Delphi4LED: LED Measurements and Variability Analysis

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Abstract

The main objective of the Delphi4LED project (funded by the Ecsel European joint undertaking) is to develop a standardized method to create multidomain LED based design and simulation flow for the solid-state lighting industry. Tools and standards will be developed at various levels to enable design and manufacturing of more reliable and cost effective LED based lighting solutions which can be brought to the market much faster than today. Beyond the modelling of thermal, electrical and optical behaviour of LEDs, modelling of process variability has been identified as an important feature that should be implemented in the final tool. Sources of process variability during LED manufacturing, measurements, as well as their impact on colorimetry are currently investigated in the Solid State Lighting industry. In the context of Delphi4LED, some preliminary electrical and optical measurements have been conducted on blue pump white Chip Scale Package (CSP) LEDs and the measurement data have been analysed statistically.

1 Introduction

The main objective of the Delphi4LED project (funded by the Ecsel European joint undertaking) is to develop a standardized method to create multidomain LED based design and simulation flow for the solid-state lighting industry. Tools and standards will be developed at various levels to enable design and manufacturing of more reliable and cost effective LED based lighting solutions which can be brought to the market much faster than today to give Europe the opportunity to outpace the global competition. Beyond the modelling of thermal, electrical and optical behaviour of LEDs, modelling of process variability has been identified as an important feature that should be implemented in the final tool. Sources of process variability during LED manufacturing [1], measurements [2], as well as their impact on colorimetry [3] are currently investigated in the Solid State Lighting industry.

In a fab, one can distinguish lot to lot, wafer to wafer and within wafer variation. Lot to lot variation is typically the dominant one as all wafers within a lot typically see the same process route (defined as the series of processing tools a wafer sees during its manufacturing). Within wafer variation is often a radial distribution (centre to edge) due to either nonhomogeneous Chemical Mechanical Polishing (CMP) or temperature gradients during annealing or Metal-Organic Chemical Vapour Deposition (MOCVD) growth phases leading to discrepancies during the recrystallization phase (presence of amorphous clusters). Addition of relevant Indium concentration inside a heterojunction allows generation of blue light. Nonhomogeneous presence of Indium inside the InGaN quantum wells permits electron-hole pair direct band to band recombination triggering blue light emission at a high enough efficiency [4]. Also, Indium composition has a direct impact on blue LED peak wavelength position [4]. Between each important process phase, wafers also see cleaning steps. If these steps are not carefully controlled and monitored, defects can remain on the surface prior to the next process step. This is especially critical prior to MOCVD post buffer epitaxy. In such a case, crystalline defects may replicate or even amplify themselves all the way to the top of the newly grown crystalline phase [1]. Quality of thermal contacts between the diode and the thermal sink, operating temperature for a given optical power may vary, this may also shift the peak position (the hotter the more it shifts towards red) as well as enlarge blue peak width if thermal contact is nonhomogeneous at the diode surface. Cross section of an AlInGaN LED is shown in Figure 2 below. Phosphor coating process control, purity, and Cerium density in YAG are also key sources of variability for the resulting white LED Spectral Power Distribution (SPD). Its degradation for long period of use at high temperature also has an impact on LED lifetime.

To assess process variability we used several statistical tools. Assessment of normality was done both by graphical inspection (kernel density plots [5], normal probability plots (a variant of QQ plots), as well as a formal dedicated goodness-of-fit test for normality (the Shapiro-Wilk test). The kernel density plots are convenient to assess the shape (symmetry, unimodality) of the data and allow for interpretation for the causes of possible deviations (more details of the method can be found in [5]), while the normal probability plot gives a more precise indication of deviations of normality but do not easily lend themselves to interpretations of deviations. Since the data sets are small and thus sensitive to outliers, we used a moderate significance value (0.01) instead of the standard 0.05 threshold for significance. Since the measurements are difficult to perform and there are therefore likely to be failed measurements, we performed a light outlier analysis by constructing box-and-whisker plots with the standard indication of outliers outside the whiskers placed at 1.5 the interquartile range from the median. All statistical analyses were performed using the statistical software R, version 3.3.2.

2 Measurement setup and experimental conditions

Our 50cm sphere is calibrated according to International Standards. Electrostatic discharge (ESD) protection material (gloves, anti-static carpet) was used while manipulating or working on samples. LED samples under investigation are blue pump white Chip Scale Package (CSP) LEDs of CRI 80 and a Correlated Colour Temperature (CCT) of 3000K, which come from a single bin. Each sample (with either FR4 or Ceramic substrate) was identified with an increment number from 1 to 11 for each type of printed circuit board (PCB) of the CSP LEDs. Cleaning of samples was checked before measurements.

First, samples electrical and thermal pads were sanded before soldering or thermocouple placement (oxidation mainly on ceramic based samples). 18cm doubled wires were soldered on electrical pads without heating too much LEDs (2 wires on each + and - pads for independent power and sense measurements). Thermal paste was applied under each PCB before placement on cold plate for better temperature control. Each PCB was then secured on a cold plate on opposite corners with specific scotch tape. One thin type K thermocouple was placed against LED case for pulsed junction temperature (and forward voltage (V_f) measurements) and another one on PCB case temperature (T_c) for cold plate control using Capton tape and thermal resistance (R_{th}) calculation.

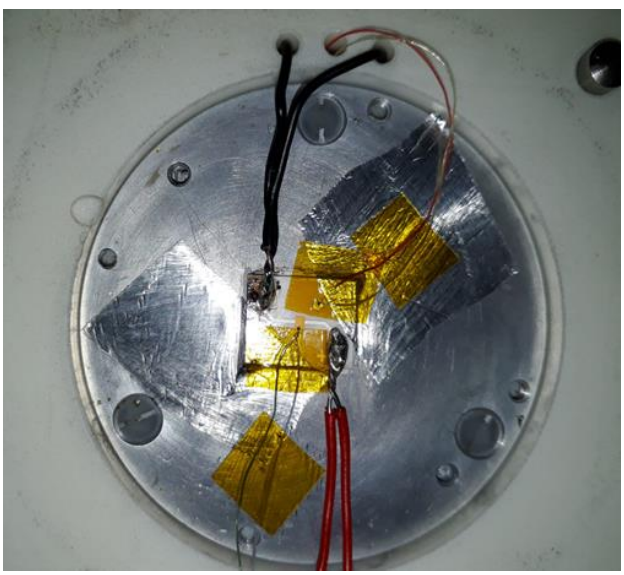

Figure 1: Cold plate and measurement setup

2.1 First step: pulsed measurements

We performed pulsed measurements with specific Keithley power supply on each LED using controlled currents and 25ms pulses from leakage current to maximum rated current. Junction temperature (T_j) was imposed by cold plate measuring LED case temperature (T_c). Associated V_f was measured to be used during continuous measurements phase as reference for correct T_j setting. Temperature calibration correction curves were used for correct measurements. Ambient temperature was always controlled between 24 and 26°C.

LEDs were controlled in forward current (I_f) for a given junction temperature and resulting V_f was measured at each of the (I_f, T_j) measurement point. Table 1 summarizes I_f and T_j values used for this analysis. For measurements onto Ceramic, applied forward currents were not exceeding 60mA while they were applied up to 250mA on FR4. Forward current values were selected in order to cover the entire operating range of the LEDs as described in its datasheet.

Table 1: CSP LED experimental design

Experimental design LED CSP				
Currents (A)/T_j (°C)	**30**	**50**	**60**	**75**
0.010	√	√	√	√
0.030	√	√	√	√
0.060	√	√	√	√
0.100	×	√	√	√
0.150	×	√	√	√
0.250	×	×	×	√

2.2 Second step: continuous measurements

Before each measurement we performed sphere form factor and sphere deviation measurements to correct flux measurements. The cold plate was mounted on a 2pi porthole. Ambient temperature was always controlled between 24 and 26°C. LEDs were then connected to Keithley electrical power supply and acquisition analyzer for current and voltage measurement still with 4 wires. For each current, cold plate temperature was then adjusted in order to reach exact V_f associated with previous pulsed T_j measurements.

2.3 Measurement uncertainties

There are a few possible sources of uncertainties during the measurements. In the pulsed measurements, proportional–integral–derivative (PID) is affecting the voltage. When several measurements are made at the same T_j, the V_f can shift in the order of 0.007 mV. These reference voltages are then used in continuous measurements. It is therefore easy to assess the error that can be made using this method.

In the continuous mode, the cold plate is regulating the temperature with oscillations (PID) which are more or less directly transferred to the voltage V_f we have reached for correct T_j measurements. However, since the voltage is never stable, measurements had to be performed on the fly which is a main source of the uncertainties of the measurements.

The uncertainty of the sphere (photometrical measurements) is documented at around 4%.

3 Results

3.1 Forward current analysis

An LED is a heterojunction biased in direct. Holes generated in the p region recombine with electrons generated in the n region inside the heterojunction and emit photons at an energy level controlled using quantum wells and specific materials. Energy barriers and LED cross-section of such a device can be found in Figure 2.

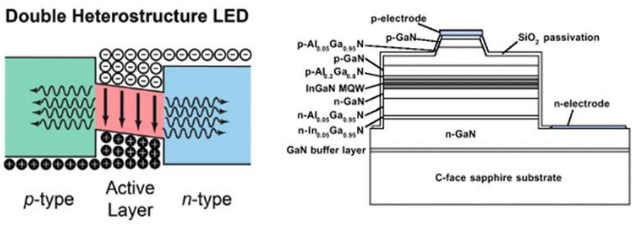

Figure 2: Left: energy diagram of a heterojunction. Right: cross-section of a typical AlInGaN blue LED [6]

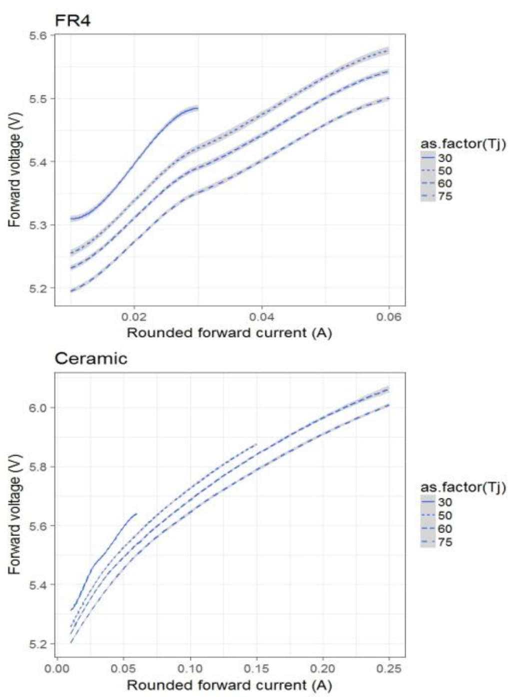

Figure 3: Top: rounded V_f vs I_f at 4 T_j temperatures on FR4. Bottom: rounded V_f vs I_f at 4 T_j temperatures on Ceramic

As seen in Figure 3 and as expected, for a given forward current (I_f), the V_f drops when T_j increases. The curve thickness (Figure 3) gives us insight on LED to LED variability (measurement + LED samples). Although it is difficult to see from the above graphs, the graphs show that the variability is larger for FR4 than for Ceramic samples.

Measurements of forward voltage (V_f) of LEDs with FR4 substrate were performed for 2 values of the forward current (0.01 and 0.03A) at 30 degrees Celsius and for 3 different values (0.01, 0.03, and 0.06A) at the other junction temperatures. For LEDs on ceramic substrate, measurements were done for 3 values of the forward current (0.01, 0.03, and 0.06A) at 30 degrees Celsius and for 5 or 6 different values of forward current at the other junction temperatures. In order to overcome the problem of few measurements per setting of the relevant parameters, we combined the measurements for a given junction temperature and type of substrate through a simple linear regression with the logarithm of the forward current as response variable (see Figure 4). The justification of combining observations through linear regression came from plotting and observing R^2 values above 0.8 as a first indication and a statistical proper confirmation using an overall F-test for significance. Normal distributions can then be derived from the residuals, if we check that the residuals have means zero and a constant variance. We observe a linear increase of the logarithm of the forward voltage at fixed temperatures, so an exponential increase of the forward voltage as a result of increases in forward current. The positive slope decreased with increasing temperature for both substrates. The FR4 substrate had higher slopes than the ceramic substrate. For ceramic we see a fairly constant spread of the forward voltage for fixed temperatures, while for FR4 we clearly see a non-constant spread, with distinct increase in many cases.

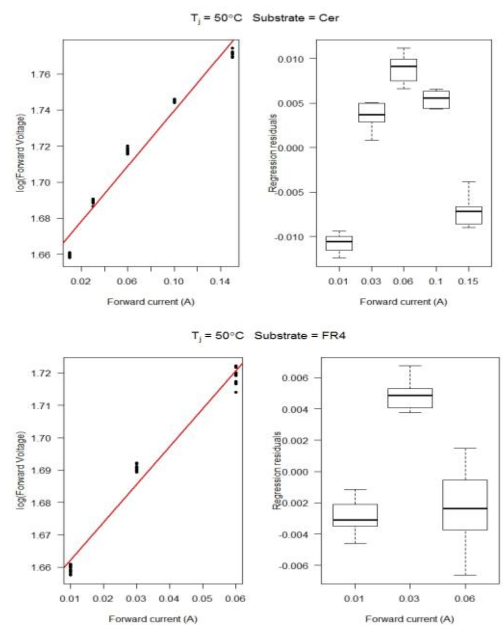

Figure 4: Simple linear regression of the log(V_f) vs I_f and the Boxplot of the regression residuals at T_j = 50 °C. Top: Ceramic. Bottom: FR4.

A similar analysis was performed for forward voltage as a function of junction temperature for fixed forward currents. In all cases we observe a linear decrease of the logarithm of the forward voltage when the junction temperature decreases. The spread is not constant, but no clear pattern could be concluded from the plots. With increasing temperature we see an increase in intercept and a steeper slope. A direct comparison of the substrates was not possible, since they were measured at different forward currents.

3.2 Efficiency (Lumen per Watt) analysis

The equation in Figure 5 below tells us that LED quantum efficiency first increases with increase in current density since spontaneous emission gets dominant. But beyond a given threshold, Auger recombination leads to droop, responsible for a loss in flux [7].

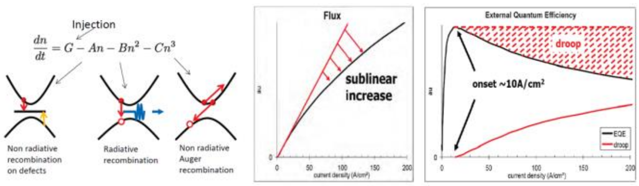

Figure 5: Effect of droop on flux and quantum efficiency [7]

We therefore expect a drop in Lumen per Watt for high current values, but this effect obviously depends on bandgap purity for the nonradiative recombination on defects and on the energy levels curvature for the nonradiative Auger recombination. And once again, this is directly related to process variability during manufacturing.

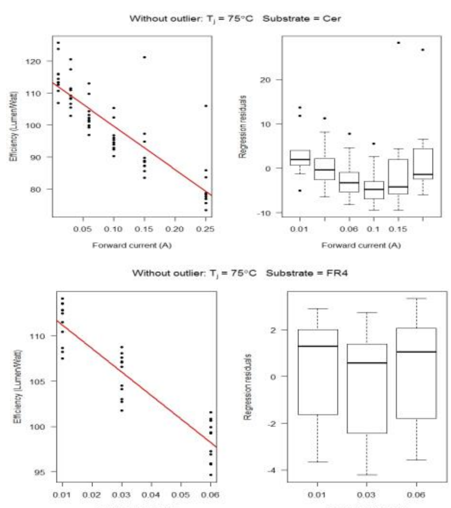

Figure 6: Simple linear regression of the Efficiency vs I_f and the Boxplot of the regression residuals at Tj = 75°C. Top: Ceramic (without removed ceramic sample). Bottom: FR4.

Measurements of radiant efficiency of LEDs with FR4 substrate were performed for 2 values of the forward current (0.01 and 0.03A) at 30 degrees Celsius and for 3 different values (0.01, 0.03, and 0.06A) at the other junction temperatures. For LEDs on ceramic substrate, measurements were done on for 3 values of the forward current (0.01, 0.03, and 0.06A) at 30 degrees Celsius and for 5 or 6 different values of forward current at the other junction temperatures. One ceramic sample has been removed from the radiant efficiency analysis because the LED case was destroyed leading to wrong optical measurements. In order to overcome the problem of few measurements per setting of the relevant parameters, we combined the measurements for a given junction temperature and type of substrate through a simple linear regression relating radiant efficiency to forward current. Normal distributions can then be derived from the residuals, if we check that the residuals have means zero and a constant variance. The linear regression of some combinations of junction temperature and substrate yields R^2 values less than 0.8, but still with significance F-test results.

We see a downward trend in the mean for all temperatures and both substrate types. Across temperatures, we see a decrease in the absolute value of the slope when temperature increases for both substrates. As expected, comparing the two substrates, we see that FR4 samples show different sensitivity to temperature changes than Ceramic. However, it is also noted that for better characterization, a larger sample size is needed. The spread in all cases is fairly constant across forward currents, temperatures, and substrates.

3.3 Spectral Power Distribution (SPD) analysis

In this part, we will discuss the impact of process variability, junction temperature and forward current on the LED Spectral Power Distribution (SPD). An example of a SPD can be found in Figure 7 below.

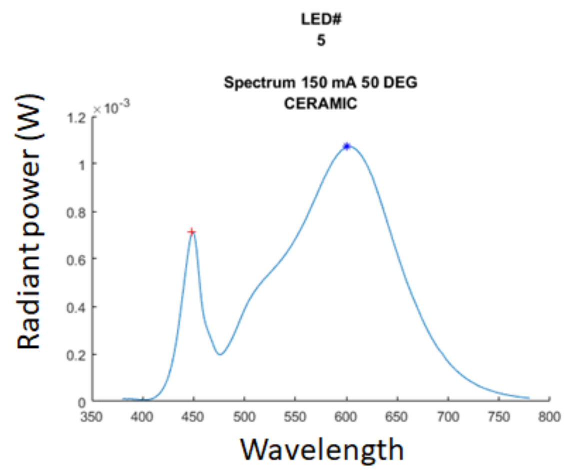

Figure 7: Example of a SPD of LED number 5 on Ceramic, at 150mA I_f and 50°Celsius T_j. We checked both peaks radiant power intensity and position in wavelength.

For the spectral density measurements, peaks were extracted for both intensity and wavelength for blue and yellow. Statistical analyses for maximum blue intensity revealed many outliers. We removed these outliers in 3 rounds for ceramic and in two rounds for FR4: after removing the first set of outliers and reanalyzing the data, we found new outliers that we subsequently removed. This process was repeated one more time after which no outliers were detected. The phenomenon of having multiple layers of residuals is known in the statistical literature as masking. We analyzed the data using multiple linear regression with intensity as response variable and both junction temperature and forward current as predictors. A residual analysis of this multiple linear regression revealed for Ceramic that the standard deviation is fairly constant and that the residuals are normally distributed (based on QQ-plot and a Shapiro-Wilk test). The trend in the mean is increasing for forward current and decreasing for junction temperature. The sensitivity with respect to forward current is almost the same for both substrates, while the sensitivity with respect to junction temperature is much larger for ceramic than for FR4, which is once again expected since thermal dissipation of ceramic is more efficient, leading to less performance degradation of the LED when T_j increases.

The analysis for the blue and yellow peak wavelength yielded that there seem to be two or more different groups in almost all of the combinations of forward current and junction temperature. Further analysis like fitting mixtures of normal distribution were not performed, since we have no physical explanation for the groups.

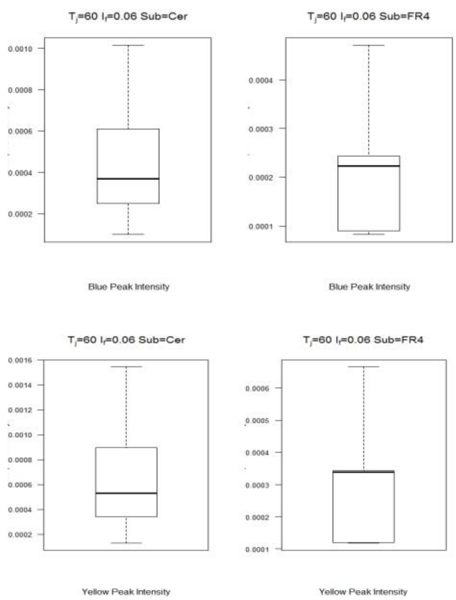

Figure 8: Boxplots comparing FR4 and Ceramic for Blue peak (top) and Yellow peak (bottom) intensities under the same T_j and I_f conditions (60 °Celsius, 0.06A)

For the blue and yellow peak intensities, we see from the boxplots (Figure 8) that Ceramic has a higher intensity and a smaller standard deviation. Heat dissipation being more efficient onto Ceramic, we believe LEDs are in general performing better, especially at high T_j. This explains the higher intensity for both blue and yellow peaks. Larger standard deviation on FR4 could be once again interpreted as the effect of its thermal properties. Note however, that the FR4 LEDs has outliers that have been removed from the box plots.

3.4 Thermals: Ceramic vs FR4

Ceramic substrates are thermally more conductive than FR4, so we expect that performance of FR4 is inferior to ceramic. In order to investigate this in more detail, we compared R_{th}, forward current, radiant efficiency, blue peak intensity and yellow peak intensity at high junction temperature and high current for both substrates.

R_{th} has been measured from the junction temperature to a spot on the PCB 4mm away from the LED. Distribution for the 11 devices can be found in Figure 9 hereafter.

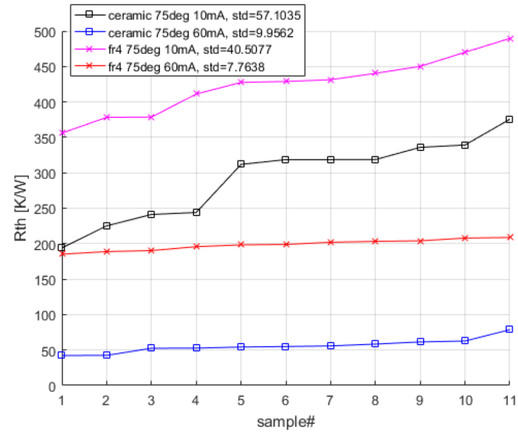

Figure 9: R_{th} at 10mA and 60mA I_f onto both Ceramic and FR4 substrates

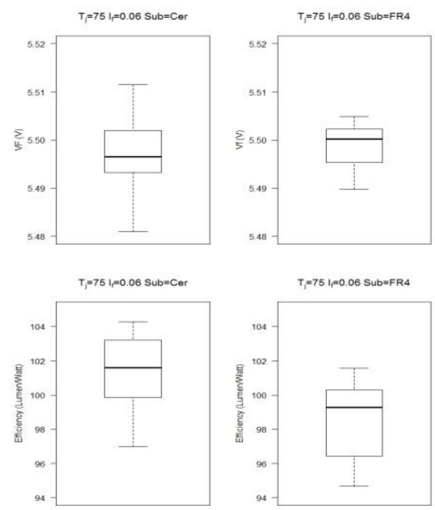

Figure 10: Boxplots comparing FR4 and Ceramic for V_f (top) and radiant efficiency (bottom) under the same T_j and I_f conditions (75 °Celsius, 0.06A)

As expected, R_{th} is significantly smaller onto a Ceramic substrate compared to a FR4 by a factor 4 at 10mA and by a factor 1.6 at 60mA. This is not surprising considering how much a better conductive ceramic is against FR4. On the other hand, R_{th} increases from 10mA to 60mA by a factor 6 for ceramic and by a factor 2.1 for FR4. Standard deviation of R_{th} is 1.41 times larger on ceramic compared to FR4 at 10mA and 1.28 times larger at a forward current of 60mA, and this despite having lower mean values. It could be that thermal paste deposition was less homogeneous on Ceramic than on FR4 or simply that homogeneity matters less on a poor thermal conductor as FR4 compared to Ceramic.

From the box plots (Figure 10) we conclude the following. FR4 has a higher forward voltage for the same applied current, but both substrates have similar spread. Note that for some most operating conditions, both substrates have a skewed distribution with opposite directions. In most operating conditions Ceramic has a higher radiant efficiency than FR4, which could be explained at first order by a better heat dissipation.

Table 2: Mean, median, standard deviation of samples at I_f 0.06A and T_j 75 ℃

Characteristic	Attribute	Ceramic	FR4
V_f	**Mean**	5.496	5.497
	Median	5.496	5.497
	Standard deviation	0.0094	0.0047
Radiant Efficiency	**Mean**	102.0331	98.3949
	Median	101.5905	99.2846
	Standard deviation	3.6317	2.3491

4 Conclusions

In the present paper, we briefly introduced the main causes of process variability responsible for the observed LED to LED difference in performance. The statistical methodology used to measure this variability was also explained. Measurement setup and experimental conditions for the measurement of the 22 LED samples were then described.

Forward current analysis was then presented. Results show exponential increase of the forward voltage as result of the increases in forward current. A linear decrease of the logarithm of the forward voltage when the junction temperature decreases is also observed in all cases. While constant spread of the forward voltage is generally observed for Ceramic substrate, it is not the case for FR4. However, although the spread is not constant, no clear pattern could be concluded from the plots.

Efficiency in Lumen per Watt analysis shows the same effect the junction temperature for both substrate. However, the results also shows that samples on FR4 seem to be more sensitive to the temperature change than samples on Ceramic.

Next part was dedicated to SPD analysis, in particular the peak intensity of blue and yellow. Multiple linear regression was used to analyze the intensity data. The presence of multiple layers of outliers was found in the intensity data. The results of the SPD analysis support the hypothesis that the substrate choice also affects the SPD performance and variability.

Based on the results, it can be concluded that analysis of LED measurements and variability using statistical tools can reveal not only the electrical and optical behavior of LED systematically, but also supply information on the material and process variability which can lead to a better modeling and design. Therefore, this work is a valuable preparatory work for the compact model choice and the selection of relevant parameters for which statistical variability should be monitored. Among existing models, multi domain compact model from Budapest University of Technology and Economics (BME) is considered as a likely candidate for integration in the Delphi4LED tool [8]. It has the key advantage to combine thermal, optical and electrical modeling with information transfer of thermal to the LED electrical and optical performance. Once the Delphi4LED model will have been finalized, results from extracted parameters on these 22 LEDs will be the subject of another paper.

Acknowledgements

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