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THERMAL RESISTANCE AND LIGHT OUTPUT MEASUREMENTS OF HIGH-POWER LED ON UN-DOPED SILICON PACKAGING SUBSTRATE

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Abstract

To reduce the thermal resistance and improve the light output of high-power LED, un-doped Silicon based packaging substrate was fabricated and the steady state thermal resistance of a commercial LED mounted on the un-doped Silicon packaging substrate was measured. The performance of the un-doped Silicon substrate has been compared with the same LED mounted on FR4, Metal Core Printed Circuit Board (MCPCB) and commercial Nanoceramic dielectric on Aluminum based packaging substrates. Taking the thermal resistance from the LED source to the bottom of the un-doped Silicon packaging substrate as a reference, the thermal resistance of LED on FR4, MCPCB and the Nanoceramic on Aluminum substrates were found to be 285.15%,120.95% and 15.81% higher respectively. Based on the thermal resistance performance, light output measurements of LED mounted on the two extreme cases of the un-doped Silicon and FR4 substrates were done at an applied constant current of 700 mA under no heat sink attachment conditions. The drop in lumen light output from initial to final stage of testing for FR4 substrate was 85.15%, whereas for the un-doped Silicon substrate, the drop in lumen light output was only 12.91%.

Keywords: *LED (Light Emitting Diode), light output, packaging substrate, silicon, thermal resistance.*

INTRODUCTION

The dawn of semiconductor Light Emitting Diode (LED) happened in 1960’s when Nick Holonyak Jr [1] developed red LED using Gallium Arsenide Phosphide (GaAsP) and vapor-phase epitaxy process. For the first time in 1990’s semiconductor LED surpassed the incandescent lamps efficiency of 15 lm/W with a 20 lm/W product. The foundation for high brightness was laid by Shuji Nakamura with the fabrication of Blue-LED in 1993[2]. In an LED about 75% to 85% of the supplied electrical energy is converted into heat due to various factors affecting the light conversion efficiency. Increasing the applied current to produce more light output in High brightness LEDs results in more heat being generated raising the LED junction temperature. The increase in junction temperature reduces the Internal Quantum Efficiency because of the negative impact on the electron-hole recombination in the active region of the LED device. The increased temperature also affects the phosphor and lens reducing the light extraction and lumen output [3]. The quantity and quality in terms of lumen output, efficacy, wavelength shift, color rendering index (CRI), life and reliability all are affected by an increase in junction temperature [4] and indeed the design of LED to achieve optimum performance has involved and continues to involve Multidisciplinary Innovation in Materials, Electrical, Thermal, Mechanical, Manufacturing and Reliability engineering as depicted in Figure 1.

To extract the heat away from the source and limit the temperature rise, LED chip level and packaging substrate level studies have been continuously made. Sapphire, the most commonly used device level substrate in the initial stages of low power LED development suffers from poor thermal conductivity to be effective for high power LEDs. To mitigate this issue, silicon (Si) [5]and Aluminum Nitride substrates [6] have been explored with success.

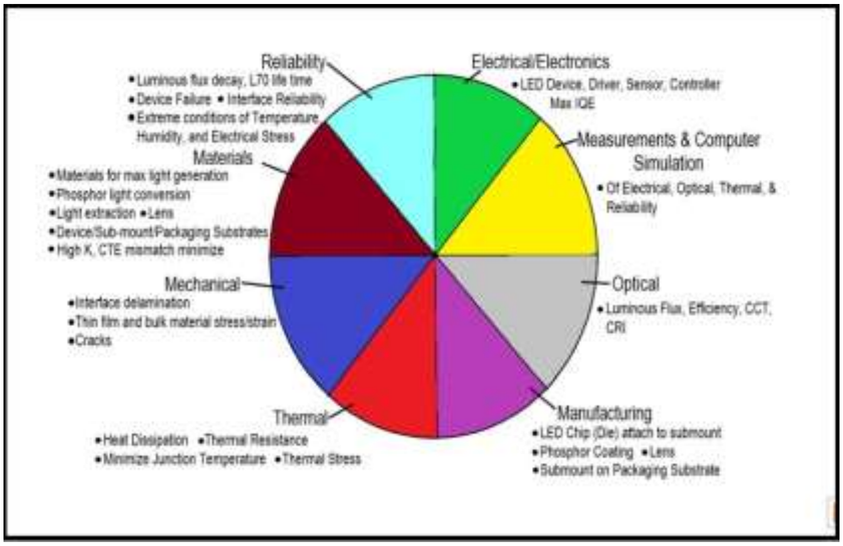


Figure 1. Multidisciplinary Innovation Aspects of LED

The next level of importance is the packaging substrate that forms the critical link between the device and the individual or module level board. In the initial stages of LED, the power levels were low and the low cost FR4 based packaging substrate was sufficient to handle the heat generated. However, with increasing brightness and power level of LED, bare FR4 -PCB was not adequate and addition of filled thermal vias helped reduce thermal resistance by 14% [7]. As the LED device level luminous efficacy in production level increased from 100 lm/W in 2008 towards 200 lm/W almost a decade later as announced by Philips in 2017, the progress followed Haitz's law [8] and the progress came with thermal management using cost effective packaging solutions. When the low cost FR4 based substrates with vias were not sufficient to handle the heat generated by LEDs, the concept of Metal Core Printed Circuit Board (MCPCB) where a metal substrate typically lightweight Aluminum with an overlying thin electrical insulation dielectric layer on which copper tracks for electrical connection of LEDs [9] was born which when used with filled copper vias reduced the LED chip to Substrate thermal resistance of FR4 by about half [10]. The thermal effect of various shapes of MCPCB [11] on LED temperature was studied using simulation indicating the importance of contribution from side surfaces of MCPCB. For automotive and other applications requiring withstanding high temperature environment, Ceramic substrates like Aluminum Nitride (AlN) have been used [12] but they are expensive compared to low-cost Alumina ceramics with relatively low thermal conductivity. Improving thermal performance of LTCC Ceramic substrate with thermal vias under the heat source was reported in [13]. Insulated Metal Substrate (IMS) is similar to MCPCB with aluminum or copper core and inorganic insulation layer [14]. In order to address the relatively low thermal conductivity of typical electrical insulation layer, polymer resin with alumina particles have been tried. Thin Nanoceramic insulation layer on Aluminum with good dielectric and thermal properties were also commercialized as a form of IMS substrate.

This paper presents the fabrication and the thermal performance study of Silicon packaging substrate made from Un-doped Silicon wafer. Steady State Thermal resistance measurement of Un-doped Silicon substrate has been compared with FR4, MCPCB and a commercial Nanoceramic dielectric insulation layer on Aluminum substrates. Light output measurements were also done with a commercial LED mounted on FR4 and Silicon Substrates to demonstrate the effect of thermal resistance on the light output.

MATERIALS AND METHODS

A. Silicon based LED Packaging Substrate

For the past more than four decades Silicon has been the main substrate material for most of the electronic devices starting from memory chips to microprocessors. Silicon has very good semiconducting properties and can be doped to form p-type and n-type materials which makes it an attractive material to make transistors. It can withstand high temperatures and is amenable to wide range of fabrication processes. Since Silicon in the form of Silica forms an estimated 25% of the Earth's crust it is available in plenty and is cost effective as a material for electronics. Since Silicon is already widely used at device level for various electronic devices, its use at Packaging level as a natural extension as device mounting substrate has the potential to provide many advantages. Also, Silicon has a reasonably high thermal conductivity of about 150 W/mK close to that of Aluminum.

So, to use Silicon as the LED Packaging substrate, in this study Un-doped Silicon wafer of 500 microns thickness was chosen with a resistivity of greater than 10000 ohm.cm. The process involves first cleaning the un-doped Silicon wafer with acetone and drying .Then, coating of the silicon wafer was done first with a thin film of Titanium (Ti) of 20 nm thickness, followed by 50 nm thickness of gold (Au) using physical vapor deposition (PVD) process using Electron Beam Evaporation system. The two layers of Ti and Au were deposited sequentially without breaking the vacuum to help achieve better adhesion and grain structure and hence improve thin film properties. Next, on the wafer, copper trace pattern for a single LED was replicated using photolithography process using AZ125nXT negative photoresist and electroplating 50 um thickness of copper over the unexposed area representing the copper trace pattern for LED attachment. As a final step, Au and Ti thin films in the non-pattern area were etched out to leave the copper LED trace pattern on the silicon wafer. The Full wafer with multiple individual LED trace pattern was then cut to each individual un-doped Silicon Packaging Substrate. The patterned Silicon wafer and the singulated individual Packaging substrate are shown in Figure 2.

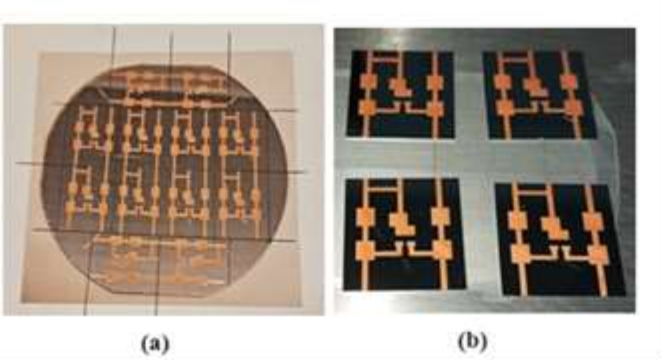


Figure 2. Full Patterned Wafer (a) and Singulated Individual (b) Silicon Substrates

To compare the thermal performance of the un-doped Silicon packaging substrate, standard low cost FR4 and the widely used Metal Core Printed Circuit Board (MCPCB) packaging substrates were fabricated and a commercially available packaging substrate with nanoceramic dielectric layer on Aluminum was purchased with the same copper trace pattern as the Silicon substrate. The different Packaging substrates are shown in Figure 3 , where (a) is FR4, (b) is Silicon, (c) is MCPCB and (d) is the Nanoceramic on Aluminum Packaging substrate respectively. The Packaging substrates are 1 inch x 1 inch (25.4 mm x 25.4 mm) in size.

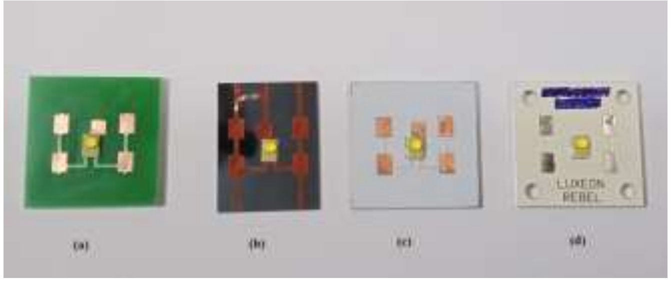


Figure 3. Different Packaging Substrates

B. Steady State Thermal Resistance Measurement of LED on different Packaging Substrates

To study the Steady state thermal performance of different packaging substrates, the LUXEON Rebel Cool White LED with Part# LXML-PWCI-0120 was chosen as the test vehicle. This LED test vehicle was mounted on the FR4, MCPCB, Nanoceramic on Aluminum and the un-doped Silicon Substrates and tested as per the test method of Joint Electron Device Engineering Council (JEDEC) standard JESD-51[15]. Equation (1) defines the Steady state LED junction to the bottom of the packaging substrate thermal resistance $R_{J\text{-}BS}$ as the difference in temperature between the LED junction temperature (T_J) and the temperature at the bottom of the packaging substrate (T_{BS}) divided by the heating power (P) at steady state equilibrium.

$$R_{J\text{-}BS} = (T_J - T_{BS}) / P \quad (1)$$

The configuration to test the thermal capability of the Packaging substrate is to do the thermal resistance test with the LED mounted Packaging substrate placed on liquid cooled temperature controlled heatsink which will direct the heat generated at the LED junction towards the bottom of the packaging substrate in contact with the heat sink as shown in Figure 4. T_J is the LED Junction Temperature and T_{BS} is the Temperature at the Bottom of the Packaging Substrate. The measurement locations of T_J and T_{BS} are as indicated. Thermal Interface Layer (TIM) in the form of thermal grease/oil is used between the bottom of the packaging substrate and the temperature controlled heatsink for better thermal contact and heat transfer.

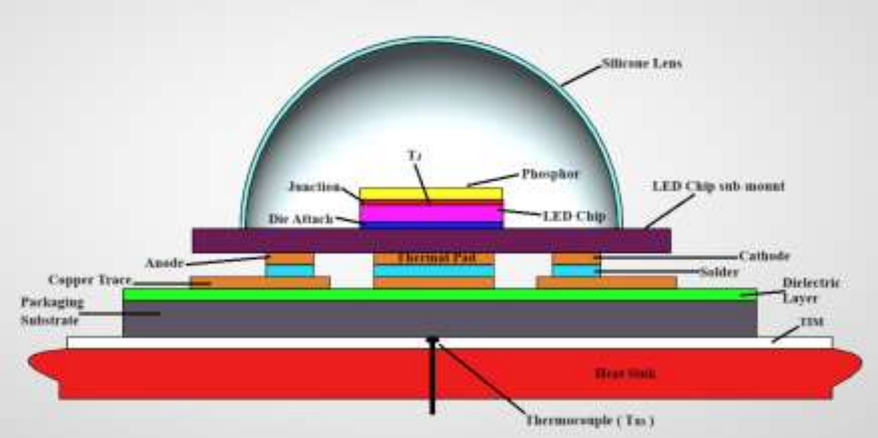


Figure 4. Diagram Showing Packaging Substrate With LED on Temperature Controlled Heatsink

The LED test vehicle was first calibrated by immersing the LED in an oil bath and slowly heating the bath up to 125°C till the LED reached equilibrium. Then, the oil bath was allowed to cool down and as it was cooling down, the LED forward voltage was measured as the Temperature Sensitive Parameter (TSP), at every 5°C drop till the LED reached the room temperature of 25°C. Measured LED forward voltage and temperature are plotted to obtain the LED junction calibration plot with the best fit to the data in red as shown in Figure 5. From the LED calibration plot it can be seen that the slope is negative with the junction voltage decreasing with increasing junction temperature. The slope from the plot is obtained to be -542.2 (°C/V) or the inverse of it is 1.84 (mV/°C). So, in the actual Thermal resistance test when the LED is powered, by measuring the LED forward voltage at the steady state condition, the junction temperature can be calculated by using the linear relationship of the LED calibration plot.

In this study, each of the LED-mounted substrates was tested under an applied constant current of 700 mA and power of 2 Watts. At steady state equilibrium, the LED forward voltage was measured using very small non heating sense current of 10 mA. The measured LED forward voltage can be used to obtain the Junction temperature T_J using the calibration plot. During the test , the temperature of the bottom of the packaging substrate T_{BS} was measured using a thermocouple. Since the applied power is known, the Steady state Thermal Resistance of the Packaging substrate can then be obtained using (1).

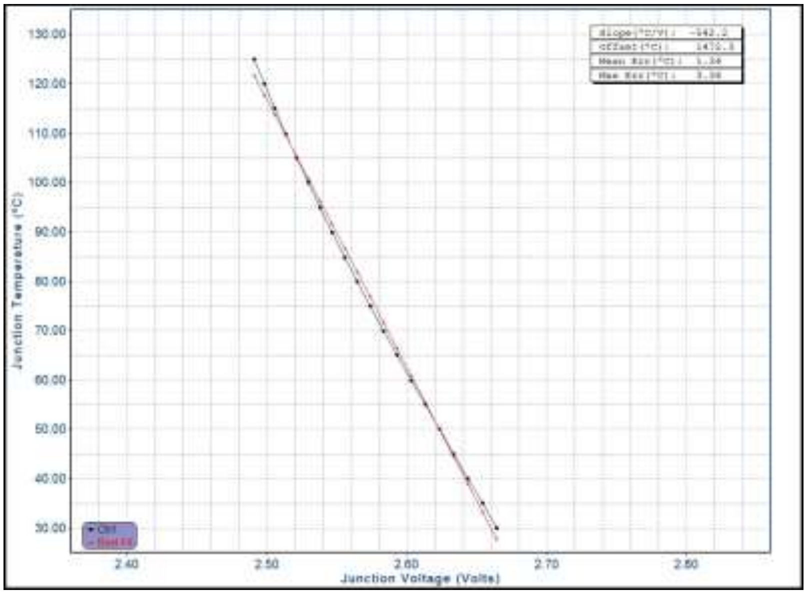


Figure 5. LED Junction Calibration Plot

C. Light output Measurements of LED on different Packaging Substrates

Light output measurements of LED on FR4 and Silicon Packaging substrates were done as per the International Testing Method IES-LM79-19[16] specifications, as two extreme cases of the Highest and the Lowest thermal resistance Packaging substrates. The Light output and degradation measurements were done for these two cases to capture the impact of the packaging substrate thermal resistance. The LED sample on Packaging substrate was placed inside a 2m Integrating sphere and the light measurements were acquired using Labsphere CDS 2600 spectroradiometer. A picture of the light measurement set up of the LED mounted FR4 Packaging substrate inside the Integrating sphere is shown in Figure 6.

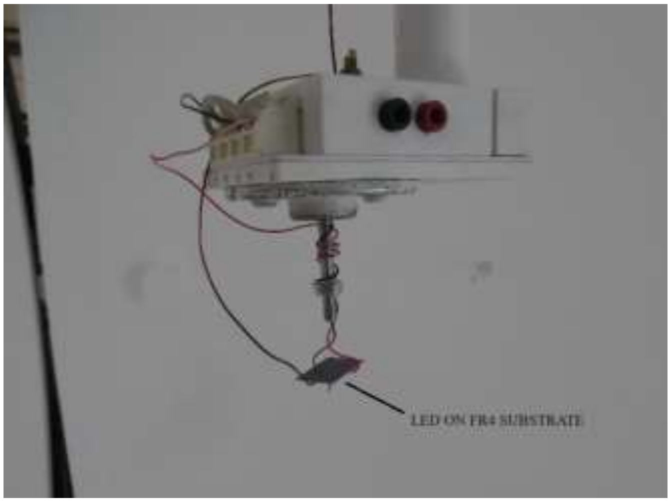
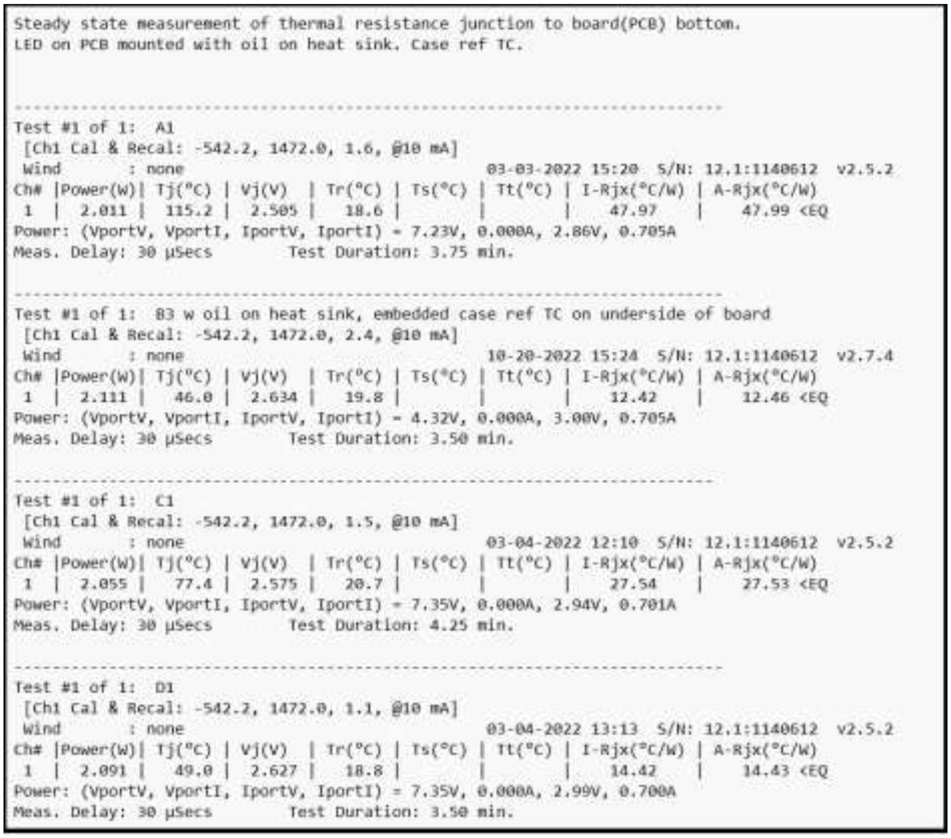


Figure 6. LED on FR4 Substrate Inside Integrating Sphere

RESULTS AND DISCUSSION

The actual measurement data of the Steady State Thermal testing of different samples are shown in Table I, where Samples labelled A1, B3, C1, D1 refer to LED on FR4, Un-doped Silicon, MCPCB and Nanoceramic on Aluminum Packaging substrates respectively.

Table I: Steady State Thermal Resistance Measurement Data



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Steady state measurement of thermal resistance junction to board(PCB) bottom.
LED on PCB mounted with oil on heat sink. Case ref TC.



---------------------------------------------------------------------------
Test #1 of 1:  A1
 [Ch1 Cal & Recal: -542.2, 1472.0, 1.6, @10 mA]
 Wind        : none                                 03-03-2022 15:20  S/N: 12.1:1140612  v2.5.2
Ch# |Power(W)| Tj(°C) | Vj(V)  | Tr(°C) | Ts(°C) | Tt(°C) | I-Rjx(°C/W) | A-Rjx(°C/W)
 1  |  2.011 |  115.2 |  2.505 |   18.6 |        |        |    47.97    |    47.99 <EQ
Power: (VportV, VportI, IportV, IportI) = 7.23V, 0.000A, 2.86V, 0.705A
Meas. Delay: 30 µSecs        Test Duration: 3.75 min.

---------------------------------------------------------------------------
Test #1 of 1:  B3 w oil on heat sink, embedded case ref TC on underside of board
 [Ch1 Cal & Recal: -542.2, 1472.0, 2.4, @10 mA]
 Wind        : none                                 10-20-2022 15:24  S/N: 12.1:1140612  v2.7.4
Ch# |Power(W)| Tj(°C) | Vj(V)  | Tr(°C) | Ts(°C) | Tt(°C) | I-Rjx(°C/W) | A-Rjx(°C/W)
 1  |  2.111 |   46.0 |  2.634 |   19.8 |        |        |    12.42    |    12.46 <EQ
Power: (VportV, VportI, IportV, IportI) = 4.32V, 0.000A, 3.00V, 0.705A
Meas. Delay: 30 µSecs        Test Duration: 3.50 min.

--------------------------------------------------------------------------
Test #1 of 1:  C1
 [Ch1 Cal & Recal: -542.2, 1472.0, 1.5, @10 mA]
 Wind        : none                                 03-04-2022 12:10  S/N: 12.1:1140612  v2.5.2
Ch# |Power(W)| Tj(°C) | Vj(V)  | Tr(°C) | Ts(°C) | Tt(°C) | I-Rjx(°C/W) | A-Rjx(°C/W)
 1  |  2.055 |   77.4 |  2.575 |   20.7 |        |        |    27.54    |    27.53 <EQ
Power: (VportV, VportI, IportV, IportI) = 7.35V, 0.000A, 2.94V, 0.701A
Meas. Delay: 30 µSecs        Test Duration: 4.25 min.

---------------------------------------------------------------------------
Test #1 of 1:  D1
 [Ch1 Cal & Recal: -542.2, 1472.0, 1.1, @10 mA]
 Wind        : none                                 03-04-2022 13:13  S/N: 12.1:1140612  v2.5.2
Ch# |Power(W)| Tj(°C) | Vj(V)  | Tr(°C) | Ts(°C) | Tt(°C) | I-Rjx(°C/W) | A-Rjx(°C/W)
 1  |  2.091 |   49.0 |  2.627 |   18.8 |        |        |    14.42    |    14.43 <EQ
Power: (VportV, VportI, IportV, IportI) = 7.35V, 0.000A, 2.99V, 0.700A
Meas. Delay: 30 µSecs        Test Duration: 3.50 min.
```

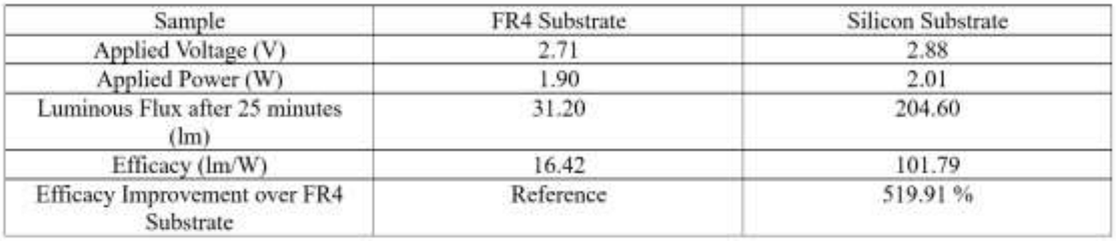
Table II , provides a comparison of the Steady State Thermal Resistance performance of the different Packaging Substrates based on the measured data as shown in Table I. From the data, it can be seen that the LED on Un-doped Silicon packaging substrate has the lowest Thermal resistance compared to other substrates with a value of 12.46 ^{o} C/W. Considering this Silicon substrate thermal resistance value as the reference, Nanoceramic on Aluminum substrate, MCPCB substrate and FR4 substrate have 15.81% , 120.95% and 285.15% higher thermal resistance respectively.

Table II: Steady State Thermal Resistance Comparison

Sample	FR4	MCPCB	Nano Ceramic on Aluminum	Silicon
Steady State Thermal Resistance (°C/W)	47.99	27.53	14.43	12.46
% Increase over Reference Silicon Substrate	285.15	120.95	15.81	Reference

Table III shows the Light output measurements of the LED on FR4, and Un-doped Silicon Packaging substrates placed inside the Integrating sphere and operated at a constant LED driving current of 700mA. The light measurement testing condition did not have any heatsink attached to the packaging substrate and as a result the junction temperature after 25 minutes of testing was high in the case of FR4 substrate because of its high thermal resistance compared to the Un-doped Silicon substrate and the Total luminous flux light output and efficacy were less for FR4 substrate as shown in Table III. The efficacy of Un-doped Silicon substrate was 101.79 lm/W compared with 16.42 lm/W for the FR4 substrate at the end of 25 minutes of testing as an accelerated light output decay testing without any heatsink attached to control the junction temperature increase under powerup condition. The efficacy improvement of Un-doped Silicon substrate is 519.91% compared to the FR4 substrate directly as a consequence of better thermal capability as indicated in Table II.

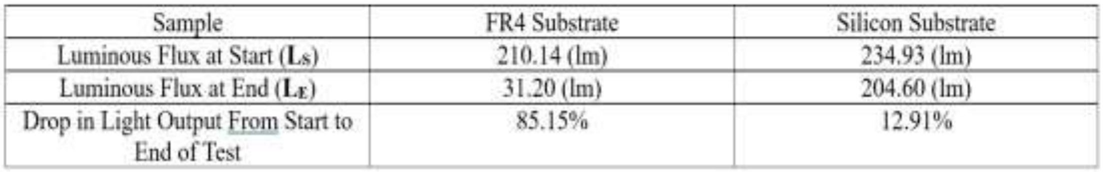
Table III: Light Output Measurements



Sample	FR4 Substrate	Silicon Substrate
Applied Voltage (V)	2.71	2.88
Applied Power (W)	1.90	2.01
Luminous Flux after 25 minutes (lm)	31.20	204.60
Efficacy (lm/W)	16.42	101.79
Efficacy Improvement over FR4 Substrate	Reference	519.91 %

Table IV shows the drop in light output, considering the Total Luminous Flux at the start (L_S) and end of 25 minutes of testing (L_E). From Table IV it can be seen that the drop in light output is 85.15% for the FR4 substrate whereas it is only 12.91% for the Silicon substrate. Thus, the Silicon substrate maintains less than 30% light output drop which is called the L_{70} life of maintaining at least 70% of the initial light output, whereas the FR4 substrate fails to meet the L_{70} life criterion under stringent accelerated testing condition of having no heatsink attachment to the substrate.

Table IV: Light Output Drop



Sample	FR4 Substrate	Silicon Substrate
Luminous Flux at Start (L_S)	210.14 (lm)	234.93 (lm)
Luminous Flux at End (L_E)	31.20 (lm)	204.60 (lm)
Drop in Light Output From Start to End of Test	85.15%	12.91%

CONCLUSION

This study analyzed un-doped Silicon as a Packaging substrate to improve thermal performance of high-power LED. To compare the Thermal performance of the un-doped Silicon substrate, two other substrates of FR4 and MCPCB were fabricated and in addition, a commercial Nanoceramic on Aluminum substrate was also procured. Steady state Thermal resistance measurements were carried out with Luxeon Rebel cool white LED as the test vehicle. Measured Thermal resistance from the LED junction to the bottom side of the packaging substrate was the lowest for the un-doped Silicon substrate with a value of 12.46 °C/W. In comparison, the thermal resistance values were 14.43 °C/W for Nanoceramic on Aluminum substrate, 27.53 °C/W for MCPCB substrate and 47.99 °C/W for the FR4 substrate. Light measurements were done for LED on FR4 and un-doped Silicon substrates as the two cases having the highest and the lowest thermal resistance. The impact of thermal resistance on light output was clearly observed with the FR4 substrate with the highest thermal resistance resulting in 85.15% drop in light output with an efficacy of 16.42 lm/W whereas the Un-doped Silicon substrate with the lowest thermal resistance resulted in only 12.91% drop in light output with an efficacy of 101.79 lm/W after 25 minutes of testing. So, the un-doped Silicon has been shown to be an effective thermal management packaging substrate material for LED to improve light output.

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