České vysoké učení technické v Praze Fakulta elektrotechnická

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Vývoj nových polovodičových LED žárovek - budoucnost v technologii osvětlení

The development of new LED light bulbs - the future in lighting technology

Praha, 2013

Summary

The work addresses need for the introduction of modern technology of powerful light sources that are predominantly remarkable after the end of production 60 W incandescent light bulbs in the European Union from September 2011.There are two alternative technologies arising: energy-saving fluorescent lamps or light sources based on LED technology. LED illumination is a very fast growing alternative in the last few years, which is due to low power, excellent efficiency and long lifetime future alternative in the illumination not only in industry, but also in homes.

An additional indisputable advantage of LED lighting is the possibility of intelligent control of light output, such as color temperature, intensity, etc. The work describes in detail the proposal for a new retrofit LED light bulb with a light output of 800 lumens (equivalent to 60 W), design of electronic parts such as electronic LED board and problem of thermal management and reliability prediction. Light sources based on LED technology are also characterized by extremely long lifetime (up to 50 thousand Hrs). Lifetime testing of such systems is very difficult. A key issue in this area is the identification of potential mechanisms resulting in failure and identification of their location. The document refers to a new method for accelerated testing of electronic components of SSL illumination light bulbs. Numerical modeling of thermo-mechanical phenomena with the calculation of lifetime is validated by newly developed systems which test the durability and reliability of SSL components.

Souhrn

Práce se zabývá potřebou zavedení moderních technologií výkonných světelných zdrojů, které jsou zejména aktuální po ukončení výroby 60 W žárovek v Evropské unii k 1. září 2011. Dnes jsou k dispozici dvě alternativní technologie: úsporné zářivky nebo světelné zdroje založené na technologii LED. Osvětlení pomocí LED diod je v posledních několika letech velice rychle se rozvíjející alternativou, která představuje díky nízké spotřebě, vynikající účinnosti a vysoké životnosti budoucnost ve svícení nejenom v průmyslu, ale především v domácnostech. Dalšími nespornými výhodami LED osvětlení je možnost inteligentního řízení světelného výstupu jako např. barevné teploty a intenzity, atd. Práce detailně popisuje návrh nové LED žárovky se světelným výstupem 800 lumenů (ekvivalent 60 W), návrh elektronických částí jako je elektronická deska s LED, dále otázkou teplotního managementu a předpovídání spolehlivosti. Světelné zdroje založené na LED technologii se kromě vynikající účinnosti také vyznačují extrémně dlouhou životností (až 50 tis. hodin). Testování doby života takových systémů je velice obtížné právě díky dlouhé době životnosti. Klíčovou problematikou v této oblasti je odhalení potenciálních mechanismů vedoucích k selhání a určení jejich umístění. V práci jsou popsány nové metody pro zrychlené testování elektronických komponent polovodičových světelných zdrojů. Numerické modelování teplotně-mechanických jevů s výpočtem životnosti je konfrontováno s nově vyvinutými systémy pro testování životnosti a spolehlivosti.

Klíčová slova

LED žárovky, teplotní management, teplotně-mechanické simulace, životnost a spolehlivost

Keywords

SSL bulbs, thermal management, thermo-mechanical simulation, lifetime and reliability

Content

1 The development of new LED light bulbs

LED (Light-emitting diodes) lamps are a fast emerging technology which is considered as the true alternative to the Compact Fluorescent Lamp (CFL). At present days we can see many commercial products that are usually available for professional use; however there is not often any LED retrofit lamps that can fulfil traditional expectations of consumers in terms of lamp shape, price, light output and other functionalities.
Solid-state lighting has the potential to revolutionize the future lighting industry. It is predicted that the LED replacement lamp market will speed up progresses in commercially available LED performance in the next a few years, as well as cost reduction are expected. SSL technology uses semiconductor light-emitting diodes (LEDs) as sources of lights instead of wildly used incandescent electrical filaments or plasma in fluorescent lamps. The term "solid state" is derived from meaning that light is emitted by solid-state electroluminescence. One of the biggest advantages in comparison to incandescent lighting is that SSL produces a light with reduced heat generation or other parasitic energy dissipation. Other benefits that come with SSL technology are: more than ten times longer life time in comparison with incandescent light technology, better quality of light output, smaller volume of light bulb. Table 1-1 compares SSL lamps to incandescent and fluorescent lamps from power dissipation and life time point of view. The data are related to 800 lumen light output:

Table 1-1: Commercially available lamp comparison

Input Power (W)	**60**	**18**	**12**
Life time (hours)	~1000	~ 8000	20 000 – 50 000
Retail price	<1 €	5-10 €	10-35 €
Total Radiant Energy	81 %	51 %	20-30 %
Visible light	8 %	21 %	25-30 %
Infra-red emission	73 %	37 %	~0 %

SSL lamp is fully dimmable (depends on driver type) like an incandescent bulb, but unlike a fluorescent lamp that has tendency to flicker. SSL lamps also do not emit ultraviolet radiation and SSL technology is considered to be “green technology”.
Light emitting diodes historically have been used for indicators. The first practical visible-spectrum LED was technologically advanced in 1962 by Nick Holonyak [1]. While the efficacy of these first LEDs was extremely low (~ 0.1 lm/W), research was continued to improve the technology over the next four decades, achieving higher efficiencies and expanding the range of emission wavelengths through the engineering of new III-V semiconductor alloys.
From the time of invention, LEDs have been used in many industrial applications as for example: displays (outdoor displays, electronic scoreboards), LCD back lighting [2]

(mobile phones, notebooks, cameras, monitors, TVs, etc.), automotive lighting [3], in communication technologies. The introduction of high brightness LEDs with white light output have managed to a movement towards general indoor and outdoor illumination applications [4]. The increased electrical driving currents have focused more attention on the thermal management and new designs of LED power packages. The luminous efficiency of LEDs brakes 200 lumens per watt in 2011[1] and the thermal challenges are opening new research areas from LED chip design level to the system level thermal management.

To generate white light output for general illumination, a narrow spectral band of an LED's must be transformed into white light that is based on three approaches:

- *phosphor-conversion;*
- *discrete colour-mixing;*
- *hybrid consisting of phosphor (white) and monochromatic packages (or different LEDs in a single package).*

The phosphor-converting LEDs produce white light by converting of the blue light (generally around 460 nm) emitted directly from the LED die with light emission converted by a phosphor [5]. Main disadvantage of phosphor-conversion technology is difficulty of maintaining consistent-quality of white light due to changes of the temperature, thickness of the phosphor layer.

Discrete colour-mixing create the white light by colour mixing optics to mix the light output from discrete colored sources. The biggest problem is the absence of efficient green light LEDs. Moreover, mixing of discrete colours requires multi-die mounting and sophisticated optics.

2 Thermal management, thermo-mechanical design and reliability

2.1 Thermal management

While incandescent lamps emit mostly infrared (IR), with a small amount of visible light, SSL lamps generate little or no IR or UV, but convert only 20%-30% of the power into visible light. The rest is converted to the heat that must be conducted from the LED die and through LED package to the underlying LED board, heat sink and housing. Table 2-1 shows the proportions of input power to heat and radiant energy conversion for various white light sources. Almost all total radiant energy in case of SSL lamp is converted to visible light. This is main advantage above incandescent and fluorescent lamps. On the other hand big portion of the heat is generated here.

[1] 200 lumens per watt were achieved by CREE LEDs with a colour temperature of 4579k and nominal drive current of 350mA.

This is a reason why thermal management is perhaps the most important aspect of successful SLL lamp system design.

Table 2-1: Estimated proportions of input power to heat and radiant energy (including visible light) conversion for various white light sources

Lamp type	Incandescent	Fluorescent	SSL lamp
Infra-red emission	73%	37%	~0%
Heat	19%	42%	70-80%
Total Radiant Energy	81%	58%	70-80%
Visible light	8%	21%	25-30%
Total energy	100%	100%	100%

If the heat is not removed, the LEDs run at high temperatures, which not only lower their efficiency, but also make the LED less reliable. Thermal management of SSL lamp is a key issue impacting colour consistency and lifetime. The junction temperature of LED components depends on the heat generation caused by loses during light emitting and thermal dissipation within the SSL lamp from the LED die through the LED package, board, heat sink and finally to the ambient.

In 1998, Lumileds developed the first high-power LED packaging[2] – Luxeon, which embeds a metal large shell size for heat dissipation. This packaging method reduces thermal resistance to about 10 K/W and can dissipate heat power up to 5W [6]. In 2006, with the improvement of used materials and attach technologies, the Luxeon K2 package can allow junction temperature up to 150°C for white LED with a driven current up to 1.5 A [7]. To reduce costs and increase the reliability issues, a ceramic based package has been developed by Lumileds (the Rebel component [8]), CREE and others. On the other hand, the thermal resistance of these packages remains typically above 10 K/W. LED boards technologies that has been developed and used recently uses FR4 boards, metal-core printed circuit boards (MCPCB), IMS (Insulated Metal Substrate).

Heat and changes of LED temperature directly affects both short-term and long-term LED performance [9]. The short-term performance effects mostly colour shift and reduced light output while the long-term performance results accelerated lumen depreciation and thus shortened useful life. The Figure 2.1 shows the light output over time for two identical LEDs driven at the same current but with an 11°C difference in LED junction temperature[3]. Estimated useful lifetime (according 70% lumen normative) reduced from about 37,000 hours to about 16,000 hours. A 10 degrees increase in temperature reduces LEDs life by approximately 50% and each following 10 degrees increase will reduce fixture life by another 50%!

[2] Patent no. 6,274,924 "Surface mountable LED package. Filed 11/5/1998, granted 8/14/2001.

[3] Experimental data sampled to 10,000 hours and extrapolated beyond

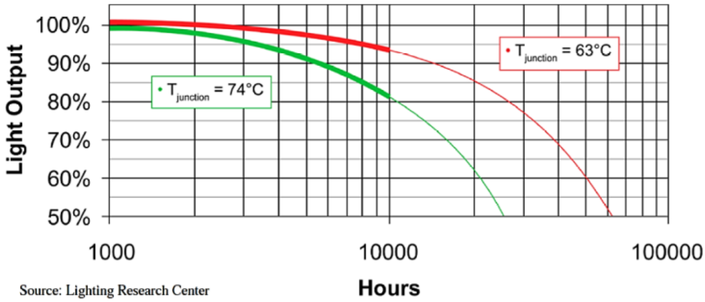


Figure 2.1: Useful life time of high brightness white LEDs at different operating temperatures [10]

Required high light output causes high temperatures dissipation inside the limited size of the SSL lamp engine. This can be especially critical for LED junction temperature and driver components temperature. Most of today research works that are dealing with SSL lamp design and thermal management are focusing on the virtual prototyping based on thermal management, thermo-mechanical modelling and reliability predicting.

2.2 Life time and reliability of SLL lamp

SLL lamp lifetime is defined as decrease of light output power in lumens. The mostly spread normative that has been adopted by many companies is SSL certification which states that an SSL lamp fails when it's light output drops below 70% of the initial light output (L70) [11] [12]. For example the CSSL lifetime specification of 12,000 h (B50L70) indicates that the expected light output of at least 50% of all 60W replacement lamps has to be maintained to a level of 70% (the lumen maintenance level) of the initial 806 lumen light output for a period of 12,000 h[4]. Unfortunately, up to now there does not exist globally accepted standard tests for SSL lamp reliability issues [13]. Life time of SSL lamps could be up to 50 000 h, nevertheless the life time strongly depends on LED die temperature [12]. Good thermal and thermo-mechanical management of LED lamps is very important and design of all other parts must be optimized for reliability.

2.3 Development of new 800 lumen SSL retrofit lamp

Heat dissipation and LED temperature were not a problem when low power LEDs were used. However, in today's high power LED applications thermal management issues must be taken into account [14] to not only ensure light maintenance and quality of LED lamps, but also guarantee the life time. The most critical parts of a LED lamp design from the reliability point of view are LED package and LED board [15]

[4] CSSL project specification document

[16]. A LED board usually contains several packaged LED dies (6-12). In a LED package a semiconductor die is usually soldered on ceramics and connected by wire or flip-chip bonding.

2.3.1 Requirements for Retrofit lamp design

Most important SSL retrofit lamp requirement is a lamp shape (customers want a "traditional" light bulb shape), light colours, distributed light angle, dimming possibilities are other very important aspect that must be taken into account.

Figure 2.2 shows a cross-section of retrofit shape SSL lamp with most important parts. Core of the lamp is LED board that include six high powers LED ceramic packages that are soldered on FR4 PCB board. Each LED package cover small silicon lens that widening light beam angle. High power LEDs emit light in a narrow blue range of the visible spectrum. Blue light has to be converted into white light by remote polycarbonate spherical conversion dome. The dome is mounted on the top of LED board. Another purpose of remote dome is wide angle light distribution. SSL lamp contains also an electronic driver, which is composed of AC-DC power suppliers, DC-DC converter and current driver controller.

LED board is mounted on top of an alumna thermal cone that dissipates a heat from LEDs and driver to a thermal conductive polymer housing (heat sink). Standard E27 cap is used for lamp mounting. White polyimide reflective cover is attached to thermal cone that reflect the light. A driver support mechanically mounts the driver and thermal interface layer (deposited between LED board and aluminium alloy thermal cone) improve thermal dissipation.

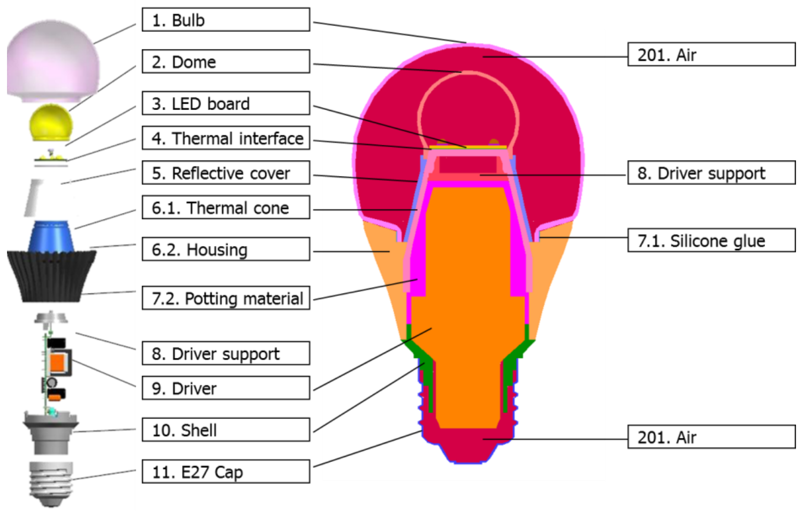


Figure 2.2: Master LED Glow 8 W lamp parts [17]

2.3.2 Modelling and validation of 400 lumen LED glow

For an evaluation Philips 400 lumen master LED glow has been chosen[5]. The multi-target simulation models (such as thermal, thermo-mechanical, reliability and optics) have been integrated to conduct multi-physics simulation of reference master LED glow to provide integrated inputs for new design. Simulations are carried out with ANSYS and CoventorWare software tools to compere not the same simulation methods. Materials properties (especially thermal conductivity) parametric study has been performed to determine problematical parts that transfer heat from power LEDs to ambient. Solutions for 800 lumen retrofit SSL lamp design were proposed.
A complete three-dimensional model of retrofit 400 lumen LED Lamp was designed taking into account all essential details (Figure 2.3) [18].

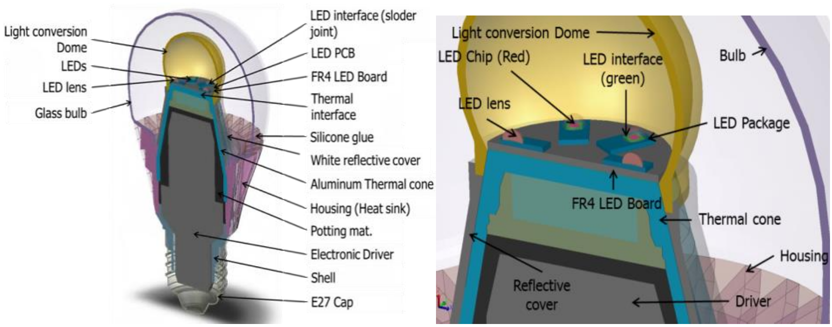


Figure 2.3: SSL Lamp 3-D model includes sixteen different compact parts. Air inside light bulb and inside light conversion dome was included to the model. The board includes six LED with Al2O3 package and LED chip [18]

Heat generation in SSL lamp take place in LED driver 1.2 W (measured value[6]), in six LEDs 4 W (calculated from datasheet) and in polycarbonate light conversion dome 1.5 W (evaluated by optical measurement[7]).
In the CoventorWare and ANSYS analysis thermal convection coefficient (5 W/m^2K) was prescribed for all outer parts of SSL lamp that are in interaction with the air. This value can be set for cases, where air velocity is small (under 0.05 m/s) [15]. Radiation affect to ambient (temperature of 22^oC) was also taken into account for all inner and outer parts of the lamp which are exposed to the air. It is very important to define

[6] Measured by CNM Barcelona.
[7] Measured by CEA Grenoble.

emissivity coefficients for all materials of used lamp components. The emissivity coefficients have been evaluated by measurement.
In the ANSYS-CFX thermal simulation natural air convection is calculated allowing for convective flow. So the simulation was performed taking into account the air flow inside bulb and dome and also around the lamp.

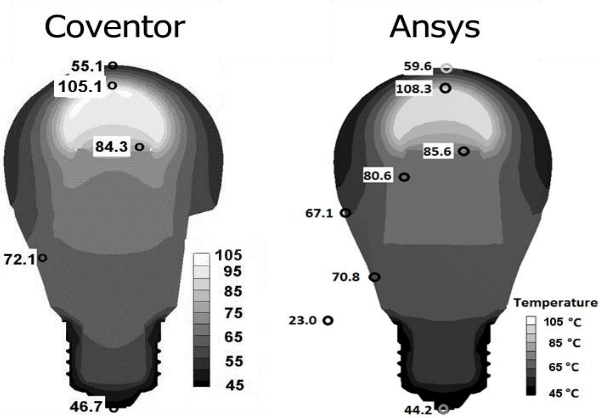


Figure 2.4: Computed steady state thermal analysis temperature distribution. Comparison between Coventor and ASYS simulation tool is shown [18]

In Figure 2.4 the temperature distribution results calculated in Coventor and ANSYS are compared. In this analysis natural air convection is not taken into account. The LED temperature is defined as the maximum temperature that occurs in the GaN LED die. The model is not complete to be able to calculate the LED junction temperature, but is adequate to calculate a LED GaN die temperature[8]. The calculated LED die temperature is 84.3°C for Coventor simulation and 85.6°C for the ANSYS simulation which shows good agreement
Direct temperature measurements were done by thermocouples, in defined monitor points inside the lamp. Figure 2.5 shows the results of the direct temperature transient measurement with temperature sensors. A steep temperature growth is observed at the beginning of the test. Within 2 hours the temperature reaches a steady-state condition. In Figure 2.5 the results of the steady-state ANSYS simulation (previous chapter) are presented and marked by symbols at time 6200 s where temperature transient has already reached steady state [18].
The temperatures calculated by ANSYS and Coventor undervalue slightly the measured temperatures of LED board (85.6 °C ANSYS simulation, 88.9 °C measurement). The underestimation might be due to the use of estimated heat generation input and a too high emissivity coefficient.

[8] More accurate calculation has been done with detailed LED board model where all details of given parts are taken into account

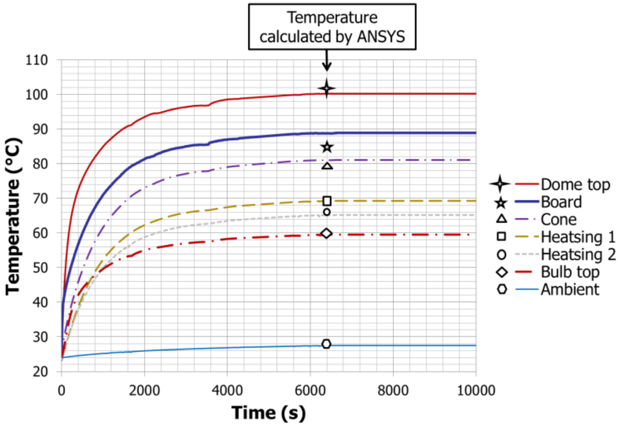


Figure 2.5: Measured (line) and calculated (symbol) temperatures of the SSL lamp [18]

The second measurement method uses an IR (infra-red) camera imaging to obtain temperature distribution of the SSL lamp. The emissivity of all SSL components have been determined by simple methodology where reference object with known emissivity (electrical tape with known high emissivity – 0.95) is heated up to defined temperature together with measured component. The emissivity on IR camera is set to that of the tape (0.95). After heating up to given temperature IR image is taken. Then emissivity can be calculated from Stefan-Boltzmann Law [18].

Figure 2.6c shows the temperature distribution sampled by IR camera with marked sampling points. The temperature distribution inside the SSL lamp was obtained when the glass bulb was dismounted Figure 2.6b. Compatibly, the light conversion dome was dismounted for LED board temperature measurement Figure 2.6d [18].

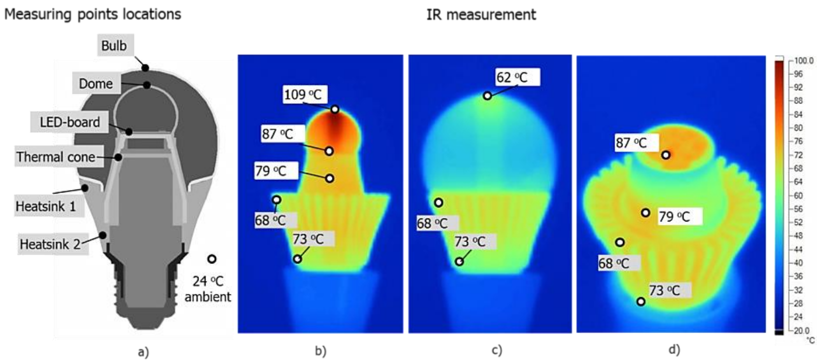


Figure 2.6: Temperature distribution sampled by IR camera. a) Thermal sensors location used for temperature measurement and comparative temperature samples from simulations. b) thermal distribution under glass bulb c) thermal distribution of the SSL lamp surface, d) thermal distribution of the LED board

2.4 Thermal modelling and characterization of SSL lamp LED board

Thermal performance of LED boards and LED packages can be compared by expressing of the absolute thermal resistance (R_{th} in K/W) which measures the temperature difference across a component when a unit of heat energy flows through the component in unit time.

LED board model (Figure 2.7) is composed of 650μm thick FR4 board with 80μm Cu layers implemented on both sides. The top Cu layer makes electrical connection between the LEDs. Thermal vias (500μm in diameter) are placed under and around thermal pad of LED package to increase thermal conductivity of FR4 board. The board includes six Luxeon Rebel LEDs based on ceramic LED package that includes one thermal pad and two electrical copper pads. A LED die is connected by 16 bumps on top side of ceramic LED package. Bottom side of LED package is soldered with FR4 top cooper metallization.

The LED board model is supplemented by a thermal cone that provide the relevant heat flux distribution at bottom side of the LED board as in case of normal operational conditions.

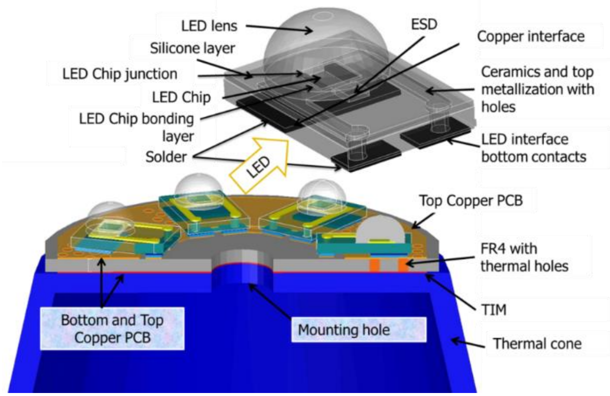
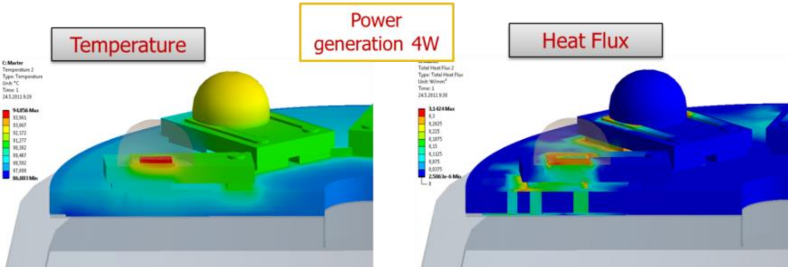


Figure 2.7: 3-D model of LED board used thermal modelling. Board includes six packaged LED packages including LED lens [19]

Figure 2.8 shows temperature and heat flux distribution of FR4 LED board design. As a result, 9.44 °K/W and 4.81 °K/W are the thermal resistance values identified for the LED package and FR4 board, respectively. Total thermal resistance of FR4 board and LED package is 14.25 °K/W [19]. To validate this result of our model, experimental thermal measurements have been carried out.



a) b)

Figure 2.8: a) temperature and b) heat flux distribution of FR4 LED. Die temperature is 95.2°C [19]

Total thermal resistance of FR4 master LED board was measured[9]. The thermal resistance between LED junction and reference temperature $R_{TH(j-C)}$ defined as:

$$R_{TH(j-C)} = \frac{T_j - T_C}{P_{TH}} \tag{2.1}$$

The junction temperature T_j is the LED die mean temperature and it is evaluated from the forward voltage drop dependence with temperature at low current ("electrical" T_j determination method). The reference temperature T_C is the backside (or bottom) LED board temperature. P_{TH} is the dissipated thermal power. It is related with the optical power P_{OP} (radiant flux) and the input electrical power P_{EL}:

$$P_{EL} = P_{TH} + P_{OP} = I_F . V_F \tag{2.2}$$

where I_F is the LED forward current and V_F the forward voltage drop. The T_j and I_F dependence of P_{OP} are required to determine P_{TH} from P_{EL}. P_{OP} dependence on I_F at 25ºC has been derived from datasheet information. The linear relationship:

$$P_{OP} = 105 \text{ mW} + 1.1286 \text{ x } I_F \tag{2.3}$$

gives a good approximation in the considered operation range. Figure 2.9 shows experimental results represented in the ΔT vs P_{TH} plane for the reference LED board. The linear fit (solid line) provides the statistical mean for describing the temperature increase dependence versus power, with an slope of 12.9 ºC/W and a standard deviation of 1 ºC/W. This value is compared with the mean value of expression (2.1) computed for the 20 experimental points (13.6 ºC/W). We obtain a good agreement between experimental and simulation results (below 5% error). This result validates our simulation approach as well as the thermal conductivity values taken from the literature.

9 Measured in Centre Nacional de Microelectrònica, CNM-CSIC, Campus UAB, 08193 Bellaterra, Barcelona, Spain

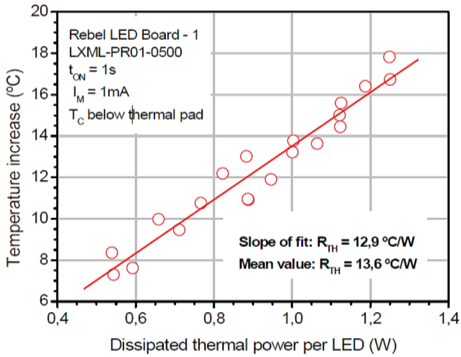


Figure 2.9 : Experimental results for the ΔT vs P_{TH} plane[10]

3 Design of new LED boards

This chapter shows how to improve thermal management of LED board and evaluate thermal stresses in LED board and LED package to investigate reliability. Very important aspect regarding reliability is keeping thermal stresses and accumulated creep strains in solder joints as low as possible. The most critical parts of a LED lamp design from the reliability point of view is usually solder interface between LED package and LED board or LED package and LED die [15] [16]. In this work five new LED boards have been designed using two new technologies (IMS and Leadframe)[11] Performance of five new LED boards (Figure 3.1) was compared to reference LED board from thermal and thermo-mechanical point of view. Six detailed models were built:

- ***Design A*** - *FR4 board of existing 8W LED lamp (reference model)* – Figure 3.1*a*
- ***Design B*** - *New LED board concept 1 with Luxeon Rebel LEDs*– Figure 3.1*b*
- ***Design C*** - *New LED board concept 2 with Luxeon Rebel LEDs* Figure 3.1*c*
- ***Design D*** - *Insulated Metal Substrate (IMS) Luxeon Rebel LEDs* –Figure 3.1*d*
- ***Design E*** - *IMS board with a new LED package design* - Figure 3.1*e*
- ***Design F*** - *New LED board concept 3 with the new LED package* Figure 3.1*f*

For each technology, a detailed 3D model has been built, including six packaged high power LEDs on the LED board. The LED board diameter and placement of LEDs on the board are the same for all cases.

[10] Measured by Xavier Perpinya, Centre Nacional de Microelectrònica, CNM-CSIC, Campus UAB, 08193 Bellaterra, Barcelona, Spain

[11] The design of new LED boards has been done with cooperation of Philips Lighting, CEA LETI and Boschmann

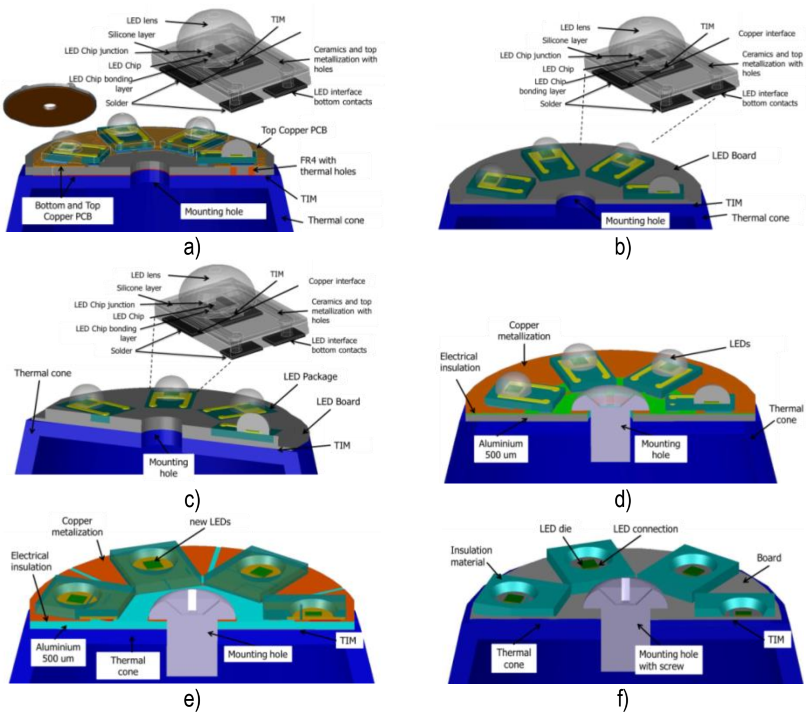


Figure 3.1: Design of new LED board models[12] [19]

The new boards were designed as possible replacement of the reference LED board. Their performance is evaluated by comparing thermal and mechanical properties.
Table 3-1 shows the thermal resistance values, computed separately for each LED package including soldering layer and for each LED board. We can see a big difference between the reference LED board with thermal resistances between 9.01 and 9.94 K/W (Design A-D), and the new LED package design where computed thermal resistance dropped to values between 2.18 and 2.83 K/W. The lowest LED board thermal resistance is calculated for the IMS board (1.89 K/W) which is more than two times lower that in case of reference model (4.81 K/W) [19] [20].
Calculations of mechanical stresses that are produced by different thermal expansion coefficients of used materials are very important for the LED board reliability. Thermal boundary conditions are set differently for two cases. The first represents LED boards in real operational temperature distribution while the second case represents LED

board stored in limit temperature -40 °C where uniform temperature distribution has been applied on all parts of the LED model.

Table 3-1 LED boards thermal resistances comparison [19]

Thermal resistances					
Board type	**LED package+ solder**	**LED Board + TIM**	**LED + solder + board**	**Aluminium cone**	**Total**
	(K/W)	(K/W)	(K/W)	(K/W)	(K/W)
Design A	9,44	**4,81**	14,24	12,88	27,12
Design B	9,94	**1,58**	11,52	14,43	25,95
Design C	9,01	**2,56**	11,57	13,58	25,15
Design D	9,35	**1,89**	11,24	13,56	24,80
Design E	2,18	**2,85**	5,03	13,23	18,26
Design F	2,83	**3,79**	6,62	13,07	19,71

Zero stress temperature for all materials has been defined according to assumed moulding and soldering fabrication processes. Figure 3.2 shows the calculated residual stress distribution comparison of all models which is based on an elastic-plastic approach.

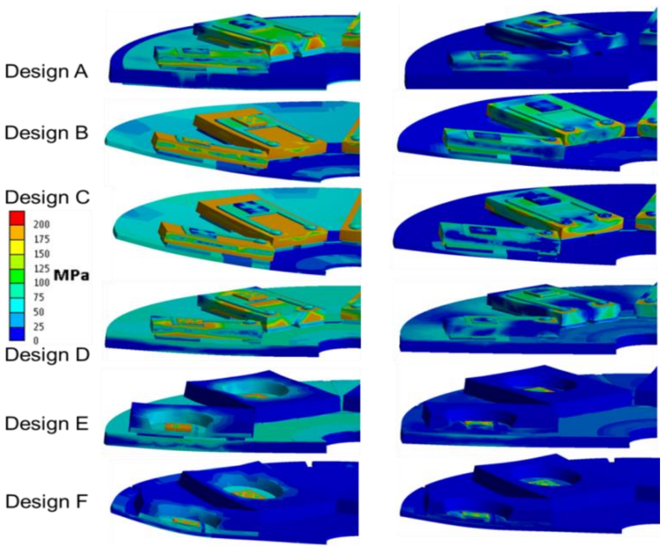


Figure 3.2: Thermal stress distribution in LED boards. Deformation is 5x magnified. for a) Master LED board Design A, b) Leadframe Design B, c) Leadframe Design C, d) IMS Design D, e) Leadframe Design E f) IMS Design F

4 Life time calculation of LED board

4.1 High speed mechanical cycling

Solder bonding and electrical metallic lines failure caused by mechanical and thermal stress is a wear-out mechanism in thermally affected electronic system designs [21]. One of the most important factors concerning mechanically or thermally stressed (thermally cycled) LED boards from the reliability point of view is electrical bonding between LED packages and PCB board. At these locations very thermal stresses usually appear [22].
The thermally induced mechanical forces acting on LED boards can be calculated using mechanical "Transient structural (Plastic)" analysis and Fatigue analysis. The corresponding mechanical force can be applied to mechanically deflect the LED board in the so-called "shaker" test set-up, as shown in Figure 4.1a. The testing apparatus is made of an electromagnetic actuator (vibrational shaker), a mechanical lever that increases periodical force applied on LED board and a clamping support for LED board. The LED board is mechanically fixed on the on the outside perimeter of FR4 board at top and bottom side. Internal mounting hole of the FR4 board is mechanically coupled to a shaft which imposes the force of the shaker Figure 4.1b.

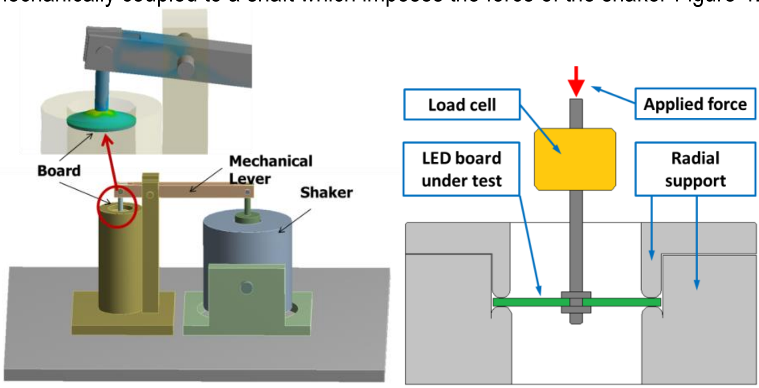


Figure 4.1: Measuring equipment: a) 3D model for FEM analysis b) detail of LED board mechanical fixation

High speed mechanical cycling life time prediction has been calculated by plastic strain based on Coffin-Manson-Basquin model. The analysis has taken into account elastic and plastic behaviour of the LED board materials and life time S-N curves [23]. The advantage of high speed mechanical bending test of LED boards is simplicity and fast testing time. Some failure mechanisms are not considered using this approach. Fast mechanical cycling does not allow incorporate creep relaxation effects, which can especially occur in solder material.

Figure 4.2 shows the calculated lifetime distribution in detail for the place where LED package is soldered on the LED board. Some parts (LED package ceramic, FR4 and insulation layer) are intentionally hidden to view the most interesting parts: the electrical and thermal pads of LED package, soldering layer, metallization vias through ceramic LED package, LED chip and LED chip bounding layer. Simulation results show that the most critical parts are LED vias and solder joints [19].

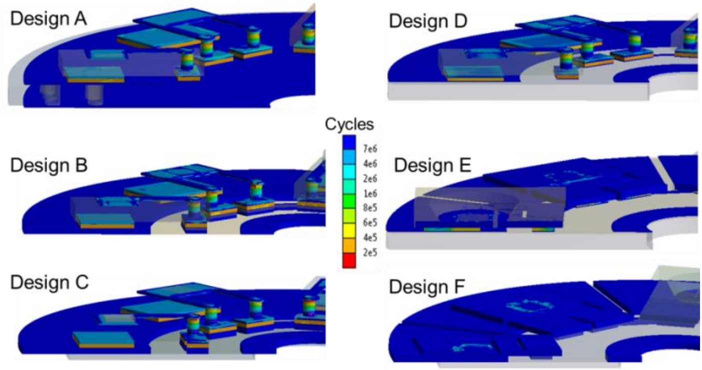


Figure 4.2: Distribution of calculated life time in the place where LED package is soldered

Bending test has been carried out to verify the solder joint life time and reliability of LED board. In this test the testing machine apply periodical mechanical load to LED board using 25 Hz sinusoidal wave with amplitude 15 N. The failure detection system is based on electrical conductivity measurement (Figure 4.3).

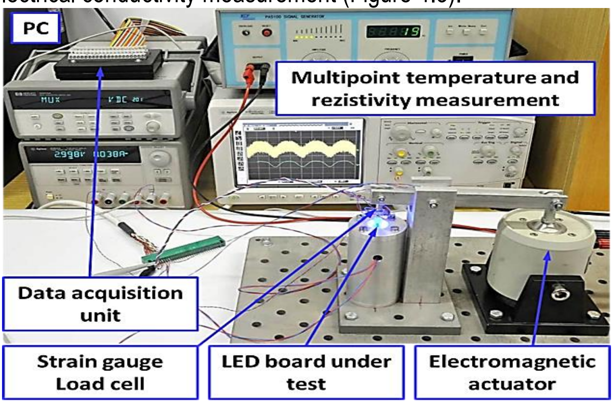
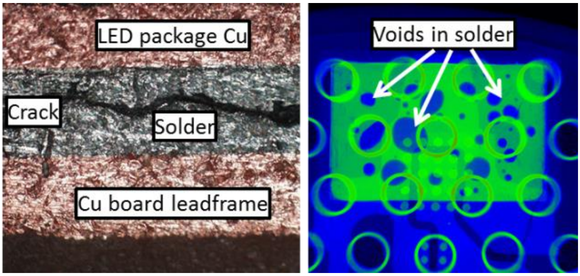


Figure 4.3: Bending test assembly for LED board life time validation[13]

Validation performed on two LED boards show the weakest point is located in solder joint between LED package and FR4 board. The mechanical fatigue life was 86 500

[13] Assembly was made by my PhD student Jan Formanek

and 97 800 respectively. Simulated life time value has a 2.07 and 1.83 times longer life (178 912). Figure 4.4a shows the optical microphotograph of the crack in the solder joint between electrical pad and FR4 board. X ray photography of mechanical pad solder joint shows a fact that during soldering process many voids appears (Figure 4.4b). This could explain differences between simulation and validation results. Voids can initiate cracks a bit earlier due to bigger local mechanical stress around the void and failure can appear sooner [24].



a) b)

Figure 4.4: a) Optical micrograph showing the crack in the solder joint. b) X-ray photograph of thermal pad showing voids in solder [24]

4.2 Low speed mechanical cycling including creep

To calculate number of cycles to failure N_f, we use the Syed model is most suitable for SSL LED board life time prediction. For two creep mechanisms (grain boundary sliding and the matrix creep) the above equation becomes:

$$N_f = (C_I \varepsilon_{acc}^{I} + C_{II} \varepsilon_{acc}^{II})^{-1} \qquad (4.1)$$

ε_{acc}^{I} is the accumulated equivalent creep strain per cycle for grain boundary sliding and ε_{acc}^{II} is the matrix creep. The constants C^I and C^{II} in the above equation have been determined for SnAgCu solders (SAC305) [25]:

$$N_f = (0.106 \varepsilon_{acc}^{I} + 0.045 \varepsilon_{acc}^{II})^{-1} \qquad (4.2)$$

The only unknown parameter in equation (4.2) is value of accumulated creep strain. Creep strain rate is usually described by creep constitutive equation. Constitutive equation for hyperbolic sine function constitutive model is:

$$\varepsilon_{cr} = A_1 \, [\sinh(\alpha . \sigma)]^n \, exp\left(\frac{-H_1}{kT}\right) \qquad (4.3)$$

where ε_{cr} is an equivalent creep strain, σ is equivalent stress, T is temperature (absolute), k is Boltzman constant, α, n and H_1 are constants defined by the measurement. Constants published in [26] are following:

Hyperbolic sine function constitutive model parameters for SAC 305 solder joints					
A_1	α	n	H_1/k	E (MPa)	CTE
277984 s^{-1}	0.02447 MPa^{-1}	6.41	6500	61251 – 58.5T(K)	20 ppm/K

The constitutive models and constants have been used in FEM modelling of solder joint life time of the SSL LED boards. Thermal cycling simulation temperature starts at temperature 180 °C which is considered as zero stress temperature for SAC 305 (the melting point of SAC305 is typically observed as 217 °C, but thermo-mechanical stresses start to form at lower temperature). Then periodical thermal cycling is applied with period 480 s where rump time 60 s was set up. The period should be long enough to make creep effect dominant.

The analysis computes residual stresses distribution based on elastic-plastic nonlinear approach at each time increment for whole LED board model. Then creep strain is calculated using double power law or hyperbolic sine constitutive model. The value of accumulated creep strain can be calculated as a difference of creep value at given point in one thermal cycle. Figure 4.5 shows creep strain distribution in electrical solder join (solder joint between FR4 LED board top copper and bottom side of electrical pad of the LED package) after five and six cycles.

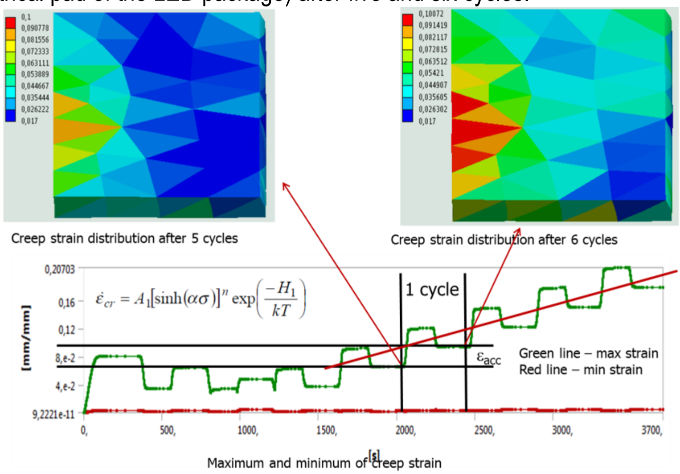


Figure 4.5: Determination of equivalent accumulated Creep strain rate in electrical solder joint

Equation (4.2) that uses total accumulated strain has been used for number of cycles to failure calculation. By post-processing script distribution of number of cycles to failure can be obtained. Figure 4.6 shows the distribution of number of cycles to failure in electrical solder join. Minimum value of cycles (788) is located in red area. Possible crack will be probably initiated in this area. Maximal number of cycles (8799) is located on bottom right corner.

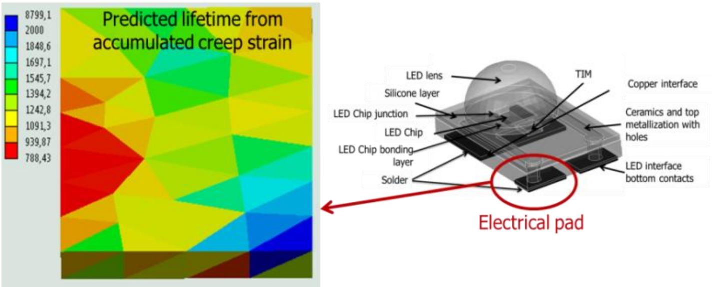


Figure 4.6: Distribution of number of cycles to failure in electrical solder

In the same way we can apply mechanical force instead of thermal cycling. The modelling flow is same as in previous case. It could be possible to replace thermal cycling test that is very slow by much faster mechanical bending test. The force magnitude must results the same value of accumulating creep strain in solder joint as in case of thermal cycling. If the thermal cycling accumulated strain value will be consistent with mechanical cycling accumulated strain, then also number of cycles to failure must be the same.

Figure 4.7 shows designed pneumatic loading system that is able to mechanically deflect LED boards by applied force in the range 0 – 150 N and frequency $3 – 1.10^{-4}$ Hz. Another advantage of proposed system is controlling of ramp time that can be adjusted by flow control valve. This is especially important while we want to emulate thermal cycling test, which has usually ram time in order of minutes. Actuated mechanical force is transmitted from compact pneumatic cylinder through load cell to the shaft that is mounted on central hole of LED board. The direction of applied force is controlled by control valve and blow off silencer.

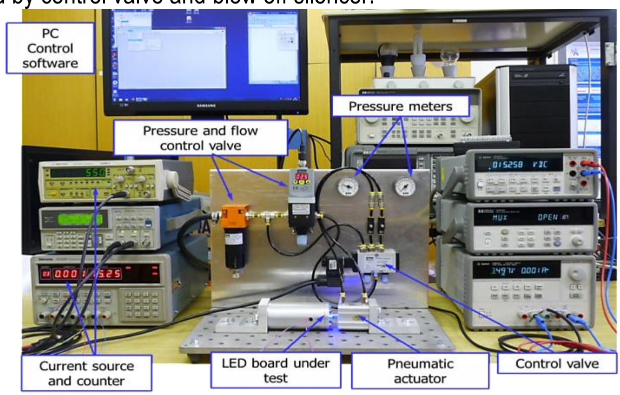
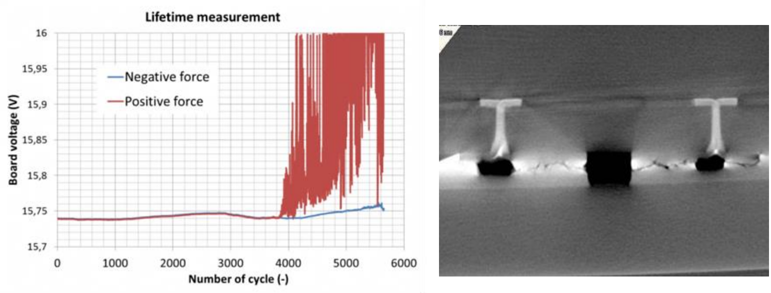


Figure 4.7: Measurement setup with pneumatic actuation[14]

[14] Measurement setup was constructed by my PhD student Jan Formanek

Figure 4.8a shows the voltage drop measured on six LEDs. It can be clearly identified that after 3870 cycles a crack appears on electrical contact of the LED package. Figure 4.8b shows the crack in solder joint detected by CT.



a) b)

Figure 4.8: a) Voltage drop measured on six LEDs, b) Crack in solder joint (CT detection)

5 Conclusion

The work provides a wide-ranging summary dedicated to the design, modeling and characterization of new high power SSL bulbs. It gives a comprehensive view of thermo-mechanical phenomena, design aspects and optimization of LED illumination systems together with estimation of lifetime and effects leading to a failure. The most important contributions of this research can be summarised in following points:

- *Thermal and thermomechanical numerical modelling and characterization of solid state lightening (SSL) Lamp;*
- *Accurate 3-D modelling of several LED board technologies mainly concentrating on thermal, thermo-mechanical evaluation and lifetime prediction of LED boards, definition of critical parts from reliability point of view and proposal for new designs;*
- *Development of accelerated characterization testing methods for LED boards. New method should replace traditional thermal cycling of power cycling characterization test. New testing method can dramatically speed up testing process keeping testing accuracy in the range of 20%*

References:

[1] Holonyak, N.; Bevaqcua, S. F., „Coherent (visible) Light Emission from Ga(As1-xPx) Junctions,“ *Applied Physics Letter,* sv. 1, č. 4, pp. 82-83, 1962.

[2] Chen, C.C.; Wu, C.-Y.; Wu, T.-F., „LED back-light driving system for LCD panels,“ v *Twenty-First Annual IEEE Applied Power Electronics Conference and Exposition*, 2006.

[3] Thomas, W.; Pforr, J., „A novel low-cost current-sharing method for automotive LED-lighting systems,“ v *13th European Conference on Power Electronics and Applications*, 2009.

[4] Lee S., Lau C.H, Chan S.P, Ma K.Y, et al., „Development and prototyping of a HB-LED array module for indoor solid state lighting,“ v *Proc HDP*, 2006.

[5] Fan, Bingfeng; Wu, Hao; Zhao, Yu; Xian, Yulun; Wang, Gang, „Study of Phosphor Thermal-Isolated Packaging Technologies for High-Power White Light-Emitting Diodes,“ *IEEE Photonics Technology Letters,* sv. 19, pp. 1121 - 1123, 2007.

[6] Haque, S., Steigerwald, D., Rudaz, S., Steward, et al., „Packaging challenges of high-power LEDs for solid state lighting,“ v *(IMAPS) - International Symposium on Microelectronics*, 2000.

[7] Krames M. R., Shchekin O. B., Mueller-Mach R., Mueller G. O., Zhou L., Harbers G., and Craford M. G., „Status and Future of High-Power Light-Emitting Diodes for Solid-State Lighting,“ *Journal Of Display Technology,* sv. 3, pp. 160-175, 2007.

[8] Philips, „www.philipslumileds.com,“ 2011.

[9] Lingard, Robert, „Thermal Management of White LEDs,“ Pacific Northwest National Laboratory, 2009.

[10] Lighting research, „Characterizing white LEDs for general lightining,“ http://lightingresearch.org/programs/solidstate/pdf/SPIE3938-39_Narendran.pdf, 2009.

[11] E. Schubert, Jong Kyu Kim, Hong Luo, „Solid-state lighting-a benevolent technology,“ *Reports on Progress in Physics,* sv. 69, p. 3069-99, 2006.

[12] S. Pimputkar, „Prospects for LED lighting,“ *Nature Photonics,* sv. 3, p. 179-181, April 2009.

[13] Chang M H, Das D, Varde P V, Pecht M, „Light emitting diodes reliability review,“ *Microelectronics Reliability,* p. in press, 2012.

[14] E. Schubert, et al, „Solid-state lighting-a benevolent technology,“ *Reports on Progress in Physics,* p. 3069-99, December 2006.

[15] Luo X, Wu B, Liu S., „Effects of moist environments on LED module reliability,“ *IEEE Transactions on Device and Materials Reliability,* sv. 10, pp. 182-186, 2010.

[16] Gladkov A, Bar-Cohen A., „Parametric dependence of fatigue of electronic adhesives,“ *IEEE Trans. Compon. Packag. Technol,* sv. 22, pp. 200-208, 1999.

[17] Jakovenko, J., Werkhoven, R., Formánek, J., Kunen, J., Bolt, P., Kulha, P, „Thermal simulation and validation of 8W LED lamp,“ v *12th Int. Conf. on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems, EuroSimE*, Linz, 2011.

[18] Jakovenko, J. , Formánek, J. , Vladimír, J., Husák, M., Werkhoven, R., „High power solid state retrofit lamp thermal characterization and modeling,“ *Radioengineering,* sv. 21, č. 1, pp. 225-230, 2012.

[19] Jakovenko, J., Formánek, J., Pardo, B., Perpiñà, X., et al. „Thermo-mechanical evaluation and life time simulation of high power LED lamp boards,“ v *2012 13th International Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems, EuroSimE 2012*, Lisboa, 2012.

[20] B. Pardo, A. Gasse, J. Jakovenko, R.J. Werkhoven, et al. „Thermal resistance investigations on new

leadframe-based LED packages and boards," v *EuroSimE*, Lisbon, Portugal, 2012.

[21] Dudek, Rainer, „Studies on the reliability of power packages based on strength and fracture criteria," *Microelectronics Reliability,* sv. 52, pp. 1255-1265, 2012.

[22] Vandevelde B, Degryse D, Beyne E, Roose E, Corlatan D, Swaelen G, et al., „Modified micro-macro thermo-mechanical modeling of ceramic ball grid array packages," *Microelectronics Reliability,* sv. 43, pp. 307-318, 2003.

[23] ASM Internationa, Atlas of Stress-Strain Curves, ASM International, 2011.

[24] Perpiñà, X. , Werkhoven, R., Jakovenko, J., Formánek, J., Vellvehi, M., Jordà, X., Kunen, J., Bancken, P., Bolt, P.J., „Design for reliability of solid state lighting systems," *Microelectronics Reliability,* 2012.

[25] Syed, A., „Accumulated Creep Strain and Energy Density Based Thermal Fatigue Prediction Models for SnAgCu Solder Joints," v *Proceedings of ECTC*, 2004.

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Work experience

Since 1999	**Assistant Professor and Research fellow** at the CTU-FEE, Department of Microelectronics
2005 - 2008	**External consultant** for CADENCE Design Systems, Seely Ave., San Jose, CA, USA; mix-signals circuits for 802.11 b, g transceiver
2005	**Wireless IC design** at CADENCE Design Systems, Seely Ave., San Jose, CA, USA (four month internship)

Education

1999-2004	**PhD degree in Microelectronics** at Czech Technical University in Prague, Faculty of Electrical Engineering, Department of Microelectronics, with thesis MEMS Structures for RF Power Measurement.
1991-1997	**MSc degree in Microelectronics** at Czech Technical University in Prague, Faculty of Electrical Engineering, Department of Microelectronics, with thesis Non-invasive Flow monitoring system.
1998	**International Business Program** - Six month study in under the frame European TEMPUS programme - European Business and Management at Hogeschool, Gent, Belgium

Research interests and scientific achievements

Microsensors and MEMS design (GaN, GaAs based Micromechanical Free Standing Hot Plates for Gas Sensors, thermo mechanical and piezoelectric design of the pressure sensor for harsh environment); Solid State Lamp design (design of new 806 lumen SSL retrofit lamp, development of new accelerated characterization methods for SSL lamp, reliability and life time modelling); Analogue and Mix-signal Integrated Circuit design.

J. Jakovenko is author and co-author of many scientific publications: 10 journal papers with impact factor, co-author of chapter in Springer book (MEMS/NEMS), 32 publication are registered in WoS.

Professional activities

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Groups in a European Team“, - microwave amplifier research; IMINAS Project GAČR GA102/09/1601 and many others.
Reviewing for scientific journals as Microelectronics Reliability, Radioengineering, Electron Device Letters, Reviewer for conferences as IMAPS EDS
Since 2004 Leader of IC and MEMS design laboratory at CTU FEE. Organization of European IC Design course IDESA and European MEMS Design course STIMESI
Member of the management board of department of Microelectronics, member of CTU FEE committee for instrumentation; 2001-2004 member of academic senate at CTU FEE

Pedagogical activities

Undergraduate and postgraduate level courses in IC design and Microelectronics (VLSI design and technologies, Design of integrated systems, Integrated system on Chip, Practice in IC design, Design of VLSI, IC design for informatics, Integrated design structures, New trends in electronics, Microelectronic, Electronics a microelectronics, Sensor systems).
Deputy of board for defence theses and final state examination in Electronics, CTU; Member of board for defence theses and final state examination, University of Technology Brno.
Member of the committee for PhD degree defence board in "Electronics" - CTU Prague
Currently supervisor of 7 PhD students, leader of more than 20 Master students that have successfully defended the final thesis

[1] Jakovenko, J., Formánek, J., Perpiñà, X., et al.: Design methodologies for reliability of SSL LED boards, Microelectronics Reliability, 2013, DOI: 10.1016/j.microrel.2013.02.017

[2] Jakovenko, J. - Formánek, J. - Janíček, V. - Husák, M. - Werkhoven, R.: High Power Solid State Retrofit Lamp Thermal Characterization and Modelling. Radioengineering. 2012, vol. 1, no. 21, p. 231-238

[3] Perpina, X - Werkhoven, R. - Jakovenko, J. - Formánek, J. - Vellvehi, M. - Jordà, X. - Kunen, J. - Bancken, P. - Bolt, P.J.: Design for reliability of solid state lighting systems. Microelectronics Reliability. 2012, vol. 9-10, no. 52, p. 2294-2300. ISSN 0026-2714

[4] Lalinský, T. - Držík, M. - Vanko, G. - Vallo, M. - Kutiš, V. - Bruncko, J.- Haščík, Š.- Jakovenko, J.- Husák, M.: Piezoelectric response of AlGaN/GaN-based circular-HEMT structures. Microelectronic Engineering. 2011, vol. 88, no. 8, p. 2424-2426. ISSN 0167-9317

[5] Lalinsky, T. - Vanko, G. - Vallo, M. - Držík, M. - Brunco, J. - Jakovenko, J.- Kutiš, V.- Rýger, I.- Haščík, S.- Husák, M.: Impact of ZnO gate interfacial layer on piezoelectric response of AlGaN/GaN C-HEMT based ring gate capacitor. Sensors and Actuators. 2011, vol. 2011, no. 172, p. 386-391. ISSN 0924-4247