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RESEARCH

A Comparative Thermal and Lumen Performance Study of Thin-film Amorphous Silicon Dielectric Coating on Aluminum as an LED Packaging Substrate

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Abstract

Lumen output and efficacy of high-power LEDs have crossed 200 lm/W, and the application of LEDs is growing beyond illumination into other areas like horticulture, UV-C LEDs for disinfection, and health-centric lighting where controlling parameters like the shift in wavelength, Color Rendering Index (CRI), etc. are important. Whether delivering high light output or controlled spectral designs for specific applications, thermal management of LEDs to lower the junction temperature is vital as it directly impacts the intended performance. The packaging substrate on which the LED is mounted plays a critical role in controlling the junction temperature. In this study, a thin film amorphous silicon (a-Si) dielectric coating on an aluminum (a-Si/Al) substrate followed by a 300 nm thick copper trace pattern for LED attachment using magnetron sputtering Physical Vapor Deposition (PVD) process has been carried out. Three other Packaging material substrates of FR4, Metal Core PCB (MCPCB), and Silicon using undoped Silicon wafer were fabricated, and a Nano-ceramic on Aluminum substrate was also procured for comparative Transient Thermal analysis study using Luxeon-Rebel Cool White LED. The Thermal resistance from the LED junction to the bottom of the a-Si/Al packaging substrate attached to the liquid temperature-controlled heat sink measured at 700 mA driving current, as per industry standard JEDEC 51–14 method, was 8.77 °C/W. Compared to this Thermal resistance value of a-Si/Al substrate, the thermal resistance of Silicon substrate, Nanoceramic on Aluminum, MCPCB, and FR4-based packaging substrates were 3.19%, 55.53%, 180.73%, and 405% higher with the corresponding Thermal resistance values of 9.05 °C/W, 13.64 °C/W, 24.62 °C/W and 44.34 °C/W respectively. Light Lumen output measurements for the substrates with the lowest and the highest thermal resistance, namely the (a-Si/Al) and FR4 substrates were also measured and the light output efficacy of the (a-Si/Al) substrate was 9.46% higher than the FR4 substrate. Also, the light output drop of the (a-Si/Al) substrate was only 1.66% compared against 10.66% for the FR4 substrate after 30 min of testing under no heatsink attachment conditions. Thus, the a-Si thin film-coated Aluminum as the LED packaging substrate can help lower the junction temperature with low thermal resistance and improve the color quality, efficacy, lumen depreciation, and reliability.

Keywords Amorphous Silicon (a-Si) · Packaging Substrate · Thermal Resistance · Thin Film · LED

1 Introduction

Analogous to Moore's law, observed by Gordon E. Moore in 1965 that the number of transistors in an integrated circuit (IC) chip will double approximately every 24 months, Haitz law by Roland Haitz predicted in 2000, a trend related to LEDs that the cost per lumen will fall by a factor of 10 every decade while the light generated per LED will increase by a factor of 20. Since 2000, within two decades, the race to achieve higher lumen output have been through efficiency improvements in light generation- Internal Quantum Efficiency (IQE)- light extraction—Light Extraction Efficiency

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(LEE), and light delivery—External Quantum Efficiency (EQE).

Impact of LED junction temperature on the reduction of IQE [1], LEE through the reduction in Phosphor Conversion Efficiency (PCE) [2] and EQE [3] have been established through different studies. Packaging substrate as the major part of LED package is the link between the LED heat source and the external heat dissipating mechanisms like the module board and heatsink. So, the thermal resistance of the packaging substrate directly influences the LED junction temperature. The life and reliability of LED also is improved with a reduction in junction temperature because in general for electronic devices every 10 °C rise in junction temperature, the useful life is reduced by half [4].

The focus of various research activities in the two decades since 2000 has offered ways to improve the efficiency of light-emitting devices addressing the three main non-radiative losses, including leakage current [5], however, lifetime degradation owing to heat generation has been critical and requires continuous innovations and improvements. Now, with LEDs finding applications in horticulture, disinfection (UV-C LEDs), communication (Li-Fi), etc., Haitz law is being given a new perspective of application-specific LED requirements of Color Rendering Index (CRI), color quality, spectral design with minimum wavelength shift and not just light output alone. Each of these requirements of different LEDs heavily depends on the Junction temperature of the LED, including the lumen maintenance as a valuable Life of LED criterion. So, thermal management of LEDs is critical to meet the LED functional requirements. Packaging substrates play a crucial role in thermal management, making LEDs more reliable, long-lasting, cost and energy efficient.

Amorphous Silicon (a-Si) thin film as a dielectric layer on aluminum (a-Si/Al) has been developed for effective heat dissipation in high-power LED applications. A thin film of a-Si was deposited using the Physical Vapor Deposition (PVD) process using magnetron sputtering. Compared to conventional polymer-based dielectric substrates, a-Si/Al substrate has the potential to provide good thermal dissipation capability with a low thermal resistance to keep the LED junction temperature low.

Different dielectric coatings on metals and Silicon have been studied in the past like Thin Film high-quality Aluminum Nitride (AlN) deposited on a silicon substrate using radio frequency (R.F.) sputtering to check the structural parameters such as dislocation density, lattice constants, crystalline size and stress/strain for potential application in nano-micro-electromechanical devices (NEMs and MEMs) [6], aerosol deposited AlN thick film of about 30 um on Al substrate [7], Boron doped aluminum nitride thin film on copper [8], Boron nitride coated aluminum as heatsink[9], Zinc oxide as dielectric on aluminum [10], Magnesium oxide thin film as thermal interface material [11], etc., are some of them. Many of these evaluations are not as packaging substrates but as a heat sink on which the LED on the packaging substrate was mounted.

Regarding amorphous silicon on aluminum, Bellanger P et al. [12], did a study on forming polycrystalline silicon films using the crystallization of amorphous silicon deposited on aluminum (Al) substrates at 550 °C using aluminum as a catalyzer. After annealing, a thin 1um polysilicon film was formed just above the Al substrate, with a thicker silicon and aluminum mix on the top. The objective of the earlier study was to use the polysilicon layer as a seed layer to grow thicker silicon film for photovoltaic applications because growing large areas of crystalline silicon is expensive. However, we aim to use the sputtered a-Si as dielectric on aluminum for the LED packaging substrate. Another paper by Braun JL et al. [13] investigated thickness-dependent size effects on the thermal conductivity of amorphous silicon thin films ranging from 3 to 1636 nm grown via sputter deposition and found that up to 300 nm, the thermal conductivity was about 1.4 W/m ^{o}C and reached about 2.8 W/m ^{o}C at 2 um thickness of the film.

In our study, the thin amorphous silicon-coated aluminum (a-Si/Al) as a packaging substrate was compared against four other substrates of FR4, Metal Core PCB (MCPCB), Undoped Silicon, and Thin Nanoceramic coated Aluminum using a Luxeon-Rebel LED test vehicle and conducting transient thermal measurements using AnalysisTech thermal measurement system according to JEDEC standard (https://www.jedec.org, jedec.org/JESD51–14) to determine the thermal resistance from LED junction to the bottom side of packaging substrate kept at constant temperature by a temperature controlled heat sink.

2 Materials and Methods

2.1 Thin Film Amorphous Silicon on Aluminum Substrate (a-Si/Al). LED Test Vehicle. Samples Preparation and Measurements

A thin film of amorphous Silicon (a-Si) was formed on top of a 6061-T6 Aluminum substrate (a-Si/Al) of size (25 mm × 25 mm × 1.5 mm) by Physical Vapor Deposition (PVD) process as shown in Appendix A. The reason for choosing 6061-T6 Aluminum is that it is heat-treatable, light, and has an excellent strength-to-weight ratio. The reason for selecting a-Si is that it is much cheaper than the device-grade silicon. For comparison, other packaging substrates like FR4, Metal Core PCB (MCPCB), and Silicon were fabricated. The Silicon packaging substrate fabrication flow is shown in Appendix B. In addition, a commercially available Nanoceramic on Aluminum substrate was

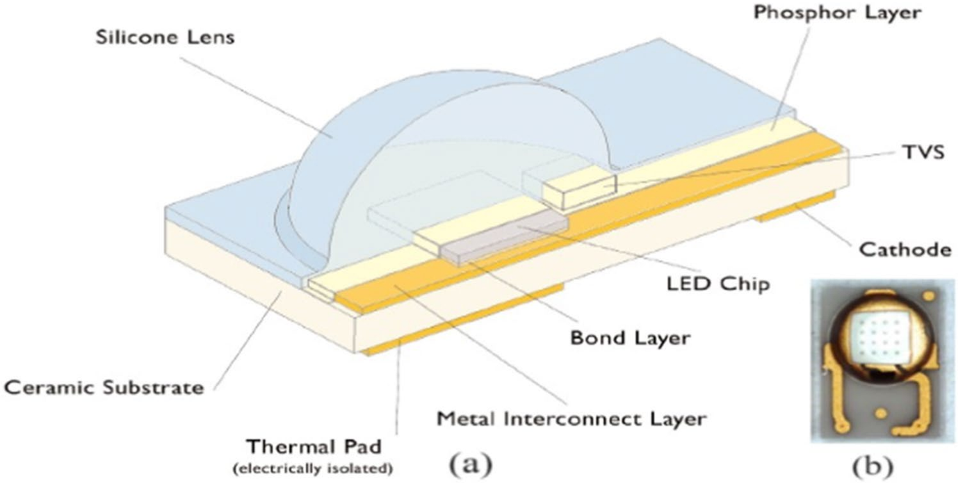


Fig. 1 Cross section diagram of the LED (**a**) and the actual LED (**b**) used

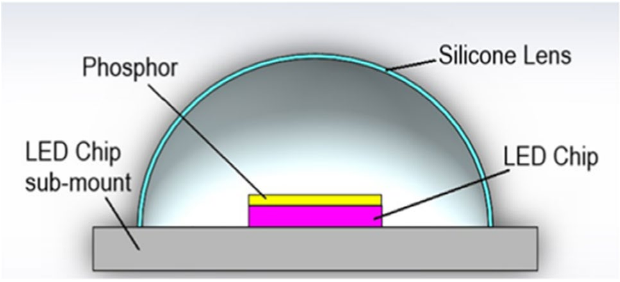


Fig. 2 LED Chip on sub-mount

procured. So, this study involved five different material types, as described above.

The LED test vehicle chosen for this study is the LUXEON Rebel Cool White LED with Part# LXML-PWCI-0120, as shown in Fig. 1. Cross Section Diagram (a) and Actual LED (b). TVS shown in (a) is Transient Voltage Suppressor. The LED Chip is a Thin Film Flip Chip (TFFC).

This LED test vehicle mounted on the five different packaging substrates as described above was tested under JEDEC standard Thermal Test conditions with the bottom of the packaging substrate in contact with a temperature-controlled heat sink. This testing configuration forces the heat generated in the LED chip to flow mainly in one direction through the packaging substrate, spreading within the substrate and flowing towards the Heat sink. This will capture the heat-handling capability of each type of substrate.

Figure 2, shows a representative diagram of a typical LED package with the LED chip on a sub-mount. Figure 3, shows the LED package mounted on a packaging substrate with a suitable thin dielectric layer on the top in contact with a heatsink. When making the thermal resistance measurements from the LED junction to the packaging substrate bottom, the heatsink will be kept at a constant temperature with a liquid cooling setup to direct the heat generated in the LED device junction active area in one dimension towards the heat sink.

Thermal transient measurements were carried out for the LED-mounted on FR4, MCPCB, Nanoceramic on Aluminum, Silicon and Amorphous Silicon thin-film on Aluminum (a-Si/Al) substrates. Figure 4, shows pictures of these different material types of Packaging substrates.

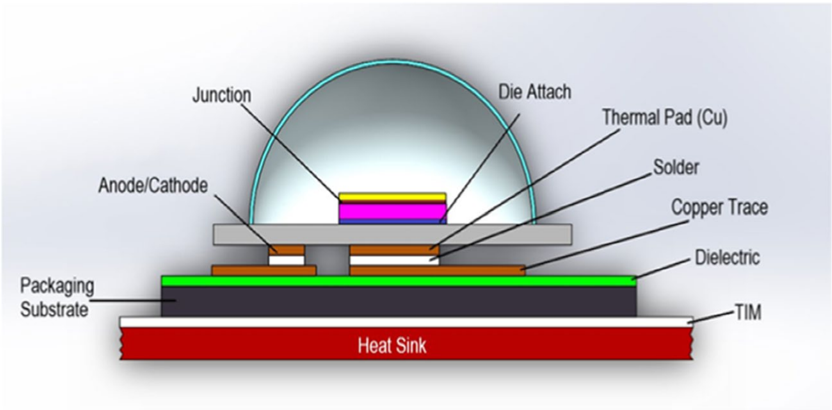


Fig. 3 Diagram showing LED Chip on sub-mount soldered on packaging substrate

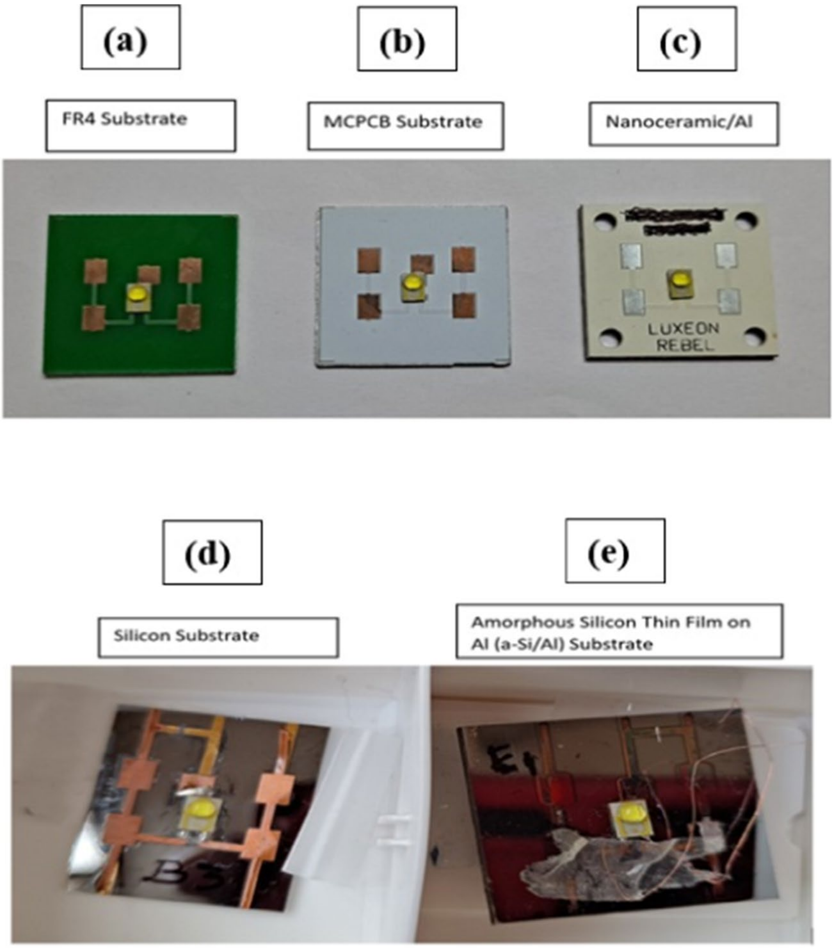


Fig. 4 FR4 (**a**), MCPCB (**b**), Nanoceramic/Al (**c**), Silicon (**d**) and amorphous silicon thin film on aluminum packaging (**e**) Substrates

The Steady-state thermal measurements provide information about each type of substrate's overall heat-handling capability. However, in a Transient thermal testing test with very fast LED voltage sensing equipment, the measured voltage can be translated into Temperature using the prior Temperature vs. Forward voltage calibration of the LED at minimal intervals. Also, from the Temperature vs. Time plot of the transient testing, the effect of each of the material layers like the LED chip, the Chip attach material, chip sub-mount material, solder attachment, and the packaging substrate can be extracted because each material interface causes a change in slope due to their thermal conductivity, thermal capacitance properties. So, when the (a-Si/Al) was fabricated, transient thermal measurements on all five packaging substrates were done. The difference in thermal performance of the packaging substrates can be obtained by superimposing individual packaging substrate Thermal transient data. The measurement results are presented in Section 3 under Results and Discussion.

2.2 LED Junction Temperature Measurement Method

Since the Temperature of the covered-packaged LED chip cannot be measured directly, a temperature-sensitive electrical parameter (TSP) that varies directly with junction temperature in a linear or nearly linear fashion is calibrated. In the case of LED, the forward voltage V_f is used as the TSP.

The LED calibration was done using an oil bath method in which the LED test vehicle was immersed in an oil bath and slowly heated to raise the temperature uniformly and slowly. This allows the LED mounted on the substrate to get uniformly heated, providing sufficient time for the LED device to reach the temperature of the oil bath. Typically, the oil bath is heated to a maximum temperature of the intended device Junction operation. After the oil bath and the LED had reached a steady state, the heating of the oil bath was stopped around 125 °C, and as the LED started cooling down, the forward voltage was measured at regular intervals

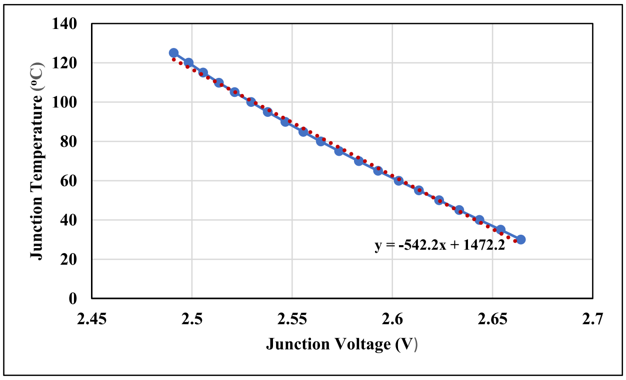


Fig. 5 LED Test vehicle calibration plot

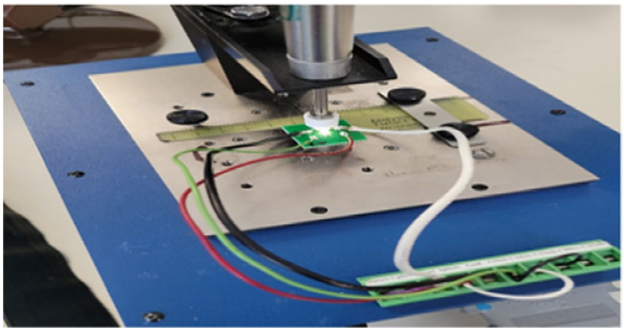


Fig. 6 Thermal measurement set up of LED on FR4 packaging substrate

of 5 °C drop. The measurements of Temperature vs. V_f were used to derive the slope K factor defined as $K = \Delta V_f / \Delta T_J$.

During calibration, a very low sensing current of 10 mA was used to measure the voltage to avoid the device heating effect. Figure 5, shows the LED's Junction Voltage VS Junction Temperature Calibration plot.

From the above LED calibration plot, the slope is -542.2, translating into a K value of -1.84 mV/°C.

During the actual LED testing under given power using constant current, diode forward voltage can be measured, and the LED Junction temperature calculated using the above relationship from the calibration.

After the calibration, the Transient thermal tests were done using the Analysis Tech Thermal testing equipment at a constant current level of 700 mA, amounting to about 2W power. The thermal measurement setup example of LED on the FR4 Packaging Substrate is shown in Fig. 6.

2.3 Light Output Measurement of Selected Samples

Light lumen output measurements of LED using 350 mA constant current were done only for the FR4, and a-Si/Al substrates as the extreme cases of thermal performance with the highest and the lowest thermal resistance, as per the IES LM-79–19 LED testing method. The Silicon substrate was also included in the measurements since thermally it was close to a-Si/Al substrate. During the light output measurement, the temperature on the copper thermal pad where the LED is attached was also measured using a thermocouple. The light output testing was done with the LED mounted packaging substrate without being attached to any heat sink to simulate the accelerated thermal testing condition. This testing can be done with reduced testing time because without any heat sink attachment, the LED junction temperature will rise faster, and the corresponding faster decay of the LED lumen light output can be captured. Measurements were done using a 2 m Integrating Sphere and Labsphere CDS 2600 spectroradiometer.

Integrating spheres come in different diameter sizes depending on the size of the light unit to be tested. The inner surface of the testing sphere is coated with a high reflectance coating like barium sulfate to scatter the light beam from the light source, such as an LED, uniformly.

Testing was performed at room temperature using 4π geometry per the LM-79–19 testing method.

3 Results and Discussion

Thermal transient response curves of the five different Packaging substrates with the LED test vehicle operated at 700 mA constant current are shown in Fig. 7. Table 1., shows the calculated Thermal Resistance values and the relative performance of the different packaging substrates.

Figure 7 and Table 1 show that the (a-Si/ Al) substrate, which was fabricated for the study, has the Lowest Thermal Resistance of 8.77 °C/W. The Silicon Packaging Substrate is also equally good, with just 3.19% higher resistance. One point to be noted is that the Copper trace thickness in the (a-Si/Al) sample is only 300 nm (0.3 microns), the PVD deposited copper thickness. Other samples had 35-micron thick copper traces. Thinner copper will have lower thermal conductivity, and as a result, the a-Si sample would have given even better results with a thicker 35-micron copper. The transient thermal curves show that the Silicon substrate and the (a-Si/Al) substrates follow closely with the Thin Film Amorphous Silicon on the Al substrate, having lower thermal resistance in the initial stages. As the steady-state approaches, both have similar close final values with about 3.19% difference.

Raman Spectrum analysis of the (a-Si/Al) sample was done using a 532 nm laser to confirm the presence of amorphous Silicon (a-Si).

The Raman spectrum is shown in Fig. 8.

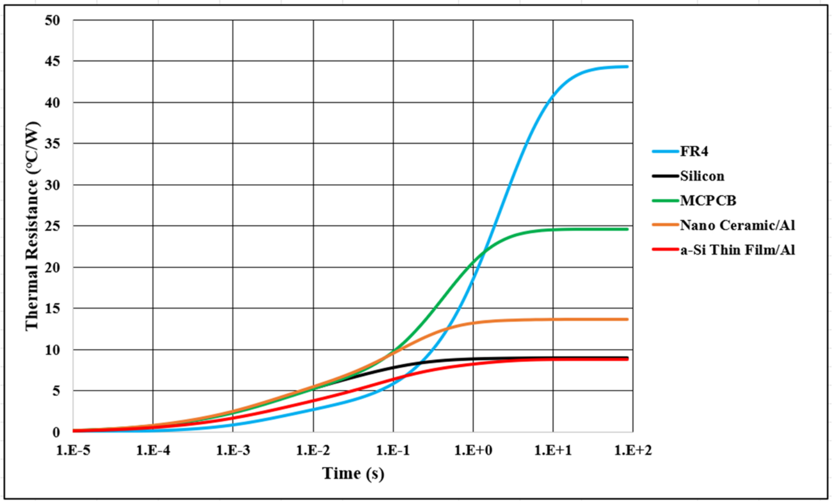


Fig. 7 Transient thermal response curves (Time (s) vs. Thermal resistance of different packaging substrate materials)

Table 1 Comparison of thermal resistance of different packaging substrates

Sample	FR4	Silicon	MCPCB	Nano Ceramic on Aluminum	a-Si Thin Film on Aluminum (a-Si/Al)
Thermal Resistance (℃/W)	44.34	9.05	24.62	13.64	8.77
% Increase over a-Si Thin Film on Aluminum	405.59%	3.19%	180.73%	55.53%	Reference

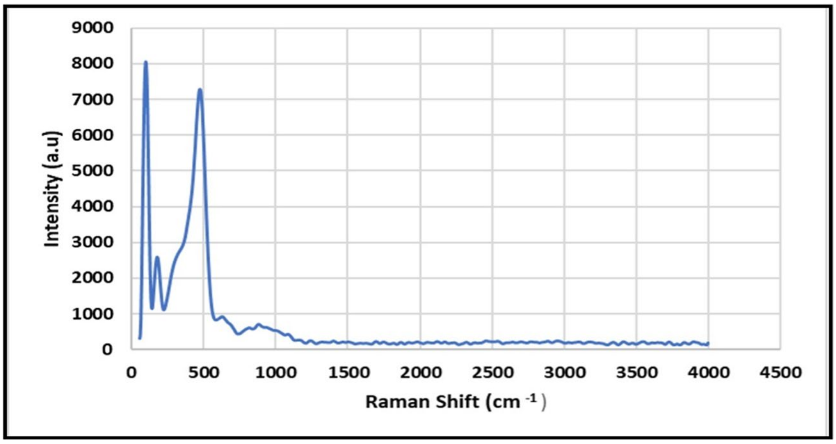


Fig. 8 Raman spectrum of a-Si thin film on aluminum

Figure 8, shows that the (a-Si) peak is centered about 480 cm^{-1}, characteristic of amorphous Silicon, thus confirming its presence.

The thickness of the PVD deposited (a-Si) film was measured using a Profilometer and was found to be 2567 nm or 2.57 microns, as shown in Fig. 9.

3.1 Light Output Measurement of Selected Samples

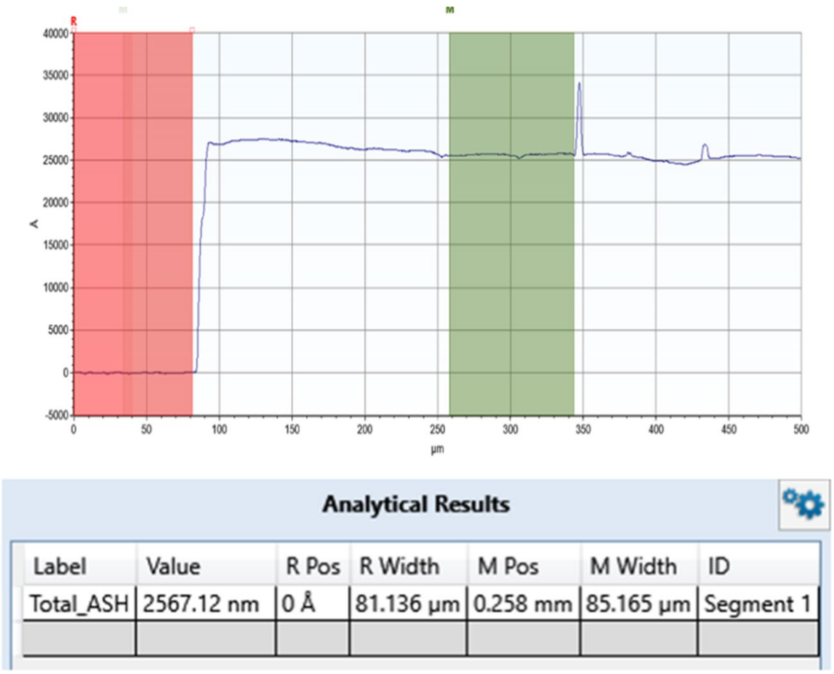
As the two extreme cases of thermal performance substrates with the lowest and the highest thermal resistance, (a-Si/Al) and FR4 samples and the closest thermally performing Silicon sample were chosen to measure Light output and Efficacy.

The light output in lumens, the applied power, and the efficacy are shown in Table 2, for the LEDs mounted on FR4, Silicon, and a-Si/Al Packaging tested at 350 mA LED driving current.

The Light output measurement setup of the LED-mounted test sample within the testing sphere is shown in Fig. 10.

Table 2 shows that at the nominal driving current of 350 mA, both the Silicon and a-Si/Al perform equally well with negligible difference in efficacy. They outperform FR4 substrate by 9.46% in light output Efficacy of lumens/Watt. At higher driving currents, the difference in performance can

Fig. 9 Measured thickness of (a-Si) thin film



Analytical Results

Label	Value	R Pos	R Width	M Pos	M Width	ID
Total_ASH	2567.12 nm	0 Å	81.136 µm	0.258 mm	85.165 µm	Segment 1

Table 2 Light output and efficacy measurement results at 350 mA current

Packaging substrate	Applied power (W)	Light output Lumens (lm)	Efficacy (lm/W)
FR4	0.96	114.40	119.20
Silicon	1.00	130.40	130.40
(a-Si/Al)	0.98	127.87	130.48

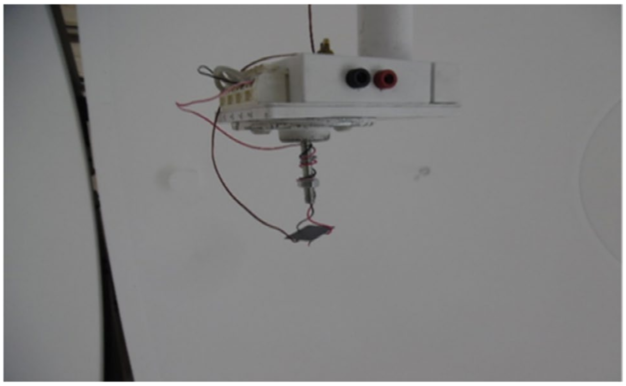


Fig. 10 LED on Substrate sample inside the Light output testing sphere

be expected to be more significant since the LED junction temperature will be higher, and the reduction in light output of FR4 will be much higher compared to thermally better Silicon and a-Si/Al substrates.

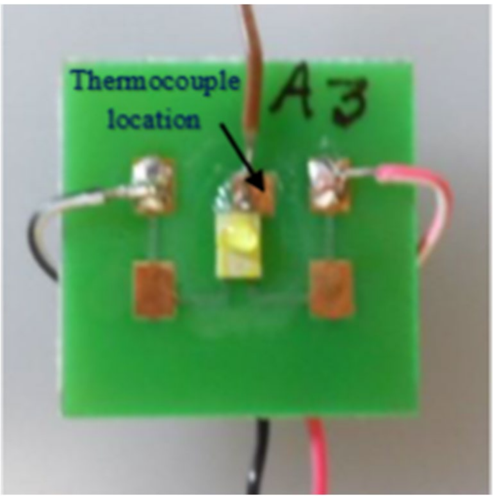


Fig. 11 Thermocouple location on the thermal pad of FR4 Substrate

Next, Light output measurements for LED on FR4 and (a-Si/Al) Substrates were done at a current level of 350 mA with a power dissipation of 1 W and no heat sink attached to the bottom of the package substrate.

As the LED was powered, the Temperature of the Thermal pad ($\mathbf{T_{pad}}$) where the LED is attached to the Substrate using a thermocouple and the Luminous Flux were measured at regular intervals. The location of the thermocouple on the thermal pad of FR4 substrate is shown in Fig. 11.

For Each Substrate type, two plots of, Time vs Temperature and Time vs Relative Luminous Flux were obtained.

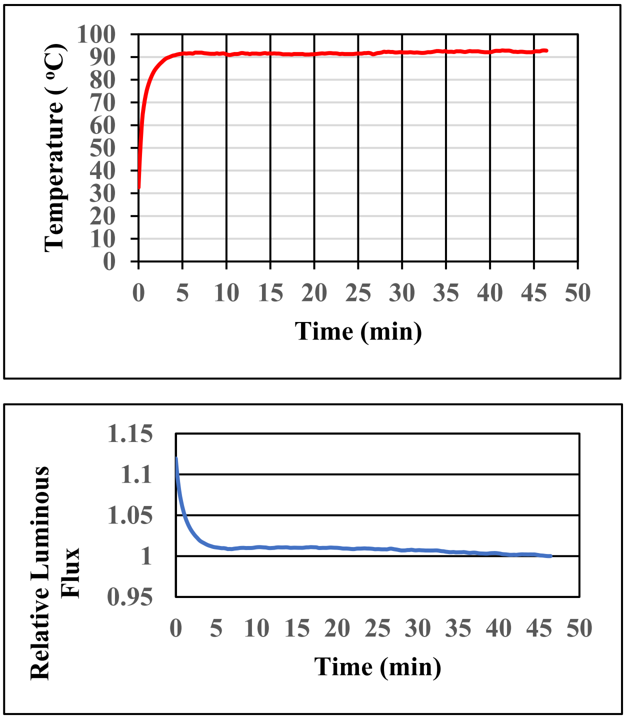


Fig. 12 Time vs. temperature and time vs. relative luminous flux plots of LED on FR4 substrate @ 350 mA current

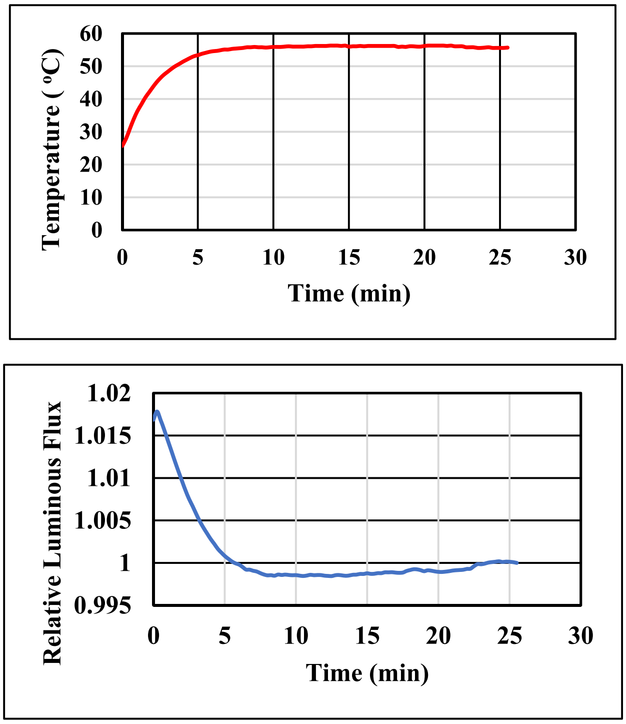


Fig. 13 Time vs. temperature and time vs. relative luminous flux plots of LED on (a-Si/Al) Substrate @ 350 mA current

Relative Luminous Flux is the ratio of the Initial Luminous Flux to the stabilized Luminous Flux after a minimum of 20 min.

The measurement results for FR4 and (a-Si/Al) substrates are shown in Figs. 12 and 13, respectively.

The Temperature plotted is the thermocouple-measured temperature of the thermal pad ($\mathbf{T_{pad}}$) where the LED is attached to the substrate. The Thermal pad temperature and the Light output are measured simultaneously at different time intervals. The actual LED junction temperature ($\mathbf{T_J}$) will be higher than the measured thermal pad ($\mathbf{T_{pad}}$) given by the relation, $\mathbf{T_J = (T_{pad} + (P \text{ x } R_{J\text{-}Tpad}))}$ where $\mathbf{T_J}$ is the LED Junction temperature, $\mathbf{T_{pad}}$ is the thermocouple temperature, **P** is the applied power corresponding to 350 mA driving current of 1 W, and $\mathbf{R_{J\text{-}Tpad}}$ is the LED Junction to Thermal Pad thermal resistance of about 14 ^{o} C/W.

From Figs. 12 and 13, for the FR4 and a-Si/Al substrates, at 350 mA current and 1 W Power, the LED Junction temperature can be obtained using the relationship, $\mathbf{T_J = (T_{pad} + (P \text{ x } R_{J\text{-}Tpad}))}$.

The calculated Max. Junction temperature for the FR4 substrate is 106.8 °C, and for the a-Si/Al Substrate, it is 69.7 °C. So, the a-Si/Al substrate makes the LED run 37.1 °C cooler than the FR4 substrate, which is a 30.5% reduction in Junction temperature.

From Figs. 12 and 13, it can be seen that the FR4 substrate takes much longer time for light output to stabilize compared with (a-Si/Al) substrate because of its higher Thermal resistance.

Comparing the Relative Luminous Flux plot of FR4 and a-Si/Al substrates at 350 mA current from Figs. 12 and 13, it can be observed that FR4 has a Relative Luminous flux ratio of 1.12, with a starting luminous flux of 128.07 lumens and ending at 114.41 lumens as measured, which is a 10.66% drop in light output.

In the case of (a-Si/Al) substrate, from Fig. 13, the Relative Luminous flux ratio is 1.02 with a starting luminous flux of 130.03 lumens and ending at 127.87 lumens as measured, which is only a 1.66% reduction in light output.

4 Conclusions

In summary, the thermal resistance of Thin Film amorphous silicon on aluminum (a-Si/Al) using the PVD process as LED packaging substrate based on the Transient thermal measurements at 700 mA driving current, as per industry standard JEDEC 51–14 method was 8.77 °C/W. Compared to this thermal resistance value of a-Si/Al substrate, the thermal resistance of Silicon substrate, Nanoceramic on Aluminum, MCPCB, and FR4-based packaging substrates were 3.19%, 55.53%, 180.73%, and 405% higher with the corresponding thermal resistance values of 9.05 °C/W, 13.64 °C/W, 24.62 °C/W and 44.34 °C/W respectively. The light output efficacy of (a-Si/Al) substrate with the lowest thermal resistance was 9.46% higher than the FR4 substrate with the highest thermal resistance when tested at 350 mA constant current. When tested under the condition of no heatsink attachment to the substrate at 350 mA constant current, the Thin Film a-Si on Al (a-Si/Al) substrate showed only 1.66% reduction in light output whereas the light output drop for the FR4 substrate was 10.66%.Thus, the (a-Si) thin film-coated Aluminum as the LED packaging substrate can help lower the junction temperature with low thermal resistance and improve the color quality, Efficacy, lumen depreciation, and reliability.

Appendix A

Thin Film Amorphous Silicon on Aluminum Deposition Process

Started with 2-inch × 2-inch and 1-inch × 1-inch 6061-T6 Aluminum plates, as shown in Fig. 14 and following the steps described.

Polishing and Cleaning of the Aluminum plate Top side

The aluminum plate was polished, planarized, and cleaned for the a-Si PVD process.

a) Polished by # 320 Ultra Fine sandpapers
b) Polished by 1000 sandpapers
c) Polished by 4000 sandpapers
d) Polished by 1 um Polishing suspension
e) Polished by 0.05 um Polishing suspension
f) The samples were washed with soap water
g) The samples were carefully cleaned by IPA

Amorphous Si deposition Process

1. Amorphous Si was deposited by magnetron sputtering:

    a) Sputter deposition rate is first measured from a test sample, and the deposition thickness is measured by an ellipsometer.
    b) The deposition rate of 0.65 nm/sec was obtained
    c) Every 250 s will cool down the targets for 4 min
    d) Overall, 123 cycles were used for 2 um thickness Si deposition for 21 h

2. 2 um Amorphous Silicon thickness was obtained.
3. Initially, the Silicon film had some peeling.
4. Added the Ti layer
5. Successful amorphous Silicon with 2 um thickness was obtained
6. The silicon coating electrical insulation from the Aluminum, measured by multi-meter > 2Mohm

Copper Trace Pattern Deposition for LED Attachment

1. Cu was deposited by magnetron sputtering:

    a) Sputter deposition rate is first measured from a test sample, and the deposition thickness was measured by ellipsometer, and transmittance.
    b) The deposition rate of 2 nm/sec was obtained
    c) 300 nm Cu was deposited in the trace pattern on top of a-Si/Al

Appendix B

Silicon Substrate Fabrication

Started with a 4-inch undoped Silicon wafer, as shown in Fig. 15.

The process involves 20 nm Ti deposition on the wafer, followed by 50 nm Au and Copper plating, followed by Au and Ti etching in non-patterned area to leave the copper LED trace pattern on the silicon wafer, as shown in Fig. 16.

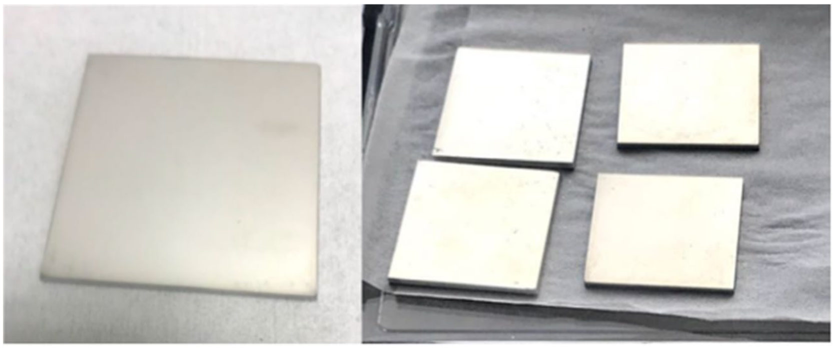


Fig. 14 2-inch × 2-inch and 1 inch × 1 inch 6061-T6 Al Plates

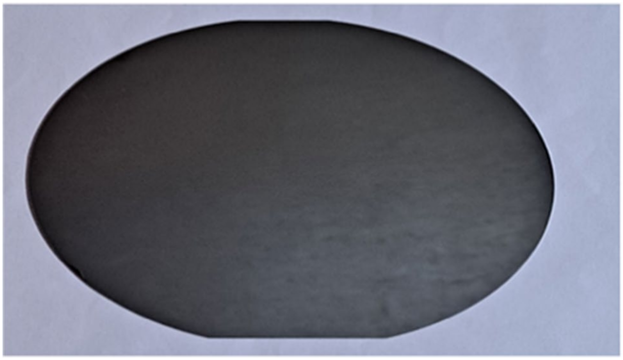


Fig. 15 Undoped 4-inch diameter silicon wafer

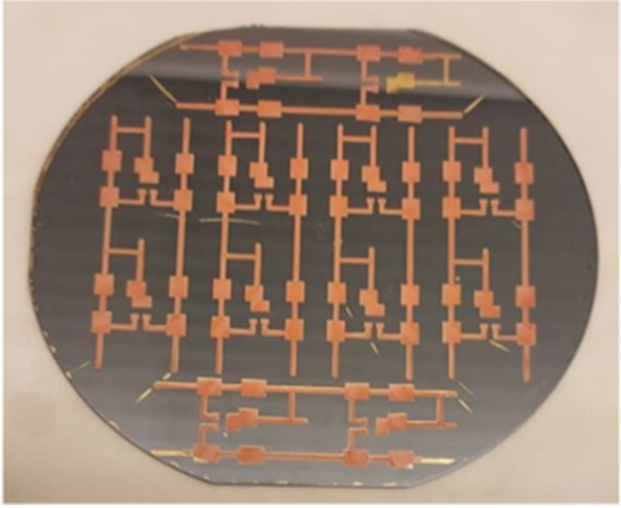


Fig. 16 Undoped silicon wafer after processing

The Full wafer is then cut into individual Silicon Substrate as shown in Fig. 17.

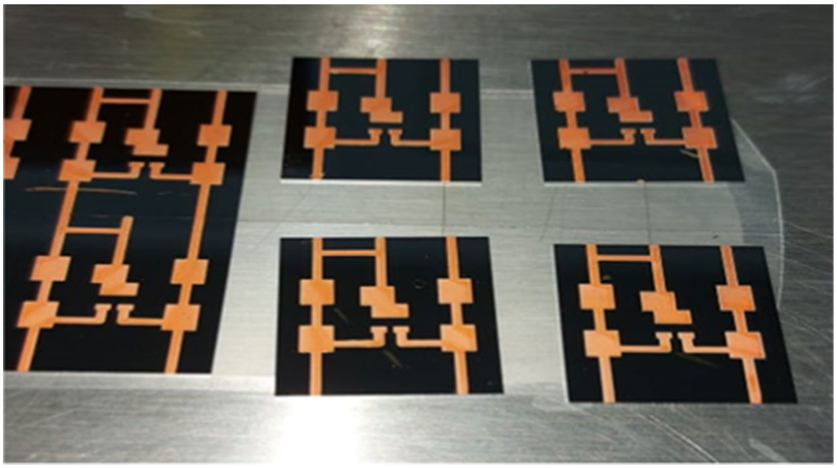


Fig. 17 The wafer cut into individual silicon substrate

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Declarations

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