Thermal Characterization and Lifetime Prediction of LED Boards for SSL Lamp

Jan FORMÁNEK, Jiří JAKOVENKO

Dept. of Microelectronics, Czech Technical University in Prague, Technická 2, 166 27, Praha 6, Czech Republic

formaja3@fel.cvut.cz, jakovenk@fel.cvut.cz

Abstract. *This work presents a detailed 3-D thermo-mechanical modeling of two LED board technologies to compare their performance. LED boards are considered to be used in high power 800 lumen retrofit SSL (Solid State Lighting) lamp. Thermal, mechanical and life time properties are evaluated by numerical modeling. Experimental results measured on fabricated LED board samples are compared to calculated data.*

Main role of LED board in SSL lamp is to transport heat from LED die to a heat sink and keep the thermal stresses in all layers as low as possible. The work focuses on improving of new LED board thermal management. Moreover, reliability and lifetime of LED board has been inspected by numerical calculation and validated by experiment. Thermally induced stress has been studied for wide temperature range that can affect the LED boards (-40 to +125^{o}C). Numerical modeling of thermal performance, thermal stress distribution and lifetime has been carried out with ANSYS structural analysis where temperature dependent stress-strain material properties have been taken into account. The objective of this study is to improve not only the thermal performance of new LED boards, but also identification of potential problems from mechanical fatigue point of view. Accelerated lifetime testing (e.g., mechanical) is carried out in order to study the failure behavior of current and newly developed LED board.

Keywords

Solid state lightning, thermo-mechanical modeling, lifetime, reliability, LED board.

1. Introduction

In the recent time commercial usage of SSL (solid state lighting) lamps has been growing almost exponentially. Solid-state lighting has the prospective to modernize the future lighting industry. It is expected that the LED lamp market will accelerate a progresses in commercially available LED performance in the next a few years. As well as cost reduction is key issue in new SSL lamp design.

SSL technology uses semiconductor light-emitting diodes (LEDs) as sources of lights instead of widely 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. SSL has many advantages in comparison to incandescent lighting. The most valuable is a light emission 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 (LEDs produce minimum ultraviolet and infrared radiation), smaller volume of light bulb (if needed). Tab. 1 compares SSL lamp to incandescent and fluorescent lamps from power dissipation and life time point of view. The data are related to 400 lumen light output.

Lamp type	Incandescent	Fluorescent	SSL lamp
Input Power (W)	60	18	12
Life time (hours)	~1 000	~ 8 000	~ 25 000
Retail price (€)	<1 €	5-10 €	10-35 €
Impact on environment	Low	1 - 5 mg of mercury	Low
On / off cycling	No	Reduce lifetime	No

Tab. 1. Comparison of commercially available lighting technologies.

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 %

Tab. 2. Proportions of input power to heat and radiant energy (including visible light) conversion for various white light sources.

Almost all modern light sources transform electric power into radiant energy and heat in various quantities. While incandescent lamps emit mostly infrared (IR), with a slight volume of visible light, SSL lamps generate very little or no IR or UV emissions. On the other hand, SSL lamps convert only 20%-30% of the power into visible light. The rest is transformed into the heat that must be conducted from the LED die through LED package to the underlying LED board and finally to a heat sink. Tab. 2 shows the proportions of converted input power into heat and radiant energy for various white light sources. As we can see, 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 dissipated heat is generated here. Hence thermal and thermo-mechanical management is one of the most important aspects of successful SLL lamp system design.

Moreover the effectiveness of whole SSL lamp system is not only related to LEDs light conversion, but also to the driver losses, and power dissipation in light conversion element. Most of the input power in an LED converts to heat rather than light (about 70% heat and 30% light).

If generated heat is not properly removed, the LEDs junction can have high temperature. It can not only lower LED efficiency, but also decrease LED reliability. The heat dissipated in LEDs is removed by conduction within the SSL lamp system and by convection and radiation outside the lamp, mostly on a heat sink and on a bulb surface. The LED junction temperature depends on the heat generation caused by loses during light emission and thermal dissipation within the SSL lamp (from the LED die through the LED package, board, heat sink and finally to the ambient).

Some of the main advantages of solid state lighting (SSL) systems are expected long lifetime. One of the most critical parts of the SSL lamp from life time and reliability point of view is LED board including soldered LED package [1]. To ensure long lifetime and good light quality, a lamp design is needed to meet strict requirements in terms of thermo-mechanical design. Lamp materials and electronics components can age at high operational temperature affecting also light output [2]. The most important objective in LED thermal management is to limit the temperature of LED die and solder connections. Mentioned parts are typically the most critical for the useful lifetime of the LED lamp.

2. LED Lamp FEM Model and Material Properties

Performance of new IMS LED boards was compared to commercial LED board (designed for 400 lumen retrofit SSL lamp) from thermal and thermo-mechanical point of view. An important aspect in 3D FEM simulation is the conception of the geometric model. The first model represents FR4 LED board (Fig. 1a) of commercially available 400 lumen retrofit LED lamp. It consists of 650 µm thick FR4 board with 80 µm Cu layers implemented on both sides. The top Cu layer makes electrical connection between the six Luxeon LEDs. Higher thermal conductivity of FR4 board is achieved by thermal vias (500 µm in diameter) placed under and around the thermal pad the of LED package. A LED die is connected by 16 bumps on top side of ceramic LED package that contains one thermal pad and two electrical copper pads. The bottom side of the LED package is soldered to the FR4 board by 80µm thick lead free solder. On each of the LEDs a silicone lens is placed in order to get a wide angle light output. (Fig. 1a).

a)

b)

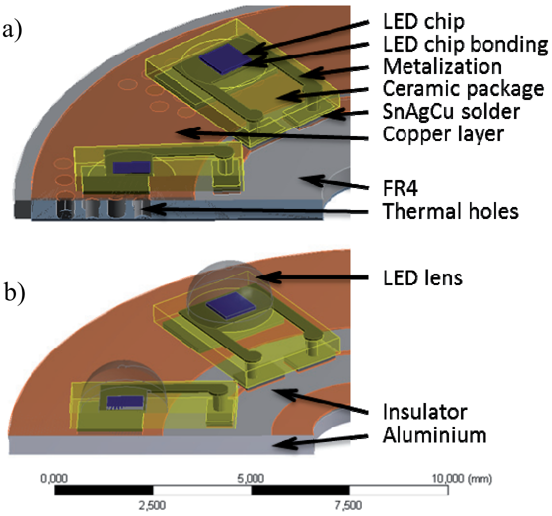

Fig. 1. SSL Lamp LED boards 3-D models: a) Commercial FR4 LED board for 400 lumen SSL lamp; b) new design of IMS board that was designed for possible replacement.

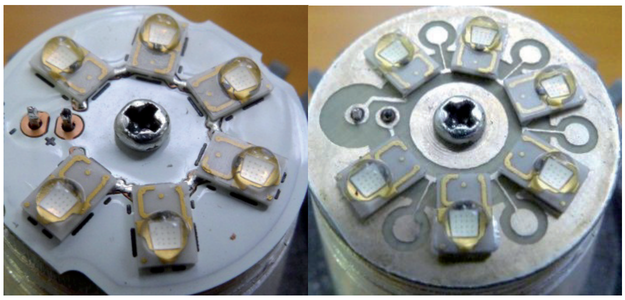

Fig. 2. LED boards: a) Commercial FR4 LED board for 400 lumen SSL lamp (left); b) new design of IMS board (right).

The second newly designed LED board model (Fig. 1b) is based on Insulated Metal Substrate (IMS) technology that promises better thermal performance (lower thermal resistance) and better reliability and life time. This LED board was designed as possible replacement of the FR4 LED board. IMS layer system contains 500 µm thick base layer of Alumna which is covered by 75 µm thick polymer based highly conductive insulation. The top 35 µm copper layer forms electrical and thermal connection for above described Luxeon LEDs (Fig. 1b). Fig. 2a shows commercial FR4 LED board while the new design of IMS LED board is in Fig. 2b.

Simulation results depend not only on precision of 3D model and its discretization mesh, but also on the correctness of the material properties data. Thermal and mechanical coefficients as thermal conductivity, specific heat, thermal expansion, Young’s modulus were taken from [3].

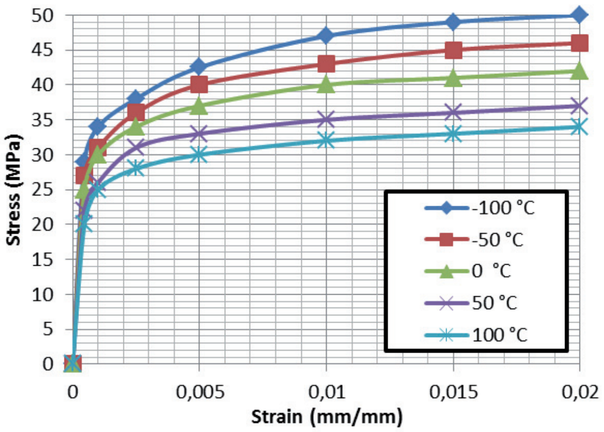

Fig. 3. The temperature dependent stress-strain curves for solder material.

Because thermal stresses caused by different CTE of used materials can in some parts exceed the yield stress, LED board material properties has been improved by adding elastic-plastic mechanical properties, which are defined by stress-strain curves. The temperature dependent stress-strain curves for copper and solder are shown in Fig. 3 [4]. Stress-strain curves for other materials as FR4, epoxide via filer, solder material and gold has been also taken into account [4], [5].

3. Thermal Validation and Characterization of SSL Lamp LED Boards

The objective of the numerical characterization and measurement validation has been to evaluate temperature performance of the new IMS LED board in comparison with the FR4 board. To ensure correct temperature distribution, the LED board was mounted on thermal cone of SSL lamp system. Temperature values were sampled on different measurement points of the whole SSL lamp system, by means of IR (infra-red) thermography and direct temperature measurements. Direct temperature measurements were done by thermocouples placed in defined points inside the lamp.

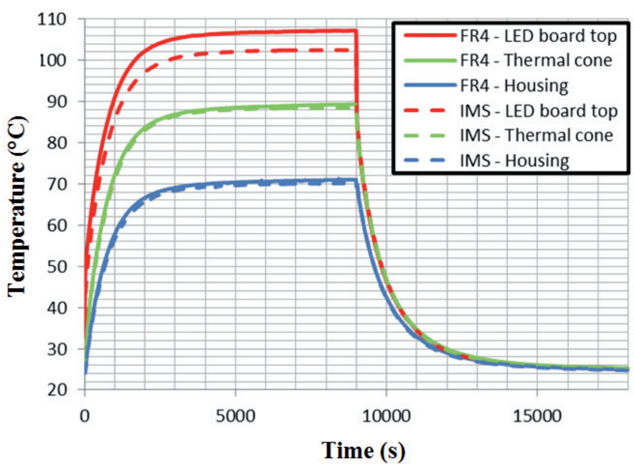

Fig. 4. Comparison of measured thermal characteristic.

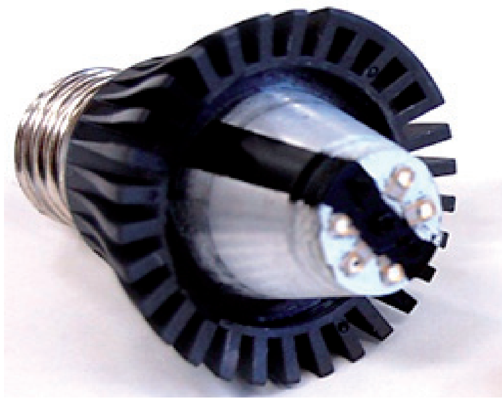

Fig. 5. SSL lamp components with black strip used for IR measurement.

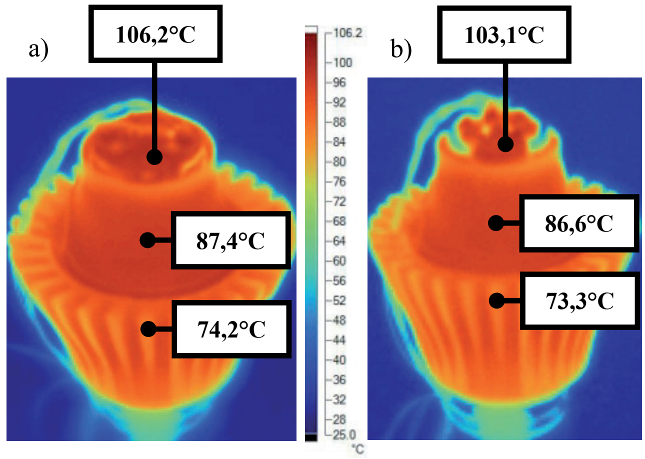

Fig. 6. Temperature distribution sampled by IR camera: a) FR4 board b) IMS board.

	Temperature (°C)			
	LED package	LED board	Thermal cone	Housing
FR4 - simulation	104,3	102,5	88,6	70,9
IMS - simulation	100,2	97,7	87,3	69,7
FR4 - direct measurement	109,7	107,2	89,3	72,0
IMS - direct measurement	103,9	102,6	88,5	71,2
FR4 - IR camera measurement	-	106,2	87,4	74,2
IMS - IR camera measurement	-	103,1	86,5	73,3

Tab. 3. Comparison of measured and calculated temperatures using different methods.

Fig. 4 shows the results of the direct temperature transient measurement with temperature sensors as a response on power ON and power OFF signal. Within 2 hours the temperature reaches a steady-state condition. Fig. 4 shows comparison of FR4 and IMS LED board performance. The second measurement method uses an IR (infra-red) camera imaging to obtain temperature distribution of the LED boards. To overcome a problem with different emissivity of diverse materials, a black strip was made on each part of measured SSL lamp (Fig. 5). The temperature is sampled on the black strip, which has the same emissivity for all materials. Fig. 6 shows the temperature distribution sampled by IR camera with marked sampling points. Tab. 3 shows comparison of calculated and measured temperatures in defined location points (bulb, dome, LED, thermal cone, housing and shell).

4. Life Time and Reliability of LED Boards

One of the most important factors concerning mechanically and thermally stressed electronics systems from the reliability point of view is electrical bonding between electronic device packages and PCB board or metallic lines itself [6]. Solder bonds and electrical metallic lines failure caused by mechanical or thermo-mechanical stress is the most common failure mechanism in electronic systems design [7].

Accelerated lifetime testing includes mechanical, electrical and thermal loading [8]. The advantage of high speed mechanical bending test of LED boards excels by its simplicity and fast testing time. However, some failure mechanisms are not considered using this approach. Fast mechanical cycling does not allow integrate creep relaxation effects, which can occur in solder material. Nevertheless, this method is good for determining of the weakest spots of the structure [9]. Qualitative comparison between different LED board technologies is possible at that point. Mechanical bending lifetime prediction can be done by numerical modeling. It calculates the response of high speed periodical mechanical loading. The loading deflects the LED board, which, in turn, imposes mechanical stresses in LED board assembly (i.e., LED package and board).

Strain based models is a good choice for the calculation of the number of cycles to failure. The most relevant method for LED board evaluation is the Coffin-Manson-Basquin model [10] that is based on a plastic-strain fatigue approach. The model calculates the number of cycles to failure based on experimental data of the plastic-strain curve of the used materials.

To obtain the appropriate force for the mechanical bending test, the thermo-mechanical analysis is carried out in two steps. The first one calculates the stress distribution caused by temperature change (-40°C and 120°C). The second step calculates mechanical force that imposes the same mechanical deflection and stress distribution in the LED board as in the first case. Calculated equivalent mechanical force is then applied as a mechanical load in the mechanical cycling test set up. The simulation takes into account an initial intrinsic stress induced in the LED board due to the manufacturing process (e.g., due to moulding and soldering processes).

Mechanical bending accelerated test applies a high speed periodical mechanical loading to LED board. Deflections of the LED board impose a mechanical stresses in LED board assembly. The duration of this test can be very short. Bending frequency can be set between 1 and 100 Hz. Expected number of cycles that cause a failure in the solder joints or in the copper metallization is in order of hundreds of thousands. Mechanical excursions are without time to induce creep relaxation effects in solder material. Hence fast mechanical bending cannot fully replace power or thermal cycling test.

For high speed mechanical loading test where a force is applied to periodically deflect the LED board under test, so-called “shaker” test set-up was developed (Fig. 9). 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 within outside perimeter of FR4 or IMS board at top and bottom side. Internal mounting hole is mechanically attached to a shaft which imposes the force of the shaker.

High speed mechanical load cycling life time prediction has been calculated by plastic strain based Coffin-Manson-Basquin model [10]:

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f}{E}\left(2N_f\right)^b + \varepsilon_f\left(2N_f\right)^c \tag{1}$$

where $\Delta\varepsilon$ is the strain range, σ_f is the fatigue strength coefficient, E is the elastic modulus, ε_f is the fatigue ductility, b is the fatigue strength, and c is the fatigue ductility exponent.

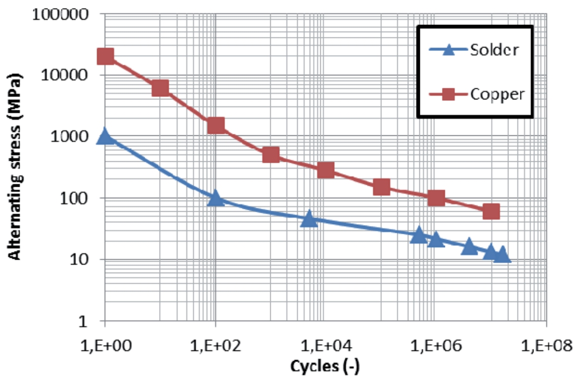

Fig. 7. S-N curve for SAC305 solder [2].

The life time analysis has taken into account the elastic and plastic behavior of the LED board materials (defined by stress-strain curves) and life time S-N curves (Fig. 7) [4]. This analysis calculates the probability of initiation and propagation of cracks in the most mechanically stressed areas and evaluates number of cycles to failure with respect to mechanical stresses that are induced by mechanical bending of LED boards.

Fig. 8 shows the lifetime (number of cycles to failure) distribution comparison between FR4 and IMS LED board that was selected for most interesting LED board parts. As we can see the most problematic areas are located in solder joints and copper metallization. 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.

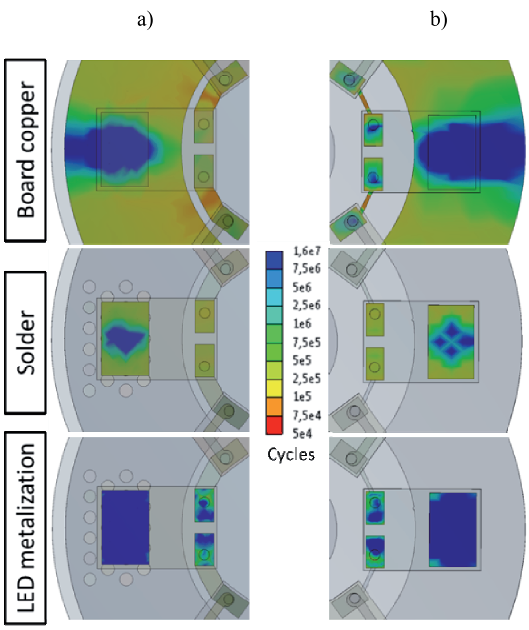

Fig. 8. Distribution of calculated lifetime in the metallic connection of the LED board: a) FR4 board, b) IMS board.

5. Testing

As has been explained in previous section, the mechanical bending test is carried out to verify the life time and reliability of LED boards. For this purpose the shaker mechanical assembly has been constructed. In this test the testing machine applies periodical mechanical load to LED board using 2 Hz periodical wave with amplitude of 50 N (value derived from modeling of thermal behavior of LED board). The failure detection system is based on electrical conductivity measurement. Changes in resistance can indicate an interconnect-related failure.

During characterization process the total resistance is measured by detecting a voltage drop when all six LEDs are supplied from reference current source. When an increase of resistance is detected, all indicated resistances are measured to detect the location of the crack. It must be noted that the interface resistance between a particular via and the Cu metallization is not measurable. This is due to discrete vias that are not accessible by probe for resistance measurements.

Fig. 10 shows the impedance drop measured on six LEDs. It can be clearly identified that after 88700 cycles a crack appears in electrical connection of the LED board. The location of the crack was identified by resistance measurement between each solder joint of LED package.

Measured results performed on two FR4 and two IMS LED boards (more LED boards will be measured in the future) show the weakest point is located in solder joint between LED package and LED board. The mechanical failure was detected in FR4 board after 88700 and 97500 respectively. In IMS board the failure was detected after 115400 and 83300. Fig. 11 shows the crack in solder joint between electrical pad and FR4 board detected by X-ray Computed Tomography (CT).

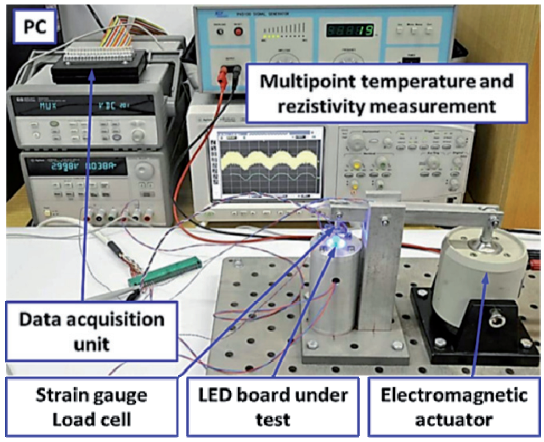

Fig. 9. Bending test assembly for LED board life time validation.

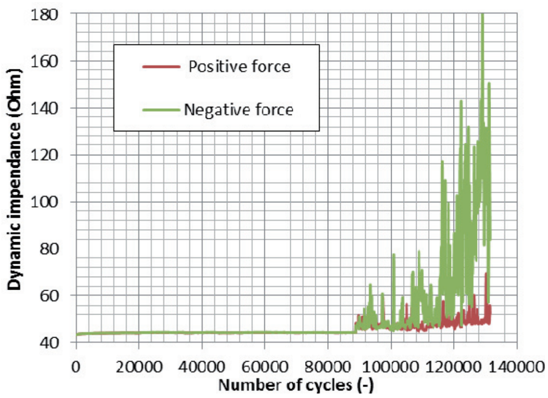

Fig. 10. Dynamic impedance measured on FR4 board with six LEDs.

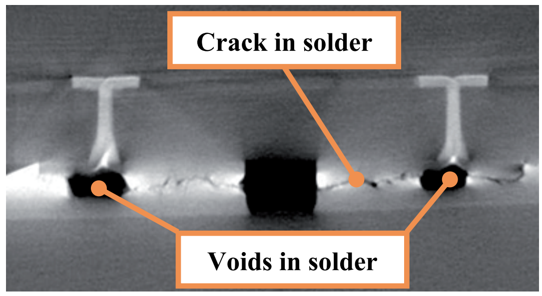

Fig. 11. Crack in solder joint (CT detection).

6. Summary and Conclusions

Accurate 3-D modeling and validation of two LED board technologies (FR4 and IMS) primarily focused on thermal, thermo-mechanical evaluation and lifetime prediction was performed. Thermal performance of newly designed IMS board was compared to commercial FR4 board. Main results were summarized in Tab. 3.

Reliability and life time was modeled using elastic-plastic analysis with nonlinear material behavior using Coffin-Manson-Basquin model. The validation was performed on designed bending apparatuses. Tab. 4 summarizes and compares lifetime performance of FR4 and IMS technology. As we can see the best performance shows IMS LED board with 121410 cycles to failure (simulated value) and 115400 cycles to failure (measured value). Failures in copper layers have not been properly detected because cracks appear mainly in solder joins. Smaller value of measured solder joints lifetimes is mostly caused by voids in real structure (Fig. 11). Geometry of simulation model should be deformed according to results of CT detection of real structures.

	Lifetime (cycles)			
	FR4 sample 1	FR4 Sample 2	IMS sample 1	IMS sample 2
Solder layer simulation	161500	-	176070	-
Cu layer simulation	118550	-	121410	-
Solder layer measurement	88700	97500	115400	83300
Cu layer measurement	n/a	n/a	n/a	n/a

Tab. 4. Measurement and numerical modeling: life time comparison for FR4 and IMS LED board.

Additional work has to be carried out to measure more LED board samples of existing reference FR4 board and newly designed IMS LED boards to get better statistical distribution of measured data.

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References

[1] YOSHIHIKO, K., YOSHIHARU, K. Evaluation of creep properties for Sn–Ag–Cu micro solder joint. *Microelectronics Reliability*, 2012, vol. 52, p. 1435 - 1440.

[2] PIMPUTKAR, S., et al. Prospects for LED lighting. *Nature Photonics*, Apr. 2009, vol. 3, p. 179-181.

[3] JAKOVENKO, J., FORMÁNEK, J., JANÍČEK, V., HUSÁK, M., WERKHOVEN, R. High power solid state retrofit lamp thermal characterization and modeling. *Radioengineering*, 2012, vol. 21, no. 1, p. 231 – 238.

[4] ASM International group. *Atlas of Stress-Strain Curves.* ASM International, 2011, ISBN-13: 978-0871707390.

[5] FIEDLER, B., HOBBIEBRUNKEN, T., HOJO, M., SCHULTE, K. Influence of stress state and temperature on the strength of epoxy resins. In *Proceedings of ICF2011*, 2011.

[6] HONG, B.-Y., YUAN, T. Integrated flow-thermo-mechanical and reliability analysis of a low air cooled flip chip PBGA package. In *48th Electronic Components Technical Conf.*. Seattle (USA), 1998.

[7] DUDEK, R., PUFALL, R., SEILER, B., MICHEL, B. Studies on the reliability of power packages based on strength and fracture criteria. *Microelectron. Reliab.,* 2012, vol. 52, p. 1255 to 1265.

[8] IPC-Association. Connecting Electronics Industries, Bannockburn. *Performance Tests Methods and Qualification Requirements for Surface Mount Solder Attachments, IPC-9701A.* 2006.

[9] PASCOE, N. *Reliability Technology: Principles and Practice of Failure Prevention in Electronic Systems.* John Wiley & Sons 2011. ISBN13: 333-0000360726.

[10] CAMPBELL, F. *Elements of Metallurgy and Engineering Alloys.* ASM International, 2008. ISBN-13: 978-0871708670.

[11] STAM, F.-A., DAVITT, E. Effects of thermomechanical cycling on lead and lead-free (SnPb and SnAgCu) surface mount solder joints. *Microelectronics Reliability*, 2001, p. 1815 - 1822.

[12] 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*, 2003, vol. 43, p. 307 - 318.

[13] SCHUBERT, E., et al. Solid-state lighting: a benevolent technology. *Reports on Progress in Physics*, 2006, vol. 69, p. 3069 -3099.

[14] HUMPHREYS, C.-J. Solid-state lighting. *Mrs Bulletin*, 2008, vol. 33, p. 459 - 470.

[15] MARONGIU, M.-J. Thermal management of high-power LED systems. *LED Professional Review*, 2009, no. 13, p. 47 – 50. ISSN 1993-890X.

[16] KIM, H.-H., CHOI, S.-H., SHIN, S.-H., LEE, Y.-K., CHOI, S.-M., YI, S. Thermal transient characteristics of die attach in high power LED packages. *Microelectronics Reliability*, 2008, vol. 48, p. 445 to 454.

[17] YOON, J.-W., CHUN, H.-S., JUNG, S.-B. Reliability analysis of Au–Sn flip-chip solder bump fabricated by co-electroplating. *Journal of Materials Research*, 2007, vol. 22, no. 5, p. 1219-1229.

About Authors

Jan FORMÁNEK was born in Most in 1985. He graduated in Microelectronics from the Czech Technical University in Prague, (FEE-CTU) in Prague in 2010. Since September 2010 he is a PhD student and a member of the Microsystems group at the Dept. of Microelectronic. Since November 2010 he is also a part-time research fellow. His work is focused on analog integrated circuit design, thermo-mechanical and reliability simulations of electronic components.

Jiří JAKOVENKO was born in Prague in 1972. He graduated in Microelectronics from FEE-CTU. Since 1996 he has been with FEE CTU, where he received PhD degree in Electronics in 2004. Currently he works as an Assistant Professor and a member of Microsystems group at the Dept. of Microelectronics and is a leader of IC design group. His activities are oriented to MEMS design and modeling, design and development of RF ICs and SSL lightning. From 2005 to 2009 he was a consultant and member of Cadence RF and Analog-Mix signal group, San Jose, USA. He is author of many scientific and technical papers, a member of the Programme and Organizing Committees of international scientific conferences.