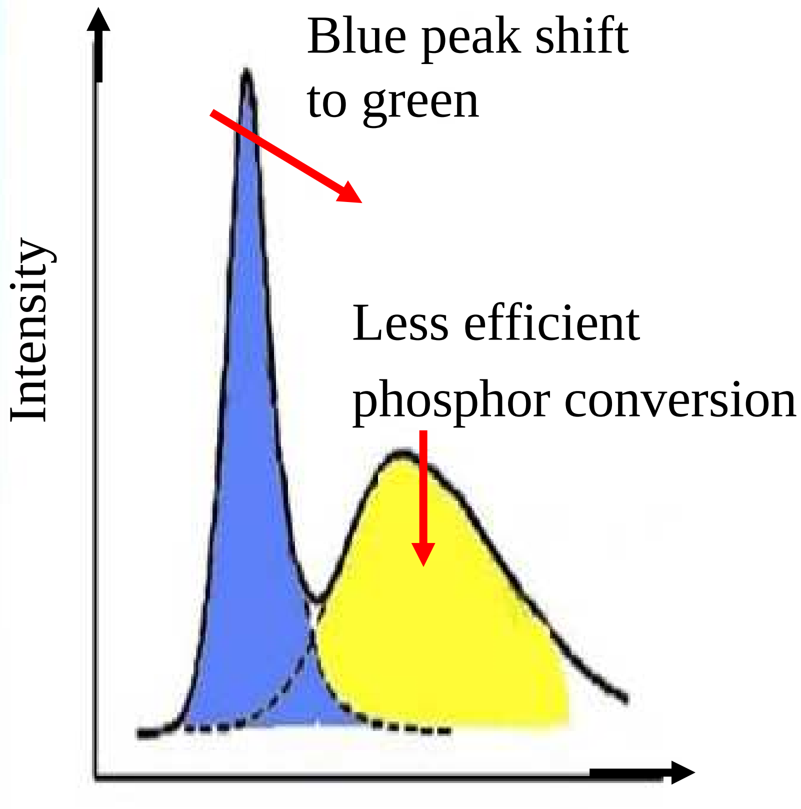
Thermal effects – Color Consistency

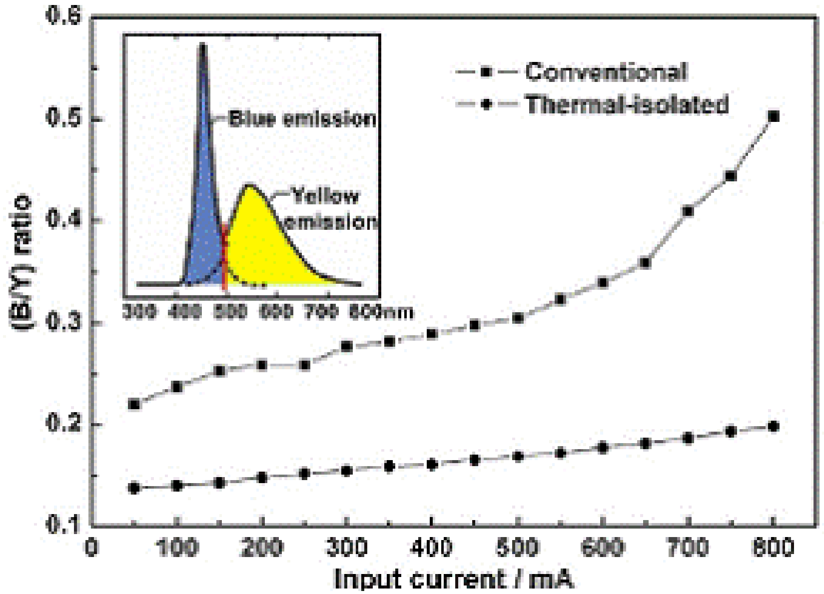
- Color shift due to the semiconductor effect
  - Different materials in RGB module → different behavior with the temperature



Thermal effects – Color Consistency

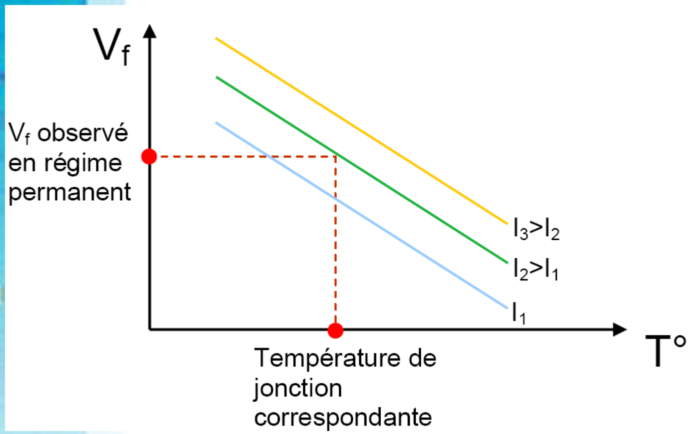
- Effect of the temperature on the color spectrum of a phosphor converted white LED

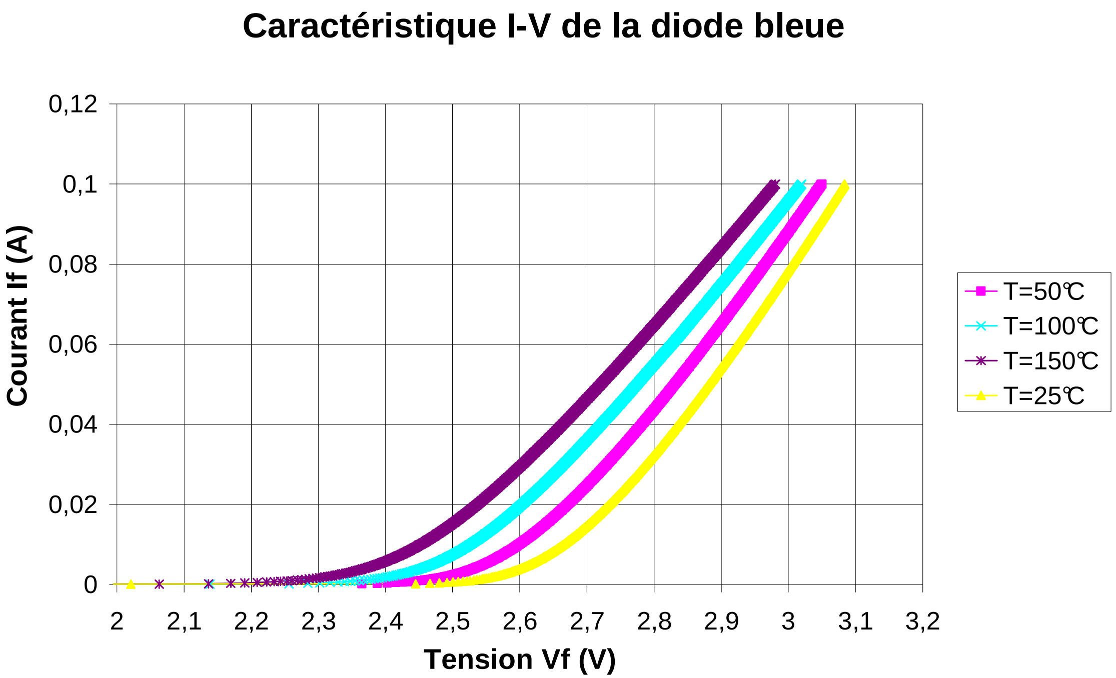




Thermal effects – Power shift

- Drop of the forward voltage with temperature
  - Semiconductor behavior





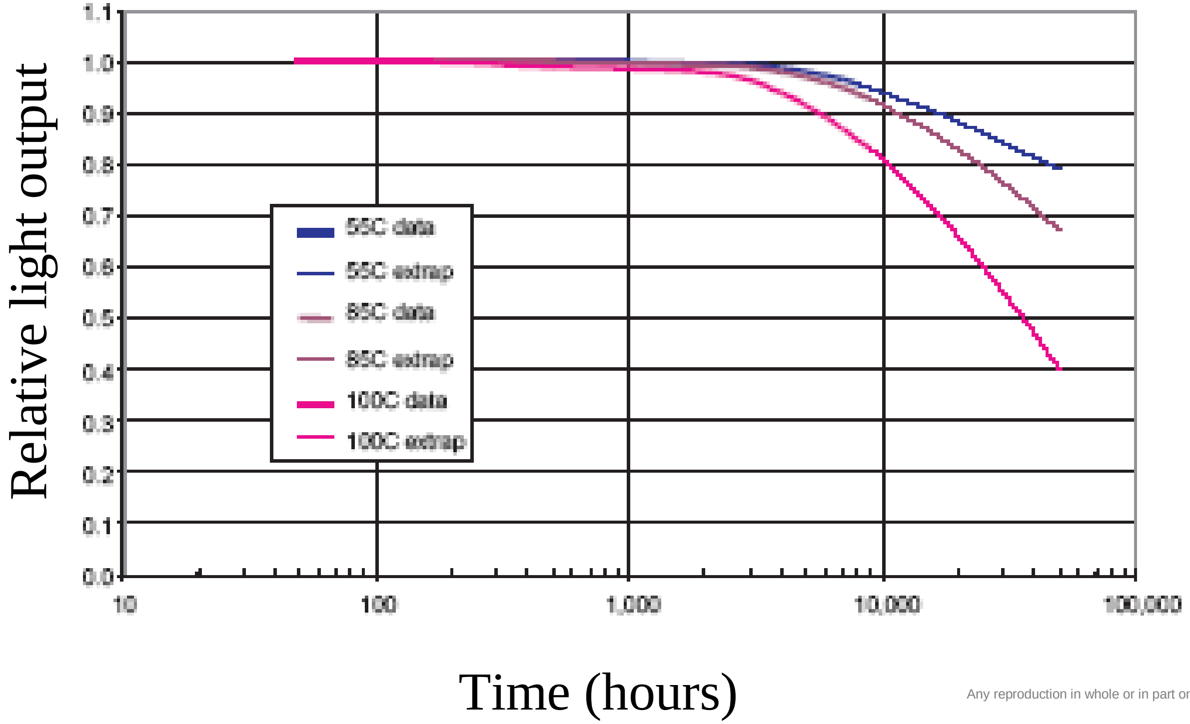
No possible Voltage driving

Thermal effects – Lifetime

- Reduced lifetime with high temperature
  - CITADEL Project for investigating reliability of LED fixtures

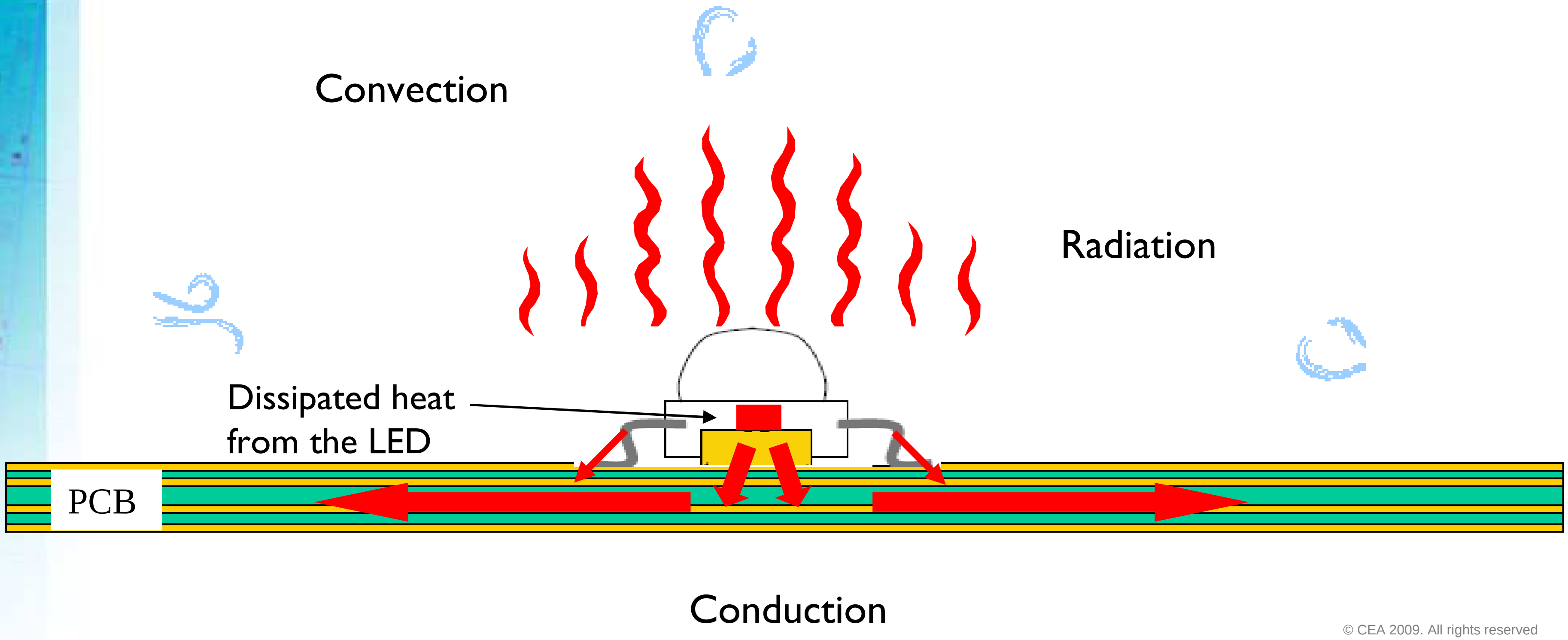
Normalized light output

InGaN LUXEON stressed at 350 mA, various slug temperatures



Thermal effects – Thermal transfers

- Heat transfer modes for electronic components

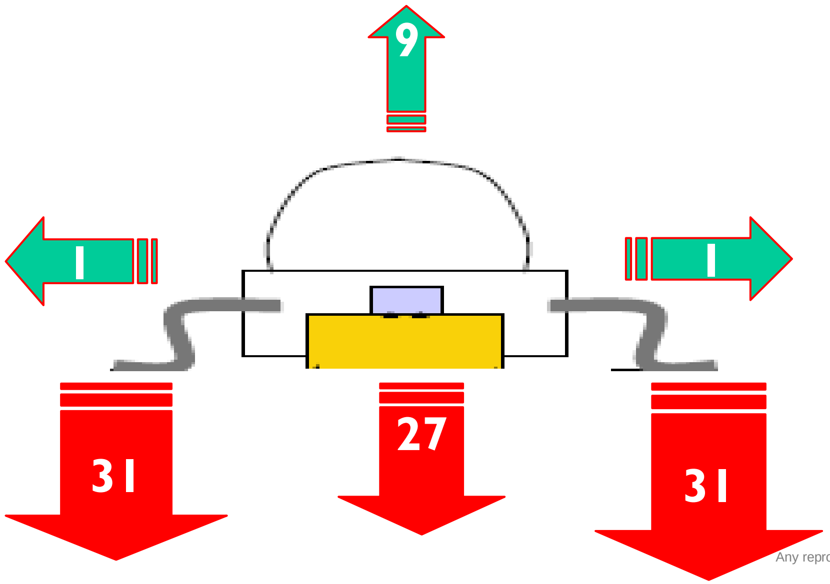


Thermal effects – Thermal transfers

- Heat transfer modes for electronic components
  - **Radiation** is low
    - Small exchange areas (1 mm²) and packaging
  - Weak **convection** inside packages
    - Relatively low temperature ~100℃

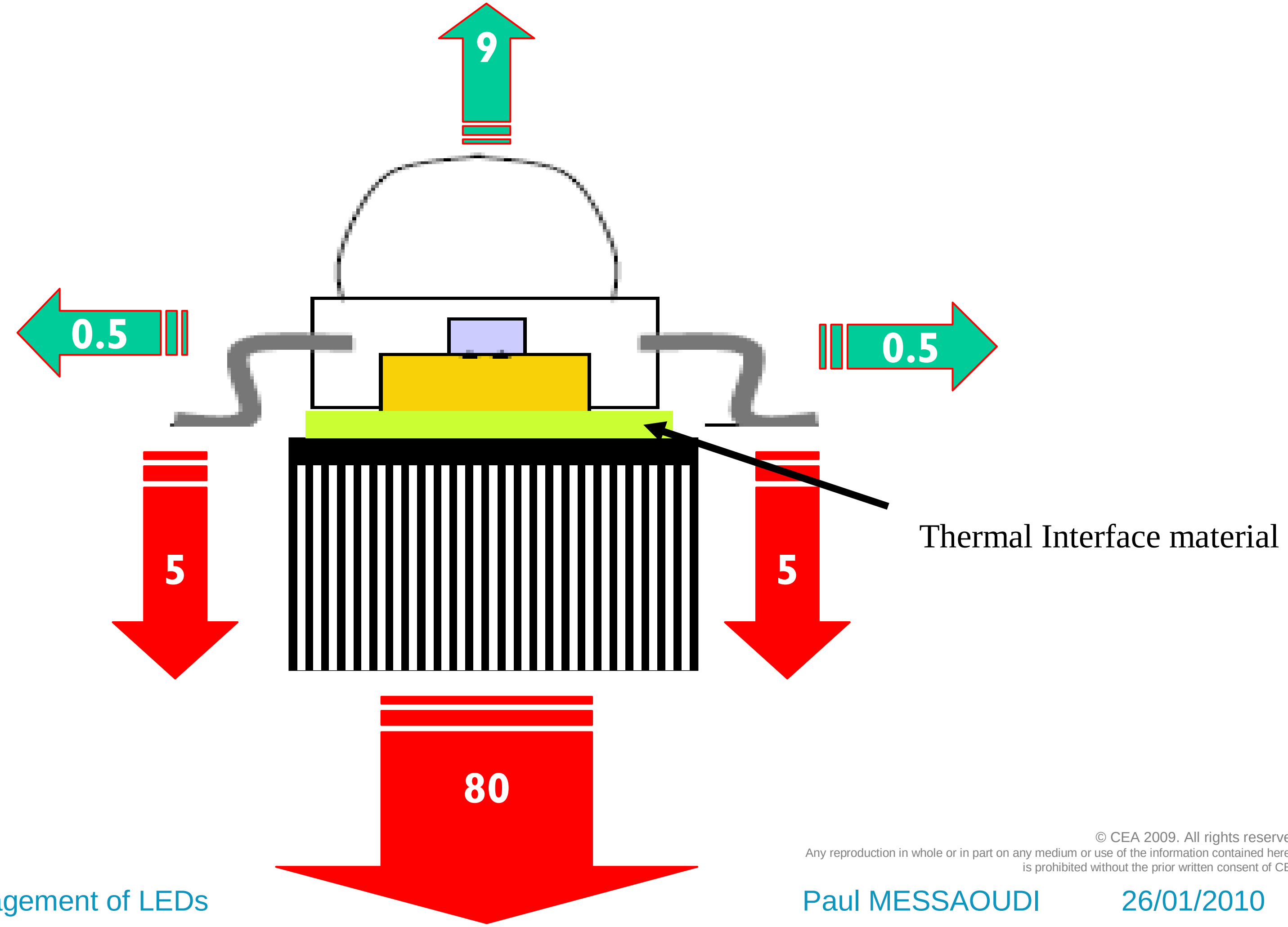
  } ~10%

  - **Conduction** is the most effective mode → ~90%



Thermal effects – Thermal transfers

- Heatsink effect on the thermal conduction



Thermal effects – Thermal modeling

■ Linear behavior or Steady-state modeling

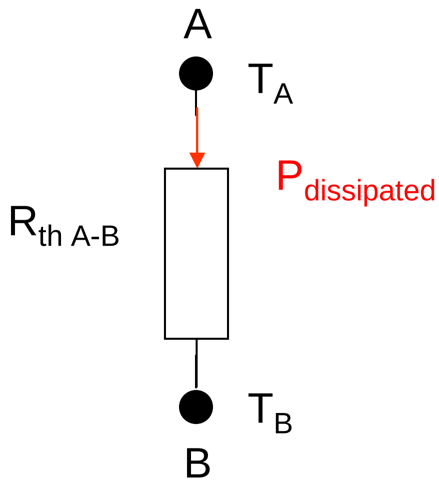
- Thermal conduction (electrical analogy)

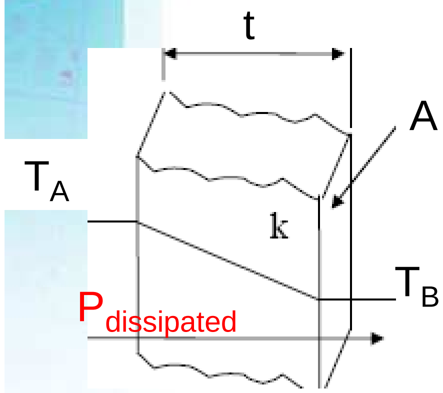
$$\Delta T_{A-B} = R_{th\ A-B} \times P_{dissipated}$$

  - ΔT, thermal gradient between A and B (°C)
  - P, dissipated power (W)

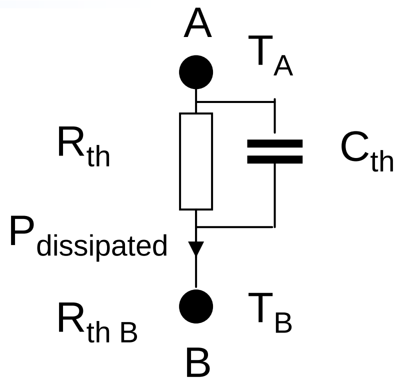
$$R_{th} = \frac{t}{A \times \kappa}$$

  - R_{th}, thermal resistance (°C/W), depends on surface A, thickness t and material's thermal conductivity κ





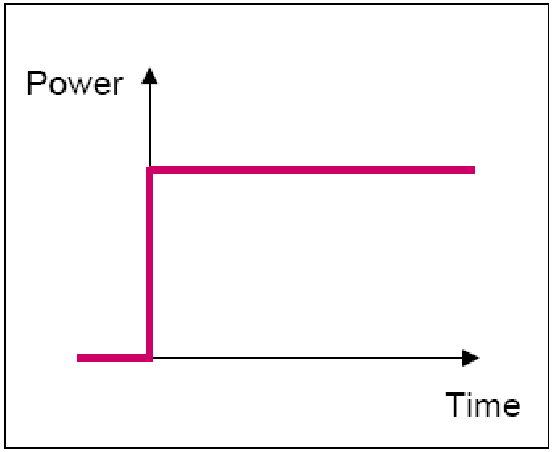
Thermal effects – Thermal modeling



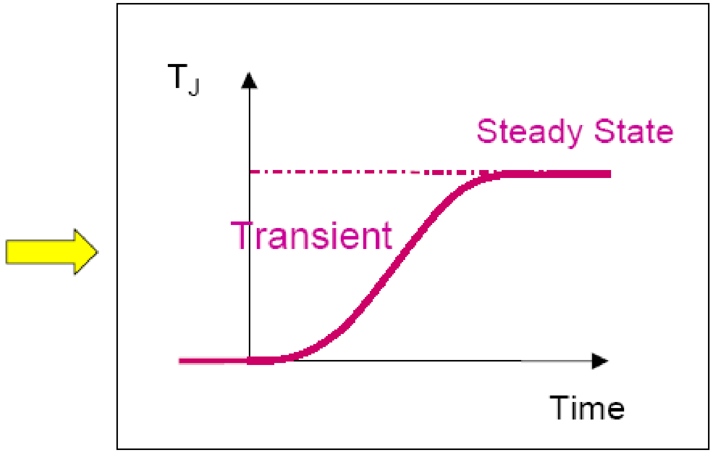
Dynamic behavior or Transient modeling

- Thermal conduction (electrical analogy)

$$\Delta T_{A-B} = T_{Junction} = P_{dissipated} \times R_{Th}\left(1 - e^{\frac{-\Delta t}{R_{th}C_{Th}}}\right)$$



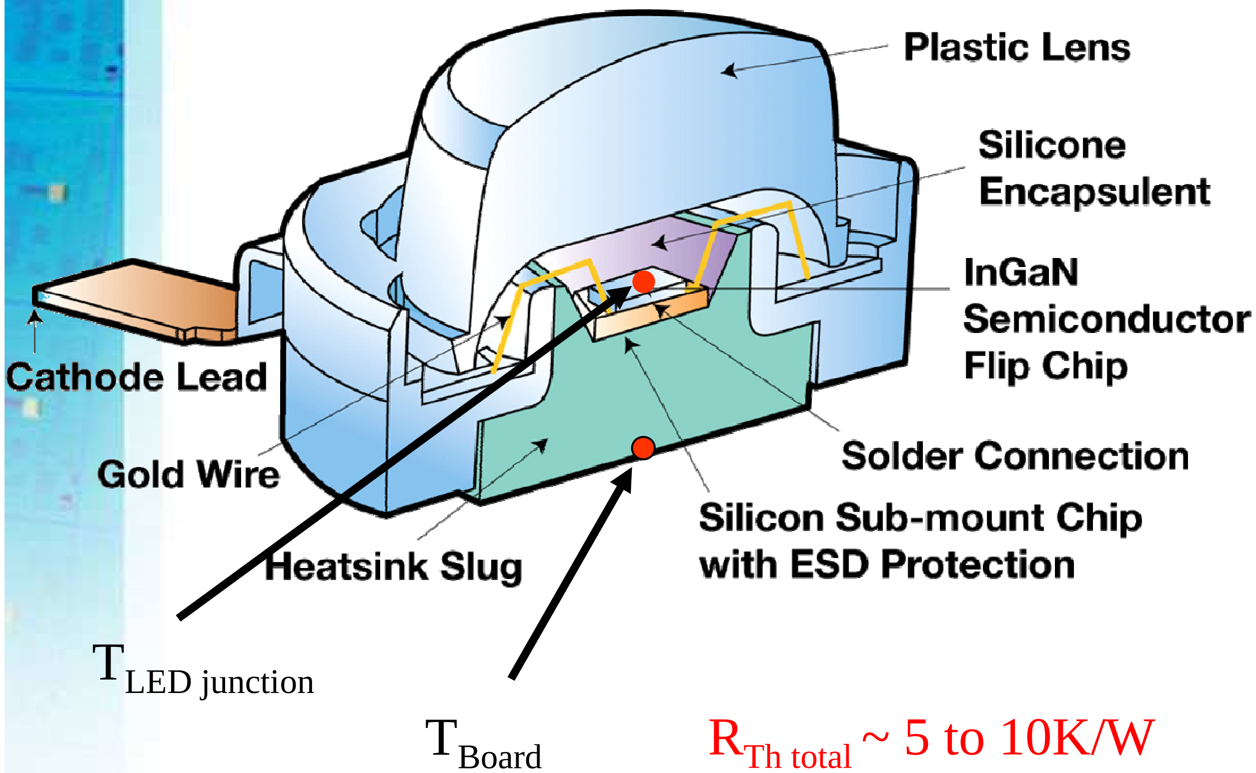
(a) Power input Step



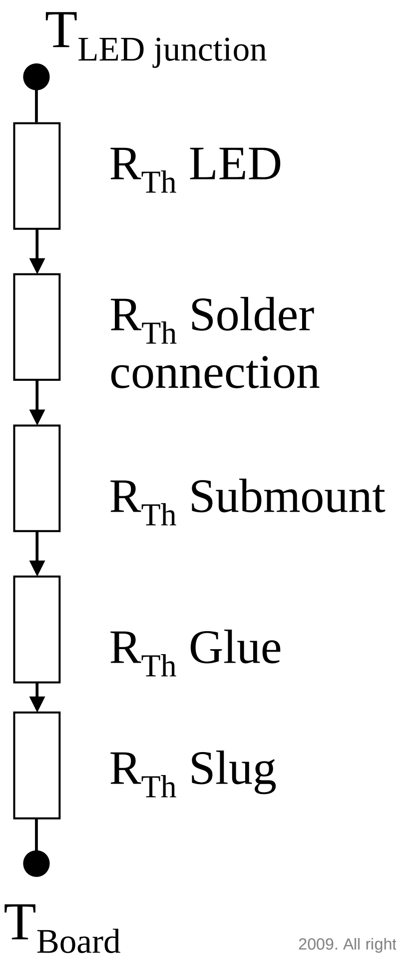
(b) Response function

Thermal effects – Thermal modeling

- Rth of the overall assembly of a K2 LED from Lumileds



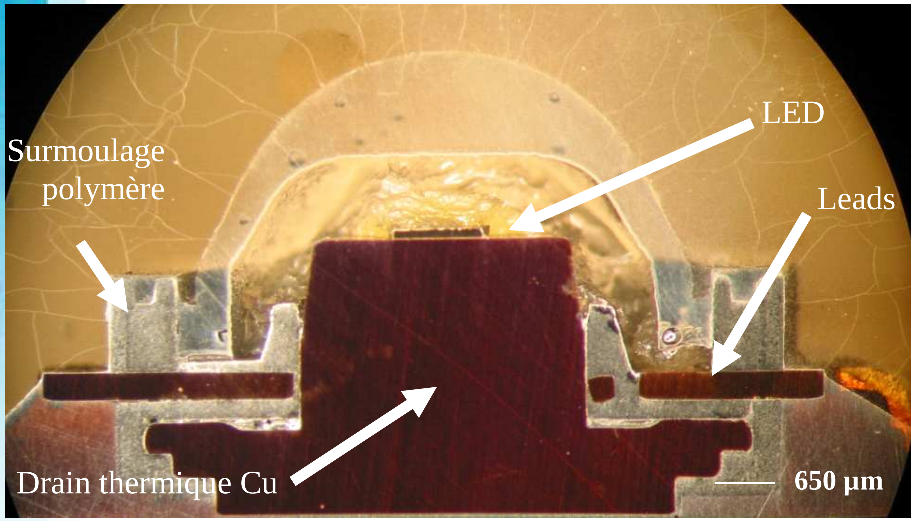
$R_{Th\ total} \sim 5$ to 10K/W



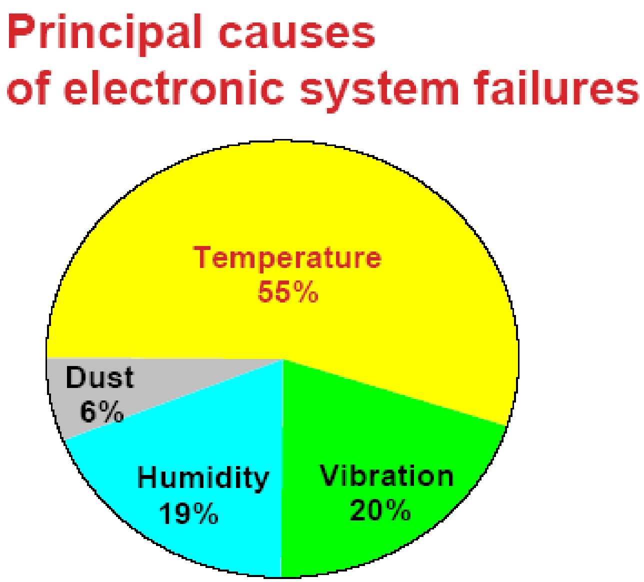
Thermal effects – Thermomechanics

Thermomechanical behavior

- LED module assembly
  - Metals, Semiconductors, Ceramic and Polymers altogether



Slice of Luxeon K2 from Lumileds
Source : CEA



Thermal effects – Thermomechanics

- Thermal dilatation coefficient : α
  - displacement and the strain due to ΔT

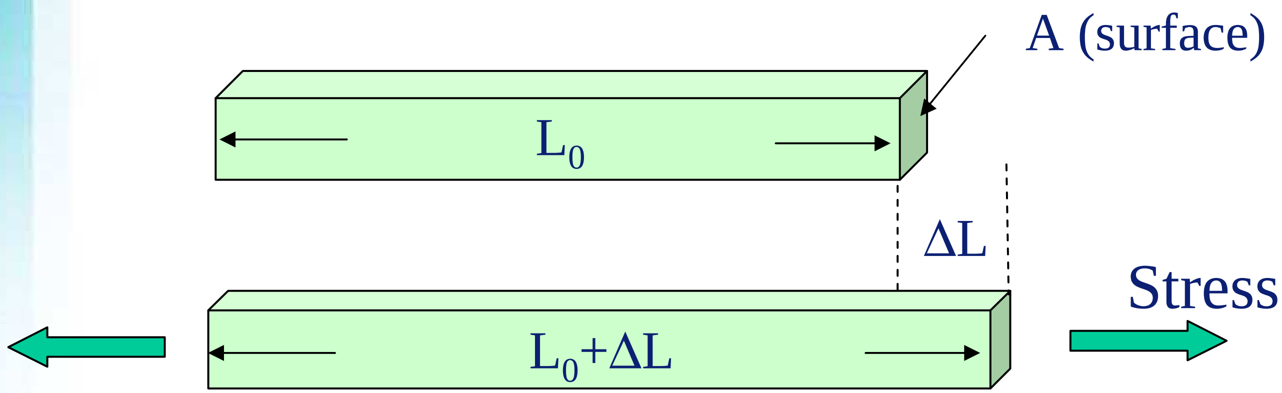
$$\varepsilon = \frac{\Delta L}{L} = \alpha \times \Delta T$$

$$\Delta L = \alpha \times \Delta T \times L$$

- Induced thermal strain : beware of CTE mismatch !!!

$$\sigma = E \times \varepsilon$$ (elastic behavior – Hooke law)

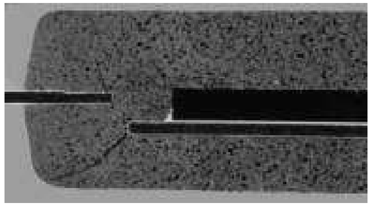
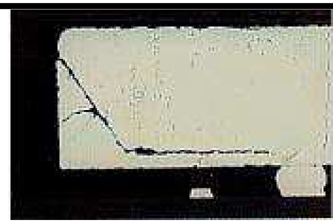
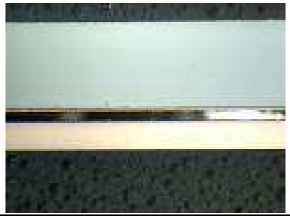
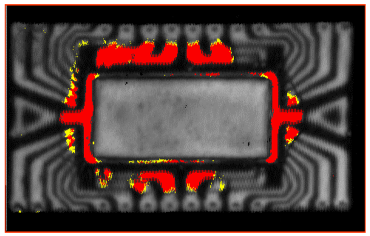
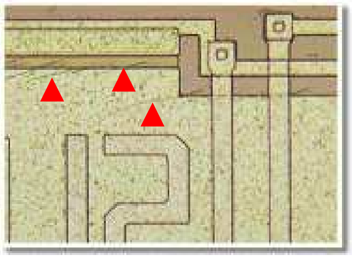
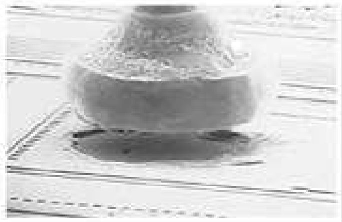
so $$\sigma = \alpha \times E \times \Delta T$$



Aluminum :
α = 24ppm/°C
Copper :
α = 17ppm/°C
Silicon :
α = 4ppm/°C

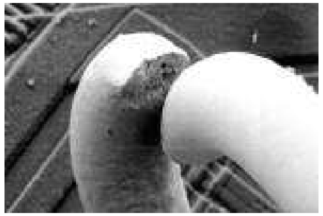
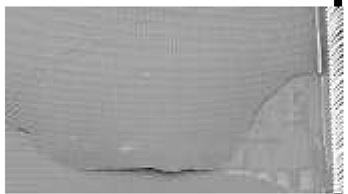
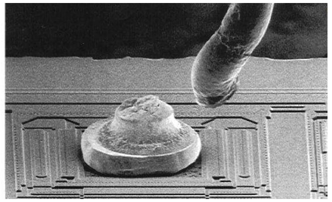
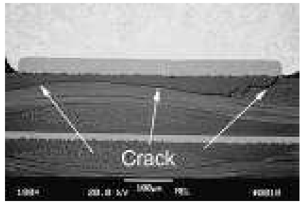
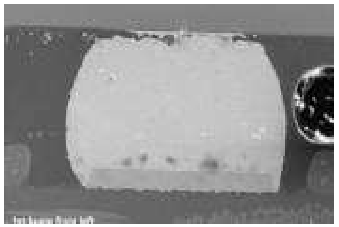
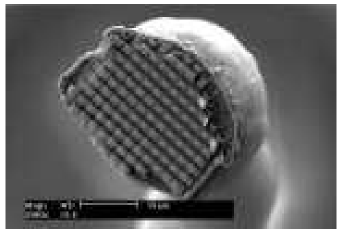
Thermal effects – Thermomechanics

Failure modes in electronics

1: Package Crack		5: Die Crack	
2: Excessive Warpage		6: Die Lift	
3: Delamination		7: Stitch Break	
4: Passivation Crack		8: Bond ball lift	

Thermal effects – Thermomechanics

- Failure modes in electronics

9: Broken Wire		12: Delaminating layers in metal IC stack	
10: Ball Neck Break		13: Substrate Cracks	
11:Solder Ball Fatigue		14: Metal Peal Off in Bondpad	

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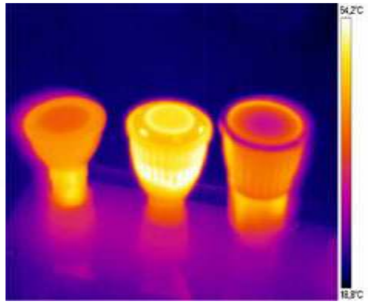
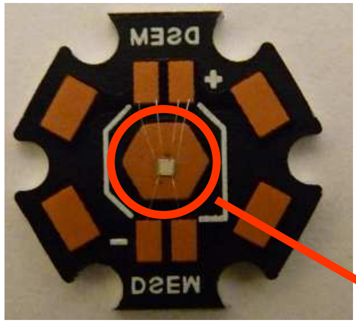
- Conclusion

Advanced characterization

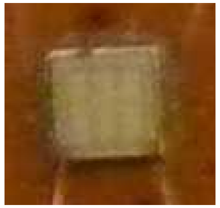


Source : Massol

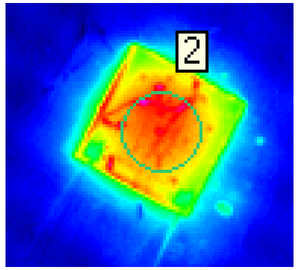
- Non-Destructive Testing :
  - Infrared Thermography



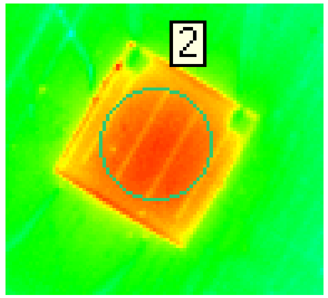
Source : CEA



In soldering



AuSn soldering

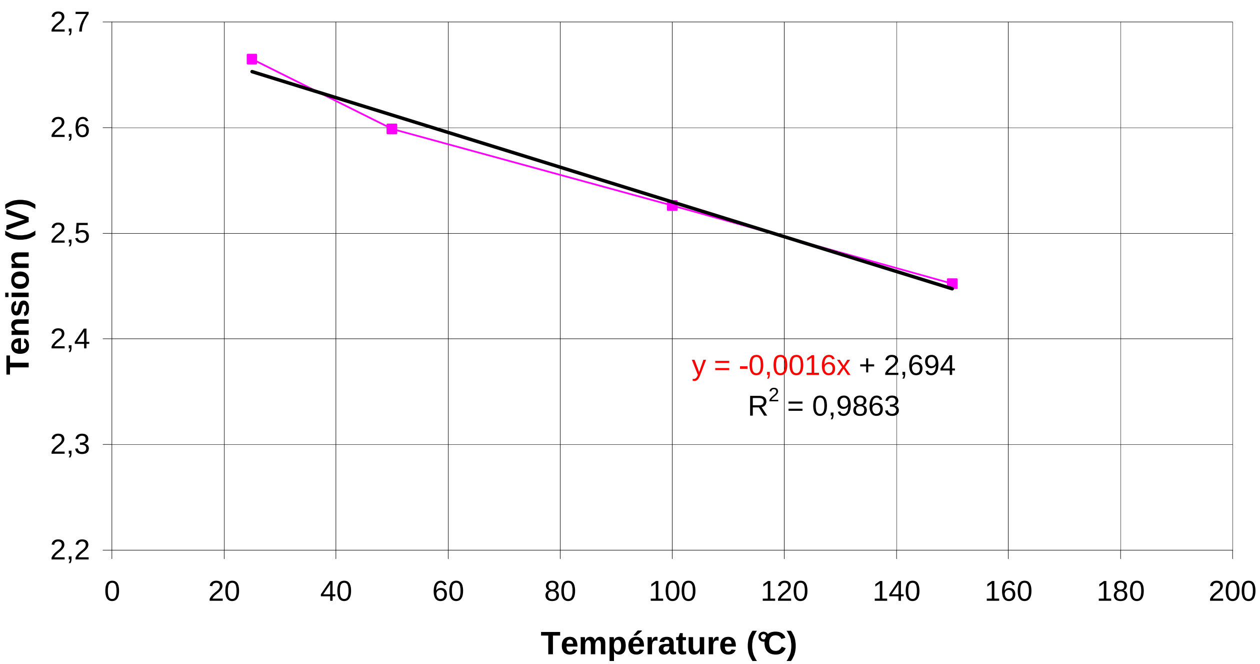


  - Only pictures of the surface
  - Difficult interpretation when multiple material are involved in the system
    - Relative emissivity is a material property

Advanced characterization

- Non-Destructive Testing :
  - Voltage drop measurement

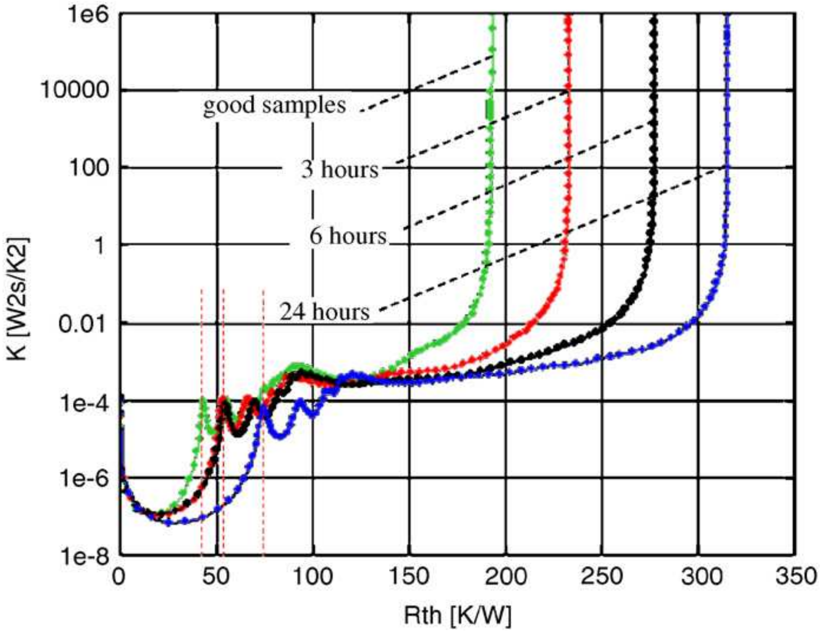
Effet de la température sur la diode bleue ($I_{LED\ Bleue}$=1mA)



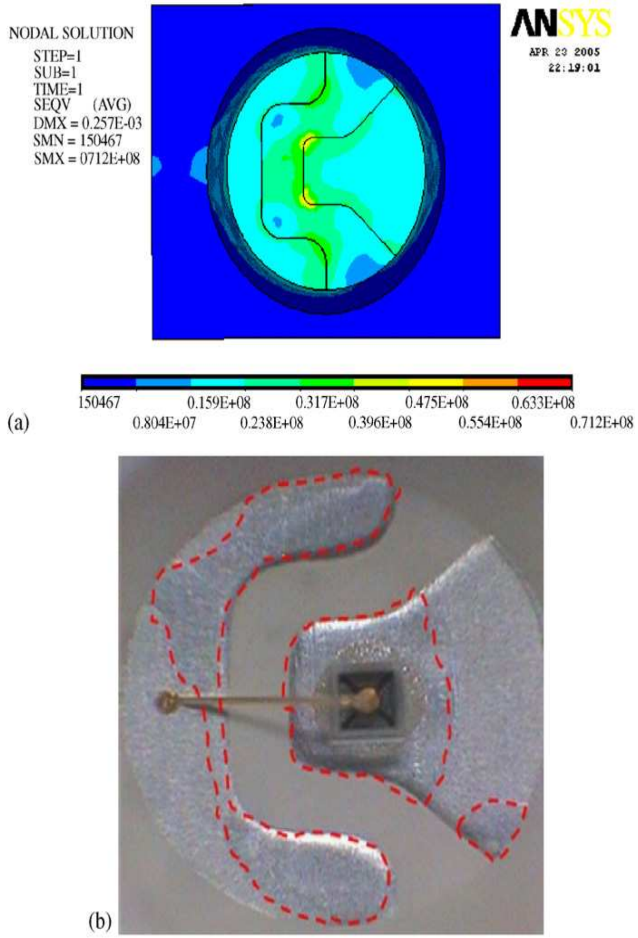
$$\left.\frac{d(V_{LED\ Bleue})}{dT}\right|_{I=1mA} \approx -1{,}6mV \cdot °C^{-1}$$

Advanced characterization

- Non-Destructive Testing :
  - Voltage drop measurement
    - T3Ster from Micred



Differential structure function of LEDs package under a risk of delamination



Thermal modeling and micrograph of a delaminated sample

Source : Mechanism and thermal effect of delamination in light-emitting diode packages, Jianzheng Hu et all., *Microelectronics Journal 38 (2007) 157–163*

Outline

- Introduction to LED technology
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- Applications of LEDs
- Advanced thermal management
- Conclusion and perspectives

Applications of LEDs – Component choice

- Be careful with LEDs specifications
  - Light ouput : candela or lumen
  - Cold/hot factor and lumen maintenance
  - Thermal Resistances and Maximum bearable temperature
    - Datasheets from Lumileds

	Temp. de jonction max	Temp. de boitier max
LUXEON® I/III AlInGaP	120/135 °C	120 °C
LUXEON® I/III InGaN	135 °C	120 °C
LUXEON® K2 AlInGaP	150 °C	135°C
LUXEON® K2 InGaN	185/150 °C	170/135 °C
LUXEON® Rebel AlInGaP	135 °C	120°C
LUXEON® Rebel InGaN	150 °C	135°C

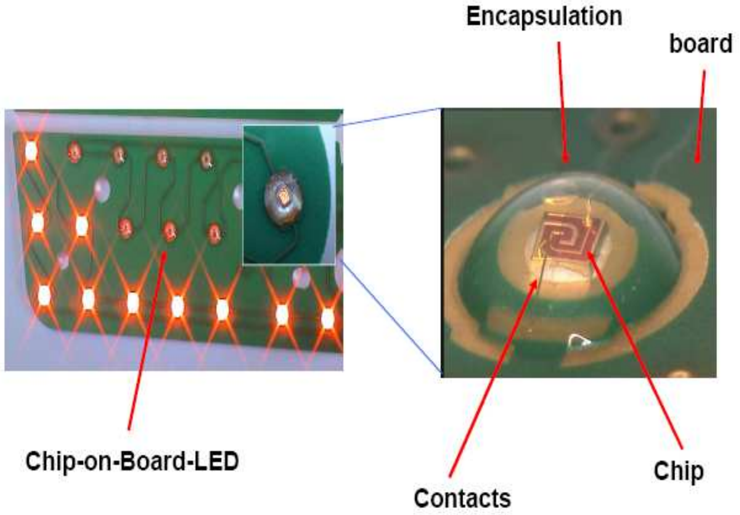
	Résistance thermique
Luxeon K2 InGan	9 °C/W
Luxeon K2 AlInGaP	12 °C/W
Luxeon K2 TFFC	5,5 °C/W
Luxeon Rebel InGaN	10 °C/W
Luxeon Rebel AlInGaP	12 °C/W

Applications of LEDs

Chip-on-Board

- Packaging-free technology

- Advantages
  - Low-cost solution
  - Flexible Design
  - Reduced thermal interfaces



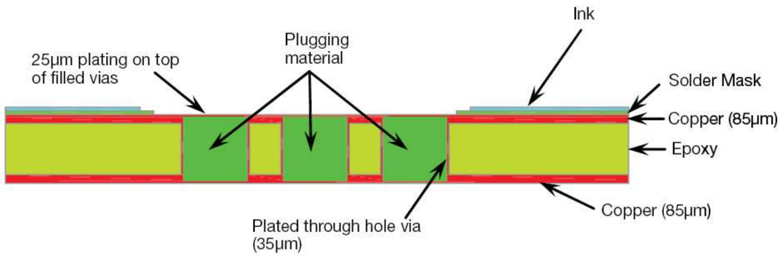
Source : GLI

- Challenges
  - Need to supply LED crystal
  - Need of managing LED assembly techniques
  - Improvement of the thermal spreading
  - Use of highly efficient PCBs

Applications of LEDs – PCB choice

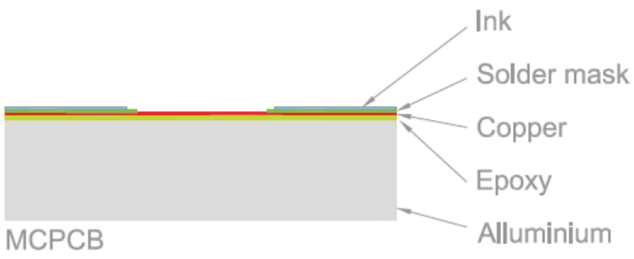
- Relevant Printed Circuit Boards (PCB) for LEDs
  - PCB with vias (filled or capped)

R_{th} ~ 5K/W



  - Metal Core PCB

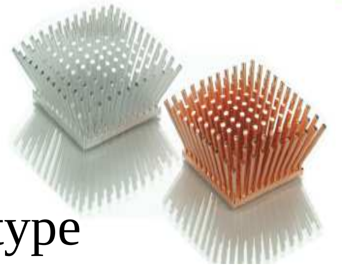
R_{th} ~ 3,5K/W



- Flex PCB generally not recommended
  - Unless having very thick copper layers for heat dissipation

Applications of LEDs – Heatsink choice

- Heatsink types



Pin fin type

Fin type

- Heatsink thermal resistance
  - Exchange area A of the heatsink
  - Heat transfer coefficient HTC of the convection
    - HTC = 5 to 20W/m².K under natural convection (indoor and not confined)
    - HTC = 50 to 1000W/m².K and more with forced convection (outdoor or with fans or fluid cooling)

Source : Lamina SoL

$$R_{th\ heat\ sink} = \frac{1}{HTC \times A}$$

P=8W and A~100cm² ⇒ If ΔT~50°C, R_{th}~6K/W so HTC~15W/m².K

Applications of LEDs - Retrofit

ADEME
Agence de l'Environnement et de la Maîtrise de l'Énergie

PACTE LED

LED challenges for Halogen replacement

- PACTELED project

	20W Halogen MR16	5W LED MR16
Luminous efficiency (lm/W)	12	50
Power Supply	DC or AC	DC
Light spectrum	continuous	discrete
Lifetime (h)	2000 to 5000	30000
Main heat transfer mode	radiation	conduction
Max temperature (°C)	400	~60°C

→ Efficiency drops with high current and high temperatures

→ Beware of the transformer compatibility

→ Color Rendering Index (CRI) > 85 wanted

→ Need of a highly capable heatsink with extended surface heat exchange area :

Source: Philips

Source: LSG

Source: Osram

Applications of LEDs – LED luminaires

- CITADEL project
  - Examples of luminaires with multiple LEDs and various heatsinks
    - Few luminaires with relevant thermal management

Outline

- Introduction to LED technology
- Thermal effects in LEDs
- Advanced characterization of LEDs
- Applications of LEDs
- **Advanced thermal management**
- Conclusion

Advanced thermal management

- Material properties to enhance
  - Interface materials are key parts for efficient cooling
  - Difficulty to know their exact thermal properties
    - Need to have all these experimental methods

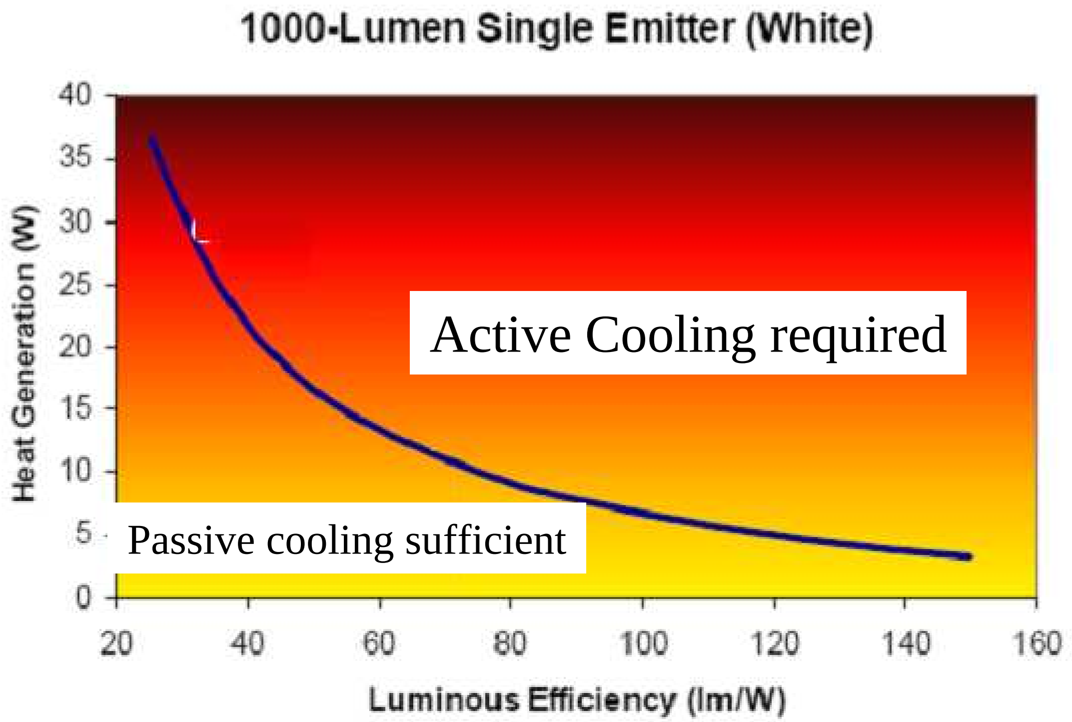
Microscopic analysis
•Scanning Electron Microscope (SEM)
•Atomic Force Microscope (AFM) Speckle,
•Dielectric Analyzer (DEA)
•Dynamic Mechanical Analyzer (DMA)
•Differential Scanning Calorimeter (DSC)
•Differential Thermal Analyzer (DTA)
•Thermogravimetric Analyzer (TGA)
•Thermomechanical Analyzer (TMA)
•CSAM, X-Ray Imaging,
•Wyko Measurement System

Strain Gauges and Extensometers
•Moire Interferometry
•Holography Interf.
•Speckle Correlation Methods
•Electronic Speckle Interferometer
•Twyman-Green Interferometer
•Shadow Moire, Projecting Moire
•Test Chip Technology
•MEMS Technology
•MicroDAC
•Raman Microscopy
•X-Ray Diffraction

Test Machines
•Microforce Test System
•Micromechanical Test System
•Universal Strength Tester
•Micro Tensile Tester
•Nano Indenter
•Micro Mechanical Fatigue Tester
•Vibration Tester
•Drop and Impact Tester
•X-Ray Diffraction
•Raman Microscopy
•CSAM, X-Ray Imaging, Wyko Measurement System

Advanced Thermal Management

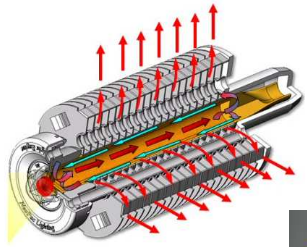
- Active cooling
  - It consumes power so use it carefully
  - Above 70 lm/W and below 13W dissipation, active is not required for a 1000 lm lamp

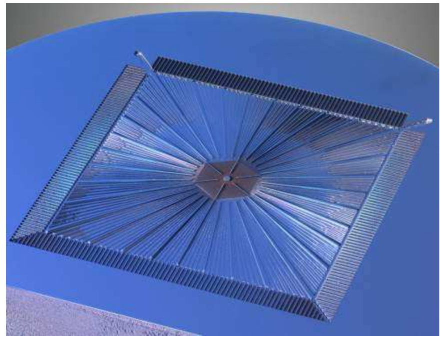


Source : NXP

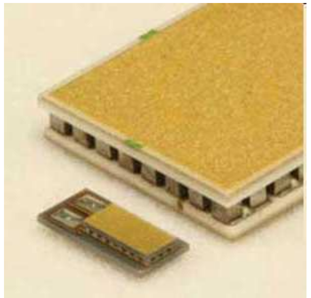
Advanced Thermal Management

- Active cooling examples
  - Heatpipes
    - NeoPac
      - Copper hetpipe with radial fins





    - CEA
      - Fully integrated Silicon heatpipe
  - Peltier module
    - OptoCooler from Nextreme



  - Acoustic cooling
    - Synjet from Nuventix

Outline

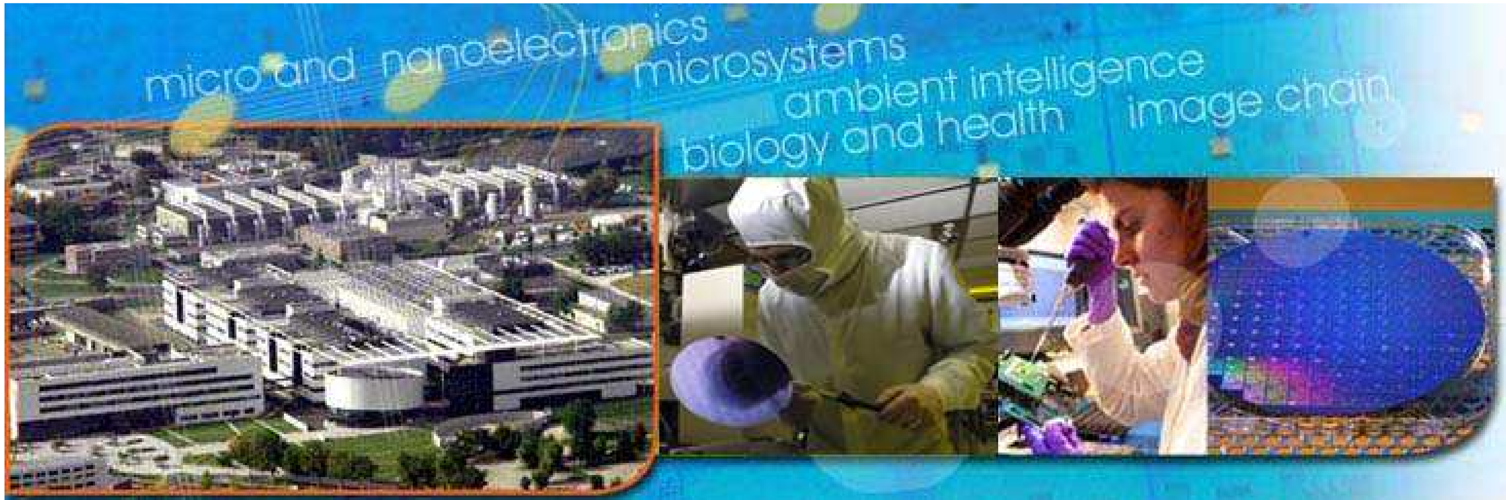
- Introduction to LED technology
- Thermal effects in LEDs
- Avanced characterization of LEDs
- Applications of LEDs
- Advanced thermal management
- Conclusion

Conclusion

- **Effects of the thermal stresses on LEDs**
  - Difficulty to use LEDs at nominal temperature (25℃)
  - Light output is sensitively shrinked
    - 80% to 50% of nominal intensity at T=100℃
  - Color shifts to higher wavelength
    - Color consistancy with RGB or phosphor converted white LEDs
  - Forward voltage drops
    - Need to drive LEDs with the current not the voltage
  - Lifetime is reduced
    - Less effective Semiconductor effect
    - Failures occur more rapidly

Conclusion

- Passive cooling needed
  - Use heatsinks and relevant PCB for mounting your LEDs
- Active cooling option
  - Use it to develop more power in tinier space
  - Always improve thermal conduction in your system before adding an active cooling device
- Thermal management has to be firstly considered before designing LED application
  - Think twice or ask a thermal expert !



Thanks for your attention

Loyalty
Entrepreneurship
Team work
Innovation