Quality Control of Chip on Board LED Packaging by Transient Thermography

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***Abstract**: A new methodology of infrared thermography (IRT) measurements for quality control of chip on board light emitting diode (COB LED) package is studied and presented. For this goal information measuring system and appropriate additional software is developed and used. COB LED samples are prepared with different kind of defects are prepared. Results from using some suitable IRT methods of passive-, pulsed-, lock in-, FMTWI-thermography are shown and relevant image processing methods are used and discussed.*

1. INTRODUCTION

Chip on board (COB) of light emitting diode (LED) is a multichip assembly of LED chips on a common substrate with “single emitting surface” in the form of a phosphor-coated disk. COB LED array possesses significant advantages like increased efficiency and lengthen service life, homogeneous light emission, high yield and cost reduction, creating the best condition for optimal cooling [1]. The COB LED market is forecast to grow at a compound annual growth rate (CAGR) of about 41% over the period 2013 to 2018 years [2].

The operating temperature and improving the reliability of light source is the bottleneck of the COB quality packaging technology. It is known that the COB LED package with low R_{th} (thermal resistance, K/W) provides an advantage over a mechanical design for a luminaire and provides better heat transfer and efficacy of the lighting system [3].

However, the thermal parameters of the packed LED vary due to random variations of the packaging process, which affects the quality and reliability. A packing design procedure by FEM simulation is analysed and probability estimation is proposed in [4]. But experimental measurements to assess the quality during and after manufacturing process have not been reported.

Although COB technology is very precise, this technology has proven very difficult and it is very sensitive to variability of voltage/current of the unaged LED chips used in the package. Results of research related to thermal management of COB LED, using Infrared thermography (IRT) are presented in [5], where thermography measurements are used to confirm (validation) of thermal spreading effect in the LED modules.

IRT measurements with their high spatial resolution can be used for assessing the transition temperature of the LED chip, as well as for the transient thermal resistance or the thermal impedance assessing [6, 7].

Our article offers IRT approaches for remote non-destructive control of packaging process, by assessing the amendment of different thermal effects of COB LED package. The goal of our study is related to the quality control of the COB LED packaging and testing capabilities of infrared thermography for that purpose.

The specifics of the used thermographic approaches in control of COBLED manufacturing are discussed. The structure of the studied COB LED and experimental setup is presented. The peculiarities in image processing of samples with different defects of the COB LED have also been analysed.

2. NON-DESTRUCTIVE THERMOGRAPHIC QUALITY CONTROL OF COB LED USING IRT

2.1. Infrared Thermography Approaches

Infrared thermography can detect naturally emitted infrared radiation from the surface of a COB LED device. All objects of the surface emit infrared radiation and the amount of emitted radiation increases with temperature. Therefore, infrared imaging allows us to see variations in temperature [8, 9]. If any electrical component is powered to too much current, or has too high resistance, its temperature will rise. Because the different thermal conductivity of the air or other atypical inclusions in the components of the COB LED structure, the surface of the module formed a non-uniform temperature field after loading heat flow on the sample for a period of time. The differences in temperature can be seen and the value of the temperature can be measured of the imaging sample.

Different thermography approaches were used for the process of COB LED assembly quality control:

- *Passive thermography* is used for mapping the temperature profile of the surface of fully packaged and powered COB LED module. It can be also use for thermal verification of the COB LED assembly test under real-life condition, it junction temperature and thermal resistance measurements.

- *Transient (active) thermography*:

\- *Pulsed thermography* (PT) was used before mounting LED chips. The examined COB package is warmed up with a short-duration, high peak power light pulse. Extracted parameter from the movie of PT is the thermal contrast

$$C(t) = \frac{T_{defect}(t) - T_{defect}(0)}{T_{sound}(t) - T_{sound}(0)} \qquad (1)$$

where $T_{sound}(t)$ is the temperature over sound (without defect) region $T_{defect}(t)$ is that over a defect region. The plot of thermal contrast vs. time over a defective region of a COB LED sample goes through a peak value at some time t_{max} which is a characteristic of the defect depth.

Lock-in thermography (LT) means that the power dissipated in the COB LED is periodically amplitude-modulated and the resulting surface temperature modulation is imaged by the camera running with a certain frame rate. This approach detects electrically active defects (as high resistive opens and shorts) of the COB package as well as the LED chips' defects (when they are electrically biased with a modulated voltage at an excitation frequency). Therefore the process can be written

$$S = \frac{1}{t_{\text{int}}} \int_0^{t_{\text{int}}} F(t) K(t)\, dt \qquad (2)$$

where S is the output signal (infrared move) $F(t)$ is a detected signal, $K(t)$ is a correlation function and t is an integration time over which signal is evaluated. The symmetric correlation functions (like sine/cosine or square wave) of the same LT frequency are used in correlation.

The defect depth can be described by the thermal diffusion length, which determines the rate of decay of the thermal wave as it penetrates through the material

$$\text{«} = \sqrt{2\sim / \text{µ}} \qquad (3)$$

where α is the thermal diffusivity of the material and ω is the modulation frequency.

A Fourier transformation at the frequency of amplitude modulation ("lockin frequency") analyses the thermography sequences at each pixel and compresses the information into amplitude and a phase image.

\- *Frequency Modulated Thermal Wave Imaging* works with linear frequency modulated heat flux. The absorbed heat energy propagates through the COB LED by conduction and produces a time varying thermal response over the surface depending on the homogeneity of the material. The thermal diffusion length of this modulated thermal wave is given by

$$\text{«} = \sqrt{\frac{\sim}{\text{®}\left(f + \frac{B}{2} t \right)}} \qquad (4)$$

where t is time, B/τ is the frequency sweep rate of the chip.

The diffusive thermal wave encounters reflections due to the presence of defects which produce the mismatch in thermal impedance of the material. The defect detection is carried out using the phase analysis where the Fourier transform of the temporal profile gives the frequency domain information.

FMTWI is used for packaged COB LED with a phosphor-coated disk, where it is desirable to apply low peak power source for the detection of subsurface anomalies in a single experiment. This approach is suitable for detecting defects after sealing process.

In active infrared thermography the thermal response gets attenuated and delayed depending upon the depth of subsurface defects. The pulse compression approach (also improves SNR) uses the cross correlation of the temporal profile of a non-defective pixel with the temporal profiles of all other pixels

$$\Phi_{xy} = \int_{-\infty}^{+\infty} x(^{2} - t)y(^{2})d^{2} \qquad (5)$$

Above mentioned IRT approaches have been used for COB LED specific defects as delamination or voids between two layers and under LED chips, shorts and opens of internal wiring (laired interconnects, bond wire), cracks.

2.2. Thermography Inspection System

The thermography system can be configured in variety of ways, depend the used thermography approach. The basic elements consist of excitation source to heat the inspection area of COB LED package, infrared camera to monitor the surface thermal emissions, interface between the computer and the excitation sources, and computer to control the data acquisition, image processing and display. The inspection system hardware includes the following: FLIR ThermaCam SC 640 infrared focal plane array camera with additional close-up lenses, interface IRX-Box based on National Instruments standard components and two types of excitation sources - Halogen Lamps 2.4 kW or controlled power supply. The power output of the lamp can be controlled from 0% to 100%. The voltage/current of the power supply can be controlled from 0V to 30V and from 0A to 6A, respectively. The system software includes: software for Non Destructive Testing (NDT) by infrared image analysis and a Matlab program with a graphical user's interface handling IR sequences. The Matlab program displays the IR images with a graphical interface from a numerical array (either a 2D matrix of size MxN or a 3D matrix of size MxNxI). The NDT software also manages the excitation sources and the camera, records and preprocesses the infrared image sequences. It supports all known measurement techniques (LT, PT and FMTWI), functions for performing automatic measurements, Excel based documentation functions, data export in different file formats (BMP, Matlab, ASCII, Excel, JPEG), and supports the entire range of excitation sources. A common conceptual scheme of functional Information Measuring Systems (IMS) for contactless check the suitability of COB LED is shown on Fig.1.

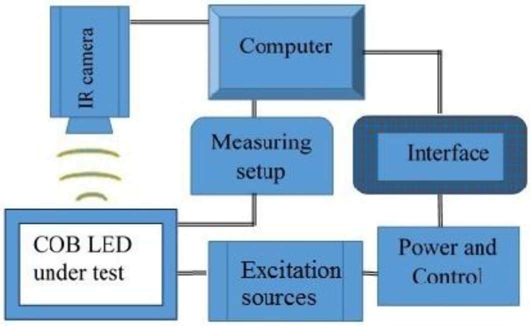


Fig. 1. Scheme of IMS for contactless check the COB LED

Furthermore a measuring setup is developed to capture the family IV-characteristics and light meters (LM) of LED at different transition temperatures shown on Fig.2. BTS256-LED tester was used as a LM, the current generator is performed with the power supply TTi PL303QMD-P, forward voltage diode measurement is carried out by multimeter Rigol DM3052 and microprocessor controlled thermoelectric cooler (PELT) is used. Software was also developed for measurement setup management, that includes virtual panels and module for series automated current-voltage-luminous flux measurements.

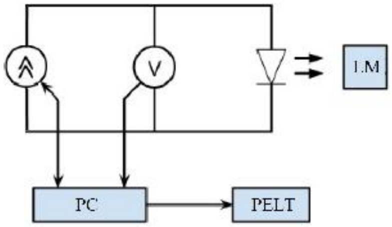


Fig. 2. Block diagram of the measuring setup.

2.3. COB LED samples

There are a number of different reasons to why an electrical part might be malfunctioning, and some of these do not even result in a rise of temperature. Some examples on different reasons for faults are: bad connections, overload and loss of contact.

A perfect die bonding is important for heat conduction. Defects such as pores and intermetallic compounds in the bonding layer will increase the junction temperature considerably, leading to premature failure of LEDs. The junction temperature of each LED is a function (almost linear) of die-attach thickness. The high junction temperature in LED reduces luminous flux, so junction temperature is detrimental to the quality of performance of the LED.

During the IRT research of the thermal resistance of the COB LED packages was found that it enhanced greatly when there is any delamination at the interfaces. Another studied important defect influencing the thermal resistance were the voids in LED packages, generated in the solders or air bubbles in epoxy glue or silicones, or even insufficient vacuum removal of air bubbles.

Many kinds of defects may be induced because of improper process parameters and instalment processes during the process of LED packaging. For example, defects such as damage of chip, breakage of wire, electrode striping may be induced during the wire bonding process. Defect locations can be in different areas: of metallization, binding interfaces, phosphor and encapsulate, wire bond electrode, LED chip etc.

The LED modules used in our experiment are shown in Fig. 3. Twenty one LED chips are mounted on a substrate as an array. Samples different defects: cracks of the substrate, delaminated layers, void in thermal paste under chips and chips with valuable tolerances were prepared.

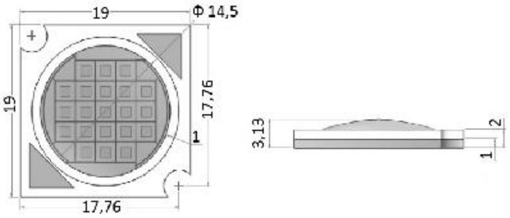


Fig. 3. COB LED package view and dimensions (in mm).

3. EXPERIMENTS

To have accurate measurements of the temperature distribution at the chip surface of LEDs (for non-capsulated COB module, we measured emissivity

$$\pounds_{ij} = \frac{T_{ij}2 - T_{ij}1}{T_{b,T_2} - T_{b,T1}} \qquad (6)$$

where ε_{ij} – emissivity of area ij; $T_{ij}1$ and $T_{ij}2$ are camera‘s signals at temperature $T1$ and $T2$; $T_{b,T1}$ and $T_{b,T2}$ are camera‘s signals of the black body at the temperatures $T1$ and $T2$.

The samples were heated with a Peltier device. The infrared images were taken between 20°C and 120°C, about every 5ºC. For each LED the power efficiency is calculated at different values of electrical power. The emissivity of capsulated module is 0.83 and for a blue LED chip is 0.47. After applying the emissivity map we have uniform temperature distribution for switched off LED over its surface. Thus delamination defects of COB substrate can be discovered using passive IRT.

Fig.3 shows the increase of the mean temperature versus the electrical power for two LED chips of a module. The measured phosphor temperature at nominal power is 320ºC – highest rather than the junction temperature.

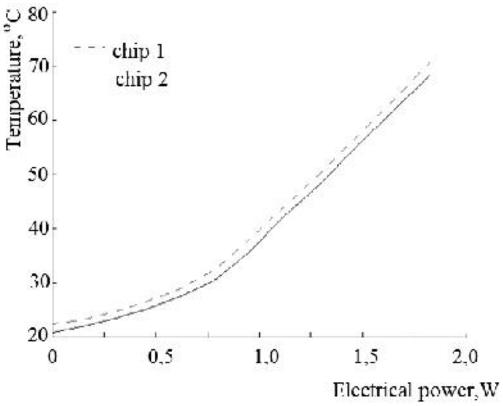


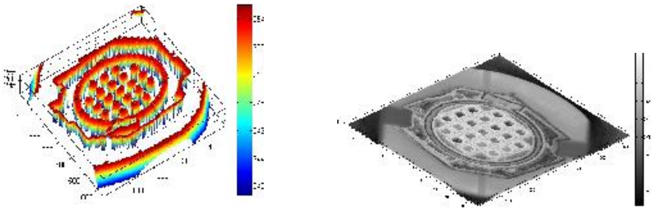
Fig. 4. Evolution of the mean temperature with the input electrical power for two LED chips on a module

It is measured and seen that the phosphor temperature increases with the elevation of the height of the phosphor layer, and the highest temperature is much higher than the substrate temperature of the LED package. When the phosphor temperature reaches a value of 300ºC, the colour conversion efficiency decreases to 15%.

As a result of continuous thermography monitoring of COB LED, a sequence of thermography images is recorded after each step of packaging.

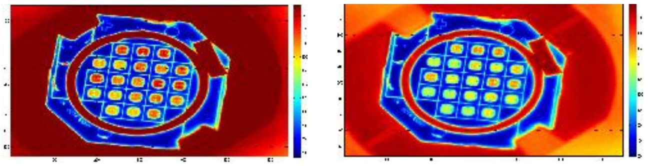
Pre-processing for noise removing is used by median filter (Fig.5a) and additive noise removing Gaussian filters (Fig.5 b) of row thermograms - shown on Fig.5c and Fig.5d. The hottest LED chips are mounted on thinner die-attach layers or with a void under chip.

Processing technique for thermal image sequences using PCA is based on reducing the information from the singular value decomposition to compactly extract spatial and temporal information of the image sequence using orthogonal empirical functions. PCA has been proposed as a method for defect depth characterization. In this quantitative approach, a link between some principal components and the thermal contrast was found (Fig. 6a, Fig. 6b). This made it possible to formulate a calibration function for the defect depth estimation.



a) 3D median filter – preprocessing

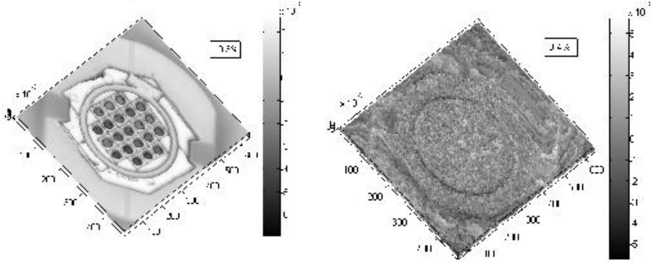
b) 3D Gaussian filter-pre-processing



c) 2D raw thermogram (0,70:090s)

d) 2D raw thermogram (1:0,5:562min)

Fig. 5. Preprocessing for noise removing.

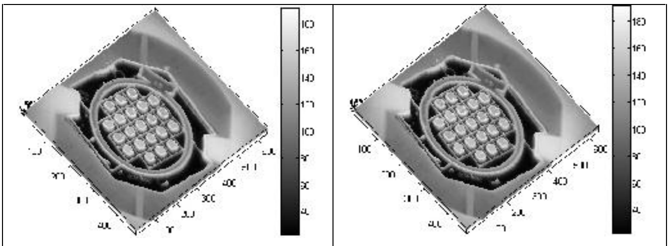


a) 3D PCA (case a)

b) 3D PCA (case b)

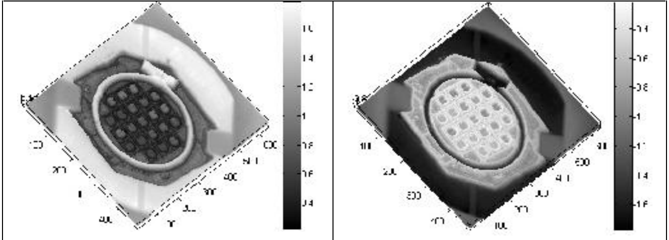
Fig. 6. A link between some principal components and the thermal contrast.

The FFA is typically used to extract amplitude (Fig.7a, b) and phase (Fig.7c, d) information. The phase is more interest than the amplitude since deeper probing is possible and the phase is less affected than raw thermal data by emissivity variations, non-uniform heating, orientation, geometry and environmental reflections.



a) 3D amplitudogram (case a)

b) 3D amplitudogram (case b)



c) 3D phasegram (case a)

d) 3D phasegram (case b)

Fig. 7. FFA processing.

Experimental result of the investigated defect under LED chip on COB without phosphor-coated disk and the comparison to the theoretical phase shift behaviour (straight line) is shown on Fig. 8.

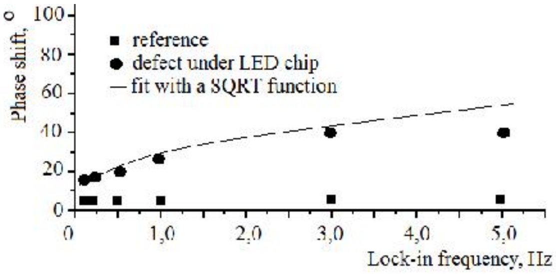


Fig. 8. Phase shift vs. Lock-in frequency for COB without phosphor-coated disk

Phase shift vs. to the applied lock- in frequency investigated both experimentally (dots) and theoretically (straight line) of defect under LED chip on COB with phosphor-coated disk is shown on Fig.9.

The correlation coefficients as an alternative way to characterize the relative difference of the temperature evolution over the time of a sequence of IR images (Fig. 10). More details about such a reference can be found in DAC contrast computation [10].

Advantages and disadvantages of used methodology are analysed according to inspection of different defect during packaging of COB light emitting diodes.

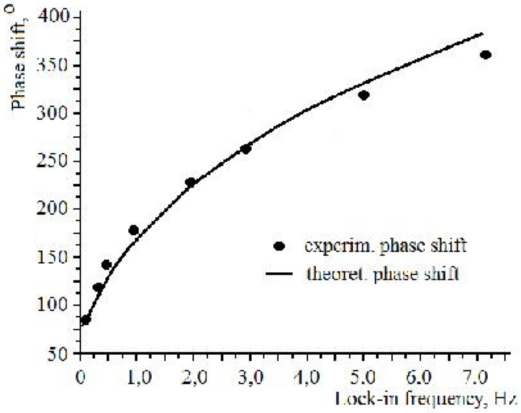


Fig. 9. Phase shift vs. Lock-in frequency for COB with phosphor-coated disk

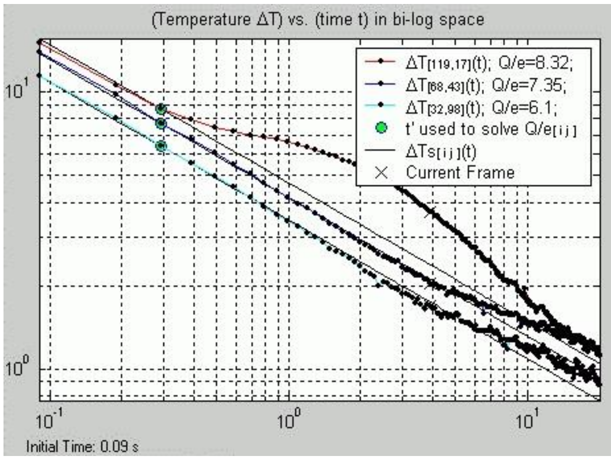


Fig. 10. Temperature evolution over the time in bilog scale.

4. CONCLUSION

The base of the research is the fact that if an electrical component is exposed to too much current, or has too high resistance, its temperature will rise. This temperature rise is an excellent target for thermography and infrared cameras. Therefore, infrared imaging allows us to see variations in temperature, to measure the absolute temperature and to find subsurface or hidden defects during quality control.

This paper has discussed the design considerations of a decision support system to be used with infrared images of COB LED. Furthermore it has described the components of such a system, which can with decent accuracy find and classify regions in infrared images.

If knowledge about the depicted objects is used and of how the image has been produced a significant amount of information can be extracted from an infrared image.

The paper presents the main results from which it follows that the use of IRT can be successfully applied to the quality control process after packaging COB LED process. Detailed results and analysis of the application of different methods to characterize specific defects will be presented in next paper.

Acknowledgement

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